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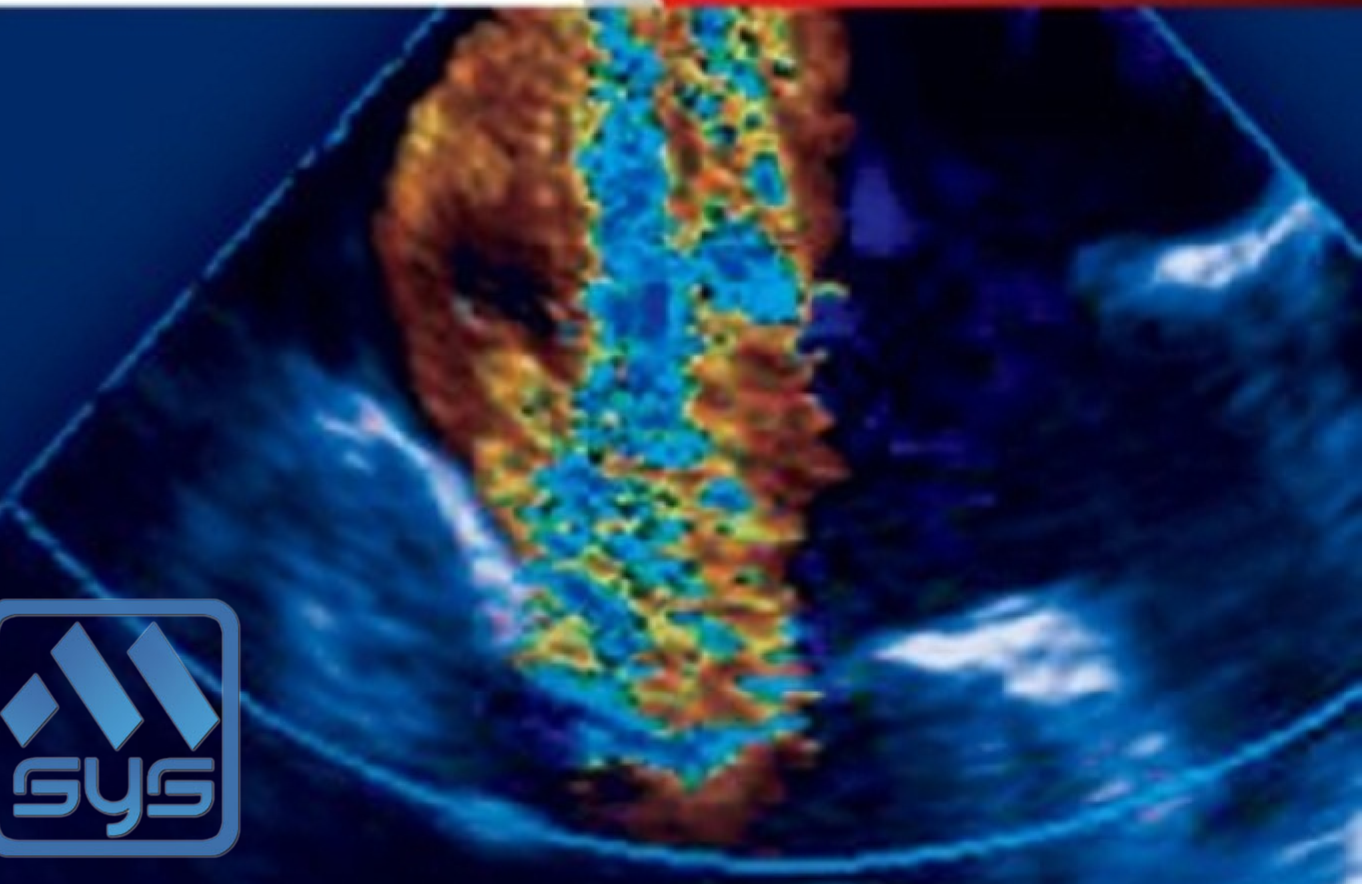

CRITICAL CARE
ULTRASOUND

Philip Lumb
Dimitrios Karakitsos

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- امکان مشاهده **abstract** رفرنسهای داخل مقالات آپتودیت
- قابل نصب بر روی گوشی و کامپیوتر
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Critical Care Ultrasound

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Critical Care Ultrasound

Philip Lumb, MB, BS, MD, MCCM
Professor and Chairman
Department of Anesthesiology
Keck School of Medicine of the University of Southern California
Los Angeles, California

Dimitrios Karakitsos, MD, PhD, DSc
Clinical Associate Professor of Medicine
University of South Carolina, School of Medicine
Columbia, South Carolina
Adjunct Clinical Associate Professor
Department of Anesthesiology
Division of Critical Care Medicine
Keck School of Medicine of the University of Southern California
Los Angeles, California

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1600 John F. Kennedy Blvd.
Ste 1800
Philadelphia, PA 19103-2899

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Senior Project Manager: Rich Barber
Senior Book Designer: Ellen Zanolle

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Charles A. Adams, Jr., MD
Chief of Trauma and Surgical Critical Care
Department of Surgery
Rhode Island Hospital
Providence, Rhode Island
Associate Professor of Surgery
The Warren Alpert Medical School of Brown University
Providence, Rhode Island
Ultrasound-Guided Peripheral Intravenous Access

Srikar Adhikari, MD, MS, RDMS
Associate Professor, Emergency Medicine
University of Arizona Medical Center
Tucson, Arizona
Point-of-Care Pelvic Ultrasound

Sahar Ahmad, MD
Division of Pulmonary Medicine
Albert Einstein College of Medicine
New York, New York
Montefiore Medical Center
New York, New York
Lung Ultrasound: The Basics

Sarah Ahmad, MD
Department of Surgery
Texas Tech University Health Sciences Center
Lubbock, Texas
Procedural Ultrasound for Surgeons-Consultant Level Examination

Georgios Anyfantakis, MD
Radiologist
Department of Radiology
Mediterraneo Hospital
Athens, Greece
Approach to the Urogenital System

Alexander Becker, MD
Director of Trauma Service
Department of Surgery A
Haemek Medical Center
Afula, Israel
Lecturer
B. Rappaport School of Medicine, Technion
Haifa, Israel
Echocardiography in Cardiac Trauma

Michael Blaivas, MD, FACEP
Professor of Internal Medicine
Department of Internal Medicine
University of South Carolina, School of Medicine
Columbia, South Carolina
Fundamentals: Essential Technology, Concepts, and Capability
Transcranial Doppler in the Diagnosis of Cerebral Circulatory Arrest-Consultant Level Examination
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Approach to the Urogenital System
The Holistic Approach Ultrasound Concept and the Role of Critical Care Ultrasound Laboratory

Danny Bluestein, PhD, MSc, BSc
Department of Biomedical Engineering
Stony Brook University
Stony Brook, New York
Improving Cardiovascular Imaging Diagnostics by Using Patient-Specific Numerical Simulations and Biomechanical Analysis

Andrew Bodenham, MB, BS, FRCA
Department of Anaesthesia and Intensive Care Medicine
Leeds General Infirmary
Leeds, Great Britain
Ultrasound-Guided Central Venous Access: The Basics
Ultrasound-Guided Percutaneous Tracheostomy

Jeffrey Bodle, MD
Department of Neurosciences, Neurocritical Care Division
Medical University of South Carolina
Charleston, South Carolina
Transcranial Doppler Ultrasound in Neurocritical Care

Claudia Brusasco, MD
Anesthesia and Intensive Care
IRCCS San Martino - IST
Department of Surgical Sciences and Integrated Diagnostics
University of Genoa
Genoa, Italy
Lung Ultrasound in Acute Respiratory Distress Syndrome (ARDS)

Jose Cardenas-Garcia, MD
Instructor of Medicine
Division of Pulmonary, Sleep, and Critical Care Medicine
Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Ultrasonography in Circulatory Failure

Astha Chichra, MD
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Pleural Ultrasound

Eric J. Chin, MD
Department of Emergency Medicine
San Antonio Military Medical Center
Fort Sam Houston, Texas
Use of Ultrasound in War Zones

Rubin I. Cohen, MD
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Ultrasonography for Deep Venous Thrombosis
Pleural Ultrasound
Ultrasonography in Circulatory Failure

Henri Colt, MD
Professor Emeritus
Pulmonary and Critical Care Division
University of California, Irvine
Orange, California
Endobronchial Ultrasound-Consultant Level Examination

Francesco Corradi, MD, PhD
Cardiac-Surgery Intensive Care Unit
University Hospital of Parma
Parma, Italy
Lung Ultrasound in Acute Respiratory Distress Syndrome (ARDS)

Daniel De Backer, MD, PhD
Professor, Intensive Care
Erasme University Hospital
Université Libre de Bruxelles
Brussels, Belgium
Evaluation of Fluid Responsiveness by Ultrasound
Perioperative Sonographic Monitoring in Cardiovascular Surgery

Sharmila Dissanaike, MD
Associate Professor
Department of Surgery
Texas Tech University Health Sciences Center
Lubbock, Texas
Procedural Ultrasound for Surgeons-Consultant Level Examination

Sassia Donaldson-Morgan, MD
Division of Critical Care Medicine
Albert Einstein College of Medicine
Montefiore Medical Center
New York, New York
Integrating Ultrasound into Critical Care Teaching Rounds

Emmanuel Douzinas, MD, PhD
3rd ICU Department
Evgenideio Hospital
Athens University, School of Medicine
Athens, Greece
Various Targets in the Abdomen (Hepatobiliary System, Spleen, Pancreas, Gastrointestinal Tract, and Peritoneum)-Consultant Level Examination

David Duthie, MD, FRCA, FFICM
Consultant Anaesthetist
Leeds General Infirmary
Leeds Teaching Hospitals NHS Trust
Leeds, Great Britain
Transesophageal Echocardiography

Lewis A. Eisen, MD, FCCP
Division of Critical Care Medicine, Department of Internal Medicine
Albert Einstein College of Medicine
New York, New York
Jay B. Langner Critical Care Service
Montefiore Medical Center
New York, New York
Ultrasound-Guided Vascular Access: Trends and Perspectives
Ultrasound-Guided Arterial Catheterization
Lung Ultrasound: The Basics
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The Extended FAST Protocol
Integrating Ultrasound into Critical Care Teaching Rounds
Ultrasound Training in Critical Care Medicine Fellowships

Mahmoud Elbarbary, MD, MBBCH, MSc, EDIC, PhD
Consultant-Pediatric Cardiac ICU
King Abdulaziz Cardiac Center
Assistant Professor-Critical Care Medicine
Secretary General-National and Gulf Center for Evidence-Based Health Practice
King Saud Bin Abdulaziz University for Health Sciences
Riyadh, Saudi Arabia
Pediatric Ultrasound-Guided Vascular Access
Ultrasound in the Neonatal and Pediatric Intensive Care Unit

Shari El-Dash, MD, PhD
Medical Intensive Care Unit
Department of Nephrology
Amiens University Medical Center
Amiens, France
INSERM U-1088
Jules Verne University of Picardie
Amiens, France
Evaluation of Left Ventricular Diastolic Function in the Intensive Care Unit-Consultant Level Examination
Evaluation of Right Ventricular Function in the Intensive Care Unit by Echocardiography-Consultant Level Examination

Jaden Evans, MD
Department of Surgery
Texas Tech University Health Sciences Center
Lubbock, Texas
Procedural Ultrasound for Surgeons-Consultant Level Examination

David Fagnoul, MD
Consultant
Department of Intensive Care
Erasme University Hospital
Université Libre de Bruxelles
Brussels, Belgium
Evaluation of Fluid Responsiveness by Ultrasound
Perioperative Sonographic Monitoring in Cardiovascular Surgery

Marco A. Fondi, MD
Consultant Anesthesiologist
Department of Anesthesia and Intensive Care
Humanitas Mater Domini Hospital
Castellanza, Varese, Italy
Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

Heidi Lee Frankel, MD, FACS, FCCM
University of Southern California
Keck School of Medicine
Los Angeles, California
Various Targets in the Abdomen (Hepatobiliary System, Spleen, Pancreas, Gastrointestinal Tract, and Peritoneum)-Consultant Level Examination
Use of Ultrasound in the Evaluation and Treatment of Intraabdominal Hypertension and Abdominal Compartment Syndrome
Integrating Ultrasound in Emergency Prehospital Settings
Soft Tissue, Musculoskeletal System, and Miscellaneous Targets

Marcelo Gama de Abreu, MD, MSc, PhD, DESA
Pulmonary Engineering Group
Department of Anesthesiology and Intensive Care Medicine
University Hospital Dresden, Dresden University of Technology
Dresden, Germany
Lung Ultrasound in Acute Respiratory Distress Syndrome (ARDS)

Zsolt Garami, MD
Houston Methodist Hospital
Methodist DeBakey Heart & Vascular Center
Houston, Texas
Transcranial Doppler Ultrasound in Neurocritical Care

Thomas Geeraerts, MD, PhD
Professor of Anesthesiology and Intensive Care
Anesthesiology and Intensive Care Department
University Hospital of Toulouse
University Toulouse 3 Paul Sabatier
Toulouse, France
Ocular Ultrasound in the Intensive Care Unit-Consultant Level Examination

Andrew Georgiou, MD
Associate Professor
Centre for Health Systems and Safety Research
Australian Institute of Health Innovation
University of New South Wales
New South Wales, Australia
Integrating Picture Archiving and Communication Systems and Computerized Provider Order Entry into the Intensive Care Unit: The Challenge of Delivering Health Information Technology-Enabled Innovation

Abraham A. Ghiatas, MD
Professor of Radiology
Department of Radiology
IASO Hospital
Athens, Greece
Approach to the Urogenital System

Amanjit Gill, MD
Staff
Interventional Radiology
Cleveland Clinic
Cleveland, Ohio
Ultrasound-Guided Placement of Inferior Vena Cava Filters-Consultant Level Examination

Lawrence M. Gillman, MD, MMedEd, FRCSC, FACS
Assistant Professor, Surgery
University of Manitoba
Winnipeg, Manitoba, Canada
Lung Ultrasound in Mechanically Ventilated Patients

Andreas Gravvanis, MD, PhD
Department of Plastic and Reconstructive Surgery
General State Hospital of Athens
Athens, Greece
Ultrasound in Reconstructive Microsurgery-Consultant Level Examination

Shea C. Gregg, MD
Assistant Professor of Surgery
Warren Alpert School of Medicine of Brown University
Providence, Rhode Island
Department of Surgery
Rhode Island Hospital
Providence, Rhode Island
Ultrasound-Guided Peripheral Intravenous Access

Yekaterina Grewal, MD
Division of Critical Care Medicine
Department of Medicine
Albert Einstein College of Medicine
New York, New York
Jay B. Langner Critical Care Service
Montefiore Medical Center
New York, New York
The Extended FAST Protocol

Ram K R Gurajala, MD, MBBS, MRCS(Ed), FRCR
Cardiovascular Imaging and Interventional Radiology
Cleveland Clinic
Cleveland, Ohio
Ultrasound-Guided Placement of Inferior Vena Cava Filters-Consultant Level Examination

Sara Guzman-Reyes, MD
Assistant Professor of Anesthesiology
Department of Anesthesiology
The University of Texas Medical School at Houston
Houston, Texas
Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

Isla M. Hains, BSc, PhD
Centre for Health Systems and Safety Research
Australian Institute of Health Innovation
University of New South Wales
Sydney, New South Wales, Australia
Integrating Picture Archiving and Communication Systems and Computerized Provider Order Entry into the Intensive Care Unit: The Challenge of Delivering Health Information Technology-Enabled Innovation

Douglas R. Hamilton, MD
Division of General Internal Medicine
Faculty of Medicine
University of Calgary
Calgary, Alberta, Canada
Hemodynamic Monitoring Considerations in the Intensive Care Unit

Dietrich Hasper, MD
Nephrology and Medical Intensive Care
Charité-Universitätsmedizin Berlin, Campus Virchow-Klinikum,
Berlin, Germany
Measures of Volume Status in the Intensive Care Unit

Jason D. Heiner, MD
Staff Physician
Emergency Medicine
University of Washington
Seattle, Washington
Use of Ultrasound in War Zones

Richard Hoppmann, MD
Dean
School of Medicine
University of South Carolina
Columbia, South Carolina
Professor
Internal Medicine
USC School of Medicine
Columbia, South Carolina
Director
Ultrasound Institute
University of South Carolina School of Medicine
Columbia, South Carolina
Ultrasound: A Basic Clinical Competency

Jennifer Howes, MD
Albert Einstein College of Medicine
Montefiore Medical Center
New York, New York
Ultrasound Training in Critical Care Medicine Fellowships

Dimitrios Karakitsos, MD, PhD, DSc
Clinical Associate Professor of Medicine
University of South Carolina, School of Medicine
Columbia, South Carolina
Adjunct Clinical Associate Professor
Department of Anesthesiology
Division of Critical Care Medicine
Keck School of Medicine of the University of Southern California
Los Angeles, California
Fundamentals: Essential Technology, Concepts, and Capability
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The Holistic Approach Ultrasound Concept and the Role of Critical Care Ultrasound Laboratory

Adam Keene, MD
Albert Einstein College of Medicine
Montefiore Medical Center
New York, New York
Ultrasound Training in Critical Care Medicine Fellowships

Mansoor Khan, MBBS (Lond), FRCS (GenSurg), AKC
Trauma/Critical Care Fellow
R. Adams Cowley Shock Trauma Center
Baltimore, Maryland
Integrating Ultrasound in Emergency Prehospital Settings

Andrew W. Kirkpatrick, MD, MHSc, FACS
Departments of Surgery, Critical Care Medicine, and Regional Trauma Services
University of Calgary
Calgary, Alberta, Canada
Lung Ultrasound in Mechanically Ventilated Patients

John D. Klein, MD
Department of Anesthesia and Critical Care Medicine
San Antonio Military Medical Center
San Antonio, Texas
Transcranial Doppler in Aneurysmal Subarachnoid Hemorrhage-Consultant Level Examination

Seth Koenig, MD, FCCP
Associate Professor of Medicine
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Ultrasonography in Circulatory Failure

Gregorios Kouraklis, MD, PhD, FACS
Second Department of Propedeutic Surgery
University of Athens, School of Medicine
Laiko Hospital
Athens, Greece
Transcranial Doppler in the Diagnosis of Cerebral Circulatory Arrest-Consultant Level Examination

Jan M. Kruse, MD
Nephrology & Medical Intensive Care
Charité-Universitätsmedizin Berlin, Campus Virchow-Klinikum
Berlin, Germany
Measures of Volume Status in the Intensive Care Unit

Ahmed Labib, MSc, FRCA, FFICM
Consultant Intensivist and Anaesthetist
Department of Anaesthesia and Intensive Care Medicine
Dewsbury and District Hospital
Dewsbury, Great Britain
Ultrasound-Guided Central Venous Access: The Basics
Ultrasound-Guided Percutaneous Tracheostomy

Nicos Labropoulos, MD, PhD, DIC, RVT
Professor of Surgery and Radiology
Director, Vascular Laboratory
Department of Surgery, Division of Vascular Surgery
Stony Brook University Medical Center
Stony Brook, New York
Overview of the Arterial System

Antonio La Greca, MD
Department of Surgery
Catholic University Hospital
Rome, Italy
How to Choose the Most Appropriate Ultrasound-Guided Approach for Central Line Insertion: Introducing the Rapid Central Venous Assessment Protocol

Kimmoi Wong Lama, MD
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Pleural Ultrasound

Alessandro Lamorte, MD
Department of Emergency Medicine
San Luigi Gonzaga University Hospital
Torino, Italy
Lung Ultrasound in Trauma

Massimo Lamperti, MD
Consultant in Neuroanaesthesia and Paediatric Anaesthesia, Neuroanaesthesia
National Neurological Institute
Milan, Italy
Pediatric Ultrasound-Guided Vascular Access
Training and Competence in Ultrasound-Guided Vascular Access

Christos Lazaridis, MD
Assistant Professor
Neurosciences Critical Care
Medical University of South Carolina
Charleston, South Carolina
Transcranial Doppler Ultrasound in Neurocritical Care
General Chest Ultrasound in Neurocritical Care

Guy Lin, MD
Trauma Director
Meir Medical Center
Kfar-Saba, Israel
Echocardiography in Cardiac Trauma

Ludwig H. Lin, MD
Medical Director, Critical Care Services
San Francisco General Hospital
San Francisco, California
Clinical Professor
Department of Anesthesia and Perioperative Care
University of California
San Francisco, California
Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

Gregory R. Lisciandro, DVM, Dipl ABVP, Dipl ACVECC
Chief of Emergency and Critical Care
Emergency Pet Center, Inc.
San Antonio, Texas
Consultant
Hill Country Veterinary Specialists
San Antonio, Texas
Ultrasound in Animals

Philip Lumb, MB, BS, MD, MCCM
Professor and Chairman
Department of Anesthesiology
Keck School of Medicine of University of the Southern California
Los Angeles, California

Fundamentals: Essential Technology, Concepts, and Capability

Yazine Mahjoub, MD
Department of Anesthesiology and Intensive Care
Amiens University Medical Center
Amiens, France
INSERM U-1088
Jules Verne University of Picardie
Amiens, France

Evaluation of Right Ventricular Function in the Intensive Care Unit by Echocardiography-Consultant Level Examination

Julien Maizel, MD, PhD
Medical Intensive Care Unit
Department of Nephrology
Amiens University Medical Center
Amiens, France
INSERM U-1088
Jules Verne University of Picardie
Amiens, France

Evaluation of Left Ventricular Diastolic Function in the Intensive Care Unit-Consultant Level Examination
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Scott A. Marshall, MD
Neurology and Critical Care
Department of Medicine
San Antonio Military Medical Center
Fort Sam Houston, Texas
Assistant Professor
Neurology, Uniformed Services University
Bethesda, Maryland

Transcranial Doppler in Aneurysmal Subarachnoid Hemorrhage-Consultant Level Examination

Maria Matuszczak, MD
Professor of Anesthesiology
Department of Anesthesiology
The University of Texas Medical School at Houston
Houston, Texas
Director, Pediatric Anesthesia
Department of Anesthesiology
The University of Texas Medical School at Houston
Houston, Texas
Director
Pediatric Anesthesia Fellowship
Department of Anesthesiology
The University of Texas Medical School at Houston
Houston, Texas
Director
Pediatric Acute Pain Service
Department of Anesthesiology
The University of Texas Medical School at Houston
Houston, Texas

Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

Paul H. Mayo, MD
Academic Director MICU
Division of Pulmonary, Critical Care and Sleep Medicine
Long Island Jewish Medical Center
New Hyde Park, New York
Professor of Medicine
Hofstra-North Shore Long Island Jewish School of Medicine

Training in Critical Care Echocardiography: Both Sides of the Atlantic

Charlotte Michot, MD
Pediatric Intensive Care Unit
University Paris VII
Assistance-Publique-Hôpitaux de Paris, Hôpital Robert Debré
Paris, France

Use of Transcranial Doppler Sonography in the Pediatric Intensive Care Unit-Consultant Level Examination

David Milliss, MBBS, FANZCA, FCICM, MHP
Clinical Associate Professor
Division of Intensive Care Medicine
University of Sydney
Head of Department
Intensive Care Services
Concord Hospital
Sydney, Australia

Integrating Picture Archiving and Communication Systems and Computerized Provider Order Entry into the Intensive Care Unit: The Challenge of Delivering Health Information Technology-Enabled Innovation

Owen Mooney, BSc, MD, FRCPC (Internal Medicine)
Department of Internal Medicine
University of Manitoba
Winnipeg, Manitoba, Canada

Lung Ultrasound in Mechanically Ventilated Patients

Septimiu Murgu, MD
University of Chicago, Pritzker School of Medicine

Endobronchial Ultrasound-Consultant Level Examination

Sarah Murthi, MD
R. Adams Cowley Shock Trauma Center
Baltimore, Maryland

Integrating Ultrasound in Emergency Prehospital Settings

Khanjan H. Nagarsheth, MD
Trauma/Critical Care Fellow
R. Adams Cowley Shock Trauma Center
Baltimore, Maryland

Use of Ultrasound in the Evaluation and Treatment of Intraabdominal Hypertension and Abdominal Compartment Syndrome

Serafim Nanas, MD, PhD
Professor of Medicine and Critical Care
First Critical Care Department
Medical School
National & Kapodestrian University of Athens
Athens, Greece

Soft Tissue, Musculoskeletal System, and Miscellaneous Targets

Mangala Narasimhan, DO
Associate Professor
The Hofstra-North Shore Long Island Jewish School of Medicine
Section Head for Critical Care
The Division of Pulmonary, Sleep and Critical Care Medicine
New Hyde Park, New York
Pleural Ultrasound

Samer Narouze, MD, PhD, FIPP
Clinical Professor of Anesthesiology and Pain Medicine, OUCOM
Athens, Ohio
Clinical Professor of Neurological Surgery
Ohio State University
Columbus, Ohio
Chairman, Center for Pain Medicine
Summa Western Reserve Hospital
Cuyahoga Falls, Ohio
Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

Apostolos E. Papalois, PhD, KGSJ
Director
Experimental–Research Center ELPEN Pharmaceuticals
Athens, Greece
Adjunct Teaching Staff
University of Athens, School of Medicine & Department of Nursing
Athens, Greece
Ultrasound in Reconstructive Microsurgery-Consultant Level Examination

Paolo Pelosi, MD
Anesthesia and Intensive Care
IRCCS San Martino - IST
Department of Surgical Sciences and Integrated Diagnostics
University of Genoa
Genoa, Italy
Lung Ultrasound in Acute Respiratory Distress Syndrome (ARDS)

Glykeria Petrocheilou, MD, MSc
First ICU Department
Evangelismos University Hospital
Athens University, School of Medicine
Athens, Greece
Overview of the Arterial System
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Mauro Pittiruti, MD
Department of Surgery
Catholic University Hospital
Rome, Italy
How to Choose the Most Appropriate Ultrasound- Guided Approach for Central Line Insertion: Introducing the Rapid Central Venous Assessment Protocol
Pediatric Ultrasound-Guided Vascular Access
Ultrasound-Guided Placement of Peripherally Inserted Central Venous Catheters

John Poularas, MD
Intensive Care Unit Department
General State Hospital of Athens
Athens, Greece
Transcranial Doppler in the Diagnosis of Cerebral Circulatory Arrest-Consultant Level Examination
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Susanna Price, MBBS, BSc, MRCP, EDICM, PhD, FFICM, FESC
Consultant Cardiologist and Intensivist
Royal Brompton Hospital
London, Great Britain
Honorary Senior Lecturer
Imperial College
London, Great Britain
Echocardiography: Beyond the Basics-Consultant Level Examination
Transesophageal Echocardiography
Echocardiography in Cardiac Arrest
Training in Critical Care Echocardiography: Both Sides of the Atlantic

Alexander Razumovsky, PhD, FAHA
Director & Vice President
Sentient NeuroCare Services, Inc.
Hunt Valley, Maryland
Transcranial Doppler in Aneurysmal Subarachnoid Hemorrhage-Consultant Level Examination

Mohammed Rehman, MD
Department of Neurology
Neurocritical Care Division
Henry Ford Hospital and Medical University
Detroit, Michigan
General Chest Ultrasound in Neurocritical Care

Lloyd Ridley, MBBS, FRANZCR
Department of Radiology
Concord Hospital
Sydney, Australia
Integrating Picture Archiving and Communication Systems and Computerized Provider Order Entry into the Intensive Care Unit: The Challenge of Delivering Health Information Technology-Enabled Innovation

Ashot E. Sargsyan, MD, RDMS, RVT
Physician Scientist, Space Medicine
Wyle Science, Technology & Engineering Group/NASA Bioastronautics
Houston, Texas
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Hemodynamic Monitoring Considerations in the Intensive Care Unit
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Richard H. Savel, MD, FCCM
Director, Surgical Critical Care
Maimonides Medical Center
Professor of Clinical Medicine & Neurology
Albert Einstein College of Medicine
New York, New York
Ultrasound-Guided Arterial Catheterization

Thomas M. Scalea, MD, FACS
R. Adams Cowley Shock Trauma Center
Baltimore, Maryland
Integrating Ultrasound in Emergency Prehospital Settings

Jörg C. Schefold, MD
Nephrology & Medical Intensive Care
Charité-Universitätsmedizin Berlin, Campus Virchow-Klinikum,
Berlin, Germany
Measures of Volume Status in the Intensive Care Unit

Bettina U. Schmitz, MD, PhD, DEAA
Associate Professor, Anesthesiology
Director Regional Anesthesia
Director Medical Student Education in Anesthesia
Department of Anesthesiology
Texas Tech University HSC-SOM
Lubbock, Texas
Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

Giancarlo Scoppettuolo, MD
Department of Infectious Diseases
Catholic University Hospital
Rome, Italy
Ultrasound-Guided Placement of Peripherally Inserted Central Venous Catheters

Ariel L. Shiloh, MD
Director
Critical Care Medicine Consult Service
Jay B. Langner Critical Care Service
Division of Critical Care Medicine
Department of Medicine
Albert Einstein College of Medicine
New York, New York
Ultrasound-Guided Vascular Access: Trends and Perspectives
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Michel Slama, MD, PhD, FACC, FAHA
Medical Intensive Care Unit
Department of Nephrology
Amiens University Medical Center
Amiens, France
INSERM U-1088
Jules Verne University of Picardie
Amiens, France
Evaluation of Left Ventricular Diastolic Function in the Intensive Care Unit—Consultant Level Examination
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Lori Stolz, MD, RDMS
Assistant Professor, Emergency Medicine
University of Arizona Medical Center
Tucson, Arizona
Point-of-Care Pelvic Ultrasound

David J. Sturgess, MBBS, PhD, PGDipCU
Senior Lecturer in Anaesthesiology and Critical Care
Mater Research Institute-The University of Queensland
Brisbane, Queensland, Australia
Transthoracic Echocardiography: An Overview
Hemodynamic Monitoring Considerations in the Intensive Care Unit

Guido Tavazzi, PhD
1st Department of Anaesthesiology
Intensive Care and Pain Medicine
IRCCS Policlinico San Matteo Foundation
University of Pavia
Pavia, Italy
Experimental Medicine
University of Pavia
Pavia, Italy
Echocardiography: Beyond the Basics-Consultant Level Examination

Adey Tsegaye, MD
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Ultrasonography for Deep Venous Thrombosis

Dimosthenis Tsoutsos, MD, PhD
Department of Plastic and Reconstructive Surgery
General State Hospital of Athens
Athens, Greece
Ultrasound in Reconstructive Microsurgery-Consultant Level Examination

Mattia Tullio, MD
Department of Emergency Medicine
San Luigi Gonzaga University Hospital
Torino, Italy
Lung Ultrasound in Trauma

Carla Venegas, MD
Division of Critical Care Medicine
Department of Medicine
Albert Einstein College of Medicine
Bronx, New York
Jay B. Langner Critical Care Service
Montefiore Medical Center
Bronx, New York
Lung Ultrasound: Protocols in Acute Dyspnea

Suzanne Verlhac, MD
Pediatric Radiologist
Department of Pediatric Imaging
Hôpital Robert Debré, Assistance-Publique-Hôpitaux de Paris
University Paris VII
Paris, France
Use of Transcranial Doppler Sonography in the Pediatric Intensive Care Unit-Consultant Level Examination

Philippe Vignon, MD, PhD
Medical-Surgical Intensive Care Unit
Limoges Teaching hospital
Limoges, France
Center of Clinical Investigation
INSERM 0801
Limoges Teaching hospital
Limoges, France
University of Limoges
Limoges, France
Echocardiography for Intensivists
Evaluation of Patients at High Risk for Weaning Failure with Doppler Echocardiography-Consultant Level Examination

Alexander H. Vo, PhD
AccessCare
Denver, Colorado
Transcranial Doppler in Aneurysmal Subarachnoid Hemorrhage-Consultant Level Examination

Giovanni Volpicelli, MD, FCCP
Emergency Medicine
San Luigi Gonzaga University Hospital
Torino, Italy
Lung Ultrasound in Trauma

Benedict Waldron, MBBS, BSc, FANZCA
Department of Anaesthesia and Perioperative Medicine
The Alfred Hospital
Melbourne, Australia
Echocardiography: Beyond the Basics-Consultant Level Examination

Shiwen Wang, MD
Institute of Geriatric Cardiology
Chinese PLA General Hospital
University of Beijing
School of Medicine
Beijing, China
Overview of the Arterial System

Yu Wang, MD
Department of Geriatric Cardiology
Chinese PLA General Hospital
Beijing, China
Intravascular Ultrasound-Consultant Level Examination

Justin Weiner, MD
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Ultrasonography in Circulatory Failure

Johanna I. Westbrook, PhD
Professor
Centre for Health Systems & Safety Research
Australian Institute of Health Innovation
University of New South Wales
Kensington, New South Wales, Australia
Integrating Picture Archiving and Communication Systems and Computerized Provider Order Entry into the Intensive Care Unit: The Challenge of Delivering Health Information Technology-Enabled Innovation

Mary White, MB, BCh, BAO, MSc, FCAI, PhD
Consultant Intensivist and Anaesthetist
Royal Brompton Hospital
London, Great Britain
Echocardiography in Cardiac Arrest

Haiyun Wu, MD
Department of Geriatric Cardiology
Chinese PLA General Hospital
Beijing, China
Intravascular Ultrasound-Consultant Level Examination

Michael Xenos, PhD
Assistant Professor
Department of Mathematics
University of Ioannina
Ioannina, Greece
Improving Cardiovascular Imaging Diagnostics by Using Patient-Specific Numerical Simulations and Biomechanical Analysis

Michael Yee, MD
Albert Einstein College of Medicine
Montefiore Medical Center
New York, New York
Integrating Ultrasound into Critical Care Teaching Rounds

Gulrukh Zaidi, MD
The Division of Pulmonary, Sleep and Critical Care Medicine
The Hofstra-North Shore Long Island Jewish School of Medicine
New Hyde Park, New York
Ultrasonography for Deep Venous Thrombosis

To Christine

*

To Lily

*

The Critical Care Ultrasound *textbook is dedicated to critical care patients and to their families.*

FOREWORD

Ultrasound is energy generated by sound waves of 20,000 or more vibrations per second. The history of ultrasonography can be premiered by Leonardo da Vinci (1452-1519), who recorded experiments in sound transmission through water. Lazaro Spallanzani (1729-1799), an Italian priest and biologist, studied the movements of bats and concluded that bats use sound to navigate.

The first reported ultrasonic source was the Galton whistle, developed by the English scientist Francis Galton (1822-1911) from his studies on the hearing frequencies of animals. In 1880, brothers Jacques and Pierre Curie discovered piezoelectricity, or electrical charges produced by quartz crystals subjected to mechanical vibration. Piezoelectricity is fundamental to creating sound waves in modern ultrasonic transducers. Later in 1903, Pierre Curie, with his wife, Marie Curie, received the Nobel Prize in Physics for their work on radioactivity.

The use of ultrasound in medicine started in the 1940s. Karl Theodore Dussik of Austria published the first paper on medical ultrasonography in 1942, based on using ultrasound to investigate brain tumors. In 1949, George Ludwick in the United States published his work on ultrasound to detect gallstones.

The 1950s and 1960s saw pioneers in the United States, Europe, and Japan work on medical applications of ultrasonography. Deserving of mention were Kenji Tanaka (Japan), Inge Edler (Sweden), and Ian Donald (Scotland). John Wild and John Reid (United States) are credited with developing the first hand-held ultrasound device, and Douglas Howry (United States) largely pioneered 2-D ultrasound imaging.

Advances in the past 20 years have seen new developments like real-time imaging, color Doppler, 3-D imaging, and now 4-D imaging. Medical applications of ultrasonography, initially used in obstetrics and cardiology, are now seen in surgery, anesthesia, critical care, emergency medicine, internal medicine, and pediatrics. Increasingly, critical care physicians rely on bedside ultrasonic examinations on their patients to diagnose, monitor, and guide interventional procedures (such as placement of needles or cannulas). By the nature of critical illness, the ICU patient's condition may change while in the unit or while in the ED or ward, to require an urgent bedside examination. An ultrasound examination may significantly help clinical management. The critical care physician would not be complete today without knowledge and relevant skills in ultrasonography.

Critical Care Ultrasound presents the application of ultrasound in critical care. It describes the indications, processes, and protocols to perform ultrasound procedures in the ICU. The field of topics presented is wide, covering neurological, pulmonary, cardiovascular, and abdominal applications, and in special settings. There are more than 80 contributors of experts and acclaimed authors. This book is a tremendous resource of practical knowledge and reference material. It will be of great help to trainees, critical care specialists, ICU nursing, allied health professionals, and anyone practicing acute medicine. Editors Philip Lumb and Dimitrios Karakitsos and the contributors are to be congratulated.

Professor Teik E. Oh, AM

MBBS, MD (Qld), FRACP, FRCP, FANZCA, FRCA, FCICM
Emeritus Professor of Anaesthesia,
University of Western Australia,
Perth,
Western Australia,
Australia

PREFACE

As a medical student in the mid-1970s, I was taught that if a diagnosis was uncertain after obtaining a history, the likelihood of obtaining an accurate understanding of the patient's condition was reduced significantly because the subsequent physical examination was likely to be unfocused. Nonetheless, the instruction was to perform the follow-up examination in the remainder of the HIPPA acronym: History, Inspection, Palpation, Percussion, and Auscultation. If, following the complete physical examination that incorporated all aspects of the "IPPA" requirements, a diagnosis remained elusive, the likelihood that the then available special investigations would provide definitive help was low. The advent of CT, MRI, and PET imaging, point-of-care testing, and a variety of additional computer-assisted techniques have made the preceding sentence irrelevant. However, today's critical care physician is challenged with an immediate need to understand and treat physiologic abnormalities that may not be amenable to patient transport to an imaging facility, or elucidated by another stat chemistry or blood gas result.

The desire to penetrate the skin's surface "visually" has been a long-standing physician's wish; however, it is not a static image but rather a dynamic portrayal of physiologic function that has eluded bedside analysis and capability. Today, portable ultrasound units afford this capability and provide physicians the ability to interrogate and "see" target organs and evaluate current function and potential reserve in real time. The most highly developed analyses involve cardiac function, but newer capabilities exist to evaluate cerebral blood flow, lung function, renal perfusion, intracranial pressure abnormalities, peripheral vascular integrity, and additional examinations detailed in this textbook. The realization that physicians can "see" and assess physiologic function in real time is a tipping point in critical care; the reality is if intensivists are not embracing the technology today, their professional development will be limited and their ability to care for their patients compromised.

The authors of *Critical Care Ultrasound* are recognized experts in the field and highly regarded practitioners. Their insights provide valuable instruction in adapting ultrasound examinations into routine clinical practice, and their experience lends credibility to the remarks and *Clinical Pearls* that accompany each chapter. The definition of a textbook's success is its ability to titillate interest and stimulate changes in practice behaviors; it is our hope that we succeed in this endeavor and that an ultrasound examination becomes a routine procedure, not only in cases of acute patient deterioration, but also in daily bedside rounds. The capability to predict adverse events cannot be underestimated; we would be intellectually remiss not to embrace the opportunity to improve our diagnostic and interventional capabilities.

Philip Lumb

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I, Dimitrios Karakitsos, wish to express my appreciation to Ashot Ernest Sargsyan and Michael Blaivas for providing continuous support in the development of the holistic approach (HOLA) critical care ultrasound concept. Also, I wish to express my gratitude to Professor Philip Lumb for supervising brilliantly this global project, as well as for his mentorship and support in my career.

We, Philip Lumb and Dimitrios Karakitsos, would like to thank our teams and associates for supporting this edition. We wish to express our gratitude to the numerous distinguished colleagues from Australasia, the Middle East, Europe, and North America who participated in this textbook by providing pearls of their own. We wish to express our appreciation to all medical students, residents, and nurses who provided inspirational criticism regarding the application of ultrasound technology in the intensive care unit.

Warm thanks to Professor Richard Hoppmann for sharing his experience regarding the integration of ultrasound training in the medical school curriculum. Also, warm thanks to Heidi Lee Frankel, Rubin I. Cohen, Phillipe Vignon, Michel Slama, Ariel L. Shiloh, and Susanna Price for providing invaluable help and instrumental interventions during various stages of the production.

Finally, we wish to personally thank the many individuals at Elsevier: William Schmitt (Executive Content Strategist), Tahya Bell (Multimedia Producer), Richard Barber, (Project Manager), Ellen Zanolle (Senior Book Designer), and our Content Development Specialist, Stacy Matusik, who have worked diligently for the completion of this edition.

Introduction

The proven benefits of on-demand bedside ultrasound imaging in the management of the critically ill patient go far beyond the initial diagnostic assessment, ranging broadly from facilitating safer and quicker procedures, to monitoring disease trends and effects of instituted therapy. Notwithstanding the rapidly growing evidence base, critical care ultrasound is still lacking conceptual definition and a clear implementation strategy in order to become a universally accepted tool for routine management of critical care patients. The setting of an intensive care unit is vastly different from pre-hospital care or emergency department, and the bedside imaging paradigms in these two settings are different as well. One of the most critical differences is that although the same patient who was cared for by pre-hospital personnel and then treated in the emergency department is now in the intensive care unit, he or she are on different points in the continuum of his or her critical illness. This means different challenges and findings are encountered, and different treatments and ultrasound approaches may be required. It is not the increasing portability of modern digital scanners or their declining cost that that will bring appropriate imaging capability to more intensive care units; it is the shared understanding among intensivists, health care managers, educators, and other stakeholders of its benefits for the patient as well as for their respective areas of activity. Such understanding is essential to minimize the time lag we are in currently between technology readiness and its full implementation into practice.

As with any technology, critical care ultrasound is only as good as the knowledge and skills of its users. The editors and authors of this volume have made a bona fide effort to create a resource for intensivists that contains a massive amount of learning and reference material presented clearly, concisely, and with clinical relevance in mind.

The *Holistic Approach (HOLA)* concept of ultrasound imaging introduced in the book defines critical care ultrasound as part of the patient examination by a clinician to visualize all or any parts of the body, tissues, organs, and systems in their live, anatomically and functionally interconnected state and in the context of the whole patient's clinical circumstances. Throughout the volume, this universality of ultrasound imaging is accentuated; generic imaging, specific imaging protocols, and image-based procedure techniques are explained in the context of critical care patient management. The authors provide a thorough, mature substantiation for the HOLA concept and its elements, which are further used to present and defend a rational implementation strategy for ultrasound in intensive care units, including another novel concept—the critical care ultrasound laboratory—an advanced facility that carries out specialized imaging techniques and image-based procedures, ensures centralized data management, and serves as an interface with radiology and other services external to the critical care facility. All these efforts have one central purpose: to help the readers integrate ultrasound into their clinical practice at the highest level possible and as broadly as desired.

Ashot E. Sargsyan
Michael Blaivas
Dimitrios Karakitsos
Philip Lumb

SECTION I

Fundamentals

1

Fundamentals: Essential Technology, Concepts, and Capability

ASHOT E. SARGSYAN | MICHAEL BLAIVAS | PHILIP LUMB | DIMITRIOS KARAKITSOS

"There is geometry in the humming of the strings . . . there is music in the spacing of the spheres"

Pythagoras of Samos, 520 BC

Christian Doppler was born in Salzburg, Austria on November 29, 1803 and lived a short and deprived life, like many scientists of his time. In an 1842 session of the Science Section of the Royal Bohemian Society in Prague, he presented a thesis entitled "*Concerning the colored light of double stars and other celestial constellations.*" Other milestones relevant to this chapter include the discovery of piezoelectric phenomenon (Curie brothers, 1880); the construction of the first sonar (Langevin-Chilowski, 1916); and the early efforts to use ultrasound for diagnostic purposes (Karl Dussik, 1942), which, along with the technologic progress in the second half of the twentieth century, paved the way to modern ultrasound imaging. Despite tremendous advances in ultrasound technology over the past 60 years, its basic principles are still the same: *operation of piezoelectric sonar with frequency analysis capability*.

Fundamentals: Principles, Terms, and Concepts

Ultrasound is a mechanical wave that requires a medium to travel (i.e., human tissue), with a frequency above the audible range ceiling of 20 kHz. Ultrasound systems are tomographic devices that transmit short pulses of ultrasound into the body and measure the round-trip time and intensity of each of the numerous echoes returning after the pulse. The time of arrival of an echo determines the distance from the transducer, that is, the location of its source in the body. The intensity of the echo is converted to brightness of a given point in the image. In other words, each pixel (element of the image) on the display device corresponds to a point inside the body, and its brightness depends on the strength of the echo that came from that location. Together, all pixels form a grayscale tomographic image. Parts of the image with mostly bright pixels (a brighter overall appearance) are termed hyperechoic, as opposed to hypoechoic (darker) areas. The relative ability of an organ or tissue to produce echoes is called echogenicity, that is, tissues or structures producing hyperechoic image are considered more echogenic.[1-7] Parts of the image with only black pixels are called anechoic or echo-free and mostly correspond to homogenous liquids (e.g., blood, urine, effusion, cystic fluid).

Frequency (measured in cycles per second [hertz, Hz]) is the number of wave cycles in 1 second. Frequency is determined solely by the sound source and not by the medium. Frequencies used by general-purpose ultrasound machines range between 2 and 15 megahertz (MHz). Higher frequencies, up to 40 MHz, are used for intravascular and other catheter-based applications and in specialized ophthalmologic and dermatologic techniques. Propagation speed is the velocity of sound in a given medium and is determined solely by the characteristics of the medium, such as density and stiffness (does not depend on the source of sound or its frequency). Ultrasound travels through soft tissues at a speed of approximately 1.54 mm/μsec, or 1540 m/sec). The stiffer the tissue, the greater the propagation speed (Figure 1-1). Ultrasound waves are generated by piezoelectric crystals (e.g., lead zirconate titanate, or PZT) that convert electrical energy into mechanical energy and vice versa (see Figure 1-1). Electrical pulses or short bursts of alternating voltage stimulate crystals to produce ultrasound pulses in the medium, causing displacement and oscillation of its molecules. Pressure change–Velocity of such oscillations in response to sound pressure determines the acoustic impedance (lower velocities correspond to higher impedance). As ultrasound passes from one medium to another (e.g., from gas to liquid), an impedance gradient at the tissue boundary causes a part of the energy to form a reflected wave (echo) while the remainder of the energy proceeds into the second medium.[1-7] Reflection occurs every time the ultrasound pulse encounters a new boundary (reflector). Specular (mirror-like) reflectors are smooth and flat boundaries larger than the pulse dimensions (e.g., diaphragm, walls of a major vessels). The echo reflection angle equals the angle of incidence; when the beam strikes a specular reflector at 90 degrees (normal incidence, Figure 1-2), a very strong echo travels back toward the source. Nonspecular reflection, or scattering, occurs when the incident beam strikes boundaries that have irregular surface or are smaller than the beam's dimensions, resulting in the beam's energy scattering in multiple different directions (see Figure 1-2). The beam travels around even smaller obstacles without scattering (diffraction). Because a higher frequency results in smaller beam dimensions, obstacles diffracting at lower frequencies act as scatterers at higher frequencies. This explains both higher imaging resolution and higher beam attenuation at higher frequencies. Refraction is the redirection of a beam when striking obliquely at a boundary between two media with different propagation speeds. Unlike reflection, refraction does not contribute to the

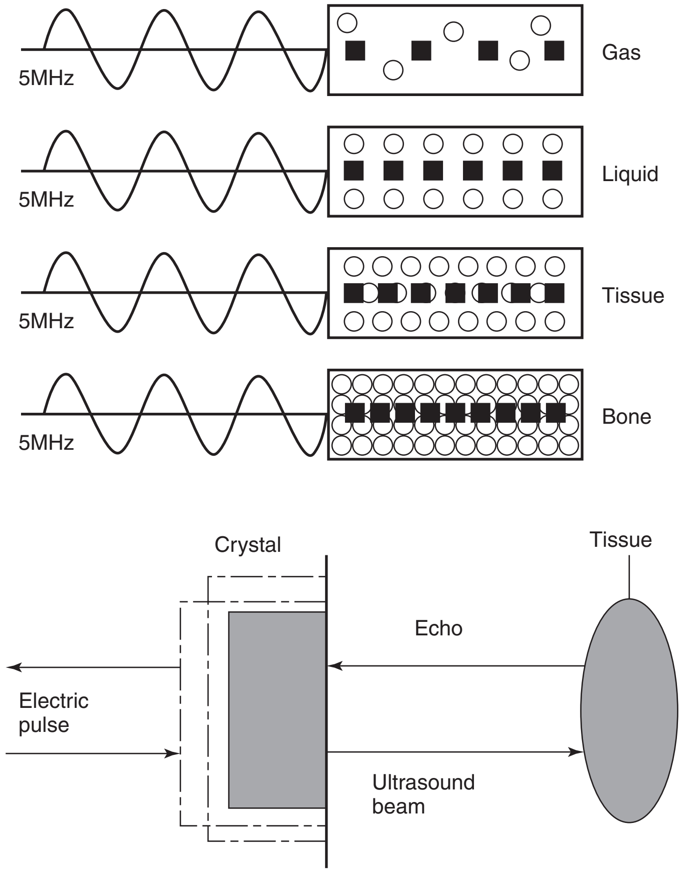

Figure 1-1 Propagation speed is different in different tissues *(top);* electrical impulses stimulate the lead zirconate titanate (PZT) crystal to produce a beam *(bottom),* while every time an echo is reflected back, the crystal deforms and vibrates, generating another impulse that is processed into an image.

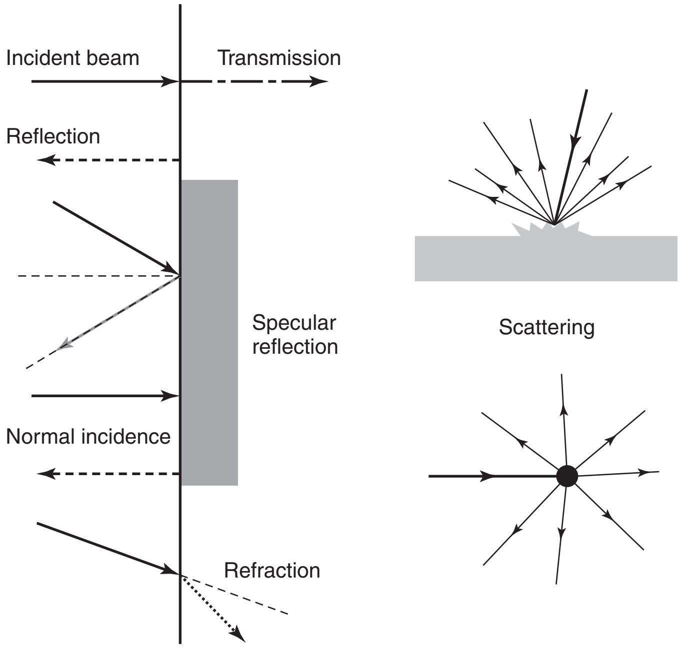

Figure 1-2 *Left panel*, Reflection *(top)*, specular reflection *(middle)*, and refraction *(bottom)* of the incident beam. *Right panel*, Scattering occurs when the incident beam strikes boundaries that are irregular in shape *(top)* or smaller than the beam's dimensions (*bottom*), resulting in the beam's energy scattering in multiple different directions.

image formation process but contributes to attenuation (see Figure 1-2). Part of the ultrasound beam's energy is transferred to the medium in the form of heat. This is absorption, which also increases proportionally to frequency in soft tissues. The bones absorb ultrasound more intensely, together with other energy loss mechanisms, producing acoustic shadows behind them. Finally, part of the original beam is converted by tissues to waves with double or higher-order frequency (harmonic waves). The total propagation losses from the combined effects of scattering, refraction, and absorption are called attenuation, which is directly proportional to frequency. Body compartments with low attenuation that allow imaging deeper structures through them are good acoustic windows (e.g., liquid cavities), while those with high attenuation are acoustic barriers (e.g., bones). *The near-total loss of ultrasound at boundaries between tissues and gas makes gas the strongest barrier;* nevertheless, important lung ultrasound techniques rely on the abundant artifacts that the aerated lung creates.

Equipment and Imaging Modes

EQUIPMENT

Ultrasound machines consist of electric pulse generators, transducers, systems for processing received echoes, and image display screens. Modern systems use digital technology and have central processing units running advanced software that forms beams and processes echoes and thereafter stores images. The key elements of transducers (probes) are PZT crystals, matching layers, backing material, cases, and electrical cables (Figure 1 E-1). Modern electronic transducers generate a range of frequencies (bandwidth) around the central frequency, and contain multiple crystal elements (arrays). This permits them to display the sequence of two-dimensional (2D) images so rapidly that motion is displayed as it actually occurs (real-time scanning). Main transducer types are phased array (sector), linear array, and curved array (Figure 1-3). Sector (phased array) transducers (2 to 4 MHz) have small footprints that produce images of sector format through small acoustic windows (e.g., cardiac and cranial applications). Linear array transducers (7 to 15 MHz) provide images in rectangular or trapezoidal format. They feature high resolution and shallow depth of view because their penetration into deeper structures is limited. Convex (curved array, curvilinear) transducers (2 to 6 MHz) of different shapes and sizes produce images in a sector-shaped format with a wide apex. Microconvex transducers (3 to 8 MHz) feature small footprints and are useful in difficult-access areas, such as the neonatal brain. Transducers generating frequencies of 2.5 to 5 MHz feature a larger curvature radius and are used for abdominal imaging. A variety of convex arrays operating at higher frequencies are used in intracavitary and transesophageal scanning. Finally, transducers with frequencies up to 50 MHz are used for endovascular applications and ultrasound biomicroscopy.[1-7]

Notwithstanding the similarities of all general-purpose ultrasound systems, it is critical for every user to be especially

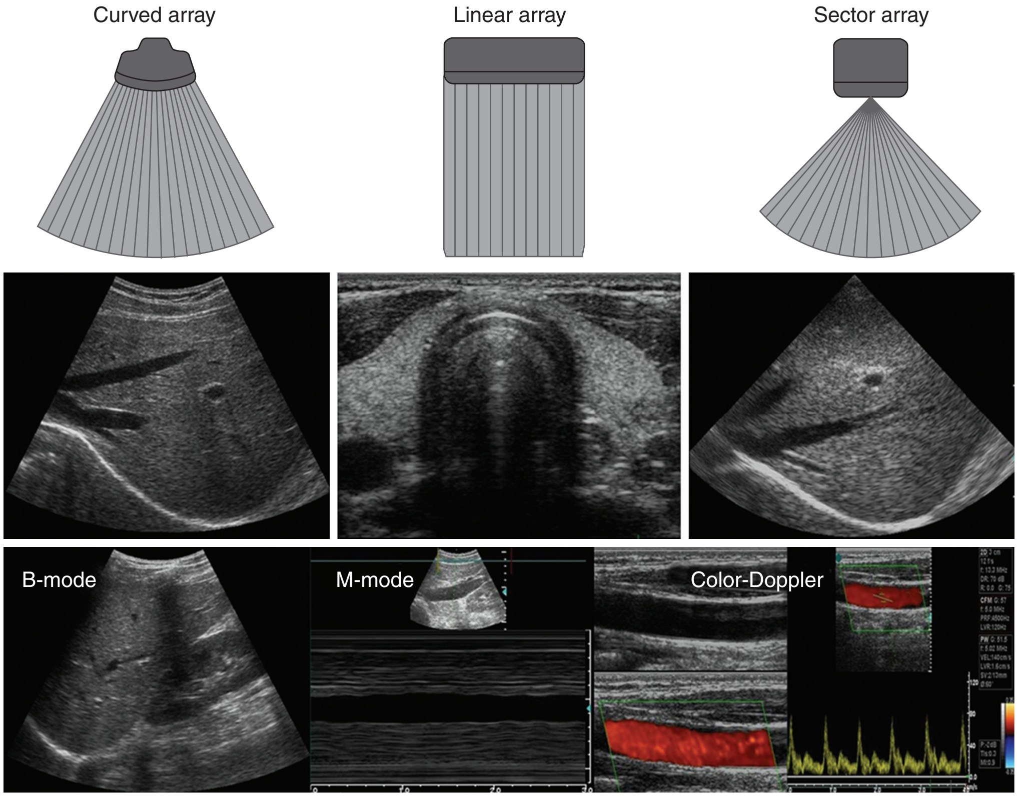

Figure 1-3 Main types of transducers and formats of their produced images *(top* and *middle);* basic imaging modes *(bottom).*

familiar with a specific machine's features, transducer choices, and controls in advance and to practice with it sufficiently in nonemergency settings. Attempting to navigate screens or modes while resuscitating a critically ill patient can be a frustrating process. A demonstration of a common ultrasound machine and its essential controls is provided in Video 1-1. The ability to switch transducers between imaging applications or their components helps optimize image acquisition; even seemingly simple examinations, such as the extended Focused Assessment by Sonography for Trauma (e-FAST) evaluation, may require a transducer change, as well as the use of depth and gain adjustment and image optimization techniques. An e-FAST examination using several transducers is demonstrated in Video 1-2, whereas Video 1-3 shows the use of various imaging modes and may be helpful for novice ultrasound users. Some imaging modes may appear to be the prerogative of advanced users; however, novices quickly learn taking advantage of the additional information they offer. Of note, correct choice of transducers and machine settings will help ensure proper identification of pathology or estimation of physiologic parameters, whereas poor preparation may render the study ambiguous or completely nondiagnostic.

IMAGING MODES (SEE FIGURE 1-3)

A-mode (amplitude) is a nonimaging mode no longer used in general-purpose machines. B-mode (brightness) is the main imaging mode of any ultrasound machine. Each grayscale tomographic image in B-mode is composed of pixels with brightness, that depends on the intensity of the echo received from the corresponding location in the body. M-mode (motion) displays the movement of structures along a single line (axis of the ultrasound beam) chosen by the operator (Figure 1-4). M-mode is used in the intensive care unit (ICU) for evaluating heart wall or valve motion (echocardiography), hemodynamic status (vena cava analysis), and documentation of lung sliding or movement of the diaphragm. Doppler modes detect frequency shifts created by sound reflections off a moving target (Doppler effect). A moving reflector or scatterer changes the frequency of the beam (Doppler shift), as in $(F_s - F_t) = 2VF_t \cos \Phi/c$, where V = the velocity of moving blood cells, c = the propagation speed, F_t = the frequency emitted by the transducer, F_s = backscattered frequency returning to the transducer, and Φ = the angle between beam and blood flow direction). If the beam lines up in parallel with blood flow (Φ = 0 degrees), cos 0 degrees = 1 (maximum Doppler shift). If the beam is perpendicular to the blood flow (Φ = 90 degrees), velocity measurements cannot be performed because cos 90 degrees = 0 (no Doppler shift). Angles in the 45- to 60-degree range are generally preferred.[7]

The Doppler effect is used in several modes. Color Doppler maps all Doppler shifts in the region of interest (ROI) by using a color scale over the grayscale anatomic image. The colors (usually shades of red and blue) denote flow toward and away from the transducer, regardless of the vessel's nature (artery or vein). The power Doppler mode, also known as Doppler angiography, displays all flow within the ROI in one color (usually orange) without regard to direction and is more sensitive (Figure 1 E-2). Spectral Doppler (see Video 1-3) refers to two different techniques: pulsed

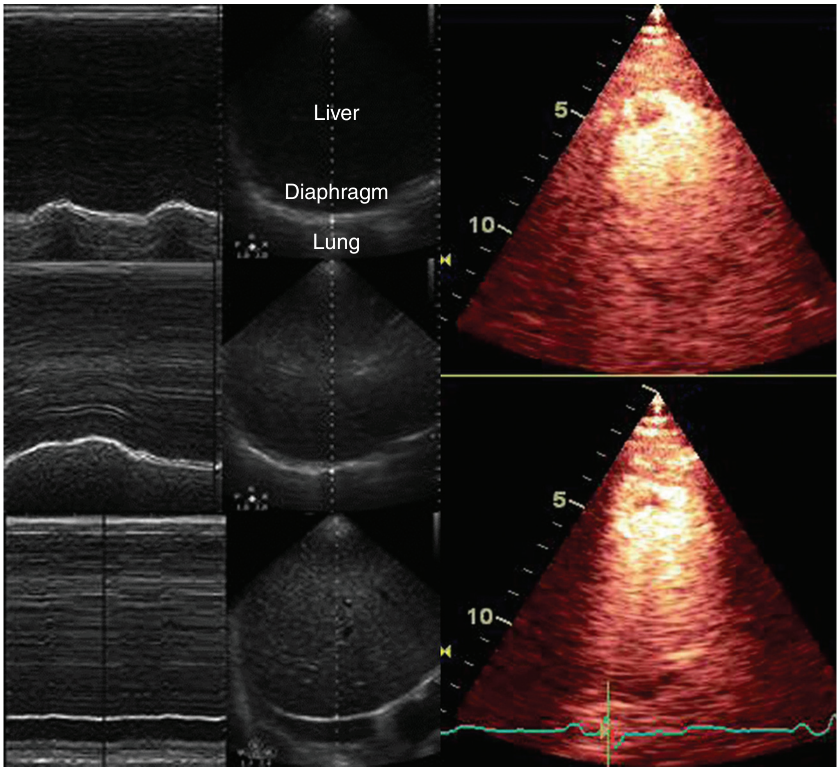

Figure 1-4 Old and new ultrasound techniques are useful in the intensive care unit. *Left,* M-mode showing diaphragmatic motion during T-piece trials (spontaneous breathing): normal movement *(top),* deep inspiration *(middle),* and flat-line in hemidiaphragmatic paralysis *(bottom). Right,* Contrast agents "light up" the left ventricle, and an apical thrombus is revealed.

wave (PW) Doppler and continuous wave (CW) Doppler. CW Doppler involves continuous (not pulsed) generation of ultrasound by one crystal and reception of echoes by another, detects all shifts along the line chosen by the operator, and detects high velocities accurately. In PW Doppler, transmission is pulsed, and reception is performed by the same crystal. The operator places a special cursor (sample volume or gate) at the point of interest (e.g., center of a vessel). Its main advantage is the ability to display a full spectrum of frequency shifts from a specific anatomic point only. However, PW Doppler is unable to measure velocities greater than 1.5 to 2 m/sec because of aliasing. The term *duplex ultrasound* refers to the combination of anatomic information of B-mode with either color or spectral Doppler information on the same display. Triplex ultrasound demonstrates a grayscale image, the color Doppler overlay, and the spectral Doppler graph on the same display. Color M-mode displays in color the pulsed Doppler information along a single line of interrogation versus time. The Doppler velocity shift is color-encoded and superimposed on the M-mode image, providing high temporal resolution data on the direction and timing of flow events and is used mainly in cardiovascular imaging. Tissue Doppler imaging (TDI) is a modality in which the small Doppler shifts from tissue movements (most $<$20 mm/sec) are detected, while higher shifts from blood flow are suppressed. It is increasingly used in echocardiography for the assessment of various aspects of myocardial performance, especially in the diastolic function and greatly contributes to the differential diagnosis and management of myocardial pathology (Figure 1 E-3).[7]

Harmonic frequencies are higher-integer multiples of the fundamental transmitted frequency that are produced as beams travels through tissues. With tissue harmonic imaging (THI), a software filter suppresses the fundamental frequency in the echoes and allows only harmonic signals to be received and processed into images. This may improve resolution and attain higher signal-to-noise ratios, minimizing the degradation effect of body wall fat. In some circumstances, however, THI image quality may actually be poor because of excessive filtering, with a resulting decrease in penetration and resolution. Anisotropic imaging is a recent evolution in ultrasound used for identifying abnormalities within normally anisotropic tissues. Anisotropy is a directional dependency of backscattered waves, which is present to varying extents in myocardium, renal cortex, tendons, and cartilage.[7]

Three-dimensional (3D) ultrasound acquires the anatomical information in a volume (3D) format. This technology undergoes continuous refinement as vendors seek to improve the performance and utility of 3D systems. By moving the 2D transducer in a controlled manner (linear-shift, swinging, or rotation), spatially tagged 2D data matrices are stored, to be reconstructed mathematically. 3D imaging can work with both B- and color Doppler modes, and its field of applications is constantly expanding (cardiology, obstetrics, neonatology, etc.). 3D images can be displayed in a variety of formats, including multiplanar reconstruction, surface rendering, volume rendering, and virtual endoscopy.[7] This technology undergoes continuous refinement as vendors seek to improve the utility and performance of 3D systems.

Contrast-enhanced imaging has been a major development in ultrasound technology in recent years. Most contrast agents are microbubbles of gas encapsulated in a polymer shell. They are much more reflective than normal tissues and thus significantly improve B-mode and color Doppler image quality (see Figure 1-4). It is a generally safe method for cardiac imaging, vascular evaluation, and parenchymal enhancement. Microbubbles in some agents "burst" when subjected to ultrasound energy, enhancing the image even further. Potential ICU applications include detection of right-to-left shunts, thrombosis, and solid organ injury, as well as assessment of renal perfusion and demonstration of ischemia.[8]

Ultrasound elastography is a new dynamic technique that evaluates tissue elastic properties by detecting and mapping, using a color scale, tissue distortions in response to external compression. Established and emerging applications are known for breast, thyroid, and prostate tumors; liver disease, musculoskeletal trauma; arterial wall stiffness; venous thrombi; and graft rejection.

When the goal is to attain unimpeded, high-resolution views of hard-to-reach tissues and structures, specialized high-frequency transducers are available. Endocavitary (vaginal, rectal) and transesophageal transducers are usually of microconvex configuration. Endoluminal imaging techniques (e.g., intravascular, endobronchial, and endourologic ultrasound) are catheter-based techniques using rotational scanning that produce 360-degree B-mode views of the vascular (ureteral, etc.) wall and adjacent tissue. Some of these invasive techniques are applied in the ICU to evaluate intraluminal disorders and guide procedures.[7]

Image Quality and Optimization

Resolution is a general term denoting the ability of the imaging method to discriminate the structural detail. The better (higher) the resolution, the greater the clarity and detail of the image. *Spatial resolution* (axial and lateral) refers to the ability of the B-mode to identify and display echoes from closely spaced echo-producing structures as distinct and separate objects. *Axial resolution* is the ability to discriminate individual echoes along the direction of the ultrasound beam (beam axis) and is approximately 0.5 to 1 mm at the operating frequency of 3.5 MHz. Higher frequencies produce better axial resolution at the expense of penetration. *Lateral resolution* is the ability to discriminate echoes located side by side at the same depth, and is approximately 1 to 2 mm at 3.5 MHz. Besides choosing the highest possible frequency that still penetrates to the depth of ROI, spatial resolution is improved by "focal zone" placement at the depth of the ROI (focus control) and by avoiding excessive gain settings. *Contrast resolution,* also known as *grayscale resolution,* is the ability to discriminate returning echoes of different amplitudes and assign different grayscale values to the respective pixels. Most ultrasound systems permit assignment of 256 shades of gray, which resolves the subtle differences among various structures. Increasing the contrast (less shades of gray) results in an image that is more pleasing to the human eye but likely contains less diagnostic information.[1-5] *Temporal resolution* corresponds to the image frame rate (refresh rate), which ranges from 15 to 100 frames per second in different imaging modes and decreases when the depth or the number of focal zones is increased.

Modern portable ultrasound systems are significantly automated and similar in their user-adjustable functionality; however, controls (knobs) of the machine are still important to know. Depth (a knob or toggle switch) controls the depth of view and should be used to keep ROI in the central area of the screen (Figure 1-5). Depth is displayed along the edge of

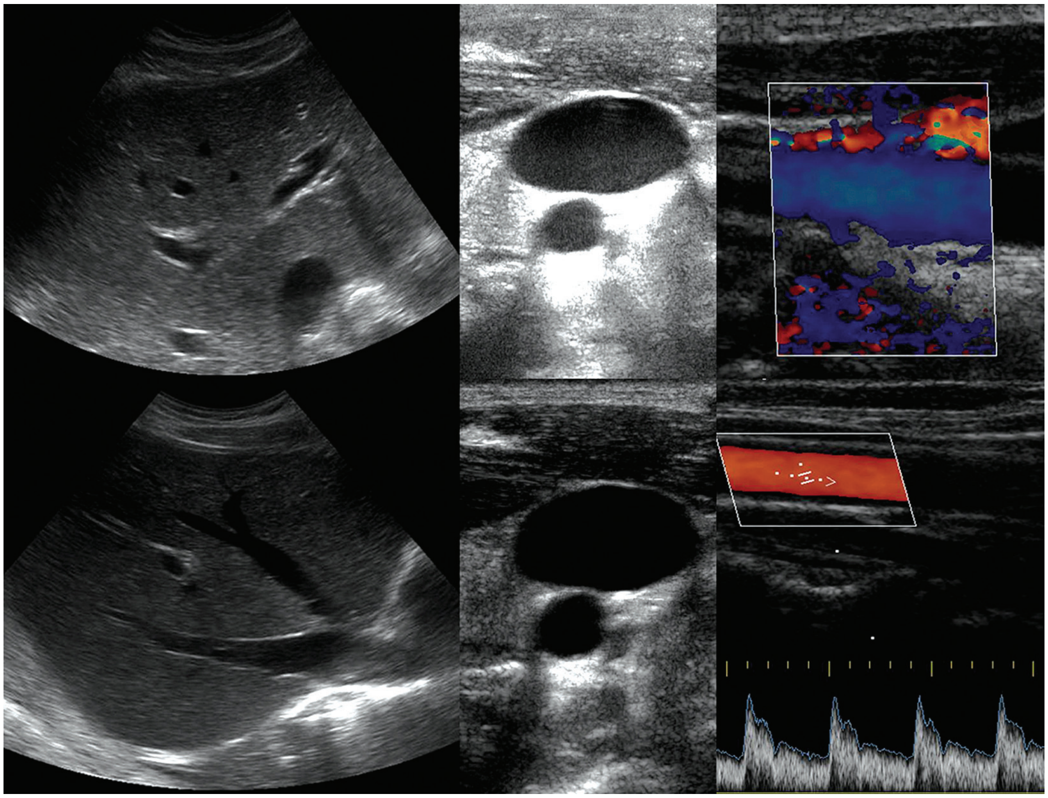

Figure 1-5 "Knobology": *Left,* Too-shallow image depth *(top)* and correct depth adjustment *(bottom)* to depict the region of interest (ROI, liver). *Middle,* Image with inappropriate (high) gain *(top)* and correctly gained *(bottom)*. *Right,* Increased color gain and large color box that is inappropriately angled *(top)* resulting in aliasing (common carotid artery) and properly sized and angled colorbox with adjusted color gain to perform color Doppler measurements *(bottom)*.

the image on a centimeter scale. Depth function alters the manner of acquisition of imaging data (preprocessing). An image at a shallower depth takes less time to form because only earlier-arriving echoes are processed, hence higher frame rates (better temporal resolution). The focus control allows moving the focal zone(s) to the ROI depth to ensure a narrower beam and therefore a better lateral resolution. The focal zone may be indicated as an arrowhead at the side of the image (usually on the depth scale). Most machines allow setting multiple focal zones; multifocusing degrades temporal resolution but improves spatial (both axial and lateral) resolution. Zoom control magnifies the selected image section without adding new information or changing the data acquisition (postprocessing). Some systems have an additional "high-definition zoom" option, whereas the machine's beam-forming and data-processing capabilities are mobilized from other areas to optimize the image of the ROI.

Gain adjusts overall image brightness by amplifying electronic echo signals; thus it works only on the receiving side and has no impact on transmitted power or bioeffects. Gain must be adjusted to such a level that anechoic structures (e.g., fluids) appear black on screen. Using too much gain can degrade the image and create artifacts, and using too little gain can negate real echo data (see Figure 1-5). In addition, most machines also have time gain compensation (TGC) controls (usually a group of slider rheostats) to adjust the gain selectively at various depths. To compensate for attenuation, echoes are electronically amplified proportional to the depth of their origin (i.e., time of their return to the transducer). TGC controls need readjustment when, for example, a large fluid-filled window is used; otherwise, the ROI behind the window will be too bright (overamplified). Further improvement of B-mode image quality can sometimes be achieved by THI.[1-5]

In the color Doppler mode, a color box is placed over the grayscale image to cover the part of the image that requires Doppler information; an excessively large color box may compromise temporal resolution. To properly assign colors to the magnitudes of Doppler shift, the pulse repetition frequency (PRF), or scale control, is adjusted. The proper color assignments to show direction of flow may fail if the Doppler shifts exceed the scale determined by the PRF. For this and other reasons, color Doppler is used for identifying and visually assessing the flow, but not for measuring actual velocities. Precise measurements of flow velocities are conducted with spectral Doppler (pulsed wave and continuous wave).

PRF is the rate of pulses used to analyze the Doppler shift. For PW Doppler measurements of arterial flow, PRF is generally set at 3000 to 4000 pulses/second or Hz, which allows a wide enough Doppler range to fit spectra with most arterial velocities. If the actual shifts exceed the scale, the peak part of the spectrum in excess of the scale appears in the wrong place (PW Doppler) or in the wrong color (color Doppler). This phenomenon is called aliasing, and the Doppler shift limit at which it occurs is called the Nyquist limit and equals ½ PRF. In color Doppler, aliasing is avoided by increasing the scale (PRF) and/or using the baseline control to dedicate a larger portion of the scale to the flow in the dominant direction (toward or away from the probe), and/or by increasing the angle between the ultrasound beam and the flow vector (e.g., from 45 to 60 degrees) to reduce the actual shifts. In spectral Doppler, similar controls are available. In veins with much lower flow velocities, a PRF setting of 1000 Hz is a typical starting frequency. Modern machines have built-in "presets" for arterial and venous examinations, with PRF set to appropriate values. Older machines may have to be adjusted manually, including frequency filters. In PW Doppler, sample volume (also known as gate) size and placement are essential for correct measurements. A smaller sample volume of 1 to 2 mm is used when detailed investigation of flow within the vessel is required (e.g., when the degree of flow turbulence is to be assessed). The sample volume is placed in the center of the vessel or at the point of peak velocity indicated by the color image. In cases where blood flow is reduced (e.g., venous circuits) a larger sample volume may be appropriate. The Doppler spectral waveforms are produced by spectral analysis of the frequencies contained in the echoes returning from the sample volume area, using real-time fast Fourier transform or similar algorithms.[1-5]

The spectral displays in most machines automatically calculate and display flow velocities, rather than the frequency shifts that they measure. The calculated velocities are correct only when the operator adjusts the angle cursor line manually, aligning it with the flow direction of the vessel (i.e., "informs" the machine about the direction of actual flow). Otherwise, the machine will likely assume an angle of 60 degrees, which may not be correct, and the displayed velocities will be overestimated or underestimated.

Artifacts

B-mode images are expected to accurately represent the cross-sectional anatomy under the probe. However, some artifacts are commonly generated; those should be readily recognized by the ultrasound operator. Artifacts are image features that are formed by mechanisms other than standard placement of pixels with grayscale assignment based on reflection and backscattering. Artifacts "are determined by real anatomy, but are not real anatomy," and may be a source of misinterpretation. Usually, they have regular vertical or horizontal shapes and differ from anatomic structures. The most common types of artifacts are detailed below.

Acoustic shadowing (Figures 1-6 and 1-7) appears as an echo-free void (shadow) in anatomy image when the beam is unable to pass through a strongly attenuating structure (e.g., a strong absorber or reflector). The orientation of the shadow is always in the direction of beam propagation (away from the probe—vertical with linear probes or radial in sector or convex probes). Shadowing because of large stones, calcifications, and bones is caused mainly by sound absorption, refraction and reflection and the associated shadow tends to be more anechoic ("clean"). In a tissue-air interface, shadowing is caused by complete reflection, whereas secondary reflections created at the interface are displayed as false low-level echoes within the shadow ("dirty shadowing"). Edge shadowing appears as shadowing from the edge of circular structures mainly because of refraction and beam spreading. It is a useful criterion for diagnosing cysts but can mimic stones, especially in the gallbladder fundus and cystic duct. Absence of shadowing from an echogenic (bright) object does not rule out a stone or calcification if it is very small (<3 mm in the most common imaging circumstances). Furthermore, some ultrasound machines use additional beams steered at angles that may bypass the small stone and create

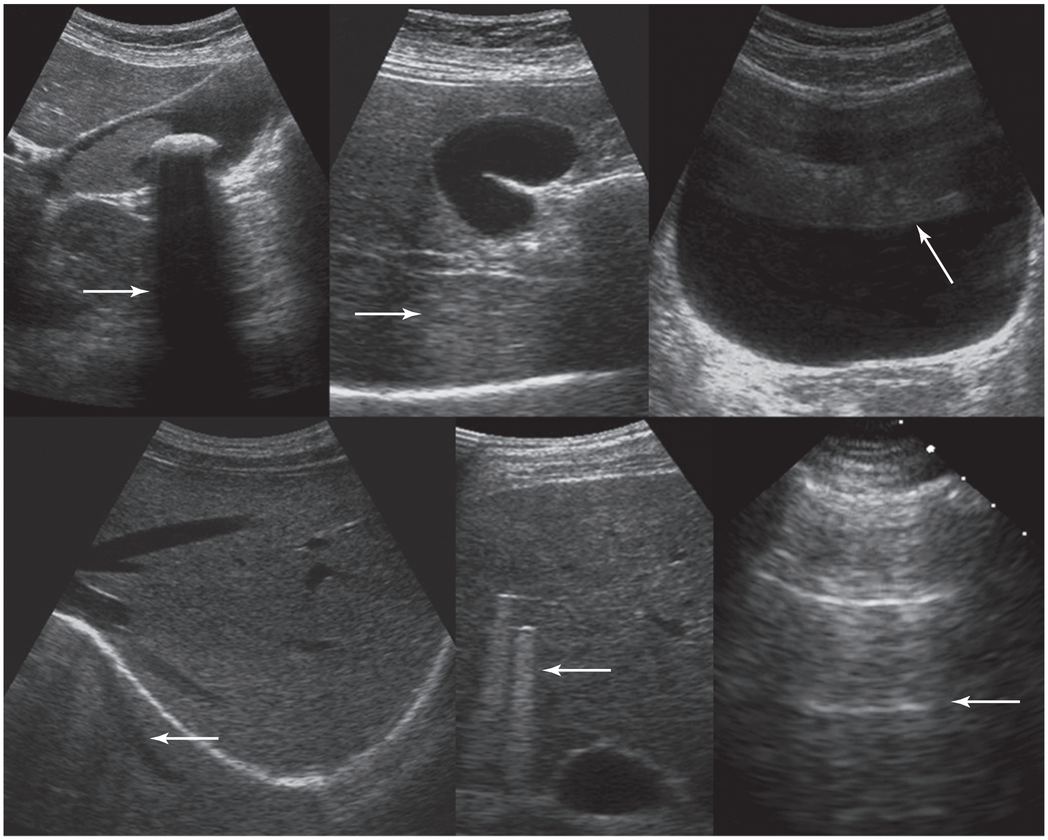

Figure 1-6 *Top, left to right,* Gallbladder stone casts acoustic shadowing, posterior acoustic enhancement (gallbladder), and reverberations *(arrows). Bottom, left to right,* Mirror image, comet-tail artifacts produced by bullets embedded in liver parenchyma, and ring-down artifacts of the pleural line *(arrows).*

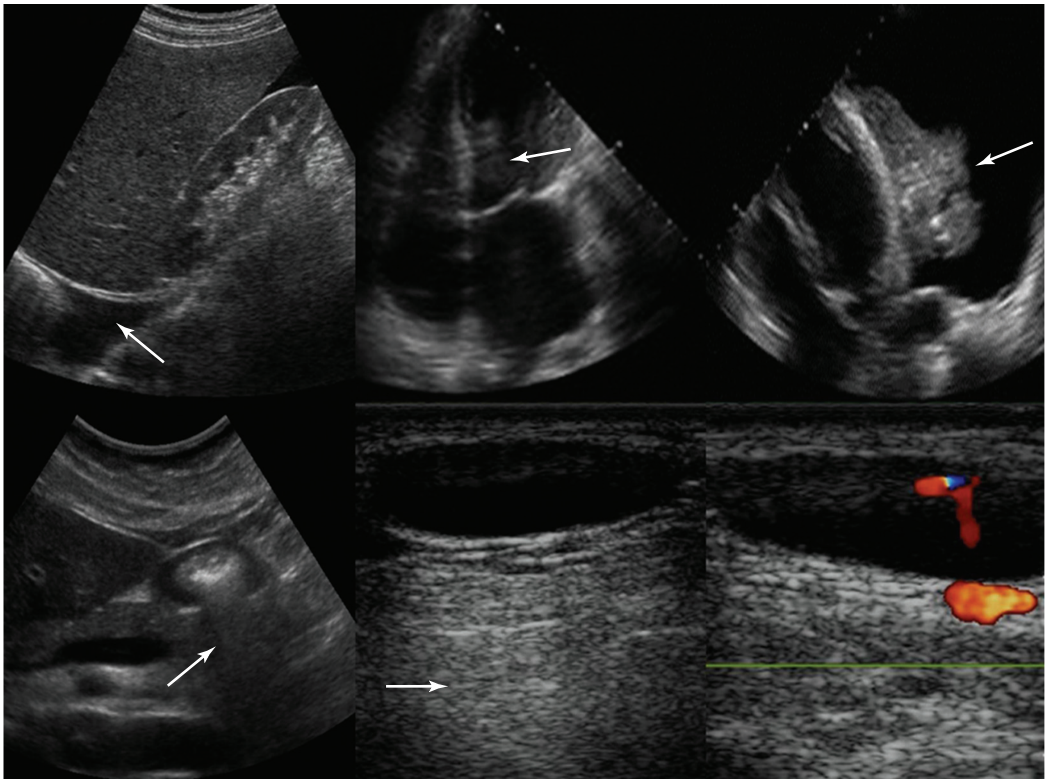

Figure 1-7 *Top, left to right,* Pleural effusion prevents mirror image duplication of liver; echo introduced falsely in an anechoic structure (left ventricle), mimicking thrombus as it is produced by a lung atelectasis (located at the same depth) floating within a pleural effusion (refraction artifact). *Bottom, left to right,* Dirty shadow cast by air-filled antrum; posterior acoustic enhancement caused by hypoechoic neck lymph node *(arrows).*

elements of true anatomic image behind it, thus suppressing the shadow. This technique is commonly known as real-time image compounding.

Posterior acoustic enhancement appears as a hyperechoic (bright, overamplified) area because of reduced attenuation by the area above it. It usually indicates the fluid nature of the weakly attenuating structure, although some low-echogenicity solid masses may cause similar enhancement patterns (see Figure 1-6).

Mirror images appear as two reflectors (true and spurious) with the spurious reflector located deeper than the true reflector and disappearing with transducer's position change (see Figures 1-6 and 1-7). Refraction artifacts appear as copies of true reflectors whenever the beam strikes a boundary; this is different from the mirror image because it is visualized side by side with the true anatomic structure at the same depth (see Figure 1-7). Reverberations appear as multiple echoes between reflectors. They appear often at the anterior aspect of the distended urinary bladder (see Figure 1-6). Special forms of reverberations include ring-down and comet-tail artifacts (see Figures 1-6 and 1-7). Ring-down artifacts occur from a large mismatch in the acoustic impedance of media (e.g., when an air bubble is encountered) and are usually displayed as a vertical line that goes all the way or almost all the way down the image. Comet-tail is another type of reverberation artifact that appears as hyperechoic trail of reverberations arising from an echogenic structure (e.g., irregularity on the lung surface, some foreign bodies, cholesterol deposits in the gallbladder wall) that fade and taper down distally. Thus the main difference between these two reverberation artifacts is in their length and character (ring-down artifact continues all the way down the image, whereas comet-tails taper fairly close to the origination point). Side-lobe artifacts appear as areas of faded duplicate image side by side with the true anatomic structure and therefore could be mistaken for sediment or septa, usually within a fluid compartment (e.g., ascites), or could artificially enlarge the image of the anatomic structure (e.g., the prostate imaged through the urinary bladder). Fortunately, small probe movements usually eliminate this artifact. Section thickness artifacts appear as a fill-in of an anechoic structure (e.g., a cyst) if the beam has a greater width than the structure in question and could mimic debris, sludge, or clotted blood. As with B-mode, imaging artifacts can arise in color Doppler imaging as well. Color flow artifacts may appear as bright black and white structures within the vessel lumen. Also, if color gain is set too high, then color may appear as pouring out of the vessel, or anechoic areas may be filled with speckled color; however, these artifacts may be also produced by tissue bruits near a vessel stenosis or subtle tissue movements resulting from respiration (*color noise*). Whenever vessels overlie boundaries (e.g., subclavian artery overlying lung and pleura) mirror-color artifacts may be produced because of multiple reflections. Finally, aliasing and changes in the angle of insonation also produce artifacts.[5-7]

Although artifacts in general degrade the image and often replace anatomic information, some important ultrasound techniques take advantage of certain types of artifacts or even completely depend on the presence or absence of certain artifacts for accurate diagnostic determination. For example, many pleural and lung ultrasound techniques are based on recognition and assessment of specific artifacts (see Chapters 19 and 20).

Ultrasound Technique and Safety Issues

Selecting the appropriate transducer depends mainly on the depth and spatial resolution requirements of the ROI; *what is gained in depth is lost in image quality or detail, and vice versa*. In general, the highest ultrasound frequency allowing penetration to the depth of interest should be selected. For superficial structures, transmit frequencies of 7 to 15 MHz are usually used (e.g., vascular and small parts imaging). For deeper structures (e.g., abdominal organs), lower frequencies of 2 to 5 MHz are necessary. Current technology offers broadband probes that permit selecting a central frequency from several choices, or multiple frequencies can be used at the same time to achieve the best possible image resolution/beam penetration balance for ROI in question (broadband imaging).

A liquid material (gel) is used to ensure a good acoustical contact between transducer surface and patient's skin by eliminating the interposed air. The transducer must be held lightly in the hand but firmly, with the thumb pointing toward its marker side. By placing the edge of his or her hand (or the tips of the fourth and fifth digits) against patient's skin, the operator ensures stability and fine control of the probe position. All transducers have an orientation marker that corresponds to the marker on the screen. Manipulation of the transducer (pressure, translation, rotation, panning, tilting) allows finding the target, optimizing the view, and reviewing the entire volume of an organ, lesion, or area of interest. Applying the correct pressure evenly can significantly improve image quality (or confirm compressibility of a vein); on occasion, more pressure can be applied on one side of the transducer (panning, or *heel-toe maneuver*) to create a necessary angle for Doppler modes. Rotating is usually used to transition between sagittal or coronal and axial scanning of the ROI (in whole-body anatomy terms) or between long-axis and short-axis views (in reference to an organ, vessel, or lesion). Tilting the transducer aids in "guiding" the scanning plane and/or direction. Panning sustains the current imaging plane but extends the view in one of the directions within the same plane. The transducer, and consequently the beam, can thus be oriented freely in any anatomic plane of the body (sagittal, axial, coronal, and any intermediate or oblique variations of these planes). For some structures, the operator may depart from the references to the anatomic body planes and use references to the structure itself (long-axis or short-axis planes). This is usually the approach to scanning vessels, kidneys, pancreas, or spleen. Real-time, multiplanar imaging capability is a unique characteristic of ultrasound that allows rapid determination of spatial relationships of examined structures. As a general rule, the transducer's marker should be directed toward patient's right side in axial planes or toward the patient's head in sagittal and coronal planes.

Basic ultrasound scanning orientation terms are shown in Figure 1-8. Coronal refers to the longitudinal scan performed from the patient's side, and the plane separates the anterior from the posterior. Transverse or axial refers to a plane that separates the cephalad from the caudad. *Sagittal* refers to the longitudinal anteroposterior plane that divides right from left. Cranial (cephalad) indicates the direction toward the head and caudad the direction toward the feet. Anterior (ventral) and posterior (dorsal) refer to structures lying toward the front or the back of the subject, respectively. Medial means toward the midline and lateral away from it, whereas proximal means toward the origin and distal away from it.[5-7]

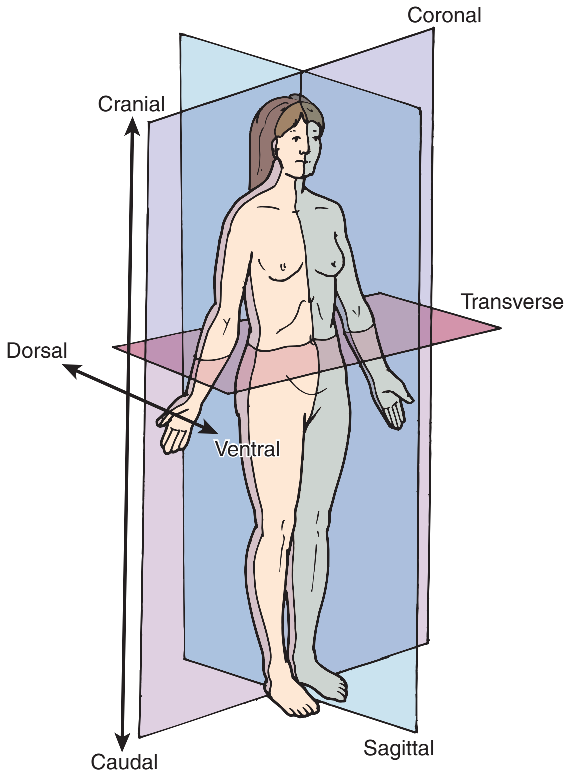

Figure 1-8 Basic ultrasound imaging planes and axes.

The American Institute of Ultrasound in Medicine (AIUM) and the U.S. Food and Drug Administration (FDA) agree that ultrasound is safe if used when medically indicated and with the output power and exposure times not exceeding the necessary levels (*A*s *L*ow *A*s *R*easonably *A*chievable—the ALARA principle).

High-intensity focused ultrasound (HIFU) is a therapeutic modality used for ablation of breast tumors, prostates, uterine fibroids, and so on, by producing intensities exceeding 1000 W/cm^2 and raising tissue temperatures by up to 25° C. Diagnostic ultrasound devices use orders of magnitude lower intensities and very small duty factors (proportion of transmitting time relative to the total examination time); its thermal effects (the first recognized adverse bioeffect—tissue heating) are expressed as the thermal index (TI), the value of which equals the predicted rise of tissue temperature in degrees C with unlimited exposure. Temperature elevations less than 1° C are considered safe even for ophthalmic imaging.[1-3]

The second notable adverse bioeffect of ultrasound is cavitation—explosive formation of microscopic bubbles in tissues caused by abrupt pressure fluctuations. This phenomenon is highly unlikely at diagnostic ultrasound intensities. However, experimental studies suggest that *contrast agents* and *agitated saline* may, under certain circumstances, promote cavitation even at moderate energies. For example, when investigating a patient with probable right-to-left shunt, agitated saline or a special contrast agent is administered to perform transcranial Doppler (TCD) for bubble detection in the middle cerebral artery (MCA) or the ophthalmic artery (OA). TCD operates at high acoustic power to penetrate the skull through the temporal window; if the same power level is applied through the orbital window, the energy passing through the low-attenuation ocular media may create cavitation within retinal arterioles containing bubbles and result in a hemorrhage. The ability of the given ultrasound mode to cause cavitation is best characterized by the mechanical index (MI), which is required to be displayed along with the thermal index on the screen of all modern ultrasound machines. Minding the vulnerability of the eye, several guidelines require lowering the energy output to limit the ocular scanning energies to levels corresponding to MI less than or equal to 0.23 and TI less than or equal to 1.0. Notwithstanding the cautious approach, all the evidence and theoretic considerations attest to a very high safety margin of diagnostic ultrasound in the clinical context, making it the safest tomographic modality, with no electromagnetic or particle radiation and very low overall energy delivery.[5-8]

Scope and Evolution of Ultrasound Imaging

Unlike most other nontomographic and tomographic imaging modalities that have a standardized data acquisition process with preprogrammed and predictable data sets, ultrasound is a hands-on patient examination method with real-time continuous display of anatomic information. This feature, along with its excellent safety profile, could make ultrasound a highly informative component of the physical examination in most medical disciplines. However, from early stages of its clinical implementation, the use of ultrasound has been adapted to the routines of radiology departments, and most medical systems do not take full advantage of the real-time nature, universality, and versatility of ultrasound imaging. Similar to other technician-performed modalities, the "radiologic," or "referred," ultrasound is mostly performed by specialized technologists trained to follow standardized protocols. Limited sets of still images are obtained for subsequent interpretation by radiologists or other appropriately trained physicians who, with rare exceptions, do not see the patient or the clinical situation at hand. Although the analysis of these data sets is comprehensive and extremely valuable for establishing a diagnosis, the data sets themselves carry only a subset of potentially useful information. Furthermore, referred ultrasound results are reported with a delay, further reducing its contribution to real-time patient management in the prehospital environment, emergency rooms, intensive care units, operating rooms, and other settings when the value of information diminishes very quickly with time. In some settings, it is not the diagnosis that is unknown but the physiology and its trends and response to therapy; the "radiologic" ultrasound cannot assist at all in most of those situations.

To satisfy the unmet need for instantaneous results and repeatable imaging data as part of the patient examination and monitoring by the physician, new branches of ultrasound technology have evolved in recent years: emergency ultrasound (EU) and critical care ultrasound (CCU). These can be considered new modalities that use the same equipment but have a different scope and different effects on patient management. They do not take the place of "radiologic" ultrasound; furthermore, many studies requiring comprehensive analysis are still referred to expert radiologists and cardiologists for thorough consideration, in addition to standardized studies performed by radiologic personnel. In the following sections, we describe the main features of EU and CCU, as well as present the innovative concept of holistic approach (HOLA) to the use of ultrasound in the emergency and critical care environments.

Emergency Ultrasound

Emergency ultrasound began strictly out of clinical necessity in the mid-1980s and has expanded based on the notion of a focused examination answering the most relevant, usually binary, clinical question. The initial applications included evaluation for ectopic pregnancy, trauma, and cardiac arrest. EU has since spread widely, and its multiple applications range from pelvic to ocular examinations. The emergency setting does not allow for lengthy examinations, and screening examinations have little place in most cases.

Besides diagnostic applications, EU plays an increasing role in procedure assistance, greatly facilitating procedures previously conducted in a "blind" fashion or rarely even attempted in the emergency department. For example, assessment and drainage of a peritonsillar abscess is facilitated by ultrasound guidance; regional nerve block greatly improves care, saves time, and avoids the dangers and increased workload of sedation. One of the key areas of attention is patient resuscitation, not only in cardiac arrest but also in periarrest and shock states. Ultrasound allows the clinician to accurately assess the patient's status, as opposed to making critical decisions based on surrogate indicators, such as pulse checks and blood pressure monitors. In addition, lifesaving procedures, such as transvenous pacemaker placement, are significantly easier under ultrasound guidance than by traditional means.

In the emergency environment, many patients are not present long enough for routine rescanning. However, the most critically ill patients, such as trauma, cardiac arrest and shock patients, may be scanned repeatedly to guide resuscitative efforts and assess the effectiveness of interventions made. Patients undergoing diuresis or being watched for expansion of a small pneumothorax may be easily monitored using lung ultrasound techniques with immediate real-time availability of accurate results; this is an important advantage over taking repeated chest radiographs or computed tomography (CT) scans. The confined setting of the emergency department was a primary driver of machine miniaturization in the mid-1990s. A small-footprint multipurpose machine with multiple probe options is ideal. The industry has made enormous progress in creating such machines capable of a wide range of applications, yet rugged enough to withstand intensive use, frequent relocation, and cleaning.

Documentation of ultrasound examinations, including ultrasound-guided procedures, is essential not only for reimbursement purposes but also for communication with other physicians. Use of electronic or permanent medical records is critical, and both image and video loop archiving are very helpful. A comprehensive hospital credentialing plan is mandatory to ensure proper training and quality assurance and to have a productive emergency ultrasound program in place that will aid patient care, not hinder it.[6]

Critical Care Ultrasound

Critical care ultrasound has many similarities with EU. Both are applied in seriously ill patients and are used to guide procedures. However, there are obvious differences, too. Critical care patients are present for routine rescanning; they are often hemodynamically unstable and have a tenuous respiratory function. Implementing ultrasound in ICU practice greatly augments patient assessment and monitoring, whereas its use in guiding invasive procedures dramatically improves patient safety.

CCU has several limitations. In the ICU, the physical examination is deprived of some basic elements. Patients are usually intubated under sedation and analgesia; they may have difficulty communicating or indicating pain. Mechanically ventilated patients are placed in a supine position, and thus usual ultrasound techniques that are applied in ambulatory patients may not be suitable. Moreover, access to the patient is obstructed by cables, electrodes, catheters, and so on, and, especially in trauma patients, by bandages, splints, burn wounds, and so on, rendering some acoustic windows inaccessible. Acoustic barriers such as bowel gas, subcutaneous emphysema, pneumothorax and pneumoperitoneum may affect clarity of images. Fluid overload is not an absolute barrier, although the presence of diffuse tissue edema in patients with systemic inflammatory response syndrome interferes with image quality.[9] Still, persistence in CCU is usually rewarded. For example, in patients with limited windows or excessive bowel gas, abdominal imaging can be facilitated by the use of small-footprint (phased array or microconvex) transducers and/or intercostal approaches.

Space is another common CCU issue. ICUs are replete with various devices, such as life-support equipment, ventilators, and hemodialysis units, around patient beds. To allow movement and imaging in the busy ICU, battery-powered laptop-sized equipment with small-footprint transducers is ideal. Early model laptop ultrasound machines exhibited poor resolution and image quality; recent models produce images of excellent quality and offer broader scanning options. We favor small-sized machines with reasonable purchase and maintenance costs and that provide good image quality and full application packages. Intensivists should adequately train and practice to take full advantage of this operator-dependent modality.

Prevention of cross-infections in the ICU is essential. Robust disinfection and procedural guidelines should be implemented in routine practice to avoid transmitting nosocomial pathogens (e.g., multiresistant gram-positive or gram-negative strains) between patients. CCU operators should wear gloves and avoid touching other parts of the device with the hand that holds the transducer. This is done by using one hand for handling the transducer and the other one for making system adjustments; alternatively, two operators may participate in the procedure. Operators should follow universal precautions for infection control. In ultrasound-guided invasive procedures, strict sterile protocols must be followed with the use of sterile transducer covers and gels. Upon completion of the examination, transducers must be cleaned immediately in the direction from the cable to the probe face, and disinfected according to the manufacturer's recommendations. Care and maintenance of ultrasound machines are critical.[10] Recent reports indicate the possibility of infection transfer through refillable gel bottles. Some medical facilities have decided to use only prefilled bottles and discard them once empty; this trend will likely continue.

So far we have underlined major CCU limitations. Sometimes, a limitation proves to be an advantage. Sedation and analgesia facilitate transducer manipulations in all diagnostic examinations. Ultrasound-guided invasive procedures are facilitated by alleviation of pain or discomfort. Myochalasis results in low muscle resistance, and thus applying transducer pressure to identify ROIs becomes easier (e.g., abdominal examination). Mechanical ventilation, although significantly interfering with surface chest ultrasound (Video 1-4), facilitates visualization of subcostal organs. In general, the advantages of an easy-to-perform bedside examination cannot be overstated. CCU in its full-fledged implementation is seen by us as a companion to physical examinations by clinicians who evaluate every new admission in the unit, and selective routine rescanning is imperative in most cases.[9,11,12] CCU considers likely complications and diagnoses unsuspected abnormalities, besides facilitating critical care monitoring.[13]

The Holistic Approach Ultrasound Concept

The HOLA concept of ultrasound imaging defines CCU as part of the patient examination by a clinician, to visualize all or any parts of the body, tissues, organs, and systems in their live, anatomically and functionally interconnected state and in the context of the whole patient's clinical circumstances. This concept is illustrated in Figure 1-9. Details about the various techniques that are integrated in HOLA-CCU are presented throughout this textbook.

The concept is based on the universality of ultrasound imaging and its real-time visual nature. An ICU that has implemented the HOLA concept and corresponding techniques is able to perform head-to-toe ultrasound imaging as if an imaginary "cocoon" of ultrasound beams is wrapping the entire body. In any given patient, certainly only a part of the available techniques will be clinically indicated, and most techniques and sites of generic scanning are omitted. In each patient, though, quick and simple views of certain organs and anatomic sites are necessary to rule out most common abnormalities, such as pathologic fluid in the potential spaces of pleura, abdomen, pericardium and scrotum; standardized pulmonary sites for interstitial status; and others.

The HOLA concept recognizes the generally accepted division of CCU applications into two categories: basic and advanced (or consultant-level) applications. Basic applications can be seen as either critical, lifesaving applications or focused uses that can significantly expedite care. To this end, ultrasound-guided procedures, focused echocardiography, e-FAST, and abdominal aortic aneurysm examinations may be lifesaving and are considered basic. Focused deep venous thrombosis (DVT) examinations and lung ultrasound as well as dynamic/patient management procedures, such as simple volume status assessment, expedite care and hence also belong in the basic category. Advanced echocardiography, including nonarrest transesophageal applications, is a consultant-level technique. The vast majority of comprehensive ultrasound examinations, such as biliary, renal, vascular, TCD, and open-ended/nonfocused ultrasound examinations are referred for comprehensive radiologic data collection and analysis and also fall into the consultant-level category. Thus practice of HOLA-CCU by a given unit does not mean that all studies are performed by intensivists; the critical care facility is part of the given medical system or hospital and uses radiology and other services as necessary. Although HOLA-CCU could be interpreted globally as the transducer being applicable to all surfaces and tissues, it rather defines the scope of critical care practice, while creating appropriate referrals that require additional ultrasound expertise (see Chapter 57).

In a fictional scenario described later, a sequence of ultrasound-supported physical examination is described to illustrate HOLA-CCU. Examination starts from the head

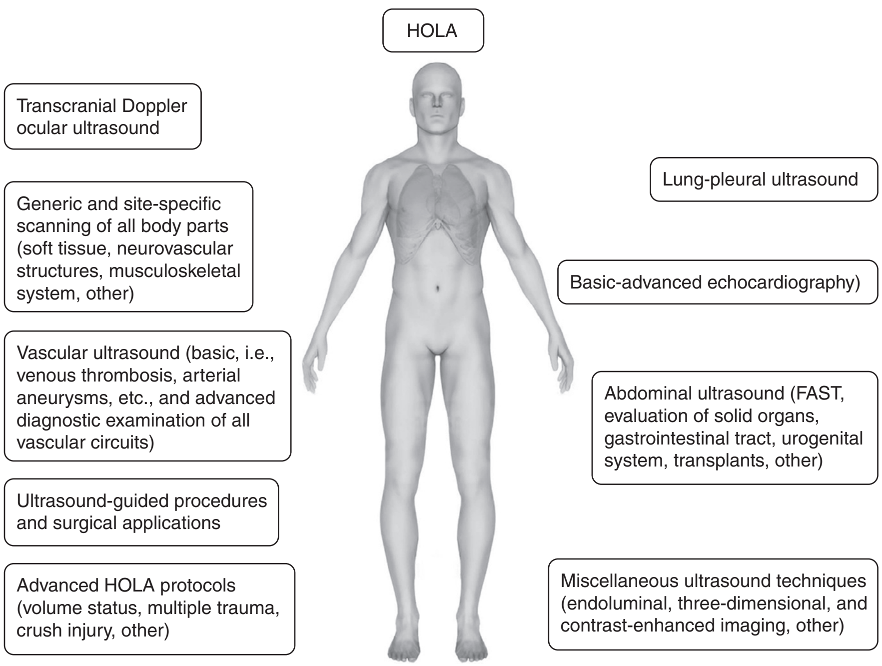

Figure 1-9 Critical care ultrasound (CCU) using a holistic approach (HOLA) concept.

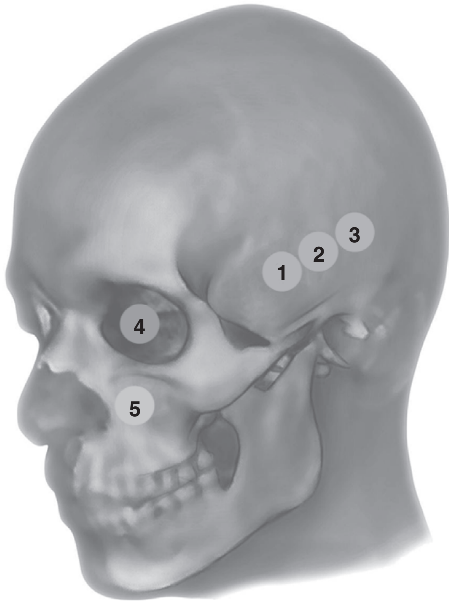

Figure 1-10 Anterior *(1)*, middle *(2)*, and posterior *(3)* temporal and ophthalmic *(4)* windows for transcranial Doppler (TCD); eye and orbit ultrasound is performed using appropriate machine settings; *(5)* examination of the maxillary sinuses and extended scanning to explore other facial structures.

(Figures 1-10 to 1-12) by accessing temporal and ophthalmic windows for TCD; eye and orbit ultrasound is performed using appropriate machine settings (see Chapters 2 to 6). Scanning of maxillary sinuses and other facial structures is also performed (see Chapter 51). Neck and upper limb exploration (Figures 1-13 to 1-19) provides information about the trachea, thyroid, soft tissues, and neurovascular and musculoskeletal structures (see Chapters 8 to 16 and 51 to 54). After both supraclavicular and infraclavicular approaches, scanning reaches the axilla and the shoulder region and is further extended to the upper limbs. The "core" of HOLA ultrasound scanning in the ICU is general chest ultrasound (Figures 1-20 to 1-24), comprising lung, pleural space, and cardiac ultrasound (see Chapters 19 to 34). Lung and pleural ultrasound explores the subpleural lung parenchyma, the diaphragm, and pleural space abnormalities. Echocardiography is essential for cardiac and pericardial pathology and for hemodynamic assessment. Abdominal scanning (Figures 1-25 to 1-28) integrates the e-FAST components for free fluid detection but also targets solids organs (e.g., spleen size), the aorta and abdominal vascular networks, the gastrointestinal tract (peristalsis, small bowel diameter and contents), and the urogenital system, as well as the peritoneum and lower pelvis (see Chapters 8 and 41 to 46). The inguinal region is often the site for vascular access and corresponding complications, such as hematomas and pseudoaneurysms. Finally, exploration of the inguinal region is protracted to the lower limbs (Figures 1-29 and 1-30). Assessing patency of venous circuits and excluding DVT is essential (see Chapters 9 and 51), whereas gathering information about musculoskeletal abnormalities is often valuable, especially in a patient with appropriate history (see Chapter 51).

Ultrasound-guided procedures and development of complex evaluation protocols[14] (e.g., combination of lung, cardiac ultrasound, and vena cava analysis, linked with clinical and laboratory data to assess volume status) are examples of clinically driven modular applications of the HOLA ultrasound concept. The latter is adjustable to meet the diagnostic and monitoring specificities of individual clinical scenarios (e.g., trauma, sepsis, etc.). HOLA-CCU is easily scaled down to specific application profiles; some of those require expert input to interpret findings that should be processed under the light of clinical judgment or require special expertise.

Although CCU routinely deals with acoustical barriers, there should be no formal or subjective barriers in the way of its implementation in routine intensive care practice. HOLA ultrasound related issues are further discussed in Chapter 57 with an inclusive set of principles to phase in and implement all CCU methods and universal generic scanning of a patient in a critical care facility. We believe that a proper mass of evidence has been reached that shows ultrasound as the "wave" moving in the direction of more vigorous, operationally responsive and efficient patient care. Appropriate application of ultrasound imaging technology can offer crucial information for diagnostic determinations as well as for optimizing management in real time. The HOLA concept is, first and foremost, a means to conceptually embrace the universality of ultrasound imaging and adopt a course toward a balanced system for its use to optimize care and improve patient outcomes, facilitate direct care by intensivists, as well as to inform health care administrators and ensure their support of rapid implementation of new powerful tools for critical care optimization.

Note: The term "holistic" in the HOLA acronym is used in its original meaning in ancient Greek, to emphasize the importance of the whole and the interdependence of its parts. The term and the acronym must not be confused with "holistic medicine," which has a different patient population, scope, and methodology. The concept of "holistic approach–critical care ultrasound," the title of the same, and the respective acronym have been suggested by Dimitrios Karakitsos (see Chapter 57). The HOLA ultrasound project has been further refined by Ashot Ernest Sargsyan, Michael Blaivas, and Dimitrios Karakitsos. We define the HOLA concept as an approach to ultrasound imaging in emergency and critical care medicine as follows: *ultrasound is part of the patient examination by a clinician, to visualize all or any parts of the body, tissues, organs, and systems in their live, anatomically, and functionally interconnected state and in the context of the whole patient's clinical circumstances.*

Pearls and Highlights

- Knowledge of basic ultrasound physics and artifacts improves scanning confidence and helps avoid pitfalls.
- High-frequency transducers are used to visualize superficial structures and low-frequency transducers for scanning deeper structures; high resolution equals less penetration.
- Ultrasound machines are easy to operate and have automated features; basic machine controls and functions are still needed for image optimization and facilitate each examination.
- Ultrasound is safe if used when clinically indicated and with minimally necessary energy exposures, following the ALARA principle (*A*s *L*ow *A*s *R*easonably *A*chievable).

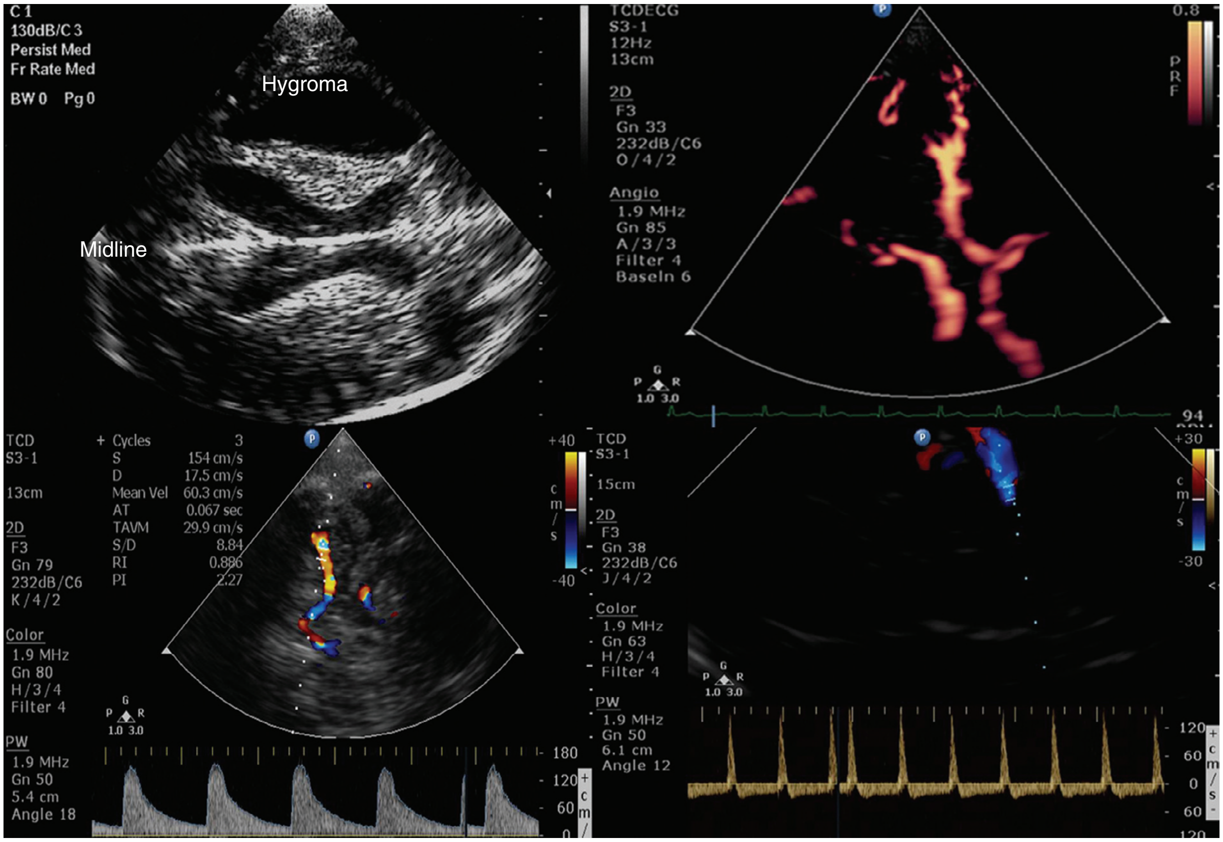

Figure 1-11 *Top*, B-mode depicting hypoechoic "butterfly-shaped" cerebral peduncles in a patient with posttraumatic hydrocephalus but no apparent shift of the midline *(left);* power Doppler showing a normal circle of Willis *(right)*. *Bottom,* Middle cerebral artery transcranial Doppler (TCD) spectral velocities demonstrating increased pulsatility index (PI) values (>2) in a patient with severe brain injury and edema *(left)* that progressed toward brain tamponade and cerebral circulatory arrest ("to-and-fro" flow patterns, *right*).

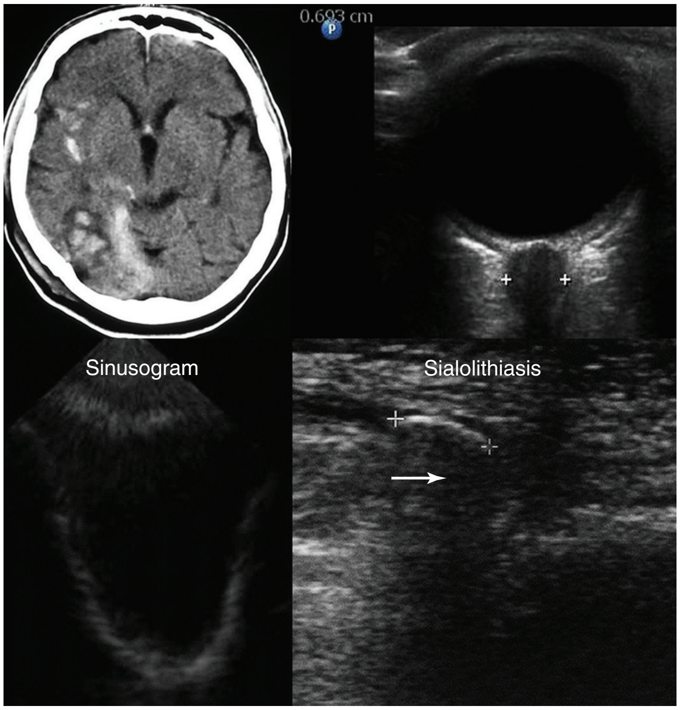

Figure 1-12 *Top*, Brain computed tomography scan demonstrating severe craniocerebral injury (Marshall scale = III, *left*) and ocular ultrasound showing increased optic nerve sheath diameter (>0.6 cm) in the same case *(right)*. *Bottom*, Visualization of the posterior and lateral walls (sinusogram) of a totally fluid-filled maxillary sinus *(left)* and view of the submandibular gland showing a dilated duct (sialolithiasis) with an intraductal stone *(arrow)* that casts an acoustic shadow *(right)*.

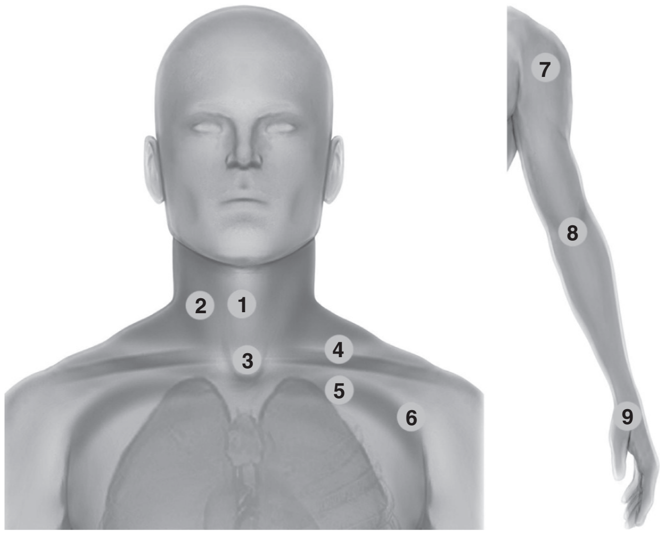

Figure 1-13 Neck scanning zones *(left):* Median line *(1)* and lateral *(2)* scanning zones; suprasternal view *(3);* supraclavicular *(4)* and infraclavicular *(5)* scanning approaches extending laterally *(6);* upper limb exploration *(7, 8,* and *9)* using the shoulder, elbow, and wrist joints, respectively, as landmarks *(right).*

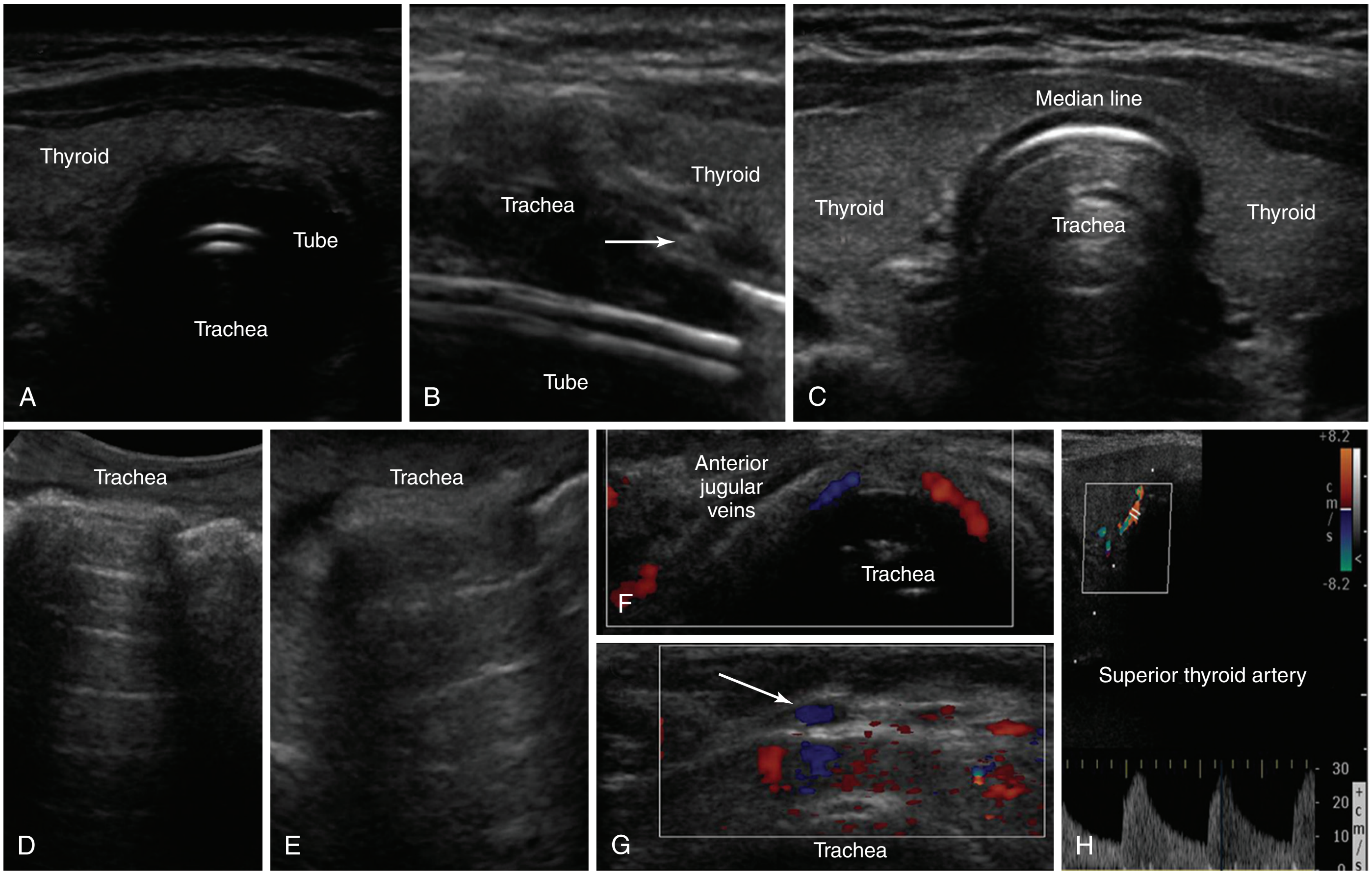

Figure 1-14 **A,** Median-line transverse view of an intubated trachea. **B,** Longitudinal view depicting the tracheal rings as a "string of beads" *(arrow)* and the endotracheal tube as echogenic parallel lines. **C,** Median-line transverse view at the level of the thyroid gland. **D** (median line) and **E** (lateral view), Oblique views of a normal trachea showing its entire anatomic configuration. Median-line transverse views demonstrating the anterior jugular veins **(F)** and tributaries *(arrow)* of the venous jugular arch, which may be helpful to identify when selecting optimal sites for performing percutaneous tracheostomy **(G)**. **H,** Depiction of a normal superior thyroid artery by color Doppler.

- Care, maintenance, and cleaning of equipment are critical.
- Most emergency ultrasound examinations are focused and ask binary questions; critical care ultrasound uses both focused techniques and complex evaluation and monitoring protocols.
- CCU is used as an adjunct to physical examination; however, ultrasound has inherent limitations related to operator abilities and the machine, patient, and ICU environment.
- The HOLA concept is based on the universality of ultrasound imaging and its real-time visual nature. In the ICU environment, HOLA is easily scaled down to specific application profiles; some of those require expert input to interpret findings that should be processed under the light of clinical judgment or require special expertise.

Acknowledgments

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For a full list of references, please visit www.expertconsult.com.

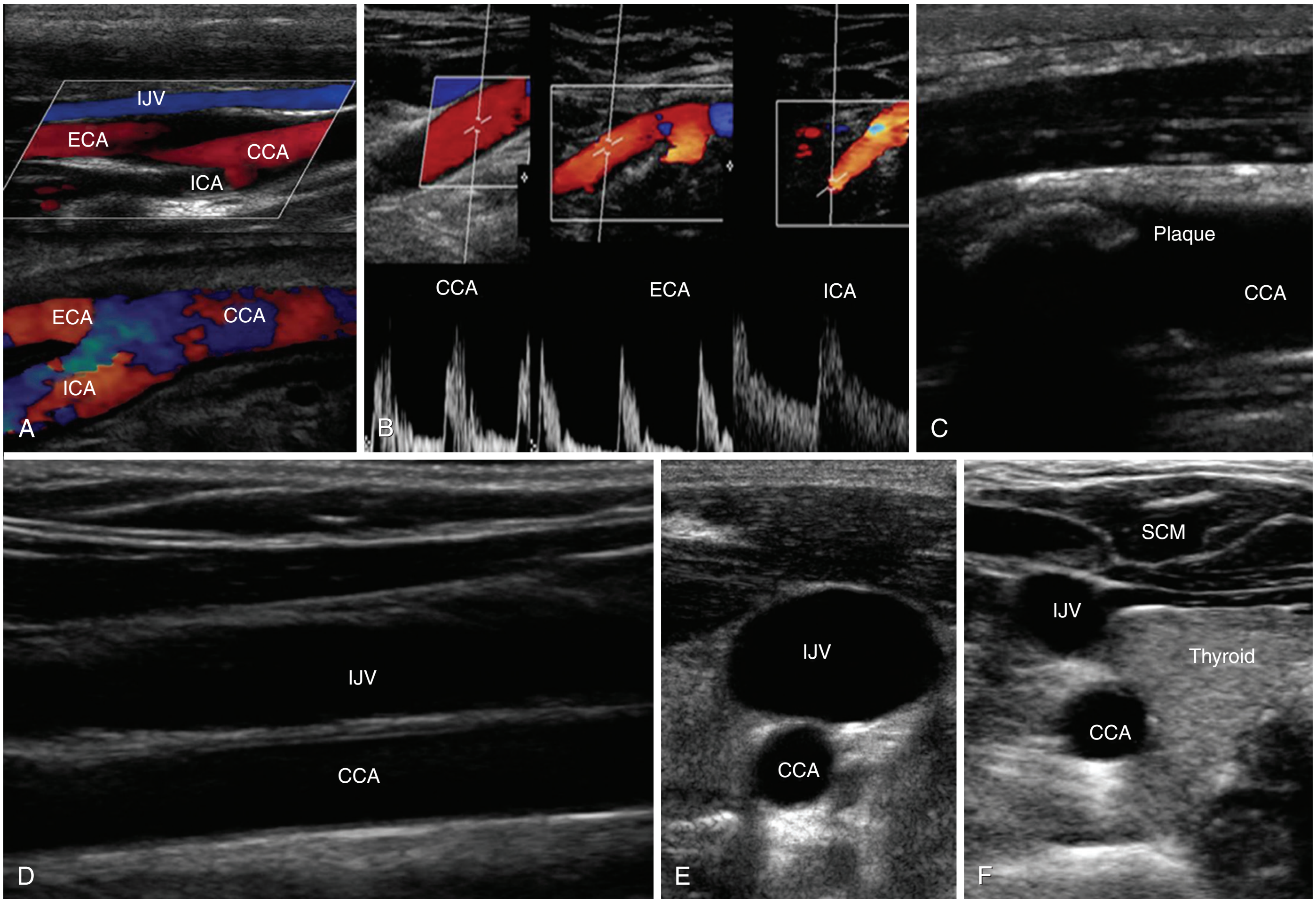


Figure 1-15 **A,** Lateral neck views of the common carotid artery (CCA) bifurcating into external carotid artery (ECA) and internal carotid artery (ICA), respectively. **B,** Doppler waveforms of the CCA, ECA, and ICA, respectively. **C,** Visualization of an atherosclerotic carotid plaque that casts acoustic shadowing. **D,** Visualization of the internal jugular vein (IJV) overlying the CCA (longitudinal view). Transverse views of the IJV and CCA showing increased and decreased IJV diameters when scanning caudally **(E)** and cranially **(F).** *SCM,* Sternocleidomastoid muscle.

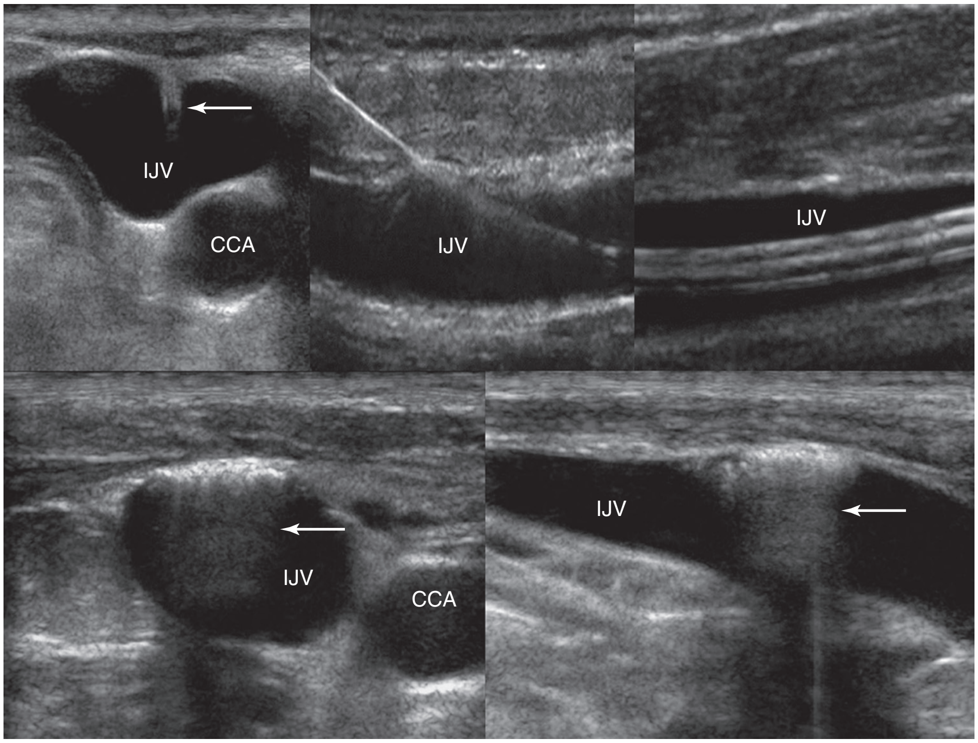


Figure 1-16 *Top, left to right,* Visualization of ultrasound-guided internal jugular vein (IJV) cannulation: longitudinal views of the vascular cannula tip (transverse view, *arrow*), wire, and triple lumen catheter, respectively. *Bottom,* Sequelae of a blind IJV cannulation: transverse and longitudinal views depicting an injury of the IJV anterior wall (hyperechoic), with trapped air enhancing posterior acoustic shadowing *(arrow).*

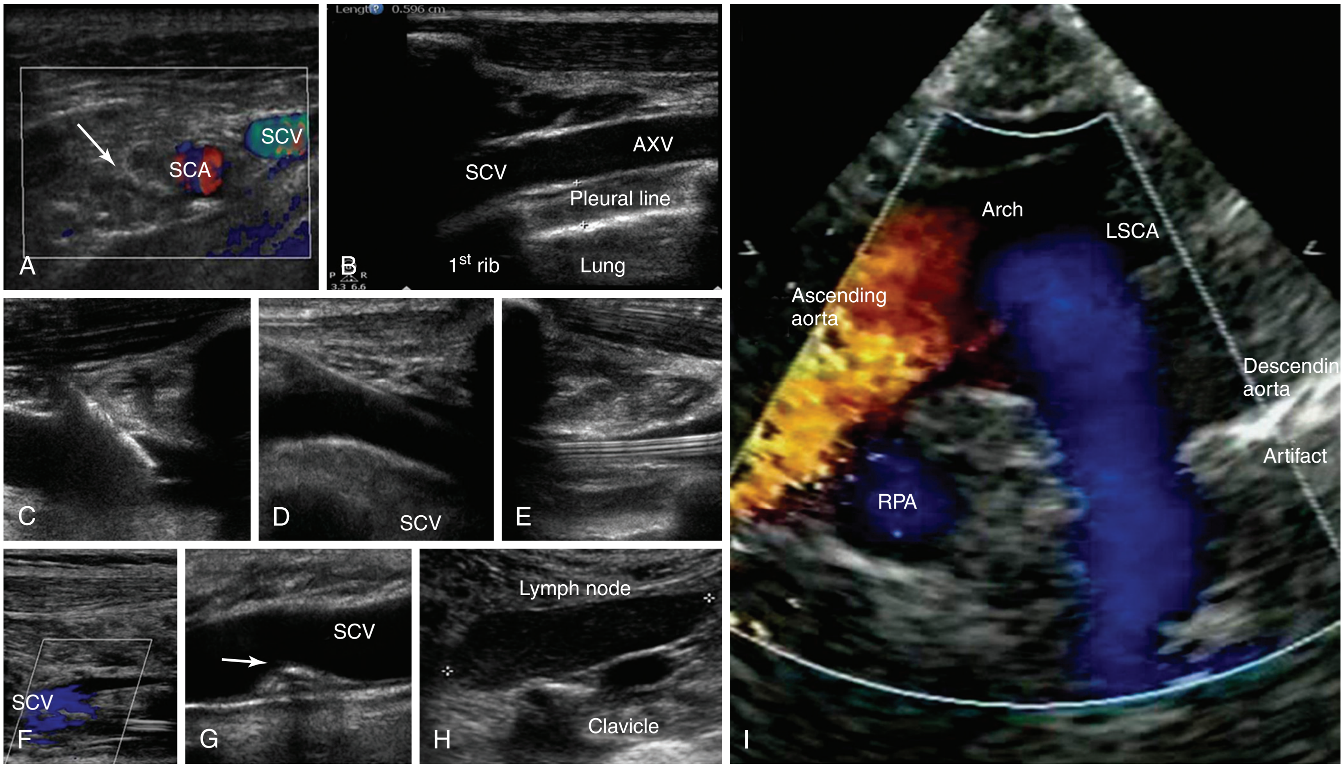


Figure 1-17 **A,** Transverse infraclavicular view of the subclavian artery (SCA), subclavian vein (SCV) and brachial plexus *(arrow)*. **B,** Longitudinal infraclavicular view of the axillary vein (AXV), which continues as the SCV (overlying the pleural line). Visualization of an ultrasound-guided SCV cannulation: longitudinal views of the vascular cannula tip **(C),** wire **(D),** and triple-lumen catheter **(E),** respectively. **F,** Depiction of partial flow in the SCV resulting from central line–associated thrombosis. **G,** Visualization of a calcified thrombi remnant *(arrow)* attached to the SCV wall (after anticoagulation treatment). **H,** Demonstration of a metastatic neck lymph node in a patient with thyroid cancer (supraclavicular view). **I,** Suprasternal view of the aorta. *LSCA,* Left subclavian artery; *RPA,* right pulmonary artery.

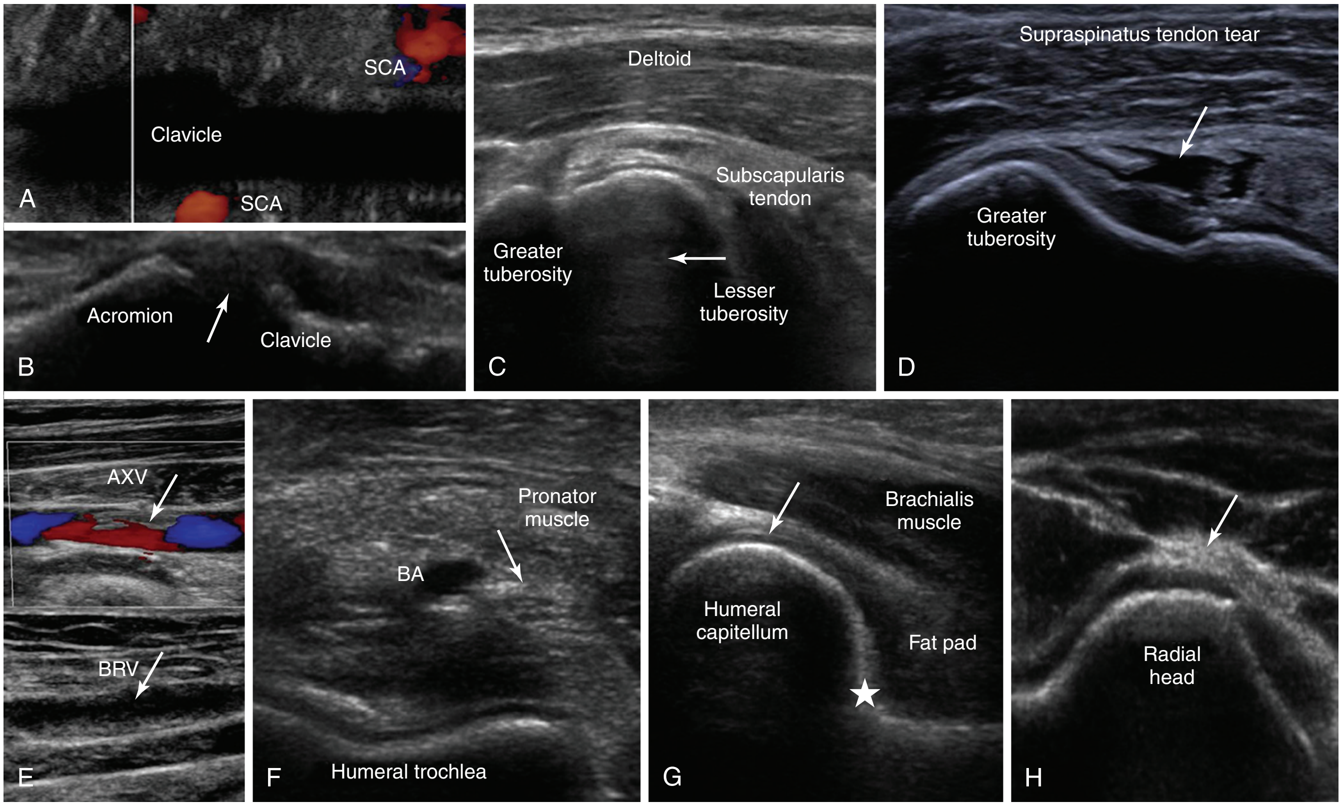


Figure 1-18 **A,** Oblique lower neck view depicting the subclavian artery (SCA) at the borders of the clavicular acoustic shadow. **B,** Coronal plane view over the acromioclavicular joint (*arrow* = joint space). **C,** Transverse view of the anterior shoulder depicting the biceps tendon's long head *(arrow)* between the lesser and greater tuberosity, respectively. **D,** Visualization of a full-thickness tear of the supraspinatus tendon in a trauma patient *(arrow)*. **E,** Partial flow in the axillary vein (AXV) resulting from thrombosis *(arrows)*, extending to the brachial vein (BRV). **F,** Transverse anterior elbow view depicting the V-shaped humeral trochlea and the brachial artery (BA), accompanied by the median nerve *(arrow)*. **G,** Medial sagittal plane of the coronoid fossa depicting the brachialis muscle and the anterior coronoid recess *(star)*, where a small amount of fluid is normally found (*arrow* = articular cartilage of distal humeral epiphysis). **H,** Lateral elbow view depicting the radial head and the posterior interosseous nerve *(arrow)*.

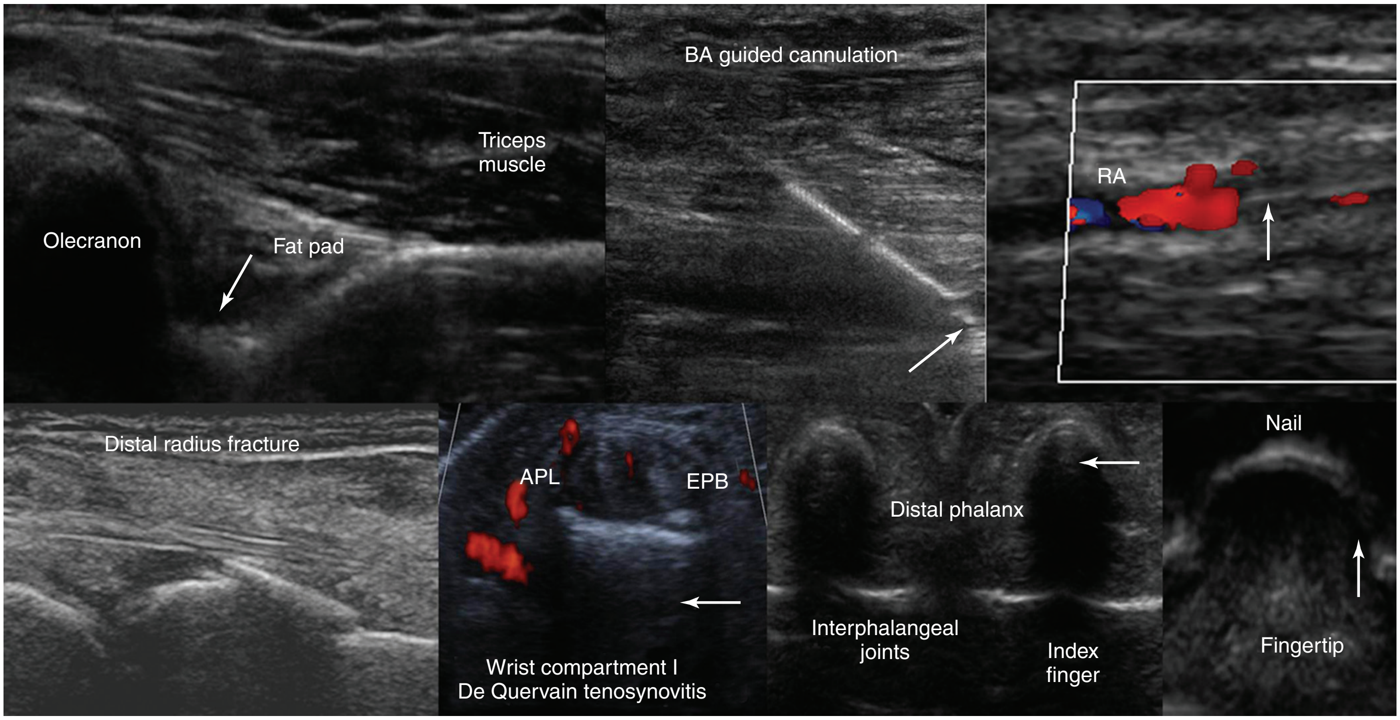


Figure 1-19 *Top, left to right*, Posterior view of the elbow (partial flexion) depicting the olecranon fossa, triceps muscle, and the posterior olecranon recess *(arrow)*; ultrasound-guided cannulation (longitudinal axis) of a brachial artery (BA) with vasospasm resulting from previous unsuccessful attempts in an obese subject with subcutaneous edema (*arrow* = artifact demonstrating the use of agitated saline and needle tip movement to confirm cannulation within the vessel lumen); longitudinal view of the lateral wrist confirming an arterial line *(arrow)* in the radial artery (RA) after guided cannulation. *Bottom, left-to-right,* Lateral/coronal long-axis scan of the distal forearm in a trauma patient, demonstrating a comminuted distal radius fracture: four distinct segments of bone with mutual misalignment, with a hypoechoic area of a likely hematoma (note the extensor pollicis brevis (EPB) tendon across the screen, parallel to the skin and the general axis of the fractured bone); focal thickening and increased vascularity surrounding the de Quervain tendons of the abductor pollicis longus (APL) and EPB at the level of the radial styloid *(arrow)* process (de Quervain tenosynovitis); transverse view of the interphalangeal joints of the index and middle fingers (*arrow* = vincula tendinum); "sonographic fingertip": transverse view (inverted) of the index finger's tip and nail (*arrow* = eponychium).

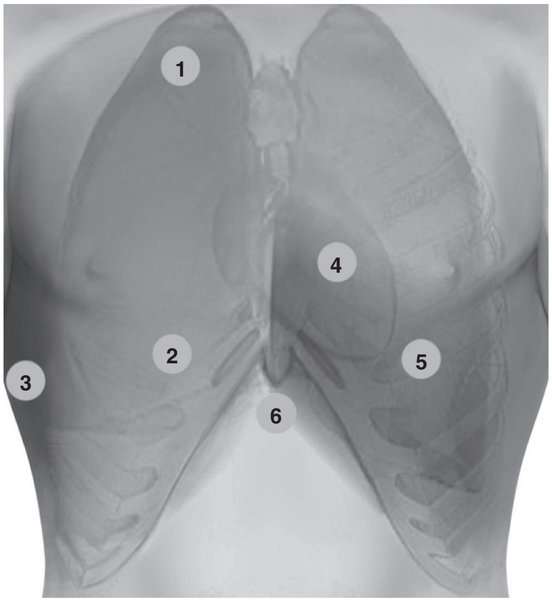


Figure 1-20 *Lung ultrasound*: Scanning the anterior chest from the lower clavicular border *(1)* to the upper border of subcostal spaces *(2),* bilaterally. *Pleural ultrasound*: flank views *(3)* advancing from the diaphragm (discrimination point between pleural and peritoneal effusions) to the axilla and from the anterior to the posterior axillary lines (including prone views if applicable). In lung ultrasound examination, it is useful to adopt a systematic scanning protocol by dividing the lung into six regions (upper and lower scans of the anterior, lateral, and posterior regions), which are further outlined by the anterior and posterior axillary lines. *Transthoracic echocardiography*: The standard parasternal approach *(4)* is obtained by placing the transducer 2 to 3 inches to the left of the sternum in the fourth or fifth rib interspace. Apical views *(5)* are obtained by placing the transducer on the fifth intercostal space (approximately left midclavicular line at the point of maximal impulse). In the intensive care unit, the above-mentioned windows are usually improvised (by sweeping the transducer to adjacent sites to visualize the heart) because mechanically ventilated patients are usually in a supine position with 30-degree head-up positioning. Hence the heart is displaced rather caudally. Image acquisition can be difficult because of the effect of mechanical ventilation and various other common lung pathologies (e.g., emphysema, acute respiratory distress syndrome). Alternatively, subcostal and subxiphoid views *(6)* can be used to visualize the heart.

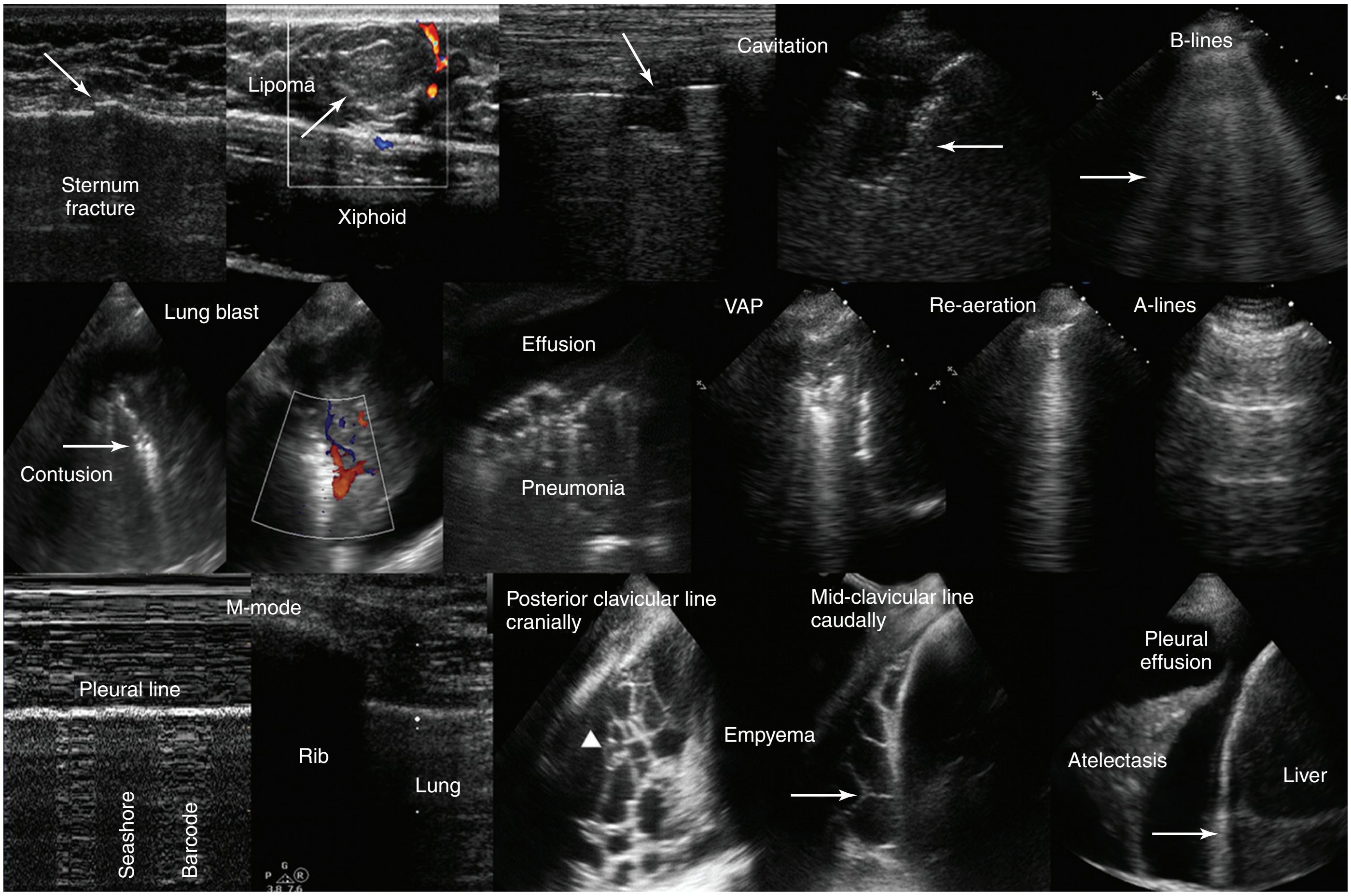
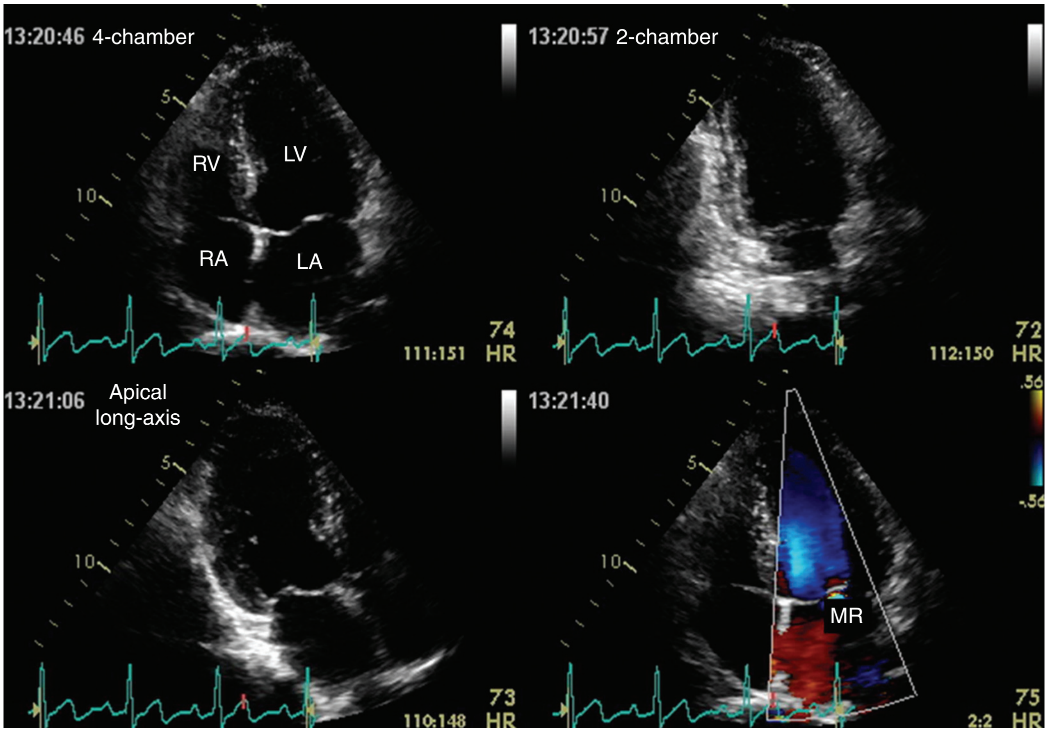


Figure 1-21 *Top, left-to-right*, Chest scanning. Visualization of a sternum fracture *(arrow);* superficial lipoma *(arrow)* over the xiphoid process; disruption of the pleural line *(arrow)* resulting from a cavitation in a patient with pneumonia (*Klebsiella* species); B-lines *(arrow)* in a patient with interstitial lung edema. *Middle, left-to-right*, Visualization of a lung blast after blunt thoracic trauma, showing a consolidation pattern of increased density with hyperechoic punctiform elements *(arrow)* and normal vascularity; visualization of pleural effusion and lung consolidation with air-bronchogram (pneumonia); demonstration of lung consolidation and atelectasis in a patient with ventilator-associated pneumonia (VAP). In the latter, after recruitment maneuvers, a B-line pattern was observed (re-aeration), and consequently an A-line pattern was evident as pneumonia subsided (normal lung). *Bottom, left-to-right*, Demonstration of the lung point by M-mode (pneumothorax): There is a fluctuation over time between "seashore" and "barcode" patterns with the transducer stationary; right flank views depicting an empyema with honeycomb appearance *(arrowhead)* and septa formation *(arrow);* and visualization of lung atelectasis floating within a pleural effusion (*arrow* = diaphragm).

Figure 1-22 Apical views of a normal heart depicted by transthoracic echocardiography. *Top*, Four-chamber (*left*) and two-chamber (*right*) views. *Bottom*, Apical long-axis view *(left)* and demonstration of mitral valve regurgitation (MR, *right*) on color mode. *LA,* Left atrium; *LV,* left ventricle; *RA,* right atrium; *RV,* right ventricle. *(Courtesy Dr. A. Patrianakos.)*



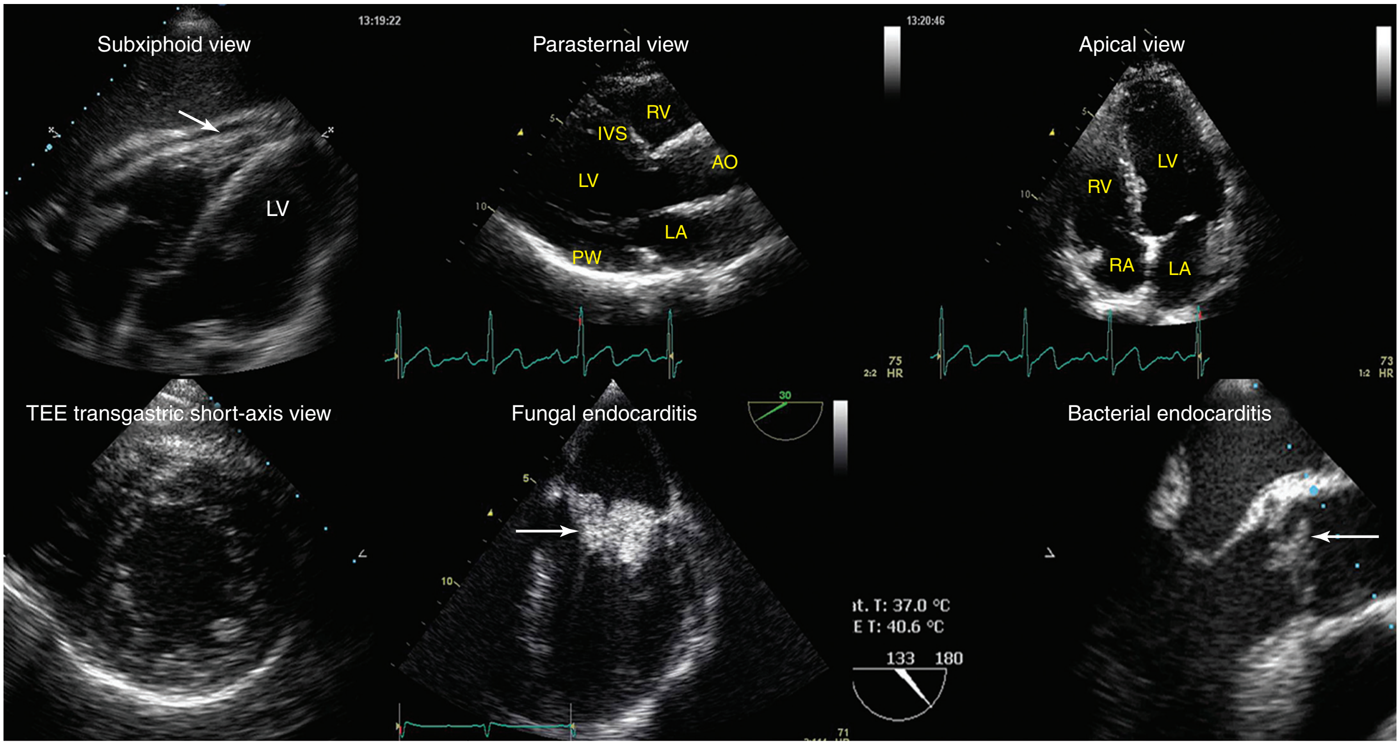


Figure 1-23 *Top, left-to-right*, Transthoracic echocardiography views. Subxiphoid view depicting a small pericardial effusion *(arrow);* parasternal and apical views of a normal heart, respectively (*AO*, Ascending aorta; *IVS*, intraventricular septum. *Bottom, left-to-right*, Transesophageal echocardiography views: transgastric short-axis view of a normal heart; midesophageal views demonstrating fungal endocarditis of the mitral valve, and bacterial endocarditis of the aortic valve, respectively *(arrows*). *LA*, left atrium; *LV*, left ventricle; *PW*, posterior wall; *RA*, right atrium; *RV*, right ventricle.

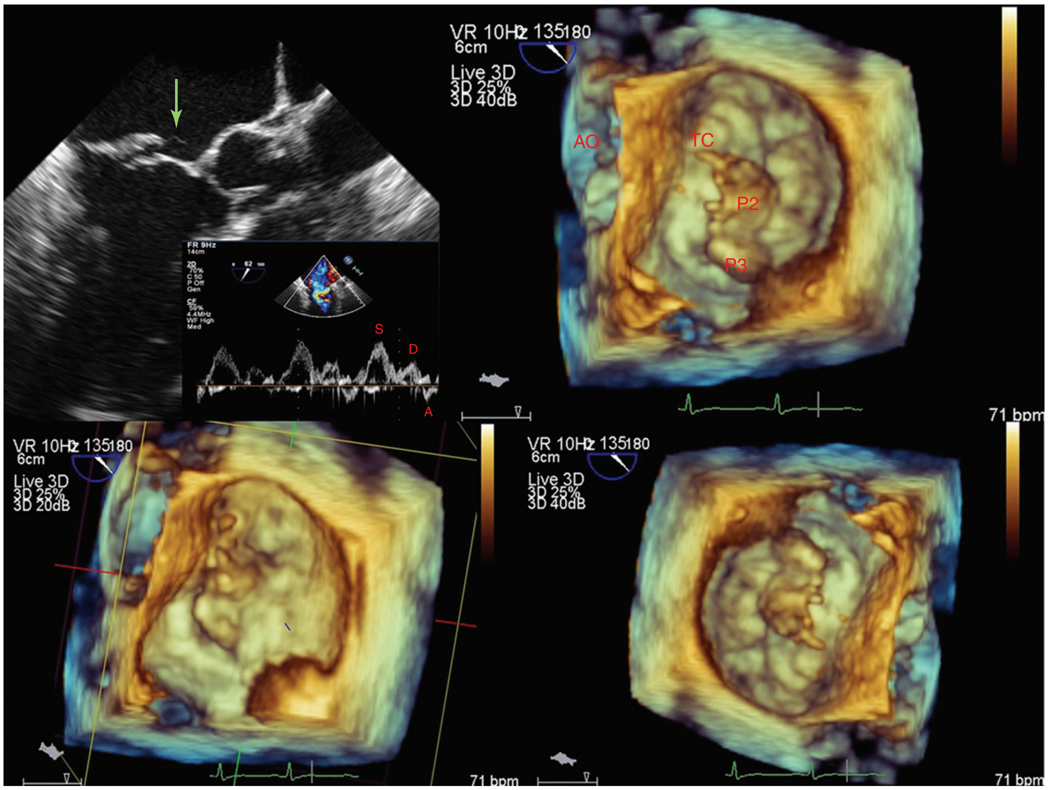


Figure 1-24 A tendinous chord rupture *(green arrow)* causing acute mitral valve regurgitation (*top left*), which is further visualized by three-dimensional transesophageal echocardiography at the level of the annulus. *AO*, Aorta; *P2* and *P3*, scallops of the posterior leaflet, which are the widest around the annulus; *TC*, tendinous chord.

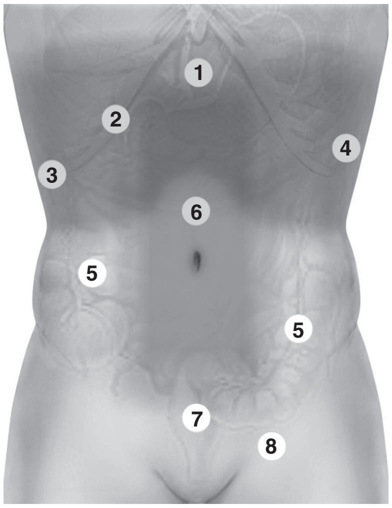


Figure 1-25 Holistic approach (HOLA) abdominal scanning paths (refer also to Figures 1-26 and 1-27). *1*, Upper abdominal scans. *2*, Extended intercostal and right subcostal oblique scans. *3* and *4*, Right and left flank scans, respectively. *5*, Small and large intestine scanning paths. *6*, Scan of the abdominal vessels (midabdominal). *7*, Suprapubic and lower pelvic views. *8*, Scan of the inguinal area.

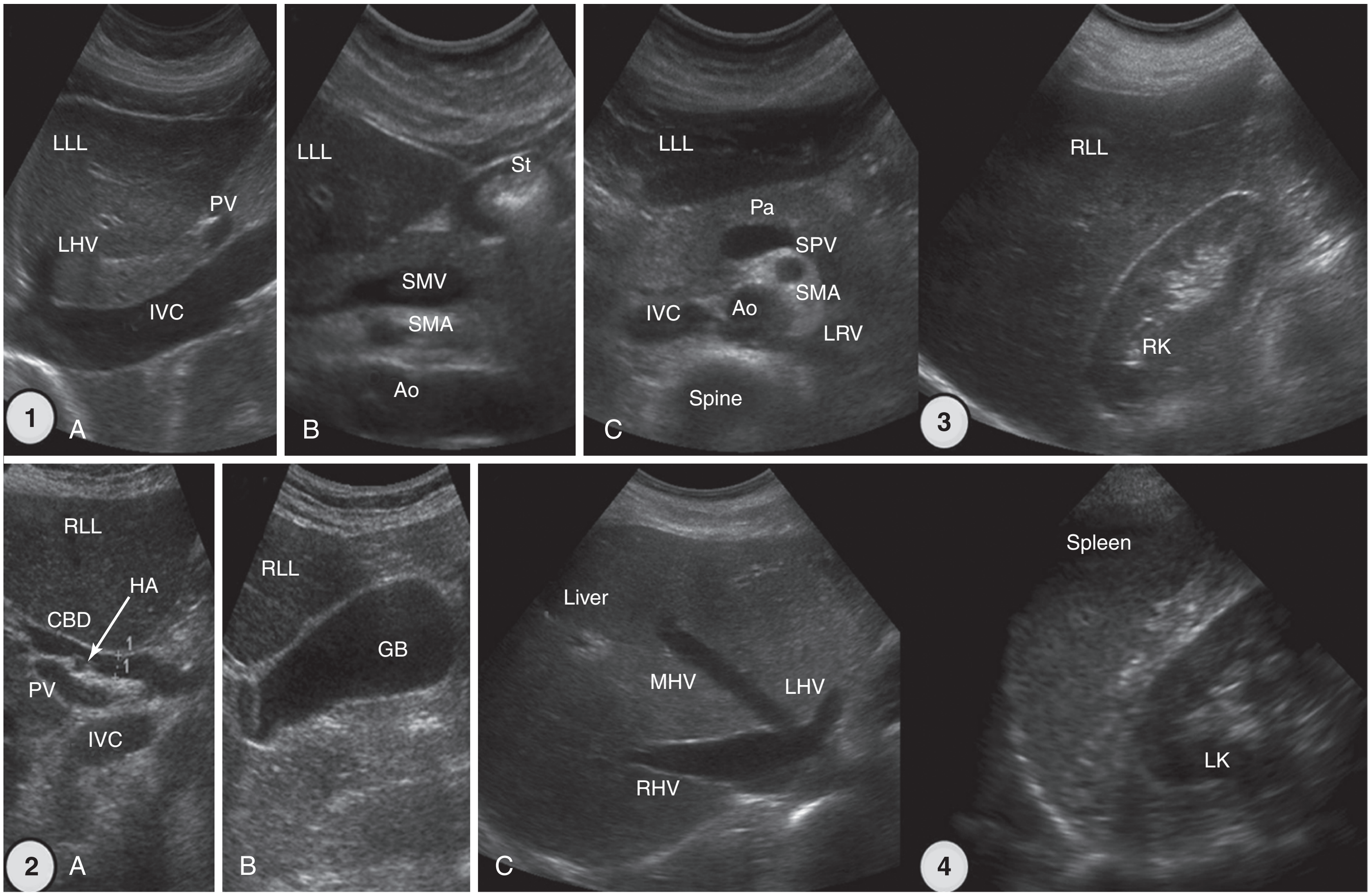


Figure 1-26 *1*, Upper abdominal longitudinal and transverse scans. *2*, Extended intercostal scans (**A** and **B**) and right subcostal oblique scan **(C).** *3*, Right flank scan. *4*, Left flank scan. *Ao*, Aorta; *CBD*, common bile duct; *GB*, gallbladder; *HA*, hepatic artery; *IVC*, inferior vena cava; *LHV*, left hepatic vein; *LK*, left kidney; *LLL*, left liver lobe; *LRV*, left renal vein; *MHV*, middle hepatic vein; *Pa*, pancreas; *PV*, portal vein; *RK*, right kidney; *RHV*, right hepatic vein; *RLL*, right liver lobe; *SMA*, superior mesenteric artery; *SMV*, superior mesenteric vein; *SPV*, splenic vein; *St*, stomach, gastric antrum.

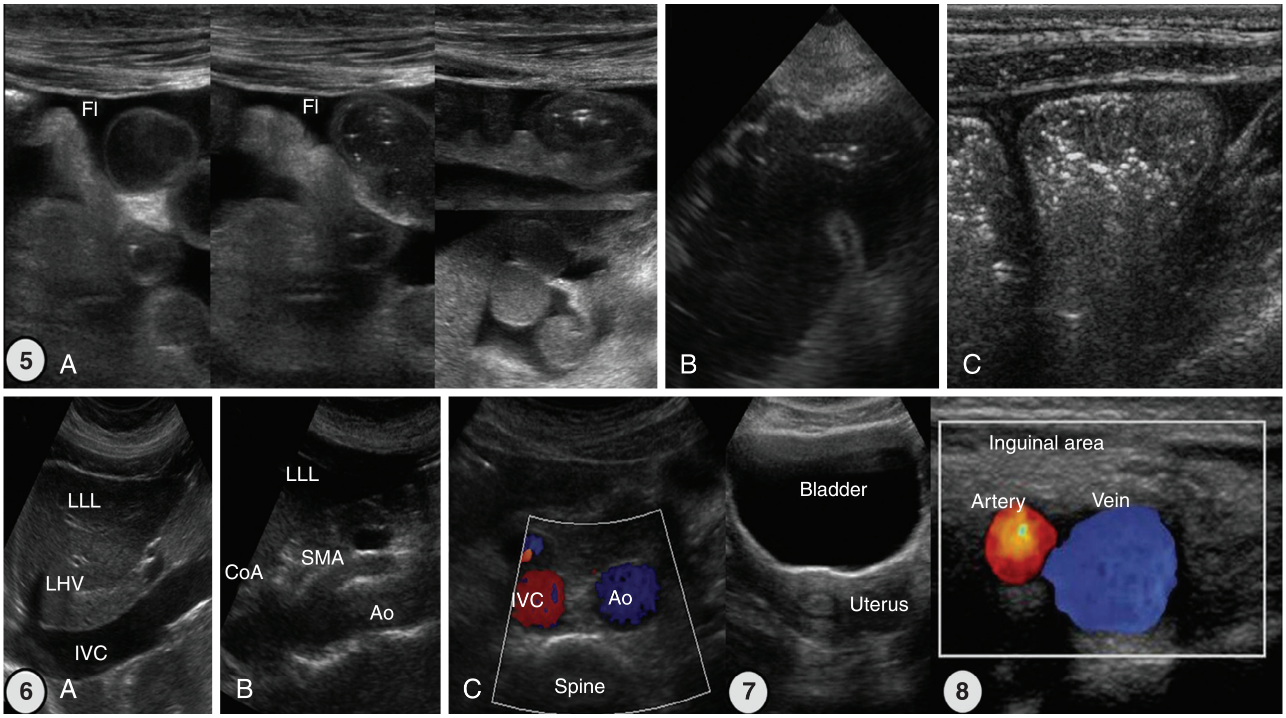


Figure 1-27 *5,* Scans of the small and large intestine. **A,** Small intestinal loops are well visualized because of intraperitoneal fluid. **B,** Caecum. **C,** Ascending colon with typical haustration. *6,* Vascular scanning path (midabdominal): longitudinal (**A** and **B**) and transverse **(C)** views. *7,* Suprapubic view of the bladder and uterus. *8,* Landmarks of inguinal area: common femoral artery and vein. *Ao,* Aorta; *CoA,* celiac artery; *Fl,* fluid; *IVC,* inferior vena cava; *LHV,* left hepatic vein; *LLL,* left liver lobe; *SMA,* superior mesenteric artery.

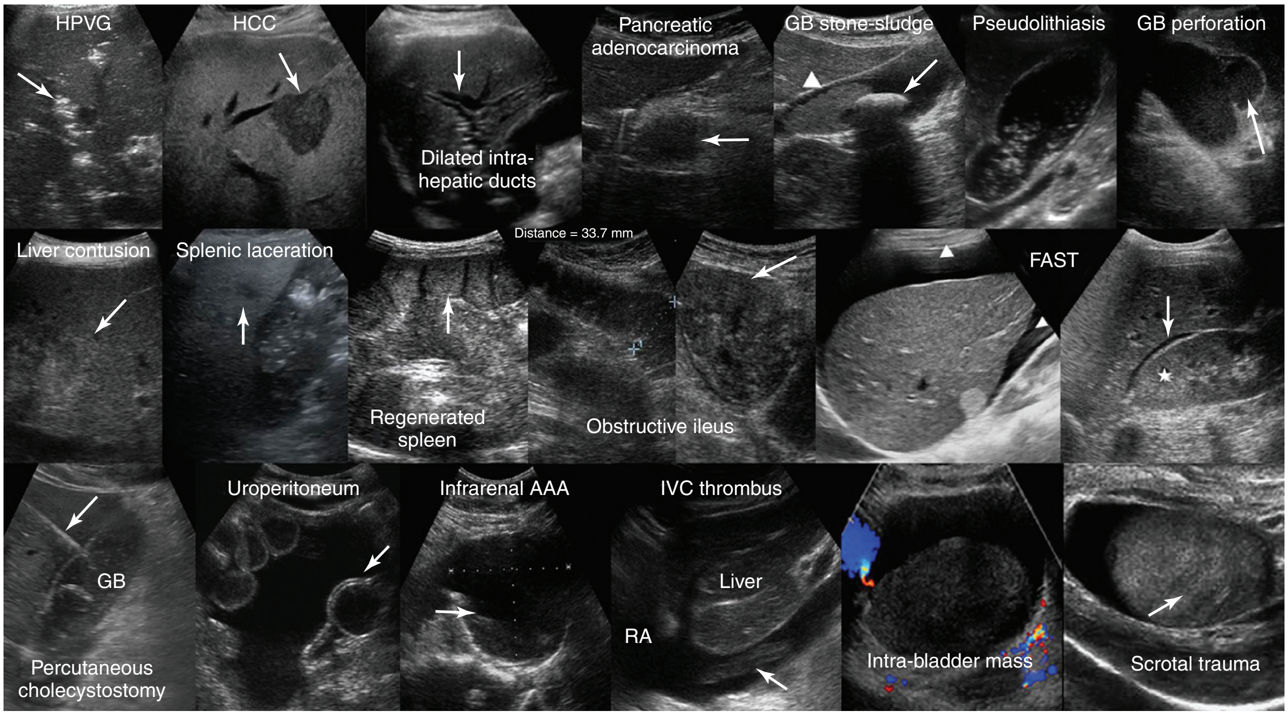


Figure 1-28 *Top, left to right,* Hepatic portal venous gas (HPVG) depicted as patchy highly reflective areas in the right liver lobe *(arrow);* visualization of hepatocellular carcinoma (HCC) as an hypoechoic liver mass *(arrow);* dilation of the intrahepatic ducts *(arrow);* visualization of an hypoechoic mass *(arrow)* at the head of pancreas (adenocarcinoma); solitary gallbladder (GB) stone *(arrow)* with acoustic shadowing and dense sludge *(arrowhead);* layer of nonshadowing midlevel echoes in the GB (pseudolithiasis); subacute GB perforation *(arrow). Middle, left-to-right,* Visualization of heterogeneous liver parenchyma *(arrow)* in a patient with liver contusion; visualization of heterogeneous splenic parenchyma *(arrow)* and perisplenic fluid delineating adjacent bowel loops (splenic laceration); a fully regenerated *(arrow)* orthotopic spleen (15 years postsplenectomy); obstructive ileus: dilated small intestinal loops resulting from a large tumor *(arrow);* focused assessed sonography for trauma (FAST) views of large perihepatic and Morison pouch effusions *(arrowheads)* as well as of a small effusion in the latter (*star* = kidney). *Bottom, left-to-right,* Visualization of a percutaneous cholecystostomy catheter *(arrow)* entering the inflamed GB in a patient with acute cholecystitis. Uroperitoneum resulting from spontaneous bladder rupture, delineating normal bowel loops (*arrow* = balloon of indwelling bladder catheter); sagittal view of a huge infrarenal abdominal aortic aneurysm (AAA) with mural thrombus *(arrow);* fresh floating thrombus *(arrow)* in the inferior vena cava (IVC) "migrating" toward the right atrium (RA); intrabladder mass without any evidence of blood flow (hematoma) that dissolved after normal saline irrigation. Heterogeneous testicular parenchyma *(arrow)* and hypoechoic fluid collection (hematoma) in a male patient with scrotal trauma. *(Top row: Images of HCC and subacute perforation courtesy Dr. K. Shanbhogue. Bottom row: Image of acute cholecystitis courtesy Dr. S. Dissanaike. Image of intrabladder mass courtesy Dr. K. Shanbhogue.)*

Figure 1-29 Lower limb examination. *1*, Exploration of the inguinal area and hip joint. *2* and *3*, Extending scanning distally, using the knee and ankle joints as landmarks.

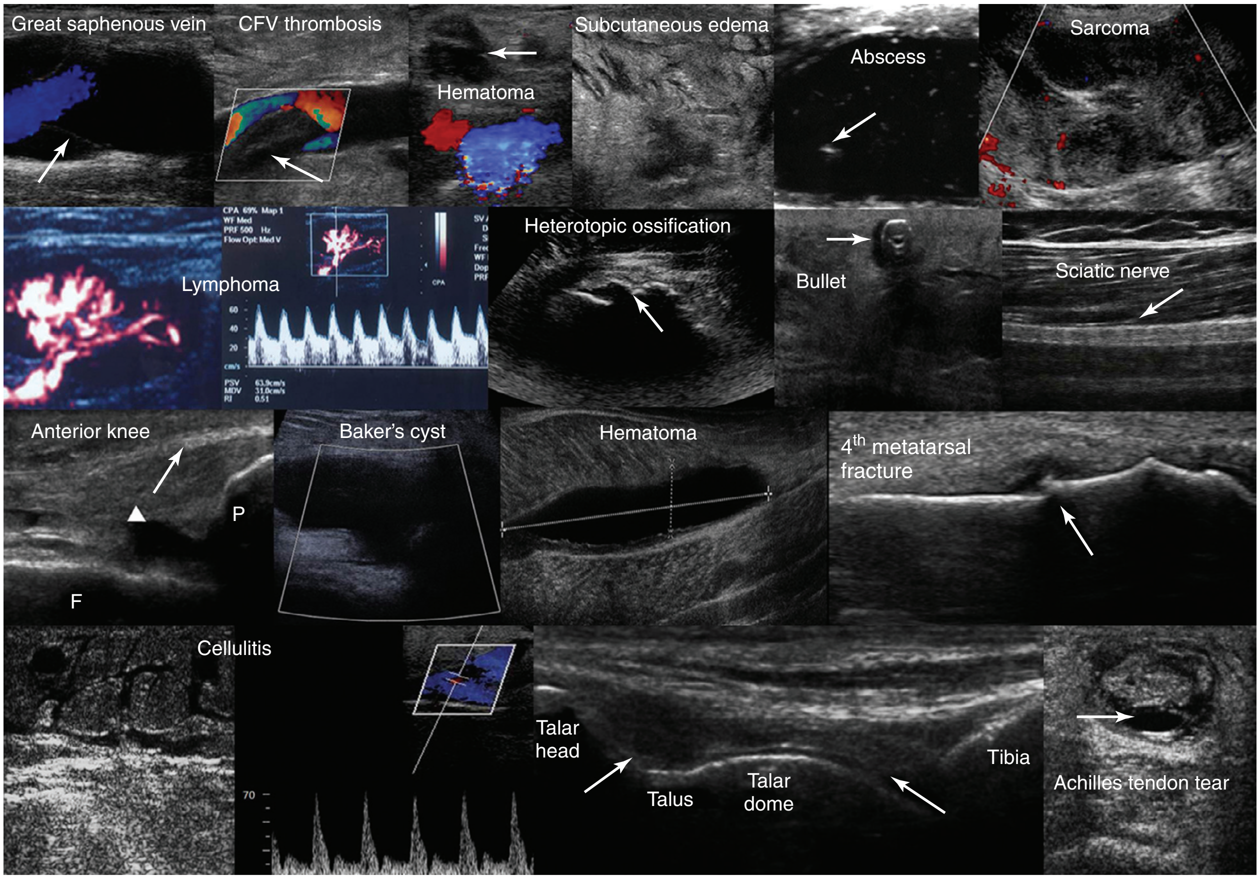


Figure 1-30 *Top row, left to right*, Depiction of normal venous flow in the great saphenous vein (*arrow* = valve); visualization of fresh thrombus in the common femoral vein (CFV); groin hematoma *(arrow)* overlying the common femoral artery and vein; cobblestone appearance of the subcutaneous tissue (inguinal area) resulting from edema; subcutaneous hypoechoic cyst (abscess) with hyperechoic punctiform material *(arrow)*. Hypoechoic groin tumor with ill-defined borders (sarcoma). *Second row, left to right*, Lymph node with a Doppler-derived RI = 0.51 (power Doppler mode) that was initially characterized as reactive and eventually proved (biopsy) to be malignant (lymphoma) with cystic necrosis. The "zone phenomenon" in heterotopic ossification: The inner hypoechoic core is surrounded by hyperechoic mineralized islands *(arrow)* within the iliopsoas muscle adjacent to the hip joint. Visualization of a bullet in the area of the thigh casting an acoustic shadow (*arrow*, "halo" sign); posterior aspect of the thigh (longitudinal plane) illustrating the sciatic nerve *(arrow)*. *Third row, left to right*, Longitudinal anterior knee view depicting the femur *(F)*, patella *(P)*, suprapatellar synovial recess *(arrowhead)*, and the distal third of the quadriceps tendon *(arrow)*; visualization of a cystic structure (absent blood flow), between the medial gastrocnemius and semimembranosus tendon, in the popliteal fossa (Baker cyst); visualization of a liquefying hematoma in the gastrocnemius muscle; longitudinal image (dorsal approach) of the fourth metatarsal bone, depicting a cortical discontinuity with step deformity and adjacent tissue damage and edema (fracture). *Bottom row, left-to-right,* Cobblestone appearance of the subcutaneous tissue (tibial area) and unusually increased peak systolic velocity derived by color Doppler in a local perforator (cellulitis); midlongitudinal plane over the dorsum of the ankle joint, showing the talar dome and the anterior recess of the tibiotalar joint *(arrows)*; transverse view of a full-thickness Achilles tendon tear (*arrow* = hematoma). *(Top row: Image of subcutaneous hypoechoic cyst courtesy Dr. J. Poularas. Image of hypoechoic groin tumor courtesy Dr. K Shanbhogue. Second row: Image of bullet in thigh courtesy Dr. K. Shanbhogue.)*

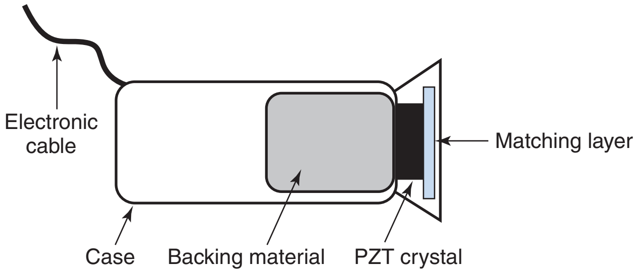


Figure 1 E-1 The basic components of a transducer.

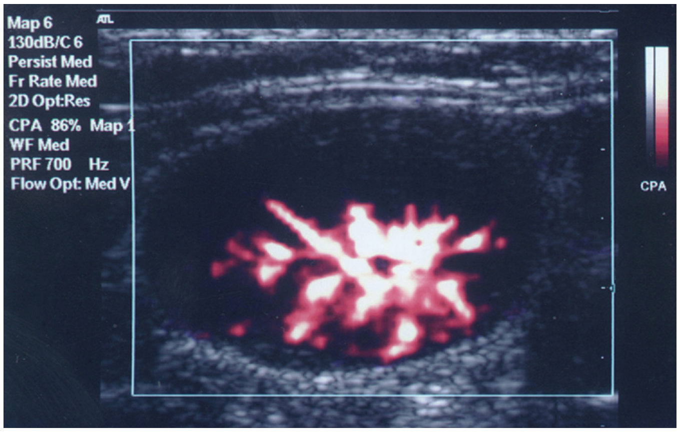


Figure 1 E-2 Power Doppler demonstrating slow flow patterns in a lymph node.

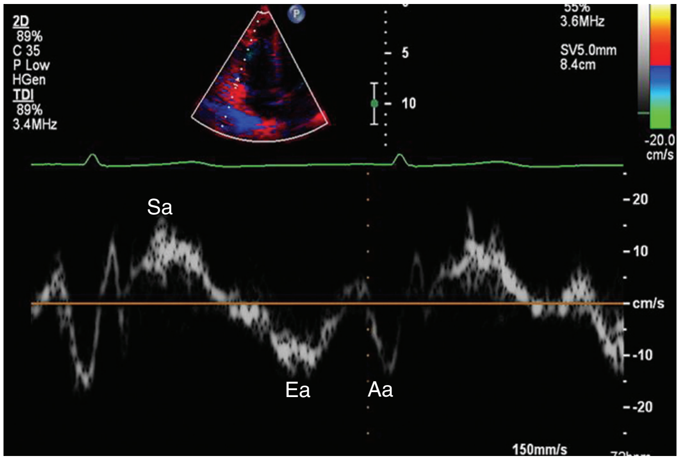


Figure 1 E-3 Pulsed wave, tissue Doppler imaging–derived myocardial velocities (peak myocardial velocities during systole = Sa, early = Ea, and late = Aa diastole, respectively) obtained adjacent to the tricuspid annulus (echocardiography). Reduced velocities have been documented in several disorders, such as postinferior myocardial infarction, chronic pulmonary hypertension, and chronic heart failure.

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SECTION II

Neurocritical Care

2

Transcranial Doppler Ultrasound in Neurocritical Care

JEFFREY BODLE | ZSOLT GARAMI | DIMITRIOS KARAKITSOS | CHRISTOS LAZARIDIS

Overview

In 1982, Aaslid et al[1] authored a paper with the title "Noninvasive transcranial Doppler ultrasound recording of flow velocity in basal cerebral arteries," describing the successful insonation and blood flow velocity (FV) measurement of the basal cerebral arteries with a range-gated Doppler transducer. These authors located an "ultrasonic window" above the zygomatic arch and 1 to 5 cm anterior to the ear, through which a 2-MHz ultrasonic pulse could be emitted and recorded. The velocity and direction of blood flow were recorded as a spectral display as recorded by the ultrasound transducer. Measurement of FV as well as direction of flow during unilateral common carotid artery (CCA) compression enabled Aaslid et al[1] to describe collateral flow as well as "steal" dynamics in real time by using transcranial Doppler (TCD). They noted that compression of the CCA resulted in decreased velocity in the ipsilateral middle cerebral artery (MCA), reversal of flow or "steal" in the ipsilateral terminal internal carotid artery, as well as increase in velocity in both the ipsilateral anterior and posterior cerebral arteries, suggesting a contribution to collateral flow through the circle of Willis.[1]

Basic Principles

TCD technology is based upon the Doppler effect principle, in which the ultrasound transducer emits a frequency, *fo*, and this frequency is reflected back to the probe as *fe*. The difference between the emitted and received frequencies, or the Doppler shift, *fd*, can be calculated as $fd = fe - fo$ (see Chapter 1). Pulsed wave Doppler refers to an ultrasound transducer that emits and receives the reflected ultrasound pulse. By using a pulsed wave Doppler, TCD can be performed at variable depths to follow the course of cerebral blood vessels. The frequency refers to the number of cycles a sound wave goes through per second. A higher frequency is used to insonate more peripheral vessels, and a lower frequency is able to insonate deep cerebral vessels. The sample volume size refers to the width of the area being insonated and is measured in millimeters (e.g., a sample volume size of 2 mm will give a more precisely localized signal compared with a sample volume size of 6 mm). The intensity or power of the ultrasound wave refers to the energy emitted through the tissue being insonated. This energy is absorbed by the tissue and converted mainly to heat. The U.S. Food and Drug Administration (FDA) regulates the amount of energy able to be transmitted by ultrasound equipment to ensure patient safety (ALARA [*A*s *L*ow *A*s *R*easonably *A*chievable] principle). Ultrasound over the eye or under the chin must be used at a lower power because these locations are not covered by bone, thus exposed to greater intensity. Attenuation refers to the decrease in intensity as the ultrasound wave passes through tissue and is higher for muscle and bone and lower for fluid-filled vessels. Based on attenuation, the reflected wave will be weaker for deeper vessels.[2]

Acoustic Windows

Acoustic windows are naturally occurring areas of cerebral bone thin enough to allow transmission of ultrasound waves. There are three commonly used acoustic windows: transtemporal, transorbital, and transforaminal. Up to 10% of people may not have adequate acoustic windows. The transtemporal window allows insonation of the anterior, middle, and posterior cerebral arteries; the transorbital window is used to insonate the ophthalmic artery as well as the cavernous portion of the internal carotid artery; and the transforaminal window allows insonation of the vertebral and basilar arteries (Figure 2-1).

Transcranial Doppler Interpretation

Evaluation of cerebral hemodynamics with TCD is quick to perform, noninvasive, and relatively inexpensive compared with computed tomography, digital subtraction angiography, and magnetic resonance imaging. Parameters including waveform morphology, pulsatility index, direction of flow, and turbulence allow the interpreting physician to make inferences regarding clinically significant vascular characteristics, including stenosis, vasospasm, intracranial cerebrovascular resistance, cerebrovascular autoregulation, proximal and/or distal vessel occlusion, and presence of microemboli.

WAVEFORM MORPHOLOGY

The waveform recorded by TCD reflects both systole and diastole, with systole represented by the upstroke and peak of the wave, and diastole represented by the decelerating downslope of the wave (Figure 2-2). The morphology of the waveform demonstrates valuable information regarding cerebral blood flow, with a normal systolic upstroke being a quick upstroke climaxing into a peak. An upstroke that is slow and dull could be representing a proximal obstruction or focal stenosis when seen in a single vessel or may be an indication of a global low-flow state resulting from cardiac dysfunction when a widespread finding. Hassler et al[3] described TCD waveform changes in the setting of intracranial hypertension. As diastolic pressure rises to approach the intracranial pressure (ICP), end-diastolic flow decreases and results in three stages of waveform changes: initially a decrease, followed by cessation, and lastly a reversal of flow (Figure 2-3). This reversal is seen in severe intracranial hypertension near *cerebral circulatory arrest* (see Chapter 4),

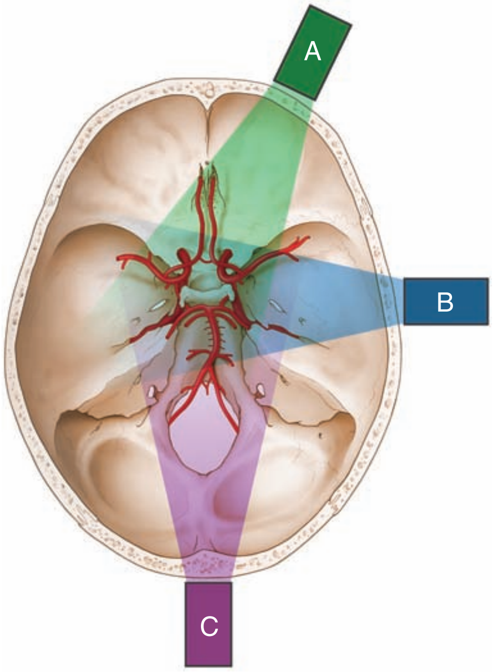

Figure 2-1 Graphic representation of commonly used windows for insonation.

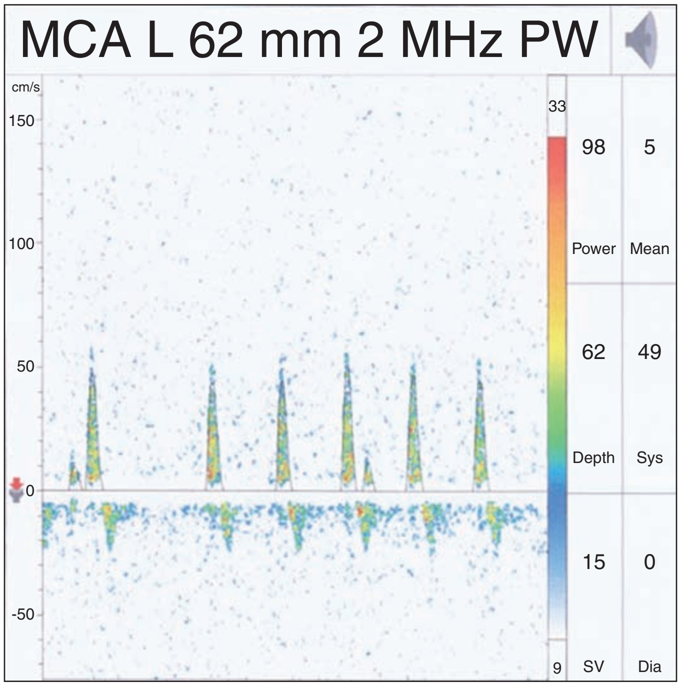

Figure 2-3 Cessation and reversal of diastolic flow, near cerebral circulatory arrest.

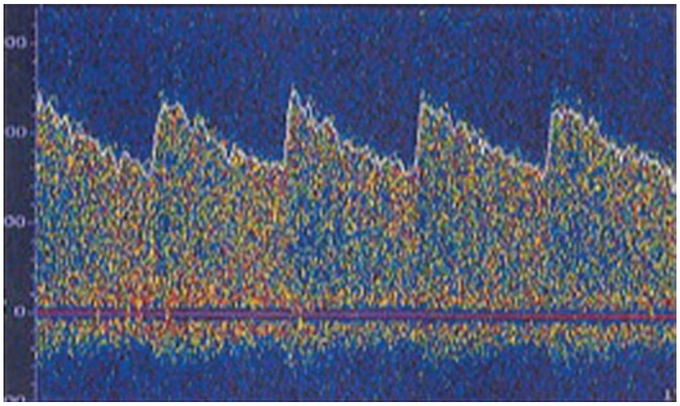

Figure 2-2 Normal morphology flow velocity waveform from the middle cerebral artery.

when the diastolic pressure rises higher than the ICP and has been coined "diastolic flow obliteration."[3]

THE PULSATILITY INDEX

Absolute pulsatility is difficult to assess by Doppler ultrasound because the amplitude of the pulsatile blood flow velocity is dependent on the angle of insonation. Gosling and King[4] proposed an angle-independent index, known as the Gosling index of pulsatility (PI), and defined it as the difference of peak systolic and lowest diastolic flow velocities referenced to time-averaged flow velocity ([FVsys − FVdia]/FV).[4] A number of earlier studies linked the PI with distal cerebrovascular resistance (CVR), suggesting an increasing index as a reflection of an increasing resistance and vice versa.[5,6] However, several settings have been reported where the link between PI and CVR was either weak or in the reverse direction than expected; *giving rise to the suspicion that the PI is not a pure measure of downstream resistance.*[7,8] Czosnyka et al[8] studied animal models in which CVR was manipulated in a controlled manner under different physiologic conditions, such as an increase in arterial carbon dioxide (CO_2) tension, or a decrease in cerebral perfusion pressure (CPP) in autoregulating animals. Microvascular resistance was quantified as CPP divided by laser Doppler cortical flux. During the hypercapnic challenge, a significant, positive correlation was found between cortical resistance and Doppler flow pulsatility. On the contrary, in all groups in which cerebral perfusion pressure was reduced, a negative correlation between PI and cerebrovascular resistance was shown. These authors concluded that the PI cannot be interpreted simply as an index of CVR. The decrease in CVR when CPP decreases is followed by an increase in pulsatility, likely resulting from combined changes in vascular resistance and compliance of large cerebral arteries. The PI increases when cerebral autoregulatory reserve is compromised by a decrease in CPP; when CPP is stable, changes in PI may reflect changes in CVR.[8]

More recently, de Riva et al[9] hypothesized that the PI is a complex function of various hemodynamic factors and explored the relationship PI-CVR by retrospectively comparing clinical data of two different physiologic situations where PI increases. The first one was intracranial hypertension, represented by ICP plateau waves (where a vasodilatory cascade is implicated); the second group involved patients submitted to a mild hypocapnic challenge, which is known to increase CVR. de Riva et al further sought to compare measured PI in both groups with a mathematical formula, expressing PI as a function of cerebrovascular impedance. Analysis of their model suggested that the PI is determined by the interplay of the value of CPP, pulsatility of arterial blood pressure (ABP), CVR, compliance of the cerebral arterial bed, and heart rate.[9]

Assessment of Intracranial Pressure

An accurate, precise and noninvasive alternative for measurement and monitoring of ICP/CPP remains a "holy grail" in neurointensive care. TCD FVs and the PI have been considered as potential surrogate candidates with variable success. Bellner et al[10] reported on a cohort of 81 adult severe traumatic brain injury (TBI) and subarachnoid hemorrhage (SAH) patients, showing a strong correlation between PI and ICP ($r = 0.938$, $P < .0001$) and a sensitivity and specificity of 0.89 and 0.92, respectively, to detect ICP higher than 20 mm Hg. The excitement from this report has since been moderated in view of more recent studies demonstrating poor correlation between PI-based estimations of ICP and invasive ICP measurements; the large prediction confidence intervals and the poor sensitivity has lead authors to discourage the use of ICP-calculating formulas that are based solely on the PI.[11,12] Zweifel et al[12] analyzed prospectively collected TCD data from severe TBI patients, finding that if the PI is less than or equal to 1, there is a chance of about 15% that the CPP is less than 60 mm Hg; with the PI less than or equal to 0.8, there is a likelihood of about 10% that CPP is less than 60 mm Hg. On the other hand, if the PI is greater than or equal to 2.2, the probability of low CPP (less than 60 mm Hg) is about 50%, and for PI greater than or equal to 3, the probability increases to 80%.[12]

Notwithstanding the above caveats, TCD FVs and PI can still serve as noninvasive screening tests for compromised intracranial compliance and potentially inadequate cerebral perfusion for selected patients. This diagnostic capability can be further enhanced by the application of an advanced TCD technique named transcranial color-coded duplex (Figure 2 E-1), which is analyzed at the end of this chapter. In a clinical and physiologic setting, serial testing and correct interpretation of waveforms and values becomes essential. Recently, Bouzat et al[13] showed that FV/PI measurements have prognostic value for secondary neurologic deterioration in patients with mild-to-moderate TBI. Using receiver-operating characteristic analysis, they found the best threshold limits to be 25 cm/sec (sensitivity, 92%; specificity, 76%; area under curve, 0.93) for diastolic cerebral blood flow velocity and 1.25 (sensitivity, 90%; specificity, 91%; area under curve, 0.95) for PI.[13] Cerebral blood flow and blood flow velocity, oxygenation, and metabolism changes have been described after decompressive craniectomy (DC).[14] TCD-derived variables can be useful in monitoring patients considered for or post-DC; studies have shown a correlation between decreasing ICP postdecompression and trends toward increasing FVs and decreasing PIs.[14-17] As noted earlier, individual patient clinical and physiologic characteristics need to be taken into account to make sensible, context-relevant use of TCD measurements in these scenarios.

TURBULENCE

Laminar blood flow in a normal vessel proceeds smoothly in layers parallel to the vessel wall, with blood closest to the wall flowing slower than the blood in the center of the lumen. High-flow states or stenosis of the vessel can disrupt this orderly parallel flow and cause turbulence. Turbulence can be visualized on TCD recording as a disorganized bright signal near the baseline and can also be heard as a "musical murmur." Turbulence on TCD in vessels with moderate stenosis has been demonstrated to be maximally recorded as between 55% to 75% of the vessel lumen in MCA recordings.[18]

MICROEMBOLI MONITORING

TCD is able to detect the passage of small emboli, either gaseous or solid, as they traverse the field of detection in real time. The presence and frequency of these microembolic signals (MESs) has been studied extensively in various conditions to predict subsequent embolic stroke risk. The conditions studied include carotid artery stenosis, intracranial stenosis, aortic arch plaques, patent foramen ovale, prosthetic heart valves, myocardial infarction, valvular stenosis, and atrial fibrillation. In 1998, the International Consensus Group on Microembolus Detection published a guideline outlining standardized detection parameters, applications for use, and limitations of microemboli TCD monitoring. The detection of MESs has been correlated with an increased risk of stroke in patients with symptomatic carotid stenosis, acute stroke, and postoperatively after carotid endarterectomy. In addition to MES detection of solid emboli representing clotting and by intravenous injection of agitated saline during TCD monitoring, the presence of MESs can identify a right-to-left cardiac shunt. Although more evidence is needed to determine exact stroke risk based on MESs, the presence and frequency of MESs can be a useful piece of information for the clinician in gauging stroke risk as well as therapeutic response to antithrombotic therapy.[19]

Transcranial Doppler Applications

Based on the above principles and interpretation of TCD, there are numerous applications that are clinically relevant and will be discussed further in upcoming chapters. These applications include detection of vasospasm in patients with SAH, screening of children with sickle cell disease for vasculopathy, vessel narrowing/occlusion, identification of collateral flow, arteriovenous malformation dynamics, cavernous carotid fistula and vertebrobasilar insufficiency detection, identification of cerebral circulatory arrest, microemboli monitoring, identification of pulmonary arteriovenous malformation using bubble study, as well as vasomotor reserve determination using techniques such as breathholding or CO_2 challenge. We will here focus on acute ischemic stroke evaluation, sickle cell disease, and blood flow autoregulation. A summary of TCD applications is provided in Box 2-1.

BOX 2-1 CLINICAL APPLICATIONS OF TRANSCRANIAL DOPPLER

- Monitoring vasospasm in subarachnoid hemorrhage
- Screening children with hemoglobin SS (HgbSS) disease (sickle cell anemia) for vasculopathy
- Determining vessel narrowing and occlusion
- Identifying collateral flow
- Identifying presence of arteriovenous malformations
- Identifying vertebrobasilar insufficiency
- Identifying cerebral circulatory arrest
- Monitoring emboli
- Identifying patent foramen ovale or pulmonary arteriovenous malformation via bubble study
- Determination of vasomotor reserve
- Sonothrombolysis

ACUTE ISCHEMIC STROKE EVALUATION

TCD can be used in the evaluation of acute ischemic stroke patients to guide therapy through real-time evaluation of vessel patency, stenosis, presence of microembolism, as well as presence of collateral flow patterns. A grading scale based on TCD waveform morphology, the thrombolysis in brain infarction (TIBI) scale, has been established as an accurate real-time measurement system of flow characteristics of occluded and stenotic vessels at the time of infarction as well as during thrombolysis, which has been validated to provide accurate assessment of stroke severity and prediction of vessel recanalization and subsequent clinical course.[20] The presence or absence of collateral flow in the setting of acute ischemic infarct can also aid the clinician in therapeutic decisions; TCD can determine the presence and direction of collateral flow, in addition to the site and extent of vascular occlusion and/or stenosis. As discussed in the prior paragraph, the presence of microembolic signals can aid in identifying an embolic source of ischemic stroke and guide management, as in the Clopidogrel and Aspirin for Reduction of Emboli in Symptomatic Carotid Stenosis (CARESS) trial, showing that in patients with symptomatic carotid stenosis of greater than 50%, the combination of clopidogrel and aspirin was more effective than aspirin alone in decreasing asymptomatic embolization as imaged with TCD.[21]

SICKLE CELL DISEASE

TCD has been established as an accurate tool in predicting stroke risk in pediatric patients with sickle cell disease. Sickled erythrocytes set off a cascade in which inflammatory mediators are triggered, leading to leukocyte adherence, endothelial dysfunction, and microvascular occlusions. In 1992, Adams et al[22] demonstrated the ability of TCD to identify pediatric sickle cell disease patients with high risk of cerebral infarction. In this study, patients with mean FV greater than 170 cm/sec had a significantly higher risk of stroke during the average follow-up of 29 months, despite otherwise similar clinical and hematologic characteristics. Subsequently, the same investigators studied the effect of blood transfusion on prevention of first stroke in pediatric patients with high risk of stroke based on TCD mean FVs of greater than 200 cm/sec, in either the intracranial ICA or MCA (Figure 2-4). These high-risk patients were randomized to receive blood transfusion or standard care without transfusion. The group receiving blood transfusions had a 92% reduction in stroke rate compared with standard care, thus prompting the study to be stopped early (see Chapter 5).[22]

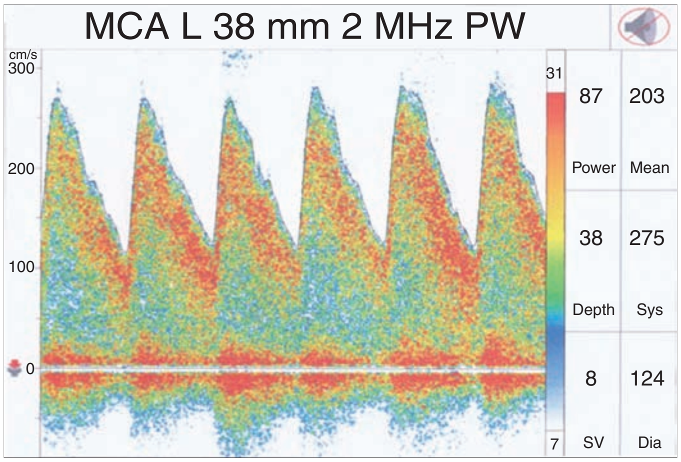

Figure 2-4 Greater than 200 cm/sec mean middle cerebral artery flow velocity in a patient with sickle cell disease.

CEREBRAL BLOOD FLOW AUTOREGULATION

Blood flow pressure autoregulation refers to a vascular homeostatic mechanism responsible for maintaining stable cerebral blood flow over a range of perfusing pressures. This vascular pressure reactivity is considered a major innate, protective mechanism of the cerebral arteriolar bed and has been shown to be disturbed in various types of acute brain injury and to correlate with secondary neurologic insults. In clinical practice, TCD is commonly used for dynamic and static measurements of autoregulation.[23] Measurement of static autoregulation requires an artificial abrupt change in arterial ABP/CPP; commonly used methods include the transient hyperemic response test (THRT), the leg-cuff deflation test, and the use of vasoactive drugs. The potential interference of such a stimulus with measurement is not fully known, and vasoactive drugs may, in addition, influence cerebral metabolism (especially in head-injured patients, in whom the blood-brain barrier is potentially damaged), leading to simultaneous changes in cerebral metabolic rate and pressure reactivity.[24] Dynamic autoregulation monitoring refers to real-time continuous correlation of spontaneous fluctuations of cerebral blood flow or surrogates and CPP. In 1996, Czosnyka et al[25] reported a new method for the continuous assessment of autoregulatory reserve. This group evaluated spontaneous slow changes in CPP that occur during periods lasting between approximately 20 seconds and 3 minutes, and also the corresponding response of the MCA FV; the correlation coefficient indices between mean flow velocity (FVm) and CPP (Mx) and between systolic flow velocity (FVsys) and CPP (Sx) were calculated and shown to have promising potential for determination of outcome after head injury.[25] Several studies have supported a strong relationship between the state of autoregulation and outcome after severe head injury. Recently, the Cambridge group[26] demonstrated that different components of FV (mean, peak systolic, and end diastolic) perform differently when used for assessment of autoregulation. The indices using systolic flow velocity consistently demonstrated the strongest association with outcome, followed by indices using mean flow velocity.[26] Similar work and findings have been shown in patients with SAH, where disturbance of pressure autoregulation has been associated with the development of delayed cerebral ischemia (DCI).[27] Finally, Budohoski et al[28] found that disturbed autoregulation in the first 5 days after SAH, as measured by TCD and near-infrared spectroscopy, correlated significantly with development of DCI but not ultrasonographic vasospasm.

Transcranial Color-Coded Duplex (Consultant Level Examination)

Transcranial color-coded duplex (TCCD) is a consultant-level examination that has advantages over the conventional TCD examination by showing the images of the intracranial anatomy and arteries by duplex B-mode while still having the capacity to measure velocities with Doppler. In other words, disparate from TCD technology, TCCD shoots multiple ultrasound beams, exposing a larger brain area at dual emitting frequencies, one for grayscale imaging and another for Doppler imaging; thus this tool can illustrate both arterial position on color flow imaging as well as on B-mode ultrasonography. TCCD tests are accurate, real time, noninvasive (bedside examination), and inexpensive for the study of intracranial circulation and the diagnosis of nonthrombosed aneurysm because of its competence to reveal flow phenomena.[29] TCCD can detect presence and severity of intracranial atherosclerosis, which may be the most recurrent source of ischemic stroke. The main limitation of TCCD is the ultrasonic windows that can limit the area of insonation of the cerebral arteries, including their proximal branching, lower spatial resolution, and could obstruct transtemporal insonation.[30] TCD- and TCCD-measured velocities are comparable, using zero-angle correction, resulting in more accurate measurement of flow velocities and allowing superior precision in defining intracranial arterial narrowing. TCCD can also more reliably provide information about blood flow in specified intracranial vessel segments as well as allowing a more exhaustive distribution of vessel pathologies. Overall, TCCD can improve both the accuracy and reliability of the conventional TCD studies. In general, TCCD is increasingly being used as an assessment tool to help evaluate occlusive disease on the main segments of intracranial arteries, as well as to serve as a subsequent guide for driving the direction of therapeutic decision-making by providing essential prognostic information of the acute stage of the ischemic stroke. Figure 2-5 shows a 90% left MCA stenosis on intraarterial digital subtraction angiography (DSA) and increased velocities on TCD and TCCD. Follow-up studies showed patent MCA and normal velocity. After successful intracranial stent placement in the left MCA, a follow-up magnetic resonance angiography (MRA) study was performed (Figure 2-7). After loading MRA dicom images onto an advanced ultrasound device, TCCD was performed via left temporal bone window insonation. By coregistration of the two imaging modalities, the MRA and TCCD images could be viewed simultaneously (Figure 2-8). MRA was unable to confirm patency of the target artery after stent placement because artifact masked the view of the left MCA. During incorporation of the TCCD and MRA, the left MCA color flow signal was integrated dimensionally and overlaid on the MRA images. These combined images provided sufficient evidence for patency of the vessel. Velocity measurement did not detect any restenosis. Fusion or combined imaging abrogated the need for a follow-up angiogram. In addition, TCCD and MRA used in combination, may also eliminate the need for intracranial DSA in most patients by providing data about both macrovascular and microvascular impairments.

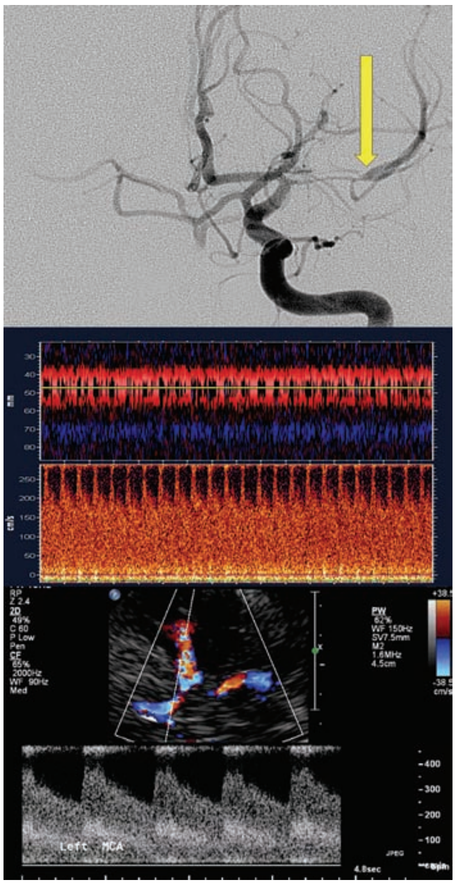

Figure 2-5 Digital subtraction angiography shows critical left middle cerebral artery stenosis *(top, arrow)*, and the corresponding transcranial Doppler signal demonstrates markedly elevated velocity *(middle)*. Transcranial color-coded duplex confirmed the increased velocity *(bottom)*.

IMAGING CASE: A LUXURY PERFUSION STATE

We present an example of TCCD dynamic monitoring that was performed in a heart failure patient with severe traumatic brain injury. The patient underwent a decompressive craniectomy. Figure 2-6 is a pertinent TCCD recording of the right MCA during vasopressor and fluid therapy (156/72(96) refers to systolic, diastolic, and mean arterial blood pressures, respectively; CI, cardiac index; HR, heart rate; SVV, stroke volume variation; whereas rSO_2 left and right refer to oxygen saturation as depicted by near-infrared spectroscopy). Postcraniectomy computed tomography showed that there was brain edema and evidence of ischemia, especially in the right side of the brain (decreased right rSO_2 values). The combination of an elevated FV 180 cm/sec, a normal PI of 0.79 and low rSO_2 could be interpreted as a luxury perfusion state with poor oxygen uptake, either because of the extent of parenchymal injury, mitochondrial failure, or exacerbation of cerebral edema. Continuous, dynamic TCCD recordings may be of value in such cases, when interpreted in the light of clinical findings, hemodynamic monitoring, and other imaging findings (e.g., computed tomography).

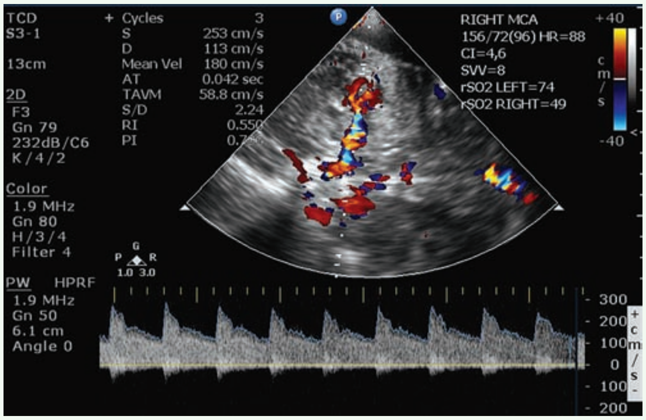

Figure 2-6 *(Courtesy Dr. D. Karakitsos.)*

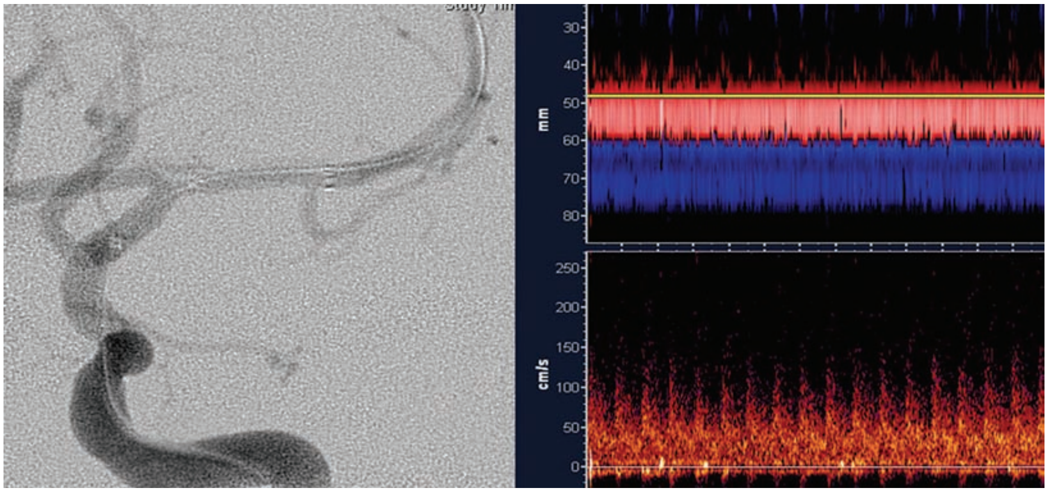

Figure 2-7 Digital subtraction angiography confirms flow in the stent without dissection *(left).* Transcranial Doppler shortly after stent placement shows marked reduction in flow *(right).*

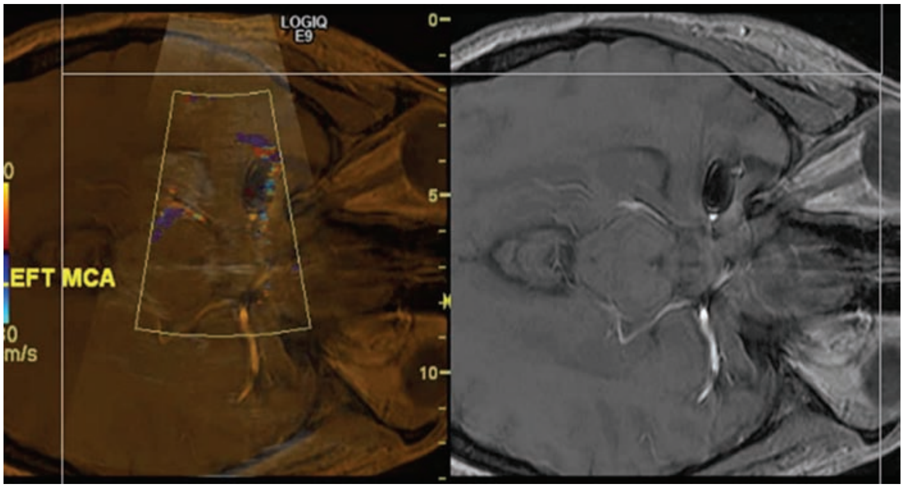

Figure 2-8 Fusion imaging displayed on the same screen: Magnetic resonance angiography and transcranial color-coded duplex showed patency and no restenosis in the M1 or M2 segments of the left middle cerebral artery.

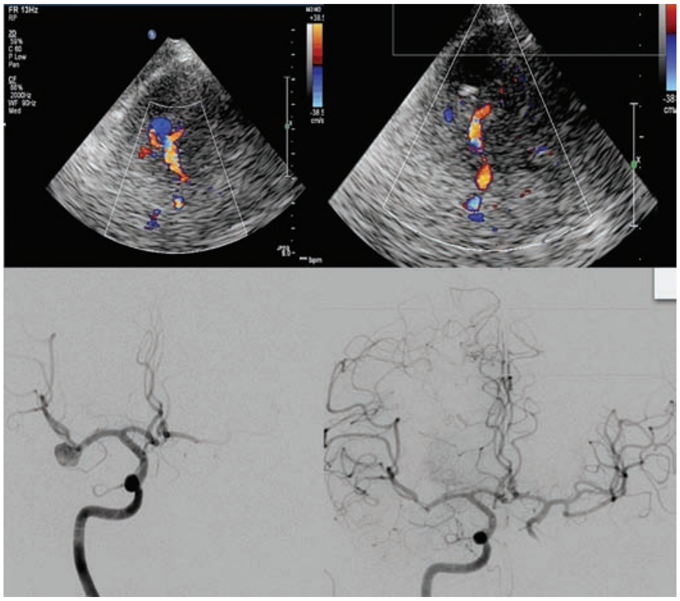

Figure 2-9 *Left panel,* Transcranial color-coded duplex (TCCD) *(top)* and digital subtraction angiography *(bottom)* of the aneurysm at the M2 middle cerebral artery (MCA) bifurcation. *Right panel,* Postcoiling placement TCCD and digital subtraction angiography showed hyperechoic coils and patent MCA branches.

Finally, TCCD can provide superb visualization at baseline and for follow-up after aneurysm coiling (Figure 2-9). MCA patency can be confirmed at bedside. TCCD can also be used in patients with traumatic brain injury for neuromonitoring purposes.

Pearls and Highlights

- TCD measurements provide information regarding the quality of cerebral blood flow, vascular flow characteristics, pulsatility of flow, resistance, and impedance characteristics of the cerebral circulation.
- Caution should be taken in assuming a linear relationship between Doppler flow velocity and CBF. Cerebral blood flow rate is approximated based on the following equation: $CBF \approx FV \times$ cross-sectional area of the insonated vessel $\times$ cosine of the angle of insonation.
- TCD has several important clinical applications, including assessment of patients with acute ischemic stroke, determination of the need for blood transfusion

in patients with sickle cell disease, and testing and monitoring of cerebral blood flow autoregulation, among others.
- TCCD has advantages over the conventional TCD examination by showing the images of the intracranial anatomy and arteries by duplex B-mode, while still having the capacity to measure velocities with Doppler.

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For a full list of references, please visit www.expertconsult.com.

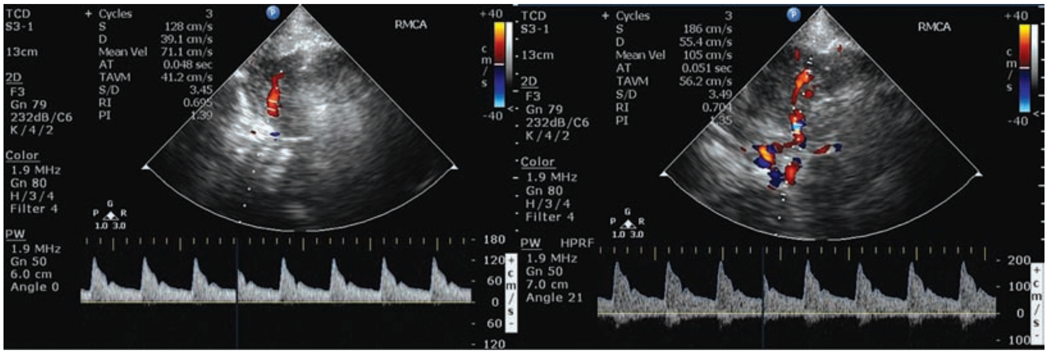

Figure 2 E-1 Transcranial color-coded duplex views. Depiction of mildly increased pulsatility index (PI) values in the right middle cerebral artery (MCA) of a patient with moderate traumatic brain injury and concomitant brain edema *(left)*. Visualization of the circle of Willis, with depiction of mildly increased PI values in the right MCA of a patient after stroke *(right)*. *(Courtesy Dr. J. Poularas.)*

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Transcranial Doppler in Aneurysmal Subarachnoid Hemorrhage

SCOTT A. MARSHALL | JOHN D. KlEIN | ALEXANDER H. VO | ALEXANDER H. RAZUMOVSKY

(CONSULTANT LEVEL EXAMINATION)

Overview

The management of aneurysmal subarachnoid hemorrhage (aSAH) and its accompanying sequelae integrates transcranial Doppler (TCD) ultrasonography for the surveillance of the emergence and course of vasospasm (VS) and delayed cerebral ischemia.[1] TCD surveillance of patients after aSAH has been advocated by the two most recent aSAH treatment guidelines, and practice standards for its use are published.[2-4] This disease is complex to manage, and TCD has emerged as an inexpensive, noninvasive tool for monitoring intracerebral hemodynamic changes seen with SAH as well as for evaluating other neurologic conditions, including intracranial arterial stenosis, arteriovenous malformations, emboli of different origin, venous sinus thrombosis, brain death, ischemic stroke and clot lysis, and sickle cell disease.[5,6]

Vasospasm after Aneurysmal Subarachnoid Hemorrhage

The phenomenon of the diminution of blood flow transiting through the cerebral vasculature seen after aSAH or severe neurotrauma resulting from the decrease in the caliber of arteries is referred to as VS.[7,8] Arterial spasm after aSAH was originally described by Ecker in 1951 and has since been the subject of decades of laboratory research and clinical investigations. The phenomena of "angiographic VS" and "clinical VS" are often discussed, both of which may culminate in eventual delayed cerebral ischemia (DCI) and permanent neurologic deficits. The exact cause of VS is not clearly understood.[1,7] VS often occurs most intensely adjacent to the subarachnoid clot burden but can occur distant from the majority of the subarachnoid blood and is predicted by clot volume, age, location, and density of the SAH seen on the initial computed tomography (CT) scan.[9,10] Because of more aggressive early surgical or endovascular treatment of ruptured aneurysms, fatality from early rerupture has now been replaced by complications of hydrocephalus and VS as the most common and serious causes of morbidity and mortality after aSAH.[11,12] Thus monitoring for VS and DCI with noninvasive techniques, such as TCD, remains a critical tool in the management of this disease.[1]

Angiographic VS is common after aSAH, occurring in as many as 67% of patients, with the highest incidence occurring between days 10 and 17 after aSAH.[12] Classically, VS is reported to occur from day 4 to 14, but variations on this general rule are common.[1,3,4,7,13] The incidence of *early* angiographic VS, detected within 48 hours of aneurysm rupture, occurs in 10% to 13% of aSAH patients and is associated with prior aSAH, large aneurysms, intraventricular hemorrhage, and worsened 3-month outcome and morbidity.[14] It is now well recognized that VS is also seen after traumatic SAH.[8]

Transcranial Doppler as a Monitor for Cerebral Vasospasm

VS is a clinical diagnosis, and findings range from nonfocal neurologic signs, such as confusion, increasing somnolence, and combativeness, to focal and localizable neurologic deficits from stroke. In 1982, Aaslid provided the first descriptions of the use of TCD for early detection of VS.[15] The gold standard for the diagnosis of cerebral VS has remained digital subtraction angiography (DSA), although this modality is not practical for use as a frequent monitor for VS. Computed tomography angiography (CTA) has emerged as a potentially helpful tool in the evaluation of VS and is often used along with TCD.[3,4]

Because of its portability for bedside testing, noninvasive nature, ease of repeated testing, and lack of known adverse side effects from its use, TCD has become one of the most used screening tools for monitoring patients with aSAH for the development of VS in practice currently. In common practice, TCD is performed daily to twice daily from the first day after presenting with aSAH until VS subsides. TCD is an operator-dependent examination, although up to 8% of patients may have skull insonation windows too thick to allow evaluation of cerebral blood flow velocities (CBFVs) in cm/sec.[13]

As described by Aaslid, TCD uses the underlying principle that the velocity of blood flow in a conduit is inversely related to the diameter of that conduit, and that as diameter is decreased, velocity will increase, and vice versa. An indirect evaluation of the vessel diameter is achieved by using the Doppler effect upon red blood cells by calculating the Doppler shift between the frequencies of the transmitted and received ultrasound waves.[16]

Indices and Technical Aspects of Transcranial Doppler Ultrasonography

TCD provides several indices that assist in the clinical decision making for patients with aSAH. The CBFV is the most used metric and is also described by parameter of the mean CBFV (mCBFV), the peak systolic flow velocity (V_s), and the end diastolic flow velocity (V_d). In clinical practice, the mCBFV is typically reported, but the other parameters are used to calculate the

Equation 1: Pourcelot Resistance Index: RI = (FVsystolic – FVdiastolic)/FVsystolic

Equation 2: Gosling Pulsatility Index: PI = (FVsystolic – FVdiastolic)

Equation 3: Lindegaard Index: LI = MFV_{MCA}/MFV_{ICA}

Figure 3-1 Relevant equations derived from the transcranial Doppler (TCD) waveform.

resistance index (RI) and the pulsatility index (PI). Both RI and PI are presumptive measures of downstream vascular resistance and may predict intracranial compliance or intracranial pressure.[17,18] Clinical decision-making based on this relationship of the PI currently remains controversial.[19] Elevated RI and PI may also occur secondary to distal VS or intracranial stenosis. The derivation of RI and PI are shown in Figure 3-1.

The Lindegaard (ratio) index (LI) is a method of correcting for increases in hyperdynamic systemic flow velocities that are either physiologically or medically induced in patients with aSAH (e.g., because of triple-H therapy: hypervolemia, hypertension, hemodilution). To calculate the LI, the mCBFV of the middle cerebral artery (MCA) is compared with an ipsilateral extracranial vessel, which is usually the proximal internal carotid artery (ICA) (Figure 3-2). This ratio helps to distinguish global hyperemia from VS, particularly when the LI is greater than 6.[3,20] Others have suggested that an intracranial to extracranial ratio for the basilar artery (BA), for instance, comparison of the BA mCBFV to the extracranial vertebral artery (VA) mCBFV, of greater than 3 is highly sensitive and specific for posterior circulation VS.[21] The extracranial/intracranial mCBFV ratio can be especially helpful in aSAH in the setting of the global hyperemia that accompanies the often-used triple-H therapy.

TCD measurements alone may not correlate with angiographic or symptomatic VS. Differing hemodynamic states may alter the effects of decreased vessel lumen diameter on flow resistance as measured by TCD. It is postulated that with moderate VS, cerebral autoregulation compensates for perfusion pressure reduction in the region of spasm, if arterial blood pressure is above the lower limit of autoregulation. The flow velocity then increases as lumen area falls, yielding good correlation between angiographic and TCD measured spasm.[22] As stenosis increases, the volume of flow is reduced, and velocity remains highly independent of diameter from ineffective attempts at cerebral autoregulation. When blood pressure is augmented with triple-H therapy, flow increases and ischemic symptoms may improve; mean flow velocity (MFV) may paradoxically have higher values than when normotensive. In this scenario, the correlation between TCD velocity and the degree of angiographic VS is likely to be poor. If vessel diameter worsens further, lower mCBFV and reduction of flow to critical values may manifest with ischemia.[22]

Interpretation of Data from Transcranial Doppler

It is recommended that TCD studies be performed in the intensive care unit (ICU) for patients with aSAH.[3,4] This data can be interpreted based on absolute criteria for VS or used to see trends in the tempo of VS over the course of several days.[3] Some have proposed a point scoring system for VS, with reported sensitivity and specificity of both at 96%.[23] The correlation between TCD mCBFV with decreases in vessel diameter on angiography have been most convincing for examinations of the MCA.[1] Ideal placement of the reference standard for mCBFV and extracranial/intracranial mCBFV ratios is debated, although potential cutoff values where mild, moderate, and severe VS is likely present is presented in Table 3-1.

TCD monitoring is typically used after an aneurysm is secured. A role for early monitoring to establish increased risk of delayed cerebral ischemia (DCI) may be emerging. In a study of 199 patients with TCD examinations within 48 hours of SAH onset, 38% of patients had MCA MFV elevation greater than 90 cm/sec, which was associated with younger age, angiographic VS on admission, and elevated white blood cell count.[24]

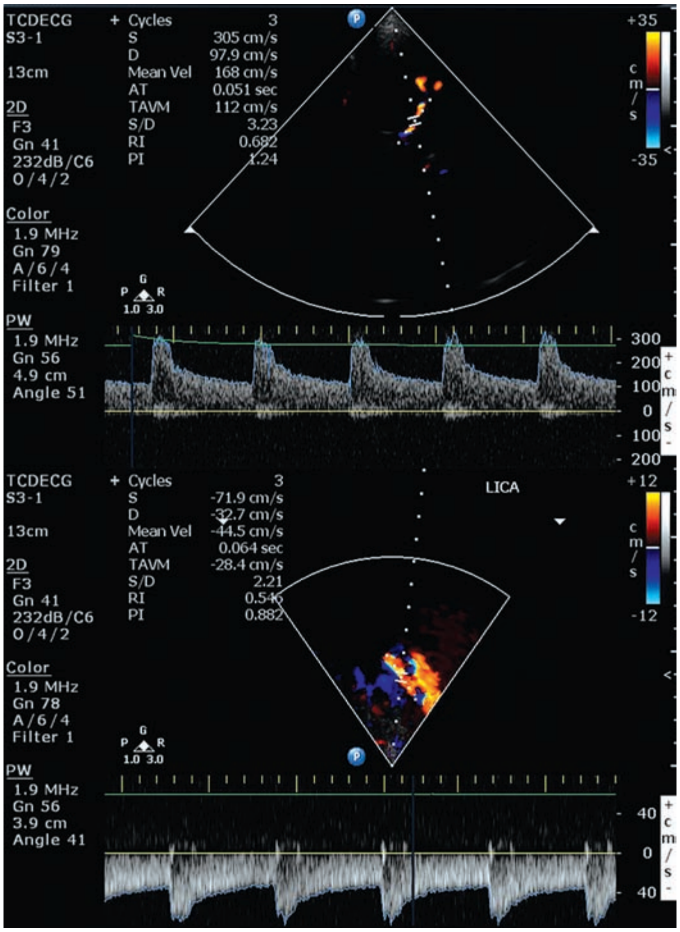

Figure 3-2 Moderate vasospasm in the left middle cerebral artery after aneurysmal subarachnoid hemorrhage as detected by real-time transcranial Doppler (TCD): mean flow velocity in the left middle cerebral artery is greater than130 cm/sec *(top)*, and the LI calculated by the ratio of the latter to the mean flow velocity detected in the ipsilateral proximal internal carotid artery (LICA, *bottom*) is greater than 3. *(Courtesy Dr. D. Karakitsos.)*

TABLE 3-1 TCD Parameters Indicating Vasospasm after Aneurysmal SAH[3,21,27]

Vasospasm	Anterior Cerebral Artery	Terminal Internal Carotid Artery	Middle Cerebral Artery	Posterior Cerebral Artery	Basilar Artery	Vertebral Artery
Mild	‡	>120	>120	‡	>60	>60
Moderate	‡	>130	>130	>110	>80	>80
Severe	>50% increase from baseline MFV over 24 hrs	‡	>200	>110	>115	>80
Intracranial/MFV Extracranial MFV	‡	‡	>3 mild* >6 severe*	‡	>3 severe†	‡

CBFV, cerebral blood flow velocities; *MFV*, mean flow velocities in cm/sec; *SAH*, subarachnoid hemorrhage; *TCD*, transcranial Doppler.
*Middle cerebral artery/extracranial internal carotid artery.
†Basilar artery/extracranial vertebral artery.
‡Data limited.

DCI occurred in 19% and was independently predicted by elevated admission MCA MFV greater than 90 cm/sec and poor clinical grade. These findings suggest that transient VS during the early phase of SAH may predict delayed arterial spasm and DCI.

ANTERIOR CIRCULATION

Anatomic factors and insonation windows may make TCD more reliable for some vessels than for others. Prior work in aSAH showed a correlation between elevated TCD CBFVs and symptomatic VS that was improved in the intracranial ICA (sensitivity, 80%; specificity, 77%) and MCA (64% and 78%, respectively) distributions compared with the anterior cerebral artery (ACA) (45% and 84%, respectively).[25] To improve the sensitivity of TCD of the ACA, Lindegaard had suggested that clinicians use both ACAs to access VS on either side, because of collateralization of the ACAs by the anterior communicating artery (ACom). Older data suggest that TCD studies of this vessel may be more useful to detect VS with trend analysis rather than absolute velocity thresholds, and that VS may be heralded by a relative increase in mCBFV of greater than 50% change over subsequent examinations or a change of 50 cm/sec in MFV over a 24-hour period.[26] Likewise, the posterior cerebral artery (PCA) offers challenges to the diagnosis of VS with TCD. Prior work reported sensitivity of 48% and specificity of 69% in technically adequate TCDs with a mCBFV cutoff value of 90 cm/sec, with increased specificity of 93% but low sensitivity if this value was increased to 110 cm/sec.[27] The PCA, similar to the ACA, has proven to be a difficult vessel for which to reliably establish TCD criteria for VS (see Table 3-1).

Increased mCBFV within the MCA is most correlated with angiographic VS. Various cutoff values of mCBFV have been proposed, and others rely more heavily on the intracranial to extracranial velocity ratio. Proposed velocity criteria are presented in Table 3-1. A LI of greater than 6 has been shown to reliably predict VS in patients with clinical findings possibly indicating ischemia.[28] Systemic factors such as hematocrit and mean arterial pressure must be taken into account when interpreting the LI.

Terminal ICA VS is well described, with retrospective data showing sensitivities of 95% for the detection of VS with an ICA aneurysm, if the MCA (M1—sphenoidal segment of the MCA) and the ICA are successfully insonated.[29] Other work with 49 patients and TCDs of 90 intracranial ICAs reported a specificity and positive predictive value of 100% when mCBFV values exceeded 130 cm/sec in the intracranial ICA.[30]

POSTERIOR CIRCULATION

TCD detection of vertebral artery (VA) or BA VS differs from the anterior circulation. A cutoff velocity of approximately 80 to 85 cm/sec in the BA predicts more frequent progression to cerebral ischemia, which could influence clinical decision-making.[21,31] An intracranial to extracranial ratio for the BA greater than 3 is highly sensitive and specific for posterior circulation VS (see Table 3-1). Further work on modifications of the LI for the posterior circulation showed normative values for the intracranial/extracranial VA mCBFV ratio (IVA/EVA) and BA/extracranial VA mCBFV ratio (BA/EVA), and evaluated aSAH patients with TCD and CT angiography (CTA).[31] A BA/EVA ratio greater than 2 was 100% sensitive and 95% specific for detection of BA VS. In addition, the BA/EVA ratio showed close correlation with BA diameter and was greater than 3 in all patients with severe VS.

Limitations of Transcranial Doppler in the Detection of Vasospasm

Several factors are known to affect TCD mCBFV measurements that may impact assessment during aSAH, including hematocrit, arterial carbon dioxide, episodic alterations in vasomotor status, the patient's level of consciousness, and the observer's level of experience. [2,32-34] At this time, there appears to be no particular advantage of continuous TCD monitoring, although further study into how moment-to-moment variability affects detection of VS is suggested.[34] Same-day interobserver variability has been reported to be about 7.5% and about 13% on different days.[35] Variations in MCA mCBFV have also been observed with age, pregnancy, menstruation, and arousal of individuals.[36,37] Some vessels may be better assessed with TCD than are others because of anatomic features and individual patient characteristics.[2,25,27] Temporal bone thickness is quite variable among individuals but has some relationship to age, sex, and race. Inability to insonate the MCA and some other anterior circulation vessels is more often associated with the elderly than the young, with women than men, and with nonwhites than whites.[38]

Management Strategy in Aneurysmal Subarachnoid Hemorrhage

Daily TCD ultrasonography examination should be considered in all patients with aSAH, along with correlation with serial clinical neurologic examinations and physiologic data. In our practice, patients admitted with aSAH are studied as soon as possible after DSA and securing the aneurysm with either surgical clipping or endovascular coiling. In the setting of clinical stability, TCDs are continued daily while patients are maintained in a state of normovolemia and normonatremia. When a patient without new examination findings enters the window for increased risk of developing VS, if TCD mCBFVs increase to generally accepted levels for VS for that vessel, fluid balance is shifted to maintaining a positive fluid state, and volume is augmented, along with serum sodium with hypertonic saline if cerebral salt wasting develops. Patients are allowed to autoregulate their blood pressure up to systolic pressures (SBP) of 200 mm/Hg or mean arterial pressures (MAP) of 120 to 140 mm/Hg, depending on the clinical status of the patient and other existing comorbidities. The application of a hemodynamic monitor may also be considered to optimize cardiopulmonary function and fluid management. If there is increased clinical suspicion for VS with either increasing TCD measured mCBFV values or clinical findings of potential ischemia, hypervolemic and hypertensive therapy is begun with either aggressive crystalloid or colloids, and phenylephrine or norephinephrine infusions, along with placement of an invasive hemodynamic monitor. Alternatively, dobutamine or milrinone may be used in the setting of *neurogenic stunned myocardium* to augment cardiac output (see Chapter 7). Based on the clinical status of the patient and the reliability of the neurologic examination, other diagnostic imaging may then be considered. The use of a perfusion study, such as CT-perfusion, may be helpful in these cases, but if the suspicion is strong for clinical worsening, then titration of MAP or SBP goals is warranted. DSA, as both a diagnostic and therapeutic intervention, may be performed at this stage. TCD follow-up is vital in assessing the results of therapy and, along with the clinical examination, will aid in the timing of repeat angiography and guide hemodynamic management.

Transcranial Doppler Ultrasonography for Traumatic Vasospasm

Several clinical applications of TCD currently exist in practice. TCD ultrasonography may be helpful in the setting of head trauma, as a marker of increased intracranial pressure (ICP), assessment of cerebral autoregulation, brain death, ischemic stroke, intraoperative monitoring, and assessment of right-to-left shunt, among other uses. Evidence has emerged regarding the incidence of VS assessed by TCD in the anterior and posterior circulation after traumatic SAH (tSAH) or blast-related head injury.[8,39,40] The incidence of VS is reported to occur at a higher rate in some populations with tSAH than aSAH, a departure from prior teaching regarding VS. In a large prospective cohort study of traumatic brain injury, hemodynamically significant VS in the anterior circulation was found in 44.6% of the patients, whereas VS in the BA (BA FV $>$ 90 cm/sec) or hemodynamically significant VS in the posterior circulation was found in 19% and 22.5% of patients, respectively. The most common day of VS onset was postinjury day 2. In this study, the VS resolved after 5 days in 50% of the patients with anterior circulation spasm and after 3.5 days in 50% of patients with posterior circulation spasm.[41]

Transcranial Doppler as a Marker of Intracranial Pressure and Compliance

The correlation of TCD PI (see Figure 3-1) and intracranial pressure is described. Early work by Klingelhöfer et al shows that ICP and RI share a direct correlation.[42] Furthermore, the PI as a ratio is sensitive to changes in ICP because downstream compression of arterioles secondary to high ICP will decrease the denominator of this equation (CBFV), which is a surrogate measure of flow. Increased downstream vascular resistance created by compression of smaller arterioles occurs without effect on the larger insonated arteries of the circle of Willis. Also, as increased ICP reduces compliance of the entire system, velocity variations resulting from the rigidity of arteries and reduced V_d will increase the numerator of this relationship. In turn, both of these factors will increase the index and may indicate increasing ICP.[18] Follow-up prospective studies of this relationship have shown this correlation to be significant in a mixed population of neurosurgical patients who underwent TCD evaluation with an extraventricular drain in place, but this relationship has also been questioned.[43-46] TCD has not gained acceptance as a surrogate for invasive ICP monitoring, although information provided noninvasively by TCD ultrasonography may guide decisions to place invasive extraventricular drains, subdural monitors, or intraparenchymal monitors for suspicion of increased ICP in patients with severe neurologic illness or trauma.[18] To the best of our knowledge, no one yet suggests using PI as an accurate method to assess quantitatively ICP in mm Hg. In numerous publications, however, it was shown that PI correlates well with ICP that was measured by invasive methods.[17,47] More studies are clearly required before we understand the relationship of ICP and TCD. Nonetheless, even today quantitative and qualitative change in TCD values and waveform morphologies may persuade physicians to undertake other diagnostic steps and/or change medical treatment that will improve the care of these patients and their subsequent outcomes.

Pearls and Highlights

- The utility of TCD in the ICU has grown substantially since its introduction 30 years ago.
- TCD currently maintains an important role in the day-to-day management and triage of more invasive and expensive diagnostic tests and subsequent intervention in the setting of vasospasm resulting from aneurysmal and traumatic SAH.
- Limitations currently exist to the use of TCD as an isolated marker of radiographic VS.
- Complete TCD evaluations, including calculation of the Lindegaard (ratio) index (LI) for the anterior circulation and a modified LI for the posterior circulation may increase the specificity for VS detected by TCD in the setting of cerebral hyperemia.
- Similar to many tools used in the ICU, TCD is best used as part of the multimodality environment that incorporates radiographic, metabolic, and clinical findings to better manage patients with SAH.

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4

Transcranial Doppler in the Diagnosis of Cerebral Circulatory Arrest

JOHN POULARAS | GREGORIOS KOURAKLIS | MICHAEL BLAIVAS | DIMITRIOS KARAKITSOS

(CONSULTANT LEVEL EXAMINATION)

" . . . To die: to sleep; No more; and by a sleep to say we end. . . ."
William Shakespeare, *Hamlet*

Overview

The role of transcranial color coded Doppler (TCCD) in neurocritical monitoring has been illustrated in previous chapters. We will here focus on its use as a confirmatory test in the diagnosis of brain death (BD). The concept of death in Western civilization has been linked to the cessation of breathing and heart beat, irrespective of cultural and religious variability. Advances in medical technology after the Second World War and the development of critical care integrating the use of mechanical ventilators, as well as the advent of successful transplantation of vital organs, presented new ethical, legal, and medical dilemmas.[1]

In 1968, the Ad Hoc Committee of the Harvard Medical School to Examine the Definition of BD concluded that BD is a strictly clinical diagnosis, defined as the irreversible cessation of all hemispheric, cerebellum, and brainstem neurologic functions.[2,3] Analyzing BD is beyond the scope of this chapter; however, readers are referred to the White Paper published by the U.S. President's Council on Bioethics in 2009, which illustrates controversies in the diagnosis of BD, while introducing the term "*total brain failure*" and defining the irreversible cessation of whole-brain function.[4,5] Controversies in the diagnosis of BD and the use of the traditional cardiopulmonary standard in the organ procurement practice, known as "controlled donation after cardiac death," have led to the development of confirmatory tests in BD diagnostic protocols.[4,6] These tests are recommended whenever specific elements of the clinical examination may be unreliable and are rarely implemented by law in certain countries.[6] Patients with severe brain injury are usually treated with barbiturates; moreover, the presence of various metabolic, thermoregulatory, respiratory, and other disturbances may prevent determination of BD by clinical criteria.[7] Confirmatory tests are used in children and neonates because clinical diagnosis of BD can be challenging in these cases.[8,9] Confirmatory tests are divided into those diagnosing cerebral circulatory arrest (CCA) (e.g., angiography) and those that demonstrate loss of bioelectrical activity (e.g., electroencephalography).[10,11]

Transcranial Doppler in the Diagnosis of Cerebral Circulatory Arrest

CCA is an element of the destructive pathophysiologic process leading toward BD. Of note, brain neurons are irreversibly damaged after several minutes of CCA, and global brain destruction can be evident within 30 minutes.[12] However, BD may occur regardless of CCA and vice versa because the specific pathophysiology can be different among patients progressing toward BD.[10-14] The common pattern is underlined by an increase in intracranial pressure (ICP) that will eventually lead to brain "tamponade" because ICP rises above mean arterial pressure (MAP), resulting thus in CCA. Another pattern is characterized by ICP increments that may not exceed MAP, although there is pathology affecting the brain on a cellular level, resulting in edema and tissue necrosis.[10,11] Early testing for CCA may lead to false-negative findings, and thus testing for neuronal function and viability may be advocated; however, in cases where brain damage becomes irreversible, CCA could finally emerge.[14] Detecting CCA requires careful timing of the initial and follow-up examinations in patients with severe brain injury progressing toward BD. Several ancillary tests to detect CCA were developed, such as cerebral angiography, intravenous digital subtraction angiography, intravenous radionuclide angiography, single-photon emission computed tomography, echoencephalography, measurement of arm-to-retina circulation time, ophthalmic artery pressure, rheoencephalography, xenon-enhanced computed tomography (CT), magnetic resonance imaging angiography, CT angiography and perfusion, and TCD.[11] Invasive angiography remains the gold standard examination in detecting CCA; however, recent developments in CT angiography (e.g., multirow CT, allowing reconstructions of intracranial vessels) is rapidly shifting current practice. This practice change is occurring even though more studies are required to evaluate its efficacy to diagnose CCA. Lack of portability and use of iodinated contrast remain major disadvantages of invasive and CT angiography.[11,14,15] Angiographic patterns indicative of BD are (1) absent filling of intracranial arteries at the skull entry (at the foramen magnum in the posterior circulation and at the petrosal portion of the carotid artery in the anterior circulation) and (2) minimal arterial opacification with absent parenchymal and venous phases.[10-14]

TCCD was used in the diagnosis of CCA after studies that proved its high agreement with invasive angiography.[11,13-15] The sensitivity and specificity of TCCD for BD confirmation, when compared with angiography, are 88% and 100%, respectively.[11,15] TCCD remains largely operator dependent, and its use is limited by various technical issues (i.e., absence of an acoustic window in up to 20% of cases), but it is a noninvasive, portable, dye-contrast agents free, and relatively cheap examination.[11,15] The American Academy of Neurology Therapeutics and Technology Assessment Subcommittee concluded that TCCD is highly specific and sensitive in detecting CCA, whereas the Neurosonology Research Task Force Group of the World Federation of Neurology emphasized that extracranial and intracranial TCCD can detect CCA and thus may be considered optional in BD diagnostic protocols.[15,16] Recommended parameters for TCCD examinations were detailed in preceding chapters. In brief, patients are placed in dorsal decubitus position, while aiming to maintain systolic blood pressure above 90 mm Hg, heart rate above 60 beats/min, and oxygen saturation by pulse oximetry (Spo_2) greater than 95%. Technical parameters are use of 1.5- to 5-MHz phased-array transducer, color and velocity scales adjusted for low amplitude, sample volume of 6 to 10 mm (Doppler mode), maximal gain, and small sample size (color Doppler mode), thus avoiding angle adjustments on Doppler mode.

CCA-specific signals depicted by TCCD are oscillating flow, systolic spikes, or no demonstrable flow in a case with previously documented flow on TCCD (Figure 4-1). As ICP is gradually increasing in brain-injured patients, TCCD diastolic and mean flow velocities are accordingly decreasing, resulting in increments of the Doppler-derived pulsatility index. Hence laminar flow of small-caliber intracranial vessels is disrupted, and this can be documented by TCCD and color M-mode analysis (Figure 4-2).[14] As brain injury deteriorates and autoregulation fails, cerebral flow is further affected, and end-diastolic TCCD velocities tend to become zero, while ICP has reached diastolic blood pressure; however, forward flow may continue in systole. When ICP equals or exceeds the systolic blood pressure forward, and reverse flow are nearly identical, a pattern known as oscillating or biphasic flow may be evident (see Figures 4-1 and 4-2). Oscillating flow may persist in patients with severe traumatic brain injury who underwent salvage decompressive craniectomy.[17] Oscillating flow may be depicted on color mode as a transitory "flickering" of cerebral circulation in both intracranial and extracranial arteries (Videos 4-1 and 4-2).[13] Progression of these phenomena can

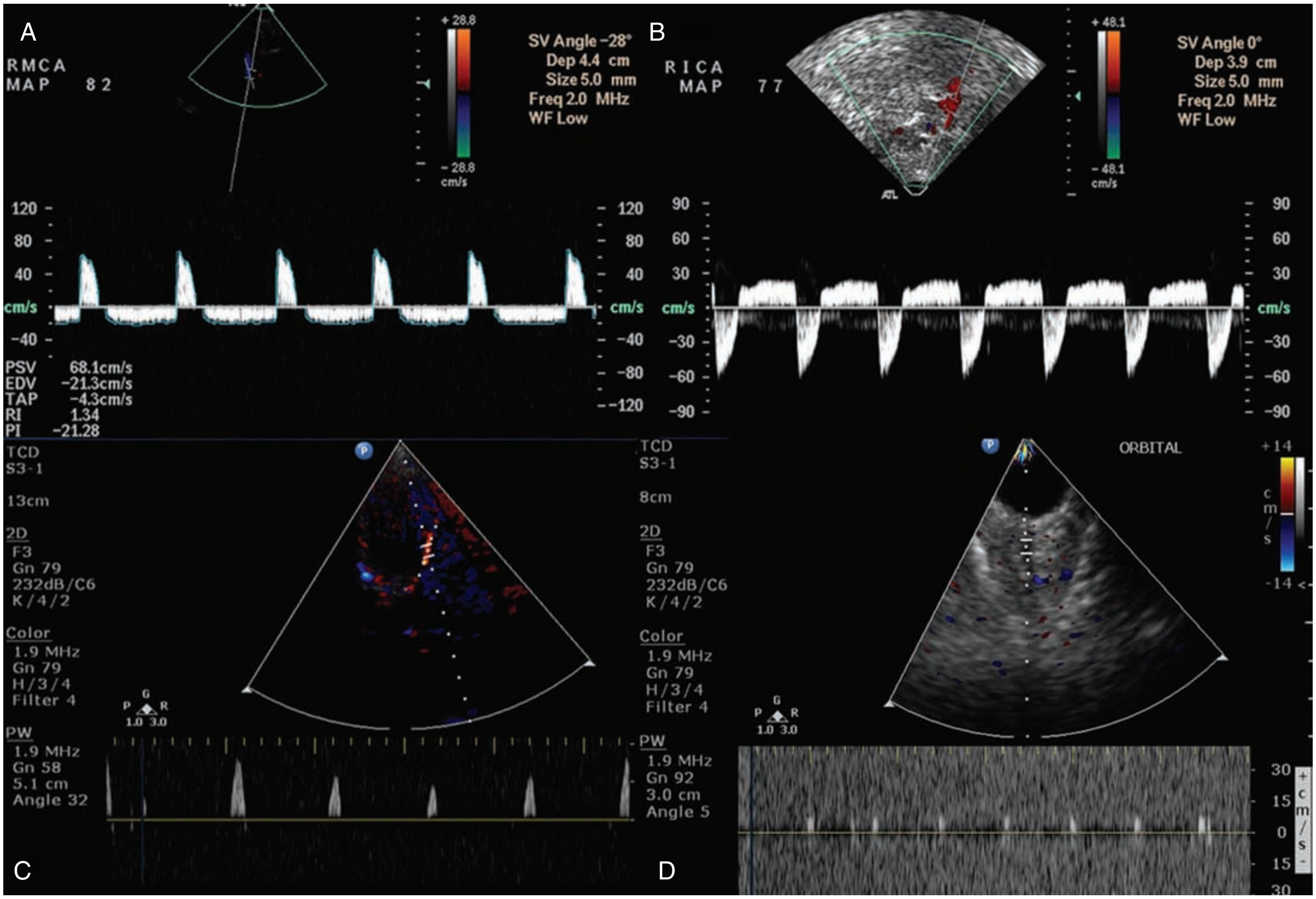

Figure 4-1 **A** and **B,** Oscillating flow depicted in the right middle cerebral (RMCA) and internal carotid arteries (RICA), respectively, in a patient with severe traumatic brain injury who was thereafter diagnosed as brain dead. **C** and **D,** Systolic spikes depicted in the left middle cerebral and ophthalmic arteries, respectively, in a brain-dead subject.

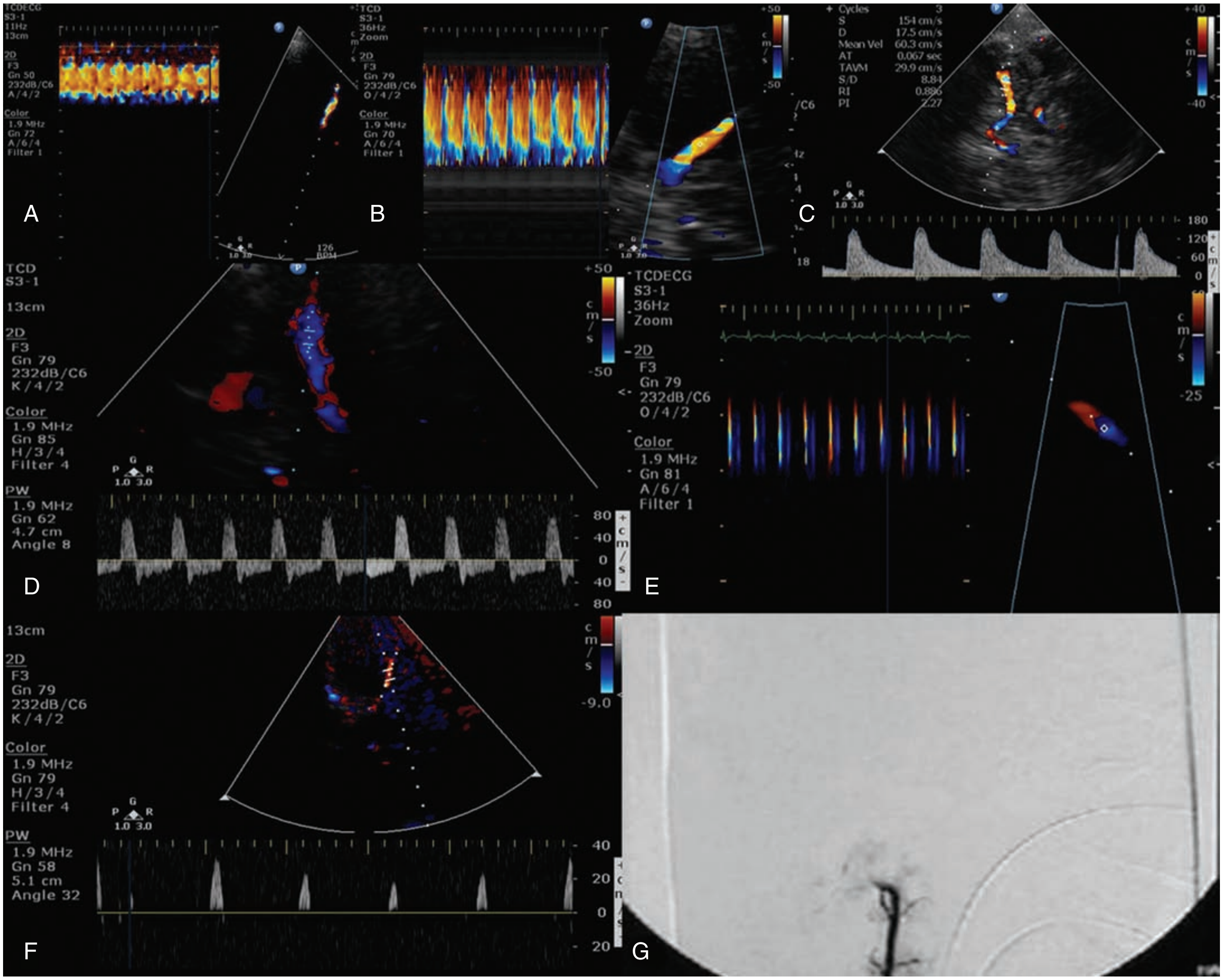

Figure 4-2 **A,** Color M-mode depicting normal laminar flow in the left middle cerebral artery (MCA). Flow anomalies in the left MCA (color M-mode), which are confirmed by increments of peak systolic velocity **(B),** while diastolic and mean velocities (Doppler mode) are gradually decreasing, resulting thus in increased pulsatility index (PI) values greater than 2 **(C)** in a brain-injured patient with increased intracranial pressure. Oscillating flow depicted by Doppler **(D)** and color M-mode analysis **(E)** in a brain-injured patient with decompressive craniectomy. The above signals persisted for approximately 48 hours; thereafter, systolic spikes **(F)** and absent intracranial flow were evident **(G).**

generate systolic spikes or absent flow on TCCD. Inability to detect flow signals because of an absent acoustic window may be solved by using transorbital and other approaches, but these techniques have not yet gained wide acceptance.[18] TCCD findings should always be evaluated along with clinical and laboratory findings, and repeating the examination within at least 30 minutes is essential.[13-20] To confirm diagnosis, extracranial bilateral scanning of the common carotid, internal carotid, and vertebral arteries should be performed.[15,16]

Suggested guidelines for the use of TCCD in detecting CCA are (1) CCA-specific TCCD signals are present in both intracranial and extracranial arteries when recorded bilaterally on two examinations within a 30-minute interval; (2) CCA-specific signals are systolic spikes or oscillating flow present in any arterial segment of the circle of Willis and depiction of the same findings in extracranial arterial segments, such as the common carotid, internal carotid, and vertebral arteries; and (3) lack of a signal during transcranial insonation of the basal cerebral arteriesis not a reliable finding, because this can be observed due to signal transmission issues—but the disappearance of intracranial flow signals in conjunction with typical extracranial signals can be accepted as proof of CCA; and (4) ventricular drains or large openings of the skull that possibly interfere with the development of the ICP are not present.[15,16] However, patients with ventricular drains and/or large skull openings may in fact develop CCA because progression toward brain "tamponade" may be slow and follow-up examinations may demonstrate CCA-specific TCCD signals.[13,14,17-20] Hence the designated 30-minute interval may be not enough to establish diagnosis of CCA in individual cases, and continuous TCCD monitoring for longer periods may be necessary.[13,14,17-20] Also, performing TCCD measurements under controlled hemodynamic, metabolic, and respiratory conditions increases the reliability of findings.[13-20] Despite its limitations, TCCD has a high level of agreement with angiography in the diagnosis of CCA, and its use may be considered optional in BD diagnostic protocols.

Pearls and Highlights

- Brain death is a strictly clinical diagnosis, although controversies about its definition still exist, leading to complex ethical, legal, and medical dilemmas.
- Ancillary tests that diagnose CCA or loss of bioelectrical activity may be integrated in BD diagnostic protocols in case clinical diagnosis is complicated or not possible.
- CCA is an element of the destructive pathophysiologic process leading toward BD.
- CCA-specific TCCD findings are oscillating flow and systolic spikes or absence of flow in a case with previously demonstrable flow.
- Despite its limitations, TCCD has a high agreement with conventional angiography in the diagnosis of CCA.

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5

Use of Transcranial Doppler Ultrasonography in the Pediatric Intensive Care Unit

SUZANNE VERLHAC | CHARLOTTE MICHOT

(CONSULTANT LEVEL EXAMINATION)

Overview

As mentioned in preceding chapters, transcranial Doppler (TCD) ultrasonography is a noninvasive technique that uses low-frequency transducers for real-time evaluation of cerebral arteries in adults and in children with a closed anterior fontanelle.[1-3] TCD has been increasingly used for cerebral circulation monitoring in the pediatric intensive care unit (PICU), and it has become an essential tool for managing sickle cell disease in children.[2,3] Two types of TCD devices are available: blind TCD and transcranial color Doppler imaging (TCDI) ultrasonography, which links pulsed-wave Doppler to color mapping for a more accurate identification of arteries. In this chapter, we present TCDI applications in the PICU.

Technique

TCDI transducers are sector or phased-array low-frequency (1.8-4.0 MHz) dedicated probes with small footprints that facilitate insonation of the intracranial arteries via the temporal window. The transducer is placed just anterior to the ear's tragus and above the zygoma, and the axial grayscale view of the base of the brain depicts the hypoechoic "butterfly-shaped" cerebral peduncles and the echogenic "star-shaped" suprasellar cistern (reference landmarks).[3] The circle of Willis, which is depicted on color mode, projects anteriorly (Figure 5-1). The middle cerebral artery (MCA) is coded red, with blood flow circulating toward the transducer. Color-scale settings should be optimized according to the blood velocities. After switching to the spectral Doppler mode, the 4- to 5-mm–wide Doppler sample gate is placed on the initial part of the MCA, and the recording is optimized by slightly tilting and sliding the transducer to obtain the cleanest and highest-velocity spectrum, which indicates that the axis of the vessel and the Doppler beam are closely aligned. Two to three spectra are recorded, and the most powerful signal at the highest mean blood velocity is used for measurement. The temporal window also allows for recording the internal carotid artery and the anterior and posterior cerebral arteries. However, because the MCA is the main cerebral artery that supplies blood to 60% to 80% of the hemisphere, its acute blood flow changes may reflect hemodynamic alterations in the entire hemisphere. Hence scanning other arterial segments is not as important as scanning the MCA, except in specific clinical scenarios. The tracing is assumed to be obtained at an optimal angle of 0 degrees. Terminal segments of the vertebral arteries and basilar artery can be insonated via the suboccipital window. The transorbital window can be used when assessing the carotid siphon if no temporal window is available. Although no side effects have been described with TCDI, it should be set at the lowest power output possible, according to the ALARA (*A*s *L*ow *A*s *R*easonably *A*chievable) principle (see Chapter 1).

Doppler Measurements

Common Doppler-derived variables are end-diastolic velocity (VD); time-averaged mean maximal velocity (TAMX), obtained after outlining manually or electronically the envelope of the waveform over a cardiac cycle, also called mean velocity (VM); and peak systolic velocity (VS) (see Figure 5-1). Spectral Doppler waveforms are described by the pulsatility index (PI) and resistive index (RI). PI is calculated according to the formula $PI = (VS - VD)/VM$ (normal values $= 0.82 \pm 0.11$). RI is calculated according to the formula $RI = VS - VD/VS$ (normal values $= 0.55 \pm 0.66$, after the neonatal period). When territorial vascular resistance decreases (e.g., vasodilation), thereafter increments of blood flow are observed during diastole, and thus PI and RI are decreased. In contrast, intracranial hypertension results in increments of PI and RI values as resistance to cerebral blood flow is increased. PI and RI are unitless and independent of insonation angles. The Lindegaard ratio helps to distinguish between vasospasm and hyperemia by comparing the VM of the MCA with the VM of the extracranial portion of the ipsilateral internal carotid artery. The normal value is less than 3.0 (median, 1.7). With an elevated VM in the MCA, a ratio of less than 3 is considered hyperemia, 3 to 6 is mild vasospasm, and greater than 6 is severe vasospasm. TCDI measurements are subjected to many limitations: inability to obtain an optimized signal or obtaining a weak signal, aliasing, absent temporal window, operator experience, clinical conditions, and effects of therapy other factors (age, anemia, dehydration, hypotension, hypoventilation or hyperventilation, pharmacologic agents).

Basic Cerebrovascular Hemodynamics

Flow velocities in arterial circuits depend on a vessel's cross-sectional area and its blood flow. VM variations reflect variations in cerebral blood flow if neither the diameter of the

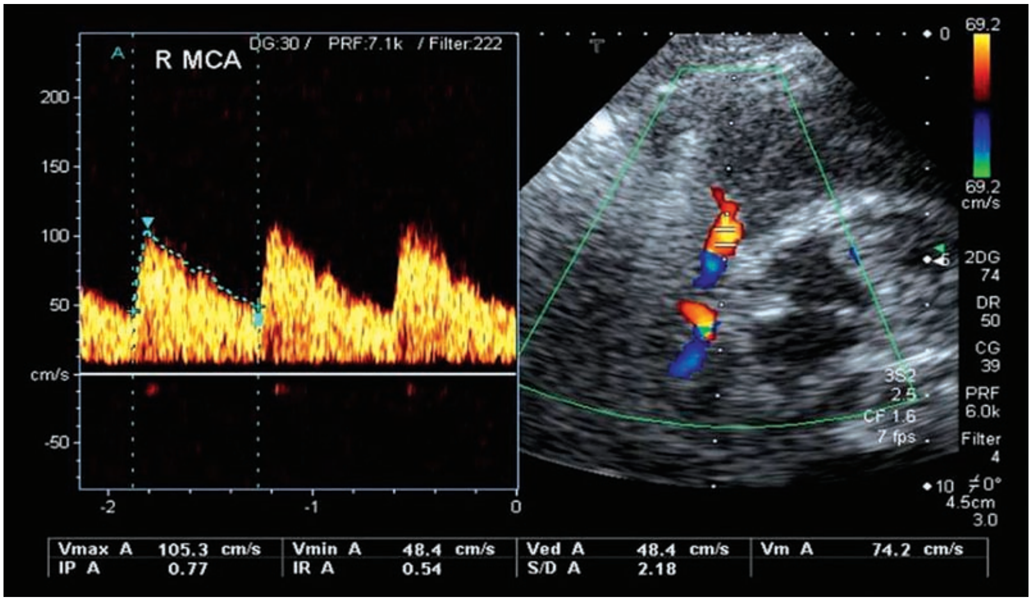

Figure 5-1 Transcranial color Doppler imaging (TCDI) (temporal window) performed in a healthy child. Middle cerebral artery (MCA) is coded red, and the spectrum is above the baseline because blood flow is moving toward the transducer (pulsatility index [PI] = 0.77, resistive index [RI] = 0.54, mean velocity = 74 cm/sec, and end-diastolic velocity = 48 cm/sec).

insonated artery nor the angle of insonation change during the examination. PI and RI may be used for indirect evaluation of intracranial pressure (ICP). Invasive ICP measurements are strongly correlated with PI values (within the range of ICP values of 5-40 mm Hg).[4] If ICP is increased, diastolic velocity is decreased, and the Doppler waveform has a high resistance profile (increased PI and RI). Because proximal segments of intracranial arteries have limited vasodilation capacities, low velocity reflects low blood flow. With increased cerebral blood flow (hyperemia), Doppler velocities are increased bilaterally, and the waveform has a low resistance profile with decreased RI and PI (Lindegaard ratio < 3). Cerebral blood flow depends on cerebral perfusion and cerebrovascular resistance. The ability of the cerebrovascular system to constrict or dilate in response to perfusion pressure changes is termed autoregulation. Various disorders, including traumatic brain injury (TBI), can impair cerebral autoregulation, rendering the brain susceptible to inadequate (ischemia) or excessive (hyperemia) cerebral blood flow. Alterations in Doppler flow velocities in response to changes in arterial blood pressure and arterial carbon dioxide pressure ($Paco_2$) may be used as markers of cerebrovascular autoregulation. Doppler measurements are influenced by various factors, such as arterial blood pressure, hematocrit, fever, and $Paco_2$. Doppler flow velocities increase with low hematocrit as increased cardiac output and decreased blood viscosity result in reduced intracranial resistance, thus allowing sustained normal brain oxygenation despite anemia. CO_2 is a powerful modulator of cerebral blood flow. Hyperventilation induces vasoconstriction of distal intracranial arterioles and significantly increases PI and RI values, whereas hypoventilation induces vasodilation and significantly decreases PI and RI values. Cerebral vasoreactivity to $Paco_2$ can be diminished or abolished by drugs, ischemia, TBI, and some forms of metabolic encephalopathy. Sleeping can slightly increase velocities with hypercapnia. Crying can decrease velocities with hypocapnia. Fever increases blood flow by about 10%. In the PICU, the influence of anesthetic medications on TCDI results should be considered. Halothane increases by 30% the MCA Doppler velocities during general anesthesia, whereas thiopenthal has a mild inverse effect. Lesions producing large diastolic runoff (e.g., large patent ductus arteriosus or aortic valve insufficiency) decrease diastolic blood flow to the brain and consequently the diastolic component of the TCDI waveform. TCDI velocities vary with age. Velocities increase rapidly after birth and then more slowly until the age of 6 to 8 years; then they decrease slowly to about 70% of the maximal velocities by the age of 18 years. Velocities are lower in the vertebrobasilar compared with the carotid system.[5]

Transcranial Color Doppler Imaging Ultrasonography in the Pediatric Intensive Care Unit

MONITORING OF CEREBRAL HEMODYNAMICS AFTER TRAUMATIC BRAIN INJURY

TBI has a detrimental effect on child morbidity and mortality. It influences cerebrovascular hemodynamics by causing cerebral hyperemia, ischemia, and vasospasm. TCDI and other monitoring tools (e.g., computed tomography scans, invasive ICP measures) may aid in guiding TBI management in the PICU. Hyperemia accompanies diffuse cerebral edema, leading to increased ICP and poor outcome in pediatric patients with TBI. Hyperemia can occur a few hours after TBI, lasts 2 to 4 days, and is followed by patterns of high intracranial resistance consistent with elevated ICP.[6] Of note, hyperemia was also observed in the first hours after an ischemic event in neonates and children. It can provoke intracerebral hemorrhage and is believed to occur because of autoregulation loss. TCDI detects increased blood flow velocities that are above the mean velocity plus 2 standard deviations in both MCAs; PI and RI are decreased, and the Lindegaard ratio is less than 3. Cerebral ischemia is another important pathophysiologic element of an evolving TBI and is usually observed after the acute phase. TCDI can detect ischemia with associated increased ICP in

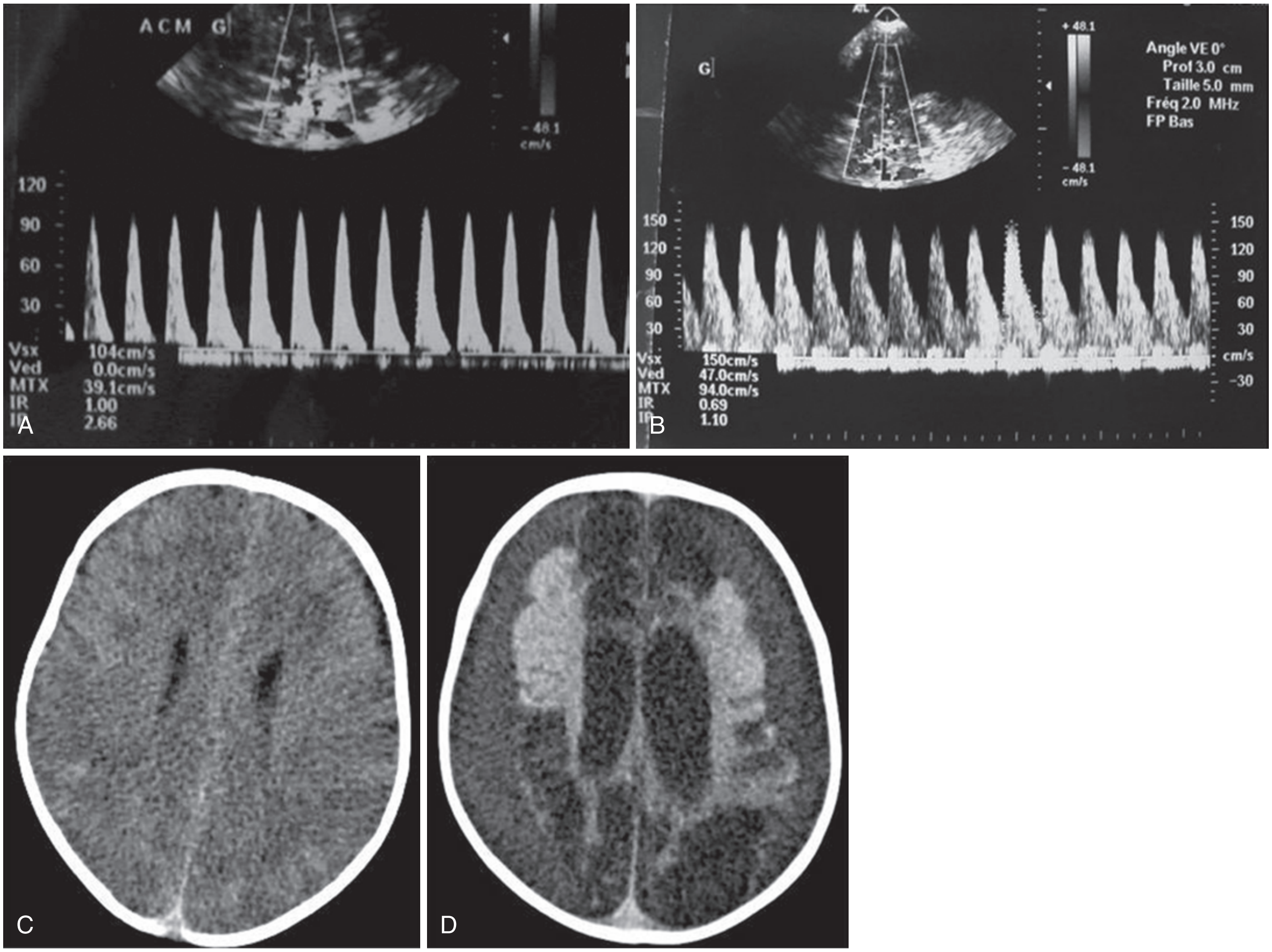

Figure 5-2 Two-month-old boy with shaken-baby syndrome and poor outcome. Transcranial color Doppler imaging (TCDI) was performed upon admission **(A)** and revealed high-resistance-profile blood flow (pulsatility index [PI] = 2.66) in the middle cerebral artery (MCA). The waveform was normal at day 12 **(B)** (PI = 1.1). Brain computed tomography (CT) scan revealed diffuse brain edema upon admission **(C)** and encephalomalacia with bilateral ex vacuo subdural hematomas 1 month later **(D).**

pediatric patients (Figure 5-2). In a prospective pediatric study of 36 children with moderate or severe TBI, diastolic velocity less than 25 cm/sec and PI greater than 1.3, revealed by TCDI performed on arrival in the emergency department after the first resuscitation phase (correction of low blood pressure, anemia, hypoxia, hypoventilation), were associated with poor prognosis.[7] TCDI is also used to monitor therapeutic effects. Vasopressors used to increase mean arterial pressure may also decrease PI and increase VD and VM, whereas mannitol increases TCDI velocities by reducing edema and increasing cerebral blood flow.[8] The level of "useful" mean arterial pressure may be estimated by TCDI.

Recent studies underlined the role of impaired autoregulation as a poor prognostic marker in brain-injured pediatric patients. Impaired autoregulation has been reported in about 40% of children at some point after TBI.[9] However, this varied according to the postinjury time, and therefore single measurements may not reflect true incidence.[10] Intracranial vasospasm is a usual complication of subarachnoid hemorrhage after rupture of cerebral aneurysm or TBI in adults, but it appears to be uncommon in children with TBI.[11-13]

DIABETIC KETOACIDOSIS IN CHILDREN

Death caused by diabetic ketoacidosis is most often related to the development of acute brain edema. The latter occurs in approximately 1% of cases of ketoacidosis, usually during the first 24 hours of treatment.[14] Its pathogenesis is complex and poorly understood. Hyperemia caused by intracranial arteriolar vasodilation secondary to acidosis may occur first (Figure 5-3), leading to intracranial hypertension and finally inadequate cerebral perfusion and ischemia.[15,16] Intracerebral hemorrhage may also occur and is believed to be caused by autoregulation loss (see Figure 5-3). The role of vasopressin, insulin, the sodium ion/hydrogen ion (Na^+/H^+) pump, hypoxia-ischemia, cytokines, as well as of insulin and fluid therapy is still debatable.

MENINGITIS AND MENINGOENCEPHALITIS IN CHILDREN

Meningitis is still associated with high mortality mainly because of cerebral herniation and compression of the brainstem as a

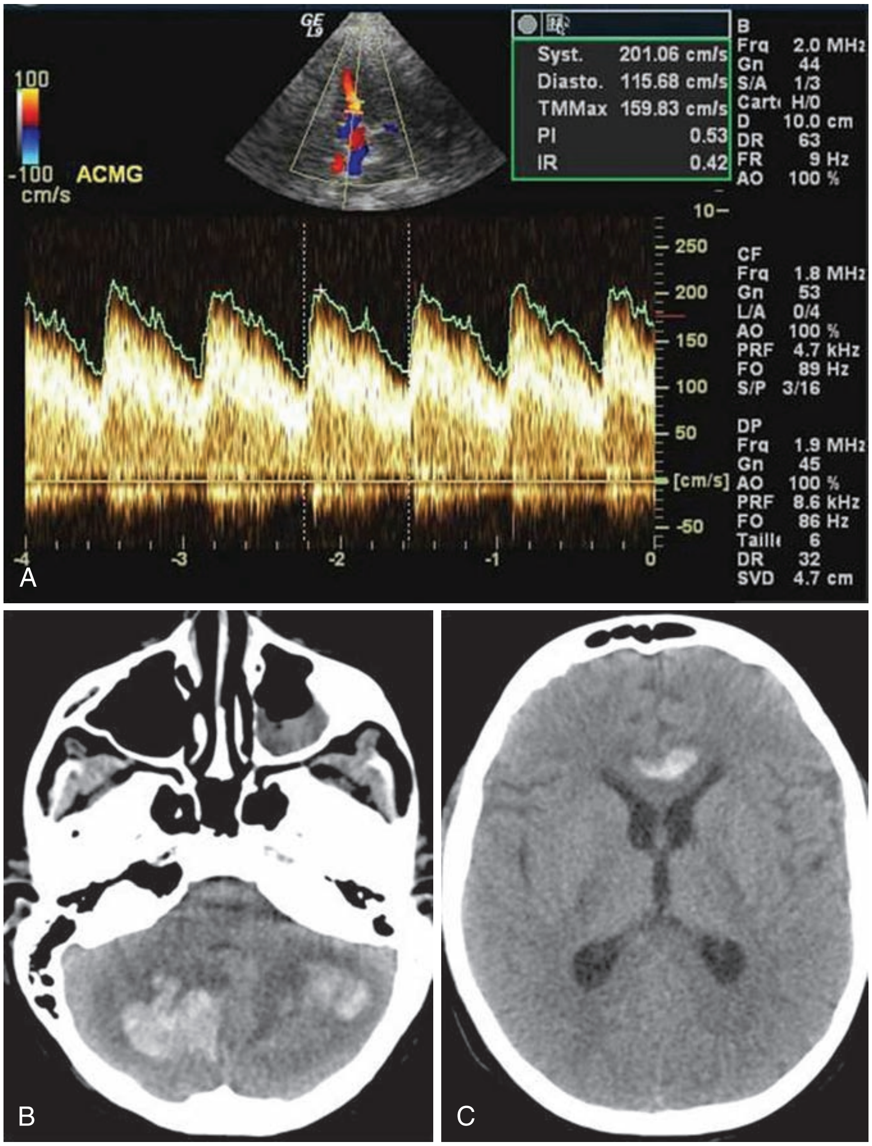

Figure 5-3 An 11-year-old boy in diabetic ketoacidotic coma. **A,** Upon admission, intracranial flow velocity was abnormally high, and the pulsatility index (PI) was low (hyperemia, mean velocity = 159 cm/sec, PI = 0.53 in the middle cerebral artery [MCA]). **B** and **C,** After 7 days, brain magnetic resonance imaging (MRI) depicted intracerebral hematomas.

result of increased ICP. Monitoring cerebrovascular hemodynamic changes may be important for early detection of cerebral perfusion compromise and to prevent further cerebral insult (Figure 5-4). In the early phase, when increased ICP may be present, the RI is useful, and RI values greater than 0.65 for children and greater than 0.80 for neonates and young infants suggest significant perfusion compromise, especially when mean flow velocity is also lower than normal.[17] PI above 1.30 and VD less than 25 cm/sec are also used as thresholds for increased ICP in this setting. TCDI can also detect arterial stenosis or vasospasm as a complication of meningitis, encephalitis, brain abscess, and sepsis. Infection likely leads to cerebral ischemia via several mechanisms, such as systemic inflammatory response, hypercoagulable state, and/or direct invasion of the endothelium.

SICKLE CELL DISEASE

Screening children aged 2 to 16 years who have sickle cell anemia to assess for and prevent ischemic stroke is the best-established, evidence-based use of TCDI (type A level of evidence and class I recommendation). Sickle cell disease is associated with progressive occlusion of intracranial arteries (most frequently the intracranial internal carotid artery and MCA), leading to stroke caused by total occlusion of these arteries or related to hemodynamic failure in the downstream territory. According to TCDI criteria for sickle cell disease, a VM less than 170 cm/sec is considered normal, and a VM of 170 to 199 cm/sec is considered "conditional." VM greater than or equal to 200 cm/sec is considered abnormal and indicates the need for transfusion therapy.[2,3] A VM greater than or equal to 200 cm/sec is associated with a risk of stroke of 40% within the next 3 years.[18] Transfusion with reduced hemoglobin S, to less than 30% of total hemoglobin, will lower this risk by 90% compared with standard care alone.[19] TCDI is repeated every 12 months after a normal scan and every 3 months with a "conditional" scan. The efficacy of this protocol has been shown in several series, as in the longitudinal French newborn cohort, with the risk of stroke by age 18 significantly decreased from 11% to 1.9%.[20]

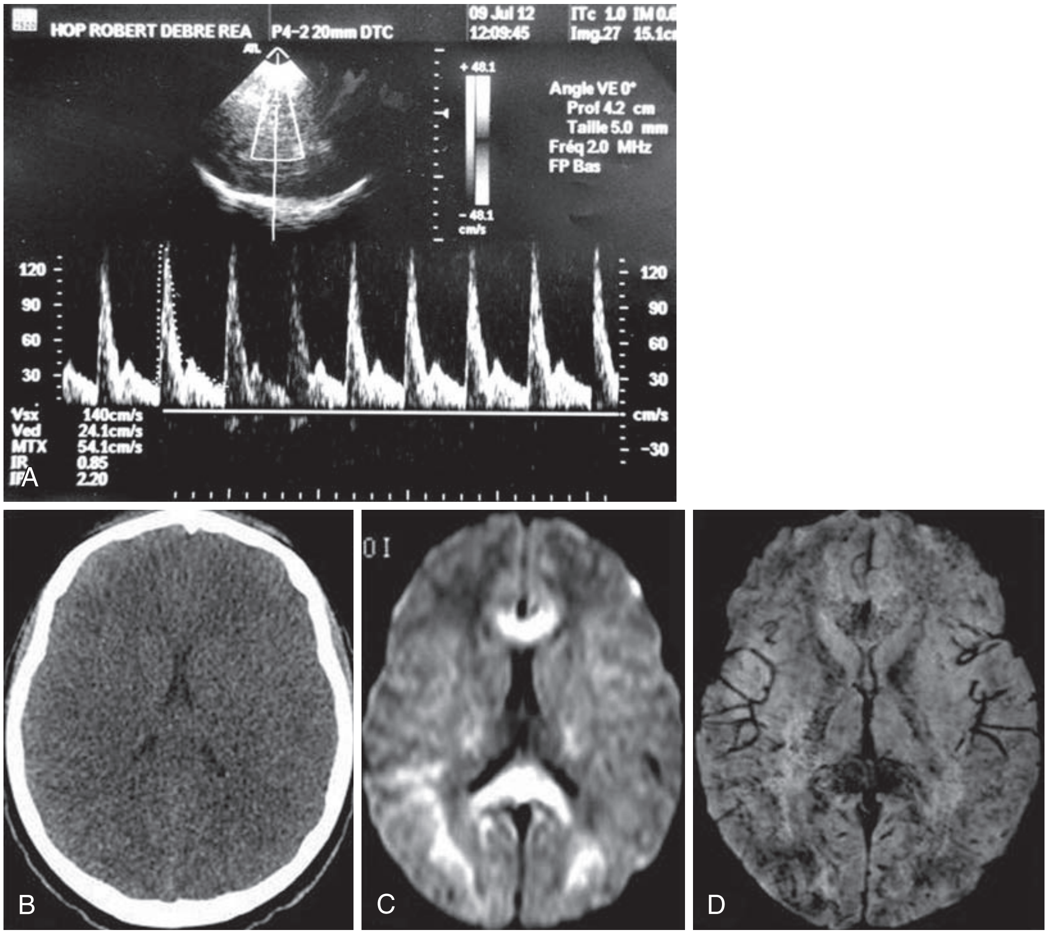

Figure 5-4 A 14-year-old girl into febrile coma after a trip to Africa (cerebral malaria). **A,** Both middle cerebral arteries (MCAs) exhibited high-resistance-profile spectra (resistive index [RI] = 0.85, pulsatility index [PI] = 2.20), whereas brain computed tomography (CT) scan revealed diffuse brain swelling **(B).** Magnetic resonance imaging (MRI) with diffusion-weighted imaging revealed extensive cytotoxic edema **(C)** and with susceptibility-weighted imaging demonstrated diffuse petechial hemorrhage throughout the brain **(D).**

Pearls and Highlights

- Impaired autoregulation has been reported in about 40% of children at some point after TBI. In its early stages, hyperemia characterized by increased Doppler MCA flow velocities (decreased PI and RI values, Lindegaard ratio < 3) is observed. As TBI evolves, cerebral ischemia commonly occurs. PI values greater than 1.3 and end-diastolic velocities less than 25 cm/sec are suggestive of intracranial hypertension and indicate the need for intensive treatment.
- TCDI is useful in monitoring pediatric patients with diabetic ketoacidosis, meningitis, or meningoencephalitis; however, screening children aged 2 to 16 years with sickle cell anemia to assess for and prevent ischemic stroke is its best-established use.
- According to TCDI criteria for sickle cell disease VM values less than 170 cm/sec are considered normal, and values in the range of 170 to 199 cm/sec are considered "conditional." VM values greater than or equal to 200 cm/sec indicate the need for transfusion because there is a risk of stroke of 40% within the next 3 years.

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6

Ocular Ultrasound in the Intensive Care Unit

ASHOT E. SARGSYAN | MICHAEL BLAIVAS | THOMAS GEERAERTS | DIMITRIOS KARAKITSOS

(CONSULTANT LEVEL EXAMINATION)

Overview

Multipurpose ultrasound systems offer a variety of eye and orbit imaging techniques relevant to critical care. Bedside ocular ultrasound can be used for the following purposes: (1) timely identification of threats to ocular health and vision and prevention of vision-related disability in trauma,[1-4] (2) assessment of nontraumatic acute change in vision and the need for immediate ophthalmologic consultation,[1] (3) measurement of the diameter of the optic nerve sheath (ONSD) as a surrogate measure for intracranial pressure (ICP),[5-9] (4) assessing the integrity of the bony orbit and periorbital tissues in severe craniofacial trauma,[10] and (5) assessing the pupillary reactivity when visual access to the pupil is impeded.[11] However, ocular ultrasound applications are somewhat unique and not standardized at this time, whereas only ONSD measurements have been partially studied in the intensive care unit (ICU) environment. This chapter illustrates specific guidance for ultrasound equipment choice and adjustment, general ocular scanning techniques, and tips to maximize the utility of the ultrasound method for eye and orbit imaging.

Equipment and Settings

In principle, any modern ultrasound system is acceptable for eye/orbit imaging if equipped with an appropriate transducer. At the time, multipurpose systems do not have either specialized transducers or factory-programmed "presets" for ocular imaging. To abide by the current safety standards, a machine should be chosen that displays the safety-related meta-data: mechanical index (MI) and thermal index (TI) on the screen. Older-generation machines do not display these values. Ocular scanning with those machines may be done only for vital indications and using the lowest possible power output. Furthermore, some results (e.g., ONSD measurements) may not be accurate because of old technology or wear and tear.

Because of the relatively shallow depths, small volume of the region of interest (ROI) and the very low attenuation in ocular media, the highest available frequencies are used, most commonly, a 12- or 14-MHz linear array transducer. Higher frequencies offer better resolution and smaller, easier-to-handle probes with a small contact surface. Lower frequencies must be used initially in severe edema of the area or a possibility of orbital fractures, globe rupture, or retrobulbar hematoma (e.g., a 5- to 8-MHz microconvex or a 4- to 7-MHz broadband linear transducer). This will ensure confident penetration without applying undue pressure on the transducer, with a commensurate compromise in spatial resolution.

The choice of transducers also depends on the scope of the examination. Some high-frequency transducers offer brilliant images of the soft tissues and anterior segment but do not focus well at depths greater than 2 cm. ONSD measurement with these probes and examination of the orbital apex area is not advisable. Thus frequency is not the only consideration. For these reasons, *initial suitability assessment must be conducted by each facility that chooses to implement and use eye/orbit ultrasound in their practice, and for each machine and each associated transducer.*

Equipment controls most frequently used in eye/orbit imaging are gain, TGC (time gain compensation), focus, and power output (see Chapter 1). Additional optimization techniques can be invoked as dictated by specific circumstances.

We highly recommend creating a customized eye/orbit preset that could be selected within seconds from the preset menu of the machine. This will save valuable time; ensure standardization; and serve as a safety, training, and quality assurance mechanism. An example is (1) select the factory-made thyroid preset from the preset menu; (2) adjust depth to 4 cm; (3) move the focus marker to 2.5 cm; (4) adjust MI to 0.23[12,13] with the power output control; (5) set TGC rheostats at their midrange; (6) scan a patient with indications for ocular ultrasound (e.g., to measure ONSD), and after identifying the terminal optic nerve, adjust gain appropriately; (7) save current settings under a new custom preset name (e.g., "eye-orbit"); (8) scan several patients to "fine-tune" the preset, and resave it with improved settings every time; (9) when satisfied, copy the preset to all machines in the department (if same model), or reproduce its features manually if machines are different. Make sure that additional setting changes do not increase MI; if they do, reduce power output accordingly. Note that perfect presets do not exist, and machine adjustments (at least, gain and TGC) will still be necessary in most patients.

General Scanning Technique and Primary Views

Eye and orbit scanning in the ICU is done with closed eyelids. The scope of the examination will depend on patient's history, status, and open clinical questions. An ICU patient may need only a limited posterior pole and optic nerve examination. However, in trauma patients, the scope of the examination may be broader (see Chapters 1, 51, and 57), and thus a holistic approach (HOLA) ultrasound ocular protocol would include scanning of the eyelids, globe and orbital contents, as well as investigation of the frontal, temporal, zygomatic and nasal bones and overlying tissues. The eye examination proper, in its turn, may be directed at checking the overall integrity of the globe or at a more thorough scrutiny of its entire volume.

The operator holds the transducer close to the contact surface, touching the patient's face with the fourth and/or fifth finger for stability. The following views are assuming a forward gaze; a straight gaze forward is highly desirable but may not be possible in unconscious or sedated patients. Directional terms used for ocular scanning are nasotemporal, superoinferior, and anteroposterior. A location within the eyeball (e.g., for a foreign body) is commonly identified in terms of the clock face (e.g., 1 o'clock) and in the anteroposterior (AP) dimension, relative to the following landmarks: macula, optic disk, equator, ora serrata, limbus, and corneal vertex; the distance from the optical axis or the wall is sometimes also used.

The AP views (sagittal and axial) are used for ocular anatomy survey and allow viewing practically all ocular structures to rule out macroscopic pathology (Figure 6-1A-C). The *oblique sagittal view of the optic disk and terminal optic nerve* is used to assess the shape of the optic disk, the terminal optic nerve with its meninges, and as a backup approach to measure ONSD in a sagittal plane (Figure 6-1E). This view may offer a possibility to visualize a longer span of the optic nerve by using a small rotation of the imaging plane. Note that the transducer is placed laterally to the cornea so that the imaging plane bypasses the anterior structures (cornea, anterior chamber, ciliary body, and the lens). The *axial view from lateral approach* allows avoiding the edge-shadowing artifact that in AP views obscures the peripheral zones of the vitreous humor and the globe wall near the equator (Figure 6-1D). The *oblique axial view with optic disk and optic nerve head* is the quickest and the most reproducible way to measure ONSD (Figure 6-2). The transducer position is on the upper eyelid (preferably with a downward gaze) with the marker to the right (for both eyes), and the plane bypasses the anterior structures. The resulting target image is similar to the sagittal view (see Figure 6-1E). The *coronal view of the iris* is used to assess the circular symmetry of the iris and the pupillary reactivity to light (Figure 6-3).

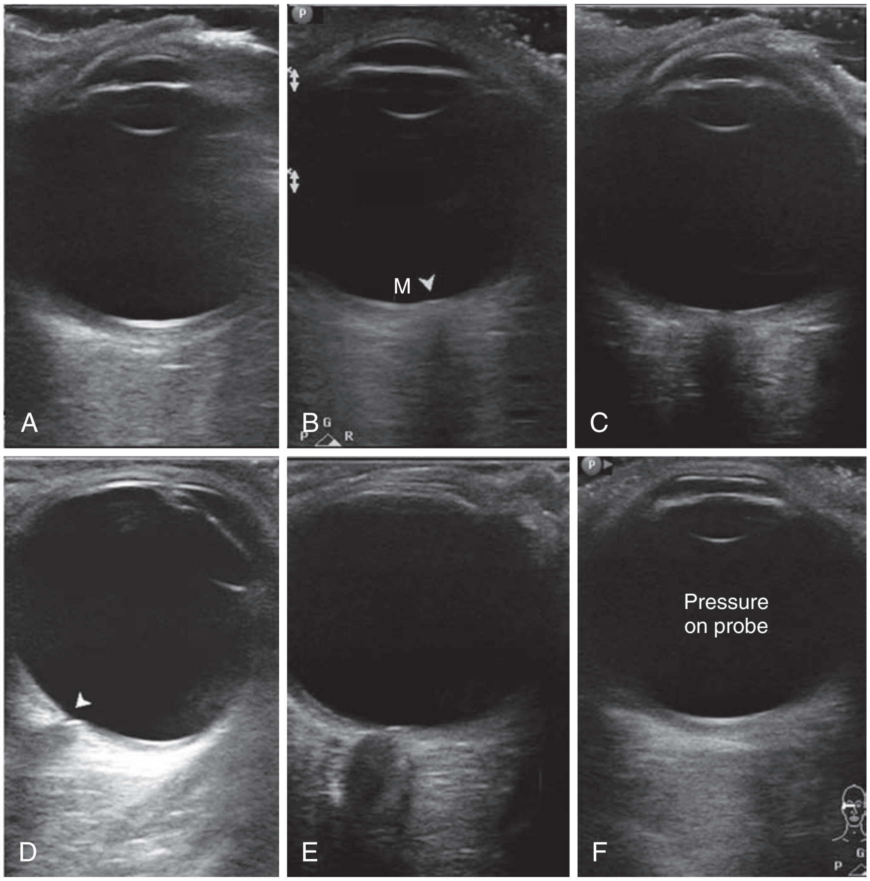

Figure 6-1 Standardized primary views in eye ultrasound. **A,** Anteroposterior (AP) view bisecting the globe sagittally from the corneal vertex to the macula (nerve not in view). Note eyelashes with trapped air affecting most of the inferior *(right)* part of the image. **B,** AP axial view with the disk area *(arrowhead)* and macular area *(M).* **C,** Similar to **A;** however, the imaging plane is shifted medially to pass through the optic nerve head. Although the nerve is visible, this image cannot be used for optic nerve sheath diameter (ONSD) measurement. **D,** Axial view, lateral approach with a good depiction of the equatorial areas. Note the cup of the optic disk *(arrowhead).* **E,** Oblique axial view through the upper lid, bypassing the anterior segment. This is an excellent image for ONSD measurement. **F,** Same plane as in **A,** with undue pressure on the probe. Note the flattened cornea.

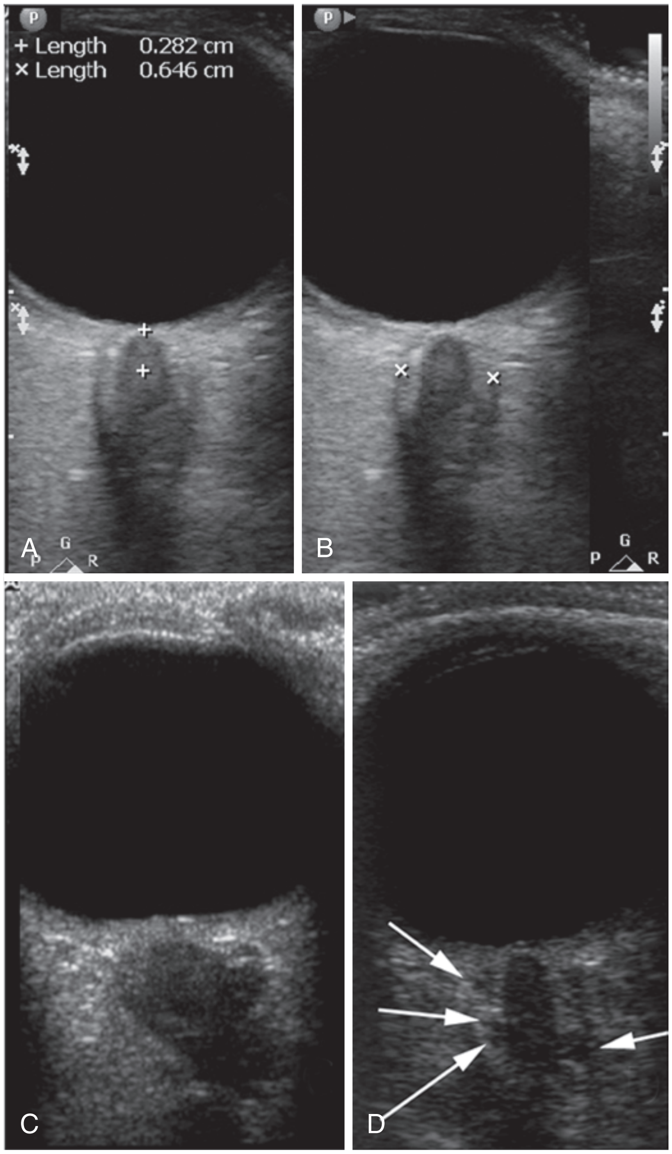

Figure 6-2 Optic nerve sheath diameter (ONSD) measurement technique and examples. **A,** Determination of the measurement location (3 mm from the vitreoretinal interface). **B,** Caliper placement for ONSD measurement. **C,** A posteriorly flattened globe; tortuous and edematous optic nerve and a severely dilated, hypoechoic, and kinked sheath with ONSD greater than 10 mm. **D,** An image of the optic nerve with a prominent (>7.5 mm) optic nerve sheath. Note the multiple anechoic fluid-filled spaces that have become visible as their size exceeded the resolution limit of the given probe at the given depth.

Trauma

The risks of eye injury are the highest in military combat[14] but always present in both professional and daily human activity. Ultrasound evaluation of the eye is indicated in any case of trauma with the following findings: disturbance of vision of any extent, suspected breech of globe integrity with or without a foreign body, any abnormal finding during visual inspection of the globe, pain or any other persisting symptom, and edema or bruising of periorbital tissues and eyelids. Use of ultrasound with traumatic eye injuries is highly sensitive and specific when performed by an experienced operator using the appropriate transducer and technique.[4,15] We will not describe the specific imaging signs of traumatic eye injuries are not described in this chapter because they are widely available from other sources.[16]

Optic Nerve Sheath Diameter Measurements and New Quality Criteria

ONSD measurement is performed as a stand-alone ultrasound examination of eye and orbit in association with known, suspected, or anticipated ICP elevation. The protocol is reasonably simple and straightforward, allowing rapid bedside evaluation in acute conditions with rapidly rising ICP, such as traumatic brain injury and brain infectious disorders, or in emergency nonhospital settings, such as triaging of multiple individuals in mass casualty situations, including assessments in the field. In the ICU, trend monitoring of ONSD alterations is an additional demand, and therefore correct recognition of the imaged anatomic substrates, standardized conduct, high-resolution image acquisition and storage, as well as precision of measurements are expected to be the norm rather than excessive detail. The ICU-based ONSD evaluation can be considered a high-fidelity version of the largely rough ONSD assessment procedures used by a number of emergency medicine centers.

The intraorbital cerebrospinal fluid (CSF) space (i.e., the space between the dural sheath of the optic nerve and the pia-covered nerve proper) is contiguous with the intracranial CSF space.[17] The authors of this chapter, as well as many others, have demonstrated a strong positive correlation between the ONSD and the ICP in animal and cadaveric models as well as in clinical observational trials, the latter primarily in head trauma or cerebrovascular accidents.[5-9,18,19] A leading notion of the published works was to demonstrate the correlation but also to find a "cutoff value" of ONSD that would indicate a pathologic level of ICP with high confidence. The suggested "cutoff," or "threshold," values have varied between trials in the range of 5.0 to 5.9 mm. In a meta-analysis of six trials involving 231 patients, Dubourg et al [20] found ONSD to have "*a good level of diagnostic accuracy for detecting intracranial hypertension*" and suggested that ONSD technique can help make triage or invasive monitoring decisions. Notwithstanding the exhaustive statistical analysis of the data, and the resulting good agreement among the six highest-quality trials, their results remain applicable only to the patient groups involved and do not necessarily discern weaknesses associated with the imaging and measurement technique and the accuracy of recognition of the optic nerve sheath borders (see quality criteria below). A general weakness, besides the lack of standardization and quality control of ONSD measurements, is the lack of normal population data that would provide an alternative approach to ONSD data interpretation, because age, gender, race, anthropometric factors, medical history, and even professional background most likely influence the individual's baseline (premorbid) ONSD. For these reasons, we strongly recommend exercising caution in using hitherto published threshold values in clinical decisions on the one hand, and making serious efforts in attaining ultrasound views with clearly visible borders of the arachnoid space, on the other. The equipment requirements and the ultrasound views and technique for ONSD measurement are described in previous sections. The first and default view for this purpose is the near-axial (oblique axial) view through the upper eyelid, with a straight-to-downward gaze (see Figure 6-2). In case of gaze deviation in superior (frontal) direction, the lower eyelid should be used. The lateral axial view should be reserved as a

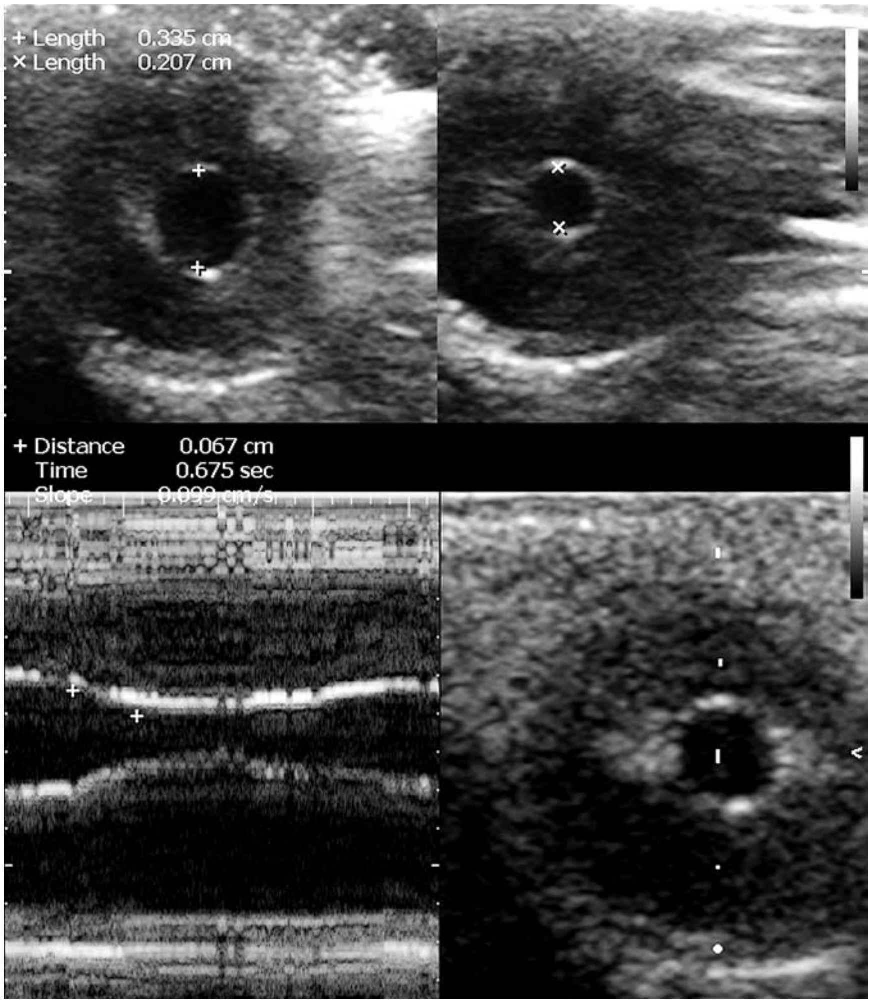

Figure 6-3 The coronal view of the globe in the plane of the iris at baseline *(top left)* and upon consensual response to contralateral stimulation with light *(top right)*. Below, M-mode cursor is placed over the middle of the iris to record the reflex against time and measure the degree of constriction, the time of response, and its velocity (slope).

backup view if the previous two views fail. As a minimum, one high-quality view of the posterior pole with the terminal optic nerve must be obtained from each side.

The quality criteria for ONSD measurements have not been well described in the literature. Images of quality acceptable for ONSD measurement are provided in Figure 6-2. *Our suggested quality criteria are summarized below:*

- ONSD measurement should not be made through the lens (even the edge of the lens may not be visible on the image); an example of unacceptable image for ONSD purposes is shown in Figure 6-1C.
- Sonographic differentiation (contrast) between the nerve proper and the arachnoid (CSF space) must be obvious (see Figures 6-1E and 6-2); measuring a "dark stripe" behind the globe without nerve and arachnoid differentiation is not acceptable.
- The outer border of the arachnoid must be identifiable for actual ONSD measurement; clear, well-focused images must thus allow confident measurement of the inner diameter of the dural sheath.
- Ideal views of the optic nerve demonstrate the point of its penetration into the globe, that is, "dark meets dark" (nerve meets vitreous without interposition of thick echogenic layer of the posterior sclera).
- Good views offer opportunities for additional information potentially useful with growing experience, such as tortuosity of the nerve, hypoechogenicity of the arachnoid, and its irregularity because of distention of CSF-containing "cells" (see Figure 6-2D); this also allows viewing the optic disk area protrusion into the globe and flattening of the posterior globe in chronic ICP elevations (premorbid), which may mimic acute states in ICU (see Figure 6-2C).
- Correct standardized measurements. Because the most distensible portion of the sheath is at the *3- to 4-mm* distance from the vitreoretinal interface (see Figure 6-2A), measurements are performed at this level in a direction perpendicular to the axis of the nerve (see Figure 6-2B). In extreme gaze deviations, this may be difficult to achieve because of the acute angle between the nerve axis and the posterior wall of the globe. This may require repeated attempts or adjustment of gaze if possible.
- It is highly recommended to measure ONSD bilaterally and in more than one image frame. This is an important quality assurance mechanism.

- For ONSD trend monitoring, the previous record with images must be reviewed to ensure similar views and measurement technique. Prior images should be available at bedside (from the machine or in printout) for reference. ONSD measured in sagittal planes should not be compared with ONSD from axial planes.

ONSD values, if measured correctly, accurately reflect the anatomic dimension of the sheath at a specific point behind the globe. A high quality of measurements and consistent technique may facilitate monitoring the ICP *trend* in some patients, although previous evidence has been disappointing in this sense.[7] This could be attributed to the fact that ONSD reaches a plateau at some point, and further distention may be too small to measure or be due to technical issues because ONSD measurements in early clinical studies have not been performed using refined methodology and according to strict image quality criteria. ONSD still holds promise for trend identification with increased measurement accuracy, at least in situations with rapidly rising ICP, when the difference in ICP between the two measurements is significant. One-time ONSD measurement should be considered with caution, and "cutoff" values reported in literature should be used as "alert levels" to prompt additional attention to ICP. The clinician must also remember that any ICU patient may have had a large ONSD before the current illness. As population distribution data become available and the quality standards are improved, better clinical criteria will likely emerge for both negative and positive prediction, and trend monitoring criteria may also be revised.

Pupillary Light Reflex Assessment

The normal pupillary light reflex evaluation is usually described by the acronym PERRLA (pupils equal, round, reactive to light, and accommodation). The assessment of this fine reflex is part of the routine neurologic examination. The prognostic significance of pupil diameter and constrictive ability in brain-injured patients is well known and has been recommended by the American Association of Neurological Surgeons. Various pupillometric methods have been described, a majority requiring both specialized hardware and visual access to the pupil. The examination of pupil diameter and reactivity by ultrasound is a new alternative method for situations when visual access to the pupil is impossible or fine quantification of the pupillary reactivity is desired.

The method was initially developed for the U.S. Space Program and is not standardized for clinical use; only two successful case studies in trauma ICU patients have been published.[11,21] The method has no real alternatives when visual access to the pupil is impossible, and its results are self-explanatory. Consensual pupillary light reflex is elicited with contralateral transillumination through the eyelids with both eyes closed. The pupillary light reflex ultrasound test can be conducted with a linear-array probe at the highest available frequency (e.g., 12-15 MHz), using the coronal primary view described earlier (see Figure 6-3 and Video 6-1). The method can be combined with ONSD measurements to evaluate a potentially catastrophic intracranial process. The method is difficult in unstable gaze. In cases of severe facial trauma, extreme care should be taken to avoid additional damage to the globe and other tissues.

Additional Specialist Evaluation

Eye ultrasound data may reveal a need for ophthalmology consultation. Images may also be reviewed by a radiologist experienced in high-resolution ultrasound imaging of the eye and orbit. Because of the substantial differences in scope, methodology, and equipment used in ultrasound B-scans in ophthalmologic practice, imagery acquired by multipurpose ultrasound machines is not commonly referred to specialists in ophthalmic ultrasound.

Safety Aspects

Diagnostic ultrasound has an excellent safety record. However, exposure of tissues to intense levels of ultrasound, well above those levels found with diagnostic ultrasound devices, has been shown to have damaging effects (see Chapter 1). Furthermore, delicate structures of the orbit, especially in trauma, can be damaged by mechanical force in case of unstable positioning, incautious movements of personnel, or involuntary movements of the subject. Use of irritant antiseptics for probe disinfection or inappropriate contact gels or lubricants can lead to chemical conjunctivitis. Failure to disinfect the transducer can potentially introduce pathogenic flora to the conjunctival sac. Therefore a set of safety rules is outlined below.

Following the ALARA principle (As Low As Reasonably Achievable), includes (1) controlling *energy* (having an "ophthalmic" preset with low acoustic output levels: TI less than or equal to 1.0 and MI less than or equal to 0.23; checking TI and MI upon each mode change; using two-dimensional gain, TGC, and other controls before increasing output); (2) controlling *exposure time* (minimizing data redundancy, minimizing "dwell time" [scanning while not looking]; deferring measurements until after procedure); and (3) controlling scanning *technique* (achieving gaze control, minimizing movement, eliminating distractions; using good ergonomics; following a plan with prioritization of views; controlling total duration of the procedure; deferring secondary views/objectives to the end of procedure; using sufficient amount of gel).

Observing chemical and biologic safety includes (1) using safe gel with safety data sheet favorable for eye contact and (2) disinfecting the transducer with 70% isopropyl or ethyl alcohol solution and air-drying before gel application. A 0.25% benzalkonium chloride solution may be used, but the residual amount of the disinfectant must be removed by applying and wiping off a small amount of gel. Other disinfectants such as Cydex are not allowed. (3) General skin hygiene is emphasized, and (4) the operator's hand hygiene and gloves are mandatory.

Mechanical safety expects that (1) operator must assume a stable and comfortable position before commencing the procedure; (2) adequate time for scanning must be available to avoid haste; (3) nonessential personnel must stay at distance; (4) good transducer manipulation technique must be used, including hand anchoring, use of bony prominences of the subject's periorbital area, and use of both hands as necessary to reliably control transducer position and prevent transducer pressure at all times; and (5) no transducer pressure may be used as a means to improve the image quality. All mechanical safety measures are emphasized in trauma, especially if there is a slightest possibility of globe rupture.

Thus we have presented equipment, technique, quality, and safety aspects of individual ocular imaging modules concerned with ocular as well as intracranial pathology. Because of limited space, we did not discuss other important ultrasound imaging opportunities, such as generic scanning of the orbit and periorbital areas for soft tissue and bone injury, transcranial Doppler (TCD), and a number of related ultrasound-based techniques that are not yet broadly accepted or standardized. Combinations of these and other techniques have been reported as promising in the assessment and monitoring of ICU patients. When following the holistic approach to ultrasound imaging in ICU, a facility may choose to devise an ultrasound protocol oriented toward intracranial pathology, which would combine TCD, optic nerve sheath measurement and possibly characterization, pupil reactivity recording and monitoring, as well as generic scanning of the facial tissues and orbital content in those with history of trauma. This chapter is as much a "how to" manual as an invitation to the reader to contribute to this specific area of critical care medicine by collecting and sharing their experience and moving together toward standardization and optimization of ultrasound use in ICU.

Pearls and Highlights

- Generic survey of regional ocular anatomy, focused imaging of the globe, measurement of the ONSD, and ultrasound assessment of pupil reactivity are all new eye and orbit ultrasound imaging techniques relevant to critical care.
- The HOLA ultrasound concept embraces both the anatomic context and the specific focused techniques in the ocular area. For example, a HOLA ultrasound ocular protocol in trauma patients would include scanning of the eyelids, globe, and orbital contents—including ONSD measurements—as well as investigation of the frontal, temporal, zygomatic and nasal bones, and overlying tissues.
- Eye imaging requires special safety measures to be implemented and followed.
- Standard multipurpose ultrasound machines with higher-frequency (10-14 MHz) transducers must be used unless severe facial edema requires deeper penetration.
- Strict image quality criteria (i.e., the recognition of both inner and outer borders of the arachnoid layer) should be applied to ensure the accuracy and validity of ONSD measurements.
- The "cutoff" values of ONSD measurements reflecting pathologic ICP have been reported at 5.7 to 5.9 mm. However, population distribution data for ONSD are not currently available, and most published data are from traumatic brain injury and cerebrovascular accident patients.
- Ultrasonic determination of pupillary reactivity may be a promising new technique in neurocritical monitoring. It is not standardized but can be used when indicated because its results are self-explanatory. This is an example of ultrasound being a part of the physical examination.

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For a full list of references, please visit www.expertconsult.com.

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7

General Chest Ultrasound in Neurocritical Care

MOHAMMED REHMAN | CHRISTOS LAZARIDIS

Overview

Neurocritical care patients often require hemodynamic monitoring to optimize cerebral blood flow and brain tissue oxygen delivery. Hemodynamic monitoring also aids in the management of usual coexisting disorders, such as acute lung injury and acute respiratory distress syndrome (ARDS), as well as shock states.[1] *General chest ultrasound* (see Chapter 1), which consists of cardiovascular and lung ultrasound, is a noninvasive bedside tool that facilitates hemodynamic monitoring in modern neurocritical care. The manipulation of the cardiac output (CO), mean arterial pressure (MAP), systemic filling pressures and volumes, as well as the assessment of dynamic markers of fluid responsiveness and evaluation for pulmonary edema are all essential in optimizing cardiorespiratory function in the acutely brain- or spinal cord–injured patient. This chapter illustrates the role of general chest ultrasound in neurocritical care.

Cardiovascular Evaluation in Neurocritical Care

Recommended transthoracic echocardiography (TTE) should include two-dimensional sector scanning, color Doppler flow mapping, as well as pulsed and continuous wave Doppler interrogation (see Chapter 26). The standard parasternal long-axis, short-axis, and apical two- and four-chamber views are used for analysis of left ventricular (LV) dysfunction. LV ejection fraction (EF) can be visually rated as normal (LVEF, 50%-55%) and mildly (LVEF, 40%-54%), moderately (LVEF, 30%-39%), or severely (LVEF $< 30\%$) depressed.

In neurocritical care, patients with aneurysmal subarachnoid hemorrhage (SAH) and other neurologic events may be hemodynamically compromised. Many of these patients have electrocardiographic (ECG) abnormalities (ST-T-segment changes, QT prolongation, U-waves, and arrhythmias), variably elevated myocardial enzymes, and LV dysfunction. In such cases, TTE is essential in diagnosing a severely reduced CO on the grounds of *neurogenic stunned myocardium* (NSM). The latter has been reported in SAH, metastatic brain tumors, seizures, subdural hematoma, brain contusion, reversible posterior leukoencephalopathy syndrome, encephalitis, hydrocephalus, Guillain-Barré syndrome, acute myelitis, and ischemic strokes. Current pathophysiologic concepts suggest that the cardiac injury may be due to increments in the sympathetic stimulation of the myocardium. This concept is further supported by a characteristic histopathologic pattern of catecholamine-induced myocardial cell death that was retrieved from the autopsies in such cases; however, analyzing this further is beyond our scope.

An intriguing syndrome that overlaps substantially with NSM is *takotsubo cardiomyopathy* (TCM), also known as apical ballooning syndrome or "broken heart" syndrome.[2] Originally described in the Japanese population, this syndrome is characterized by transient LV dysfunction that produces a distinctive configuration during systole on the ventriculogram that resembles a Japanese octopus catcher pot. The diagnostic features of takotsubo cardiomyopathy include reversible LV regional wall motion abnormalities beyond a single coronary artery distribution (typically involving the LV apex and midventricle, with relative sparing of the basal segment), ECG abnormalities, minor elevation in cardiac markers, and absence of significant coronary artery disease. LV ballooning depicted by TTE in TCM is usually apical, although midventricular and basal ballooning may be rarely observed. The terminology is still ambivalent because it was lately suggested that TCM should not be referred to as apical ballooning syndrome. Moreover, the overlapping with NSM is obvious. Outside of the neurocritical care setting, both syndromes may occur in postmenopausal women after a stressful event and are accompanied by a massive catecholamine surge.

Of note, the Mayo Clinic criteria for classifying a stress-induced cardiomyopathy consist of transient wall motion abnormalities of the LV midsegments (with the regional wall motion abnormalities extending beyond a single epicardial artery distribution in the absence of obstructive coronary artery disease, pheochromocytoma, or myocarditis), with or without apical involvement, and new ST-segment elevation and/or T-wave inversion or modest elevation in cardiac troponins. NSM fits these criteria with the exception that it allows global LV dysfunction without regional wall motion abnormalities as observed in TCM. Hence this remains largely an issue of classification of various echocardiographic findings. A summary of NSM features is presented in Table 7-1.

Despite the aforementioned terminology issues, in neurocritical care, both syndromes have a favorable prognosis because, with supportive measures, LV function spontaneously ameliorates within days, whereas in-hospital mortality remains less than 1%.[3-5] However, cardiogenic shock requiring mechanical circulatory support and rare complications, including LV apical thrombus or fatal LV rupture, have been occasionally reported.[6,7]

Although uncommon, *dynamic obstruction within the LV outflow tract* should be evaluated because it has been described with apical ballooning syndrome and is believed to be caused by compensatory hyperkinesis of the basal segments. This obstruction can be exacerbated by low filling pressures or decreased afterload. Mitral valve regurgitation (MR) can be encountered, resulting from acceleration of blood through the dynamic obstruction, leading to a Venturi effect, with the anterior mitral leaflet being sucked into the LV outflow tract.

TABLE 7-1 Neurogenic Stunned Myocardium

Clinical setting	Acute brain insult High intracranial pressure Sudden emotional stress
Clinical presentation	Biventricular failure Cardiogenic shock
Echocardiography	Apical hypokinesis/ballooning Hypercontractile base Dynamic left ventricular outflow obstruction Mitral regurgitation
Coronary angiography	Absence of occlusive coronary artery disease
Serum cardiac markers	Troponin elevation of a lower degree than from coronary artery occlusion for similar cardiac function
Lung ultrasound and radiography	Pulmonary edema (cardiogenic features)
Hemodynamic monitoring	Depressed biventricular output Elevated filling pressures Dynamic preload variables suggesting plateaued ventricular function (Frank-Starling curve)
Clinical management	Vasopressor and inotropic support guided by cardiac ultrasound and invasive hemodynamic monitoring Intraaortic balloon pump to be considered in refractory cases
Prognosis	Favorable Reversible

As a result, significant hypotension could be expected secondary to both poor LV systolic function, as well as dynamic obstruction of the LV outflow tract. In this setting, avoiding the administration of systemic vasodilators and inotropic stimulation, which can worsen the outflow tract gradient, is a prudent therapeutic strategy. In addition, fluids should be cautiously used because patients often have elevated left-sided filling pressures and evidence of pulmonary edema.[8]

PRELOAD AND RESPONSIVENESS

Preload assessment and fluid responsiveness evaluation are essential in the hemodynamic management in the intensive care unit (ICU). The frequently used static preload filling-pressure markers, such as central venous pressure (CVP) and pulmonary artery occlusion pressure (PAOP), have been shown to correlate poorly with ventricular filling volumes and fluid responsiveness in healthy volunteers and critical care patients, leading investigators to discourage their use for the purpose of fluid management.[9-11] The goal of volume expansion by the augmentation of stroke volume entails biventricular preload dependence. Stated on Frank-Starling terms, it requires both ventricles to be operating on the ascending part of their performance curves. The finding of systolic obliteration of the LV cross-sectional area ("kissing" papillary muscles sign) by TTE (via the parasternal short-axis view) may indicate severe hypovolemia.[12] Also, Feissel et al[13] and Barbier et al[14] suggested that the quantification of respiratory variation in the diameter of the inferior vena cava (dIVC) by the use of bedside ultrasound is a reliable marker of fluid responsiveness in mechanically ventilated patients. In both studies, with only slightly different cutoffs for dIVC (Feissel, 12% and Barbier, 18%) fluid responders and nonresponders could be discriminated with sensitivity and specificity greater than or equal to 90%. Recently, Moretti and Pizzi[15] found a cutoff dIVC greater than16% to be 70% sensitive and 100% specific in predicting fluid responsiveness in 29 patients receiving mechanical ventilation and advanced hemodynamic monitoring for the management of SAH. Traditionally, patients with acute brain injury, and especially patients with SAH, have been managed with a fluid liberal strategy based on daily and cumulative fluid balances, leading to hypervolemic states and significantly positive fluid balances. Based on recent literature, this strategy not only seems unjustified but in fact harmful, leading to respiratory complications, longer ICU and hospital stays, and worse neurologic outcomes.[16] Hopefully, the application of dynamic preload variables will lead to rationalization of fluid administration and better outcomes.

Pulmonary Evaluation: Neurogenic Pulmonary Edema

The implementation of lung ultrasound in routine practice offers new opportunities in the respiratory and hemodynamic management of neurocritical patients. Lung ultrasound is analyzed elsewhere in this book. In brief, the most commonly appraised artifacts of lung ultrasound are the lung rockets or B-lines (see Chapter 19). The latter are created mainly by repetitive reflections of the ultrasound wave within the lung parenchyma because of a higher concentration of physiologic or pathologic fluid. B-lines are mainly encountered in the alveolar interstitial syndrome. B-lines separated by less than 3 mm characterize predominantly alveolar abnormalities as opposed to interstitial lung disorders.[17] Alveolar abnormalities usually accompany cardiogenic and/or noncardiogenic pulmonary edema.

Although known for over a century, acute neurogenic pulmonary edema (NPE) is a potentially underdiagnosed clinical entity that can be encountered after virtually any form of acute brain injury, such as in patients with SAH, intracerebral/intraventricular hemorrhage, seizures, stroke, and traumatic brain injury.[18] The main features of NPE are summarized in Table 7-2. NPE is characterized by an increase in extravascular

TABLE 7-2 Neurogenic Pulmonary Edema

Clinical setting	Acute brain insult High intracranial pressure
Clinical presentation	Hypoxemic respiratory failure
Lung ultrasound and radiography	Bilateral infiltrates Pulmonary edema (can be either hydrostatic, permeability, or combined) Preserved ventricular contractility
Hemodynamic monitoring	High extravascular lung water Normal cardiac function High pulmonary vascular permeability index (for nonhydrostatic)
Clinical management	Mechanical ventilation Diuresis guided by cerebral and systemic hemodynamics (not as effective in the setting of high permeability) Novel use of α-blockers (phentolamine)
Prognosis	Favorable

lung water in patients who have sustained a sudden change in neurologic condition. Its pathophysiologic mechanism remains obscure, and two divergent theories have been proposed to explain its development: increased lung capillary permeability and increased pulmonary vascular hydrostatic pressures. Increased permeability as a mechanism of NPE is supported by animal studies that have shown high interstitial (lung lymphatic) or alveolar protein concentrations and time-dependent ultrastructural changes in pneumocyte type II cells after brain injury. Increased permeability may be caused by damage of the capillary endothelium or by direct neural influences on capillary permeability. Nevertheless, hydrostatically induced pulmonary edema can occur without endothelial damage. One possible sequence leading to NPE is an acute increase in sympathetic tone that abruptly increases LV afterload and causes intense vasoconstriction, thereby elevating LV filling pressures and inducing elevated pulmonary artery capillary pressures, leading to hydrostatic pulmonary edema. This was confirmed by experimental and clinical data.[19,20] However, pulmonary edema can occur with normal PAOP, suggesting a neurally mediated increase of capillary permeability. In addition to the above-mentioned hypotheses, pulmonary edema of cardiogenic origin should be considered. In fact, the early hemodynamic changes that occur in the setting of NPE may lead to the conclusion that the pulmonary edema is of cardiac origin. Smith and Matthay[21] reported, as have others, that early analysis of NPE fluid reveals a low fluid-serum protein ratio consistent with hydrostatic edema. TTE becomes invaluable in this setting, to investigate both LV and right ventricular function and to rule out a NSM or right ventricular failure. Mutoh et al[22] recently studied three patients with SAH-related pulmonary edema by using transpulmonary thermodilution and suggested that its origin can be either due to cardiogenic/hydrostatic or noncardiogenic/high pulmonary vascular permeability mechanisms.

Lung ultrasound can be used to elucidate the underlying mechanism in NPE. Copetti et al[23] reported that demonstration of a heterogeneous alveolar-interstitial syndrome with spared areas, pleural line modifications, and lung consolidations is strongly predictive in an early phase of noncardiogenic pulmonary edema. Targeting fluid and vasoactive medication management to individualized patient pathophysiology enhances the ability to satisfy the often competing clinical goals of cardiorespiratory optimization and cerebral perfusion. A specific diagnosis becomes even more relevant in light of recent work suggesting a potentially novel treatment for NPE with the use of *α-receptor blockade* and direct antagonism of the "*sympathetic storm*" that is thought to be the triggering factor behind the syndrome. In 2012, Davison et al[24] reported the successful use of *phentolamine* in a patient who developed refractory hypoxemic respiratory failure after intracerebral hemorrhage and documented the co-linear behavior between serum catecholamines, hypoxemia, pulmonary edema, and its resolution.

IMAGING CASE

A 42-year-old woman was admitted to the neurocritical care unit because of a ruptured right posterior communicating artery aneurysm and subarachnoid hemorrhage with clinical Hunt-Hess and radiographic modified Fisher scores of 4. The patient was mechanically ventilated (oxygen saturation by pulse oximetry [Spo_2] 89% on 70% fraction of inspired oxygen [Fio_2], with a positive end-expiratory pressure [PEEP] of 10 cm H_2O) and had systolic/diastolic arterial blood pressure of 80/50 mm Hg, HR of 110 beats/min, and poor urine output. TEE revealed LV global hypokinesia and MR. There was minimal inferior vena cava variation. Lung ultrasound showed multiple B-lines with no pleural abnormalities.

An initial decision to use dobutamine was complicated by further hypotension and worsening MR. A diagnosis of NSM with MR and dynamic outflow obstruction, as well as cardiogenic pulmonary edema, was made. Addition of norepinephrine infusion allowed significant improvement in mean arterial pressure and Spo_2. Cardiorespiratory stabilization was followed by placement of an extraventricular drain to address hydrocephalus and to relieve intracranial hypertension. Subsequently, the patient was taken to the neuroangiography suite for aneurysm coiling. In the following 48 hours, her clinical and neurologic status improved dramatically. A repeat TTE showed normal LV function with resolution of MR.

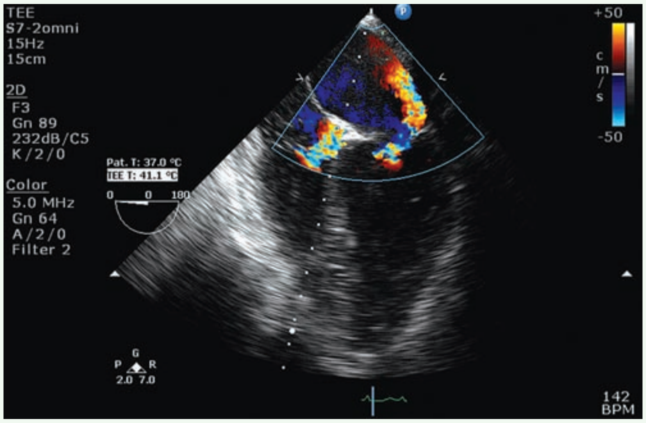

Figure 7-1

Pearls and Highlights

- General chest ultrasound comprising of echocardiography and lung ultrasound is an essential tool in the hemodynamic and respiratory monitoring of neurocritical care patients.
- NSM and TCM are overlapping clinical entities with different echocardiographic appearances, which may be seen in patients with SAH and other neurologic disorders.
- Dynamic preload variables, such as the inferior vena cava variation, need to be used in neurocritical care to minimize injudicious fluid administration that has been linked with worse systemic and neurologic outcomes.
- NPE can lead to severe hypoxemic respiratory failure. It should be considered in the patient with severe acute brain injury and noncardiogenic pulmonary edema. Lung ultrasound can diagnose, quantify, classify, and monitor the resolution of NPE. Diagnosis of NPE by means of general chest ultrasound allows the implementation of targeted therapies, such as the recent use of α-blockers.

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For a full list of references, please visit www.expertconsult.com.

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SECTION III

Vascular Ultrasound

8

Overview of the Arterial System

DIMITRIOS KARAKITSOS | GLYKERIA PETROCHEILOU | SHIWEN WANG* | MICHAEL BLAIVAS | NICOS LABROPOULOS

" . . . swift as wind . . . delicate as the river. . . ."
Sun Tzu, 610 BC

Procedural and diagnostic vascular ultrasound applications are essential in the intensive care unit (ICU). This chapter presents a synopsis of arterial disorders, whereas evaluation of venous thrombosis and ultrasound-guided vascular procedures are presented in Chapters 9 to 18.

The Arterial System

The left-sided aorta couples the left ventricle to the arterial system. Transthoracic ultrasound detects the ascending aorta (left parasternal view) and the aortic arch (suprasternal view). In the ICU, however, these acoustic windows may be impossible to obtain. Transesophageal echocardiography (TEE) is invaluable in visualizing the thoracic aorta in the ICU but typically cannot image the entirety of the thoracic aorta. Usually, the brachiocephalic trunk, left common carotid artery (CCA), and left subclavian artery (SCA) originate from the arch, in that order. The right CCA begins at the bifurcation of the brachiocephalic trunk, whereas the right vertebral artery (VA) originates from the right SCA. One third of patients have a common origin of the left CCA and brachiocephalic trunk, or the former originates from the proximal segment of the latter. The left VA may originate from the arch, and the right SCA may exhibit an aberrant origin. A right-sided aorta is rare and frequently associated with other types of congenital cardiovascular disease.[1,2]

The CCA is detected sonographically in the lateral aspect of the neck by using high-frequency transducers (7.5 to 10 MHz) in both the longitudinal and transverse planes. The CCAs run upward to about the upper border of the thyroid cartilage before branching. The normal Doppler spectral waveform (DSW) of the CCA has a narrow peak systolic and forward diastolic flow (Figure 8 E-1). The CCA bifurcates into the internal (ICA) and external (ECA) carotid arteries. The ICA does not branch in the neck and has a low-resistance DSW with forward diastolic flow. The ECA branches in the neck and has a high-resistance DSW with reversed diastolic flow. The VA runs toward the sixth cervical vertebra and enters the base of the skull accompanied by its vein. The SCA becomes the axillary artery after crossing the first rib, and the latter continues as the brachial artery (BA) after the posterior axillary fold. The BA ends about 1 cm distal to the elbow by dividing into the radial artery (RA) and ulnar artery (UA). The RA becomes the deep and the UA the superficial palmar arch, respectively, which join in the hand. The DSW of upper extremity arteries is triphasic.

The descending thoracic aorta is detected sonographically via the cardiac apical window. The abdominal aorta (AA) begins at the aortic hiatus of the diaphragm and ends at the fourth lumbar vertebra (bifurcation). The AA is detected sonographically on longitudinal, transverse, and oblique planes by using convex transducers (2.5 to 5 MHz), and its DSW is biphasic. The AA gives off several main branches: the celiac artery (CA), which supplies the liver, gallbladder, stomach, intestines, and pancreas and in turn branches into the splenic, left gastric, and common hepatic arteries (see Figure 8 E-1); the superior mesenteric artery (SMA), which originates approximately 1 cm inferior to the CA and supplies the intestines and pancreas; the inferior mesenteric artery (IMA), which supplies the colon and rectum; and the renal arteries, which branch off last and supply the kidneys and adrenal glands. The AA bifurcates into the right and left common iliac arteries at the level of the umbilicus, and these vessels travel distally to divide into the internal (IIA) and external (EIA) iliac arteries. The EIA enters the thigh at the inguinal ligament and becomes the common femoral artery (CFA). The CFA bifurcates into the superficial (SFA) and deep (DFA) femoral arteries. The DFA travels laterally and medially to supply the deep thigh muscles. The SFA travels distally through the adductor canal (Hunter canal) into the popliteal fossa and becomes the popliteal artery (POPA). The POPA gives off several branches (e.g., sural) and bifurcates into the anterior tibial artery (ATA) and the tibioperoneal trunk (TPT). The ATA travels anteriorly and laterally between the tibia and fibula and becomes the dorsalis pedis artery (DPA) as it travels across the foot. The TPT bifurcates into the posterior tibial artery (PTA) and peroneal artery. The PTA travels posterior to the medial malleolus and peroneal artery and down the calf. The PTA bifurcates into the medial and lateral plantar arteries in the foot. The latter join with the plantar metatarsal arteries to form the plantar arch. The lower extremity arteries have a triphasic DSW (see Figure 8 E-1).[1,2]

Disorders

An *aortic aneurysm* is defined as aortic dilatation (diameter >1.5 times the normal aortic diameter), and rupture of it is associated with high mortality. Aneurysms result from weakening of elastin and collagen within the medial layer of the arterial wall. A *thoracic aortic aneurysm* (TAA) resembles a mediastinal mass. Use of TEE and computed tomography (CT) is often

*Deceased.

necessary for accurate diagnosis. TAAs are commonly thrombosed and saccular. An *abdominal aortic aneurysm* (AAA) is the most common type of aortic aneurysm and is qualitatively defined as having a diameter greater than 3 cm (Figures 8 E-2 and 8 E-3). The AA has no vasa vasorum to facilitate repair; moreover, the ratio of elastic fibers to collagen changes from 3.1:1 in the proximal ascending aorta to 2.8:1 in the midthoracic region to 0.8:1 in the AA. AAAs are true aneurysms (fusiform, saccular) and can remain asymptomatic. They are usually atherosclerotic and infrarenal and have a predicted expansion rate of 0.2 to 0.5 cm/yr. Mild aortic dilatation (>2.0 and <3.0 cm) is described as ectatic, a moderate AAA is 3 to 5 cm in diameter, and a severe AAA is larger than 5 cm and corresponds to increased risk for rupture necessitating surgical repair (>80% mortality). In the ICU, surface ultrasound could be a useful examination to evaluate the aorta, although several limitations such as obesity, edema, abdominal gas, and trauma may hinder proper evaluation. Regardless, the vast majority can be imaged if alternative views such as coronal scanning through the liver are used when needed. Indications for performing ultrasound examination of the AA are surveillance of a known AAA, detection of an abdominal bruit on auscultation, unexplained shock, abdominal pain, pulsatile aorta or mass, history of hypertension or smoking, age older than 50 years with a family history of AAA, aneurysm in another vessel, aortic coarctation, lower extremity arterial disease, and the presence of emboli in the absence of another source. Ultrasound can be used to estimate the anteroposterior and transverse AAA diameter from outer wall to outer wall (Figure 8-1). The DSW through an AAA may reveal systolic dampening and diastolic reversal along with swirling of blood flow. A thrombus (mural or circumferential), usually of mixed echogenicity, or atherosclerotic plaque (hyperechoic areas confined to the aortic wall) may be found. Rupture or leakage is indicated by depiction of free fluid in the abdominal spaces, particularly retroperitoneal hematoma. Contrast-enhanced CT is used to confirm the findings and is the method of choice for diagnosis of leakage.[1,3]

Aortic dissection, which is more common in patients with cardiovascular risk factors, is defined as separation of the aortic intima from the media by blood. The *Stanford* classification divides dissections into those occurring proximal (type A) or distal (type B) to the left SCA. *DeBakey* classified dissections into type I (involving the entire ascending and descending aorta), type II (involving just the ascending aorta), and type III (involving just the descending aorta), which is further subdivided into IIIa (limited to the descending thoracic aorta) and IIIb (extending below the diaphragm). An intimal *flap*, which can be depicted sonographically as an echogenic band floating in the anechoic lumen (Figure 8-2), divides the latter into true and false lumens; however, echogenicity may be variable

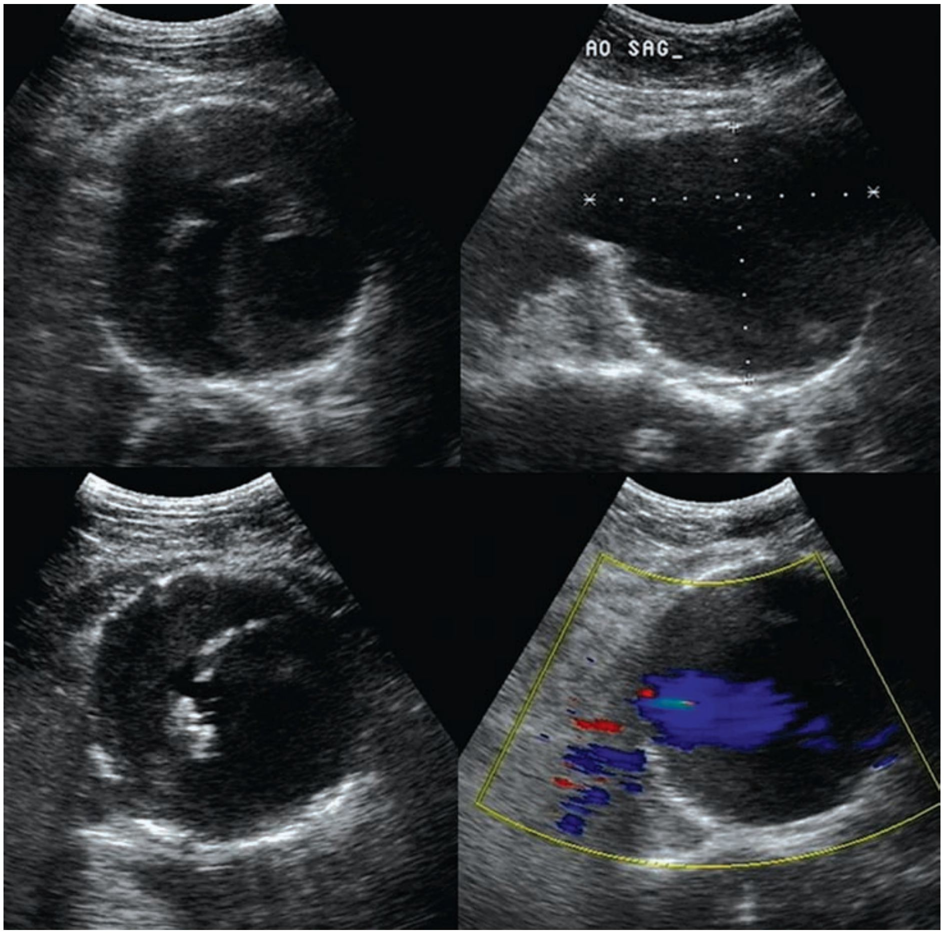

Figure 8-1 Huge infrarenal abdominal aortic aneurysm (anteroposterior diameter, 7.5 cm) with a mural thrombus and calcifications (*top*: transverse and sagittal views; *bottom*: transverse views).

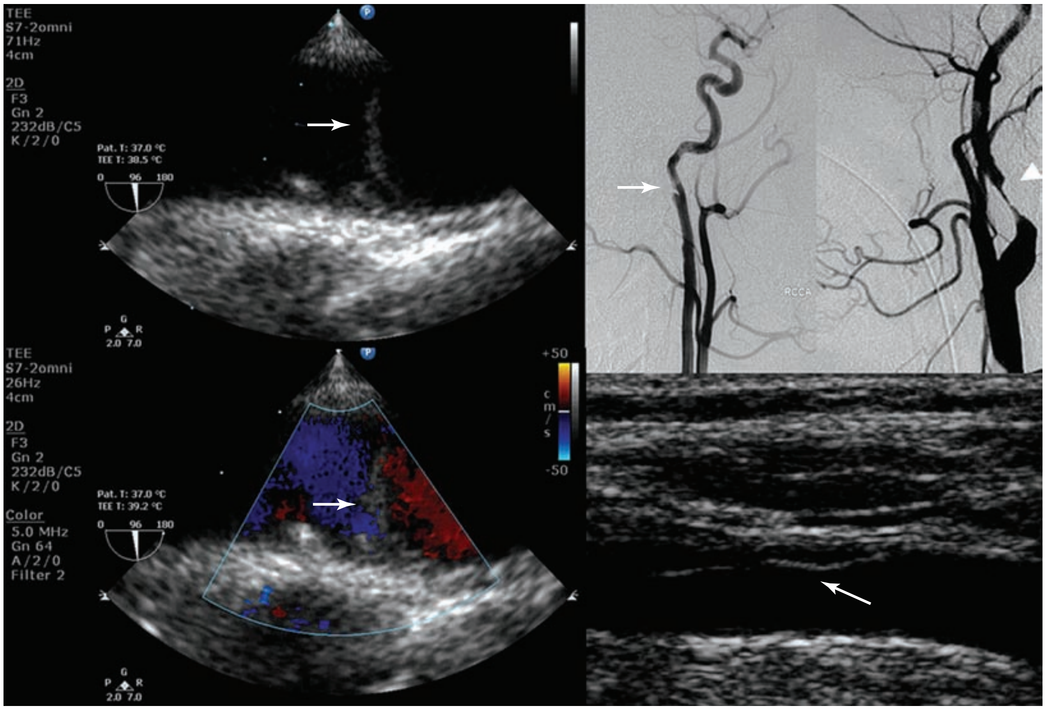

Figure 8-2 *(Left)* Transesophageal echocardiography showing posttraumatic aortic dissection (type A); *(right top)* invasive angiography depicting posttraumatic internal carotid artery (ICA) *(arrow)* and distal ICA *(arrowhead)* dissection; *(right bottom)* ultrasound showing common carotid artery dissection. Please note the echogenic flaps within the anechoic lumens *(arrows)*.

if echogenic thrombotic occlusion or atherosclerotic plaque coexist (Figure 8 E-4). Duplex ultrasound depicts lower flow velocity in the false lumen or absent flow in the case of thrombosis. Changes in the DSW reflect additional hemodynamic abnormalities such as stenosis or occlusion. Invasive evaluation (e.g., degree of lumen compromise, length of dissection) can be performed with intravascular ultrasound (IVUS), as well as with angiography. Thoracic trauma is an indication for cardiac (e.g., hemopericardium) and aortic (e.g., traumatic aortic dissection, aneurysm formation) ultrasound evaluation in the ICU. The role of TEE in detecting aortic dissection, especially DeBakey type II, is important (see Figure 8-2). An *abdominal aortic hematoma* is usually the result of rupture secondary to trauma or an AAA. Rupture may be confined to the aortic wall or, most commonly, to the retroperitoneum. In cases of intraperitoneal rupture, blood can flow inside the peritoneal cavity and be seen, but it is short-lived because of rapid exsanguination. Rarely, an AAA may rupture into the gastrointestinal tract and cause massive hemorrhage (aortoduodenal fistula). Contrast-enhanced ultrasound may be useful in detecting aortic rupture. Impending rupture is indicated by intramural hematoma (thickened hypoechoic vessel wall). A *retroperitoneal hematoma* has mixed echogenicity (a hyperechoic zone reflecting clots and a hypoechoic one reflecting serum) and can be detected via a translumbar or abdominal approach.[1,3]

Disorders of the carotid system and peripheral arteries are common. Ultrasound of the CA is performed with high-frequency transducers (5 MHz is reserved for deeper vessels such as the VA or SCA). The sample volume of pulsed wave Doppler is kept as small as possible and placed in the center of the vessel at an insonation angle of 60 degrees. In tortuous vessels, smaller angles can be used, but angles larger than 60 degrees should be avoided because of large errors in estimation of peak systolic velocity (PSV). *CA stenosis* is observed commonly and is due to atherosclerotic plaque located at the carotid bulb (bifurcation) and proximal ICA. B-mode classifies plaque into (1) *anechoic*, *hypoechoic*, or *hyperechoic* (calcified and when dystrophic may indicate areas of hemorrhage or necrosis); (2) *homogeneous*, which reflects a uniform echo pattern (e.g., hypoechoic fibrous plaque with soft gray echoes), or *heterogeneous*, which is more symptomatic and reflects a complex echo pattern (e.g., hypoechoic plaque with hyperechoic echoes); and (3) *smooth* (more stable) or *irregular* (more likely to ulcerate or embolize and cause stroke). Plaque can also be monitored with contrast-enhanced ultrasound, three-dimensional techniques, and IVUS. Strict ultrasound criteria exist only for the evaluation of ICA stenosis because these criteria do not apply in the case of ECA or CCA stenosis (Table 8-1). With occlusion of the ICA, PSV is usually undetectable, whereas hemodynamic changes in other vessels secondary to the occlusion (e.g., close to zero flow in end-diastole in the ipsilateral CCA or increased end-diastolic flow in the contralateral CCA) could be present (Figure 8 E-5). Invasive or computed tomographic angiography (CTA) confirms the findings.[4-7]

Ultrasound examination of the VAs should assess the direction of flow (antegrade or retrograde), and retrograde flow should raise suspicion for SCA stenosis (occlusion) or subclavian steal syndrome (Figure 8 E-6). SCA stenosis is identified by loss of the reversal component in the DSW, increased PSV, and poststenotic turbulence. *Cervical artery dissection* (CAD) is usually observed following trauma (see Figure 8-2). Underlying arteriopathies may predispose to CAD as a result of

TABLE 8-1 Ultrasound Criteria for Stenosis of the Internal Carotid Artery

Degree of Stenosis (%)	ICA-PSV (cm/sec)	Plaque (%)	ICA-EDV (cm/sec)	ICA/CCA-PSV Ratio
Normal	<125	None	<40	<2.0
<50	<125	<50	<40	<2.0
50-69	125-230	≥50	40-100	2.0-4.0
≥70	>230	≥50	>100	>4.0
Near occlusion	High, low, or undetectable	Visible	Variable	Variable
Total occlusion	Undetectable	Visible, nondetectable lumen	N/A	N/A

CCA, Common carotid artery; *EDV*, end-diastolic velocity; *ICA*, internal carotid artery; *N/A*, not applicable; *PSV*, peak systolic velocity.
Plaque was estimated and the diameter of the ICA calculated by B-mode and duplex ultrasound.

protease hyperactivity (e.g., patients with CAD have an increased incidence of fibromuscular dysplasia of the involved artery). Ultrasound may reveal mural hematoma and thrombosis (thickened, hypoechoic vessel wall). If hemodynamic abnormalities (e.g., stenosis) are present, the sensitivity of duplex examination is increased.

Common mechanisms of *peripheral arterial disease* include atherosclerosis (stenosis or occlusion), thromboembolism (plaque or thrombotic fragments originating from the heart or an aneurysm, hypercoagulable states, insertion of an arterial line), vasospasm (transient constriction, usually of the digital arteries), extrinsic arterial compression (tumors, hematomas, anomalous anatomic configurations), aneurysms, pseudoaneurysms, and congenital or acquired arteriovenous fistula (AVF).[1-3] In the *lower extremities*, arterial obstruction secondary to atherosclerosis is commonly observed in the DFA (60%), at arterial bifurcations, or at the level of the POPA (entrapment syndrome). It may also result from intimal hyperplasia or radiation injury. High-frequency ultrasound is used for evaluation. *Stenosis* in peripheral arteries is depicted by B-mode as thickening of the vessel wall, narrowing of the lumen, or an echogenic filling defect. Doppler evaluation includes determination of PSV and flow direction, V_2/V_1 ratio (with V_2 representing the PSV of a stenotic segment and V_1 being the PSV of the proximal normal segment), and changes from a triphasic DSW to a biphasic (sharp systolic upstroke with loss of diastolic flow reversal), monophasic (blunted systolic upstroke), or severely blunted DSW described as "*parvus tardus*" (weak and slow systolic upstroke and downstroke). When using Doppler to evaluate arterial stenosis, (1) *low velocity* can be detected by reducing the velocity scales and applying power Doppler; (2) *greater than 50% stenosis* corresponds to at least double PSV of the proximal normal segment with accompanying changes in the DSW and poststenotic turbulence; (3) a "staccato" DSW indicates an *upcoming occlusion*; and (4) with *total occlusion*, zero intraluminal flow is evident, collaterals are seen in chronic cases, and secondary changes in flow in the arterial and venous circuits of the regional network may be observed (Figures 8 E-7 and 8 E-8).[1-3]

Pseudoaneurysms are pulsating, encapsulated hematomas in communication with the lumen of a ruptured vessel via a patent neck, and their walls may consist of adventitia, hematoma, and fibrous tissue. Color mode depicts turbulent flow ("yin-yang" sign) in the sac of the pseudoaneurysm (Figure 8 E-9), and Doppler mode detects to-and-fro flow patterns within its neck; coexisting thrombosis is common. In the ICU, pseudoaneurysms may form as a result of trauma or invasive procedures and can be repaired by ultrasound-guided compression (60% to 90% success rate). They could be also treated by ultrasound-guided injection of thrombin: the transducer is directed over the pseudoaneurysm, a 22-gauge spinal needle is inserted into its center, and 0.2 to 1.0 mL (1000 U/mL) of thrombin is injected. *Peripheral aneurysms* are dilated arterial segments twice the size of normal proximal arterial segments. Within the aneurysm, slow whirling of blood flow may be observed (Figure 8 E-10). Common sites of peripheral aneurysms are the POPA and CFA (3% of patients may have a POPA aneurysm). POPA or CFA aneurysms can coexist with an AAA (60% of male patients with a POPA aneurysm and more than 50% of patients with a CFA aneurysm could have an AAA). An important complication of POPA aneurysms is not rupture, but thrombosis. Surgical repair is reserved for peripheral aneurysms with a diameter of 2 cm or larger. An *AVF* is an abnormal connection of an artery and vein and may be posttraumatic or iatrogenic (Figure 8 E-11). It is characterized by color noise on duplex along with high velocity and a low-resistance DSW as arterial flow bypasses tissues and capillaries and drains straight into the vein (enhanced pulsatile venous flow).[1,8] Ultrasound guides procedures such as venous and arterial cannulation, placement of inferior vena cava filters, vascular bypass, and carotid surgery. It can also be used to monitor the patency of vascular grafts and endovascular stents by identifying aneurysms, endoleaks or perigraft leaks, stenosis, thrombosis, and stent malposition.[9,10] Finally, experimental studies have targeted plaque inflammation and neovascularization with contrast-enhanced ultrasound, and promising results have been shown.[11,12]

Pearls and Highlights

- Arterial stenosis is commonly due to atherosclerosis. It is diagnosed by increments in Doppler PSV and changes in DSW. Strict ultrasound criteria exist only for classifying ICA stenosis.
- Total arterial occlusion is characterized by zero intraluminal flow and secondary hemodynamic changes in the arterial and venous circuits of the regional network.

IMAGING CASE

Left panel—top: Physical examination of a trauma patient revealed swelling and edema at the area of the left gastrocnemius muscle. Ultrasound depicted a partially thrombosed POPA pseudoaneurysm (anteroposterior and craniocaudal diameters: 3.5 and 3 cm, respectively) that was repaired surgically. Left panel—bottom: After several blind attempts at placing a central line in the femoral vein, ultrasound detected an SFA pseudoaneurysm (anteroposterior and craniocaudal diameters: 3.7 and 2.8 cm, respectively) that was confirmed by CTA (shaded surface display) and repaired surgically. Right panel: Physical examination of a trauma patient revealed swelling in the lateral aspect of the thigh. Ultrasound demonstrated a pseudoaneurysm (craniocaudal and anteroposterior diameters: 6.5 and 3.2 cm, respectively) with a to-and-fro pattern of flow in a DFA branch (rare site) that was confirmed by CTA and treated surgically.

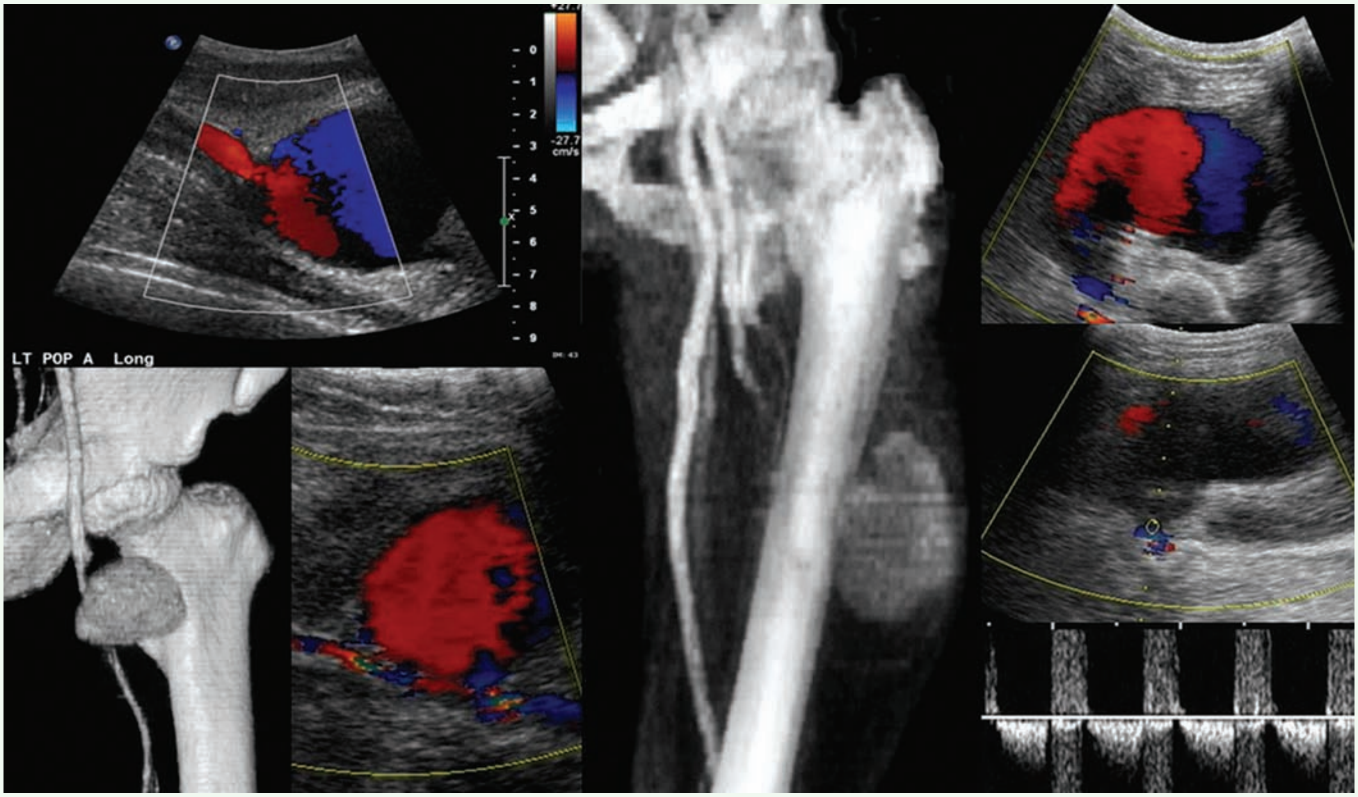

Figure 8-3

- AAAs are usually atherosclerotic and infrarenal, and their predicted expansion rate is 0.2 to 0.5 cm/yr. If an AAA is larger than 5 cm, the risk for rupture increases and surgery is necessary (mortality rates exceed 80%).
- POPA and CFA aneurysms are the most common peripheral aneurysms and may coexist with an AAA.
- Pseudoaneurysms are usually posttraumatic and can be repaired by ultrasound-guided compression or thrombin injection.

REFERENCES

For a full list of references, please visit www.expertconsult.com.

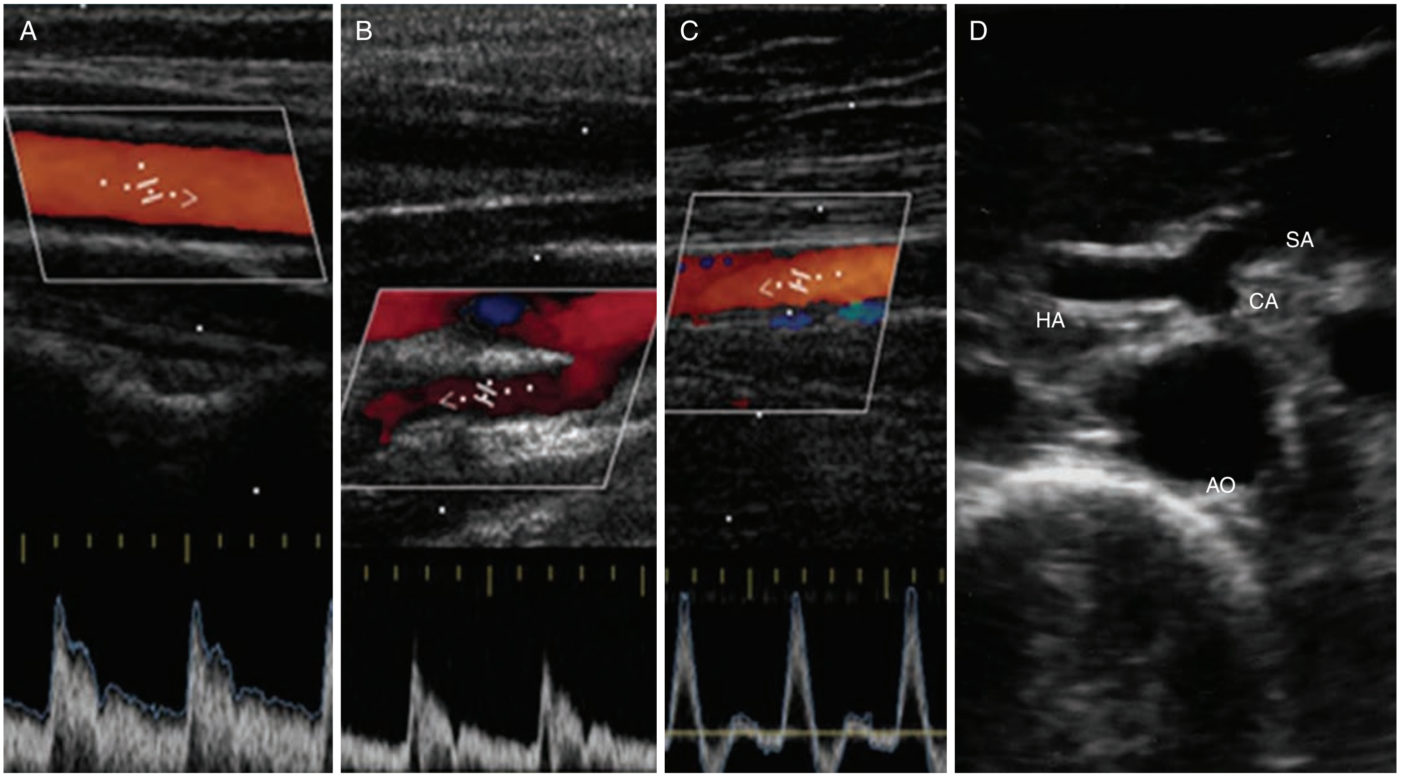

Figure 8 E-1 Normal Doppler spectral waveform of the common carotid artery **(A),** internal carotid artery **(B),** and superficial femoral artery **(C)**. **D,** Abdominal aorta (AO) giving off the celiac artery (CA), which branches into the splenic artery (SA) and hepatic artery (HA).

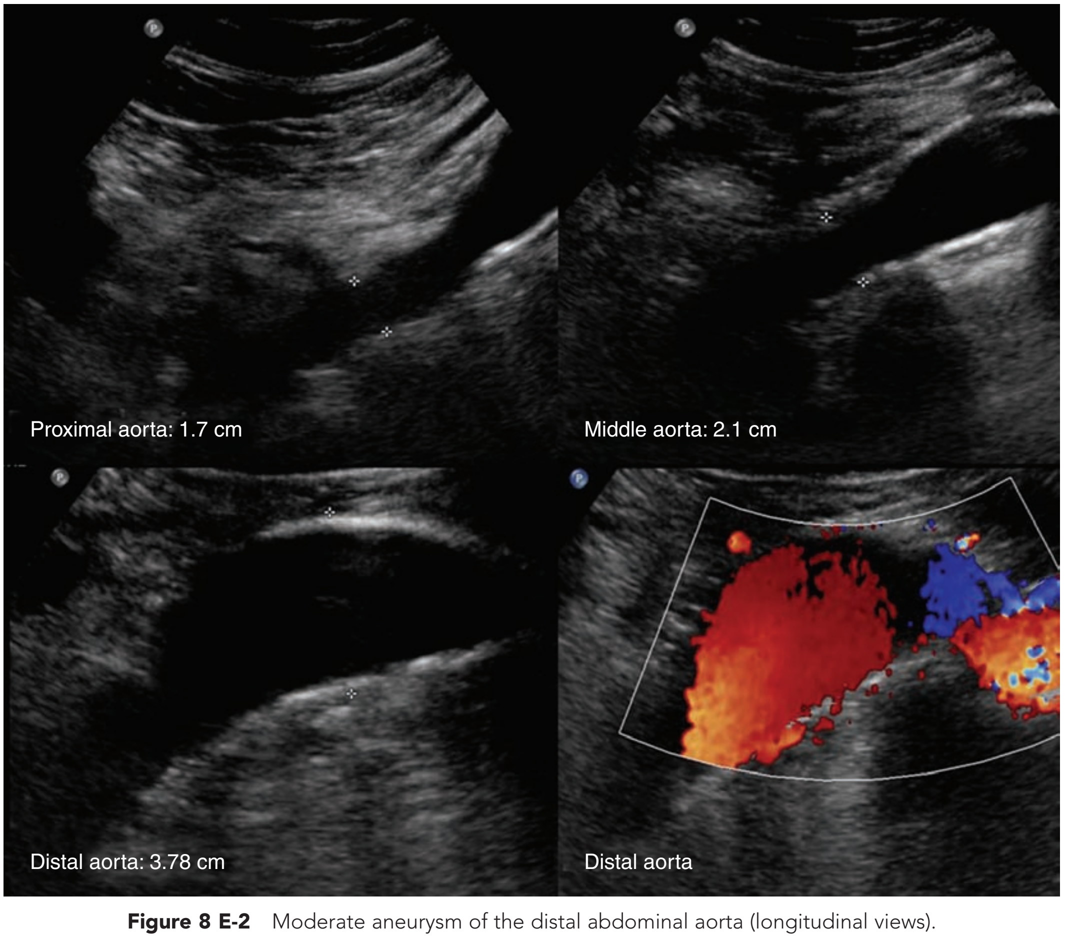

Figure 8 E-2 Moderate aneurysm of the distal abdominal aorta (longitudinal views).

Figure 8 E-3 *(Top)* Multiple views of an abdominal aortic aneurysm (AAA) with a mural thrombus extending to the common iliac arteries; *(bottom)* computed tomography scan depicting a ruptured AAA with a mural thrombus *(arrow)*. *(Courtesy Dr. G. Anyfantakis.)*

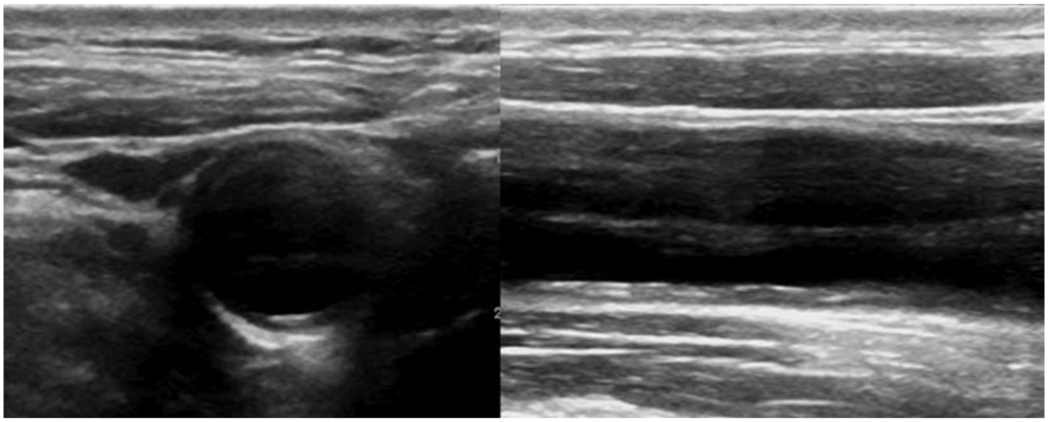

Figure 8 E-4 B-mode showing common carotid artery dissection of variable echogenicity (presence of echogenic flap and thrombus).

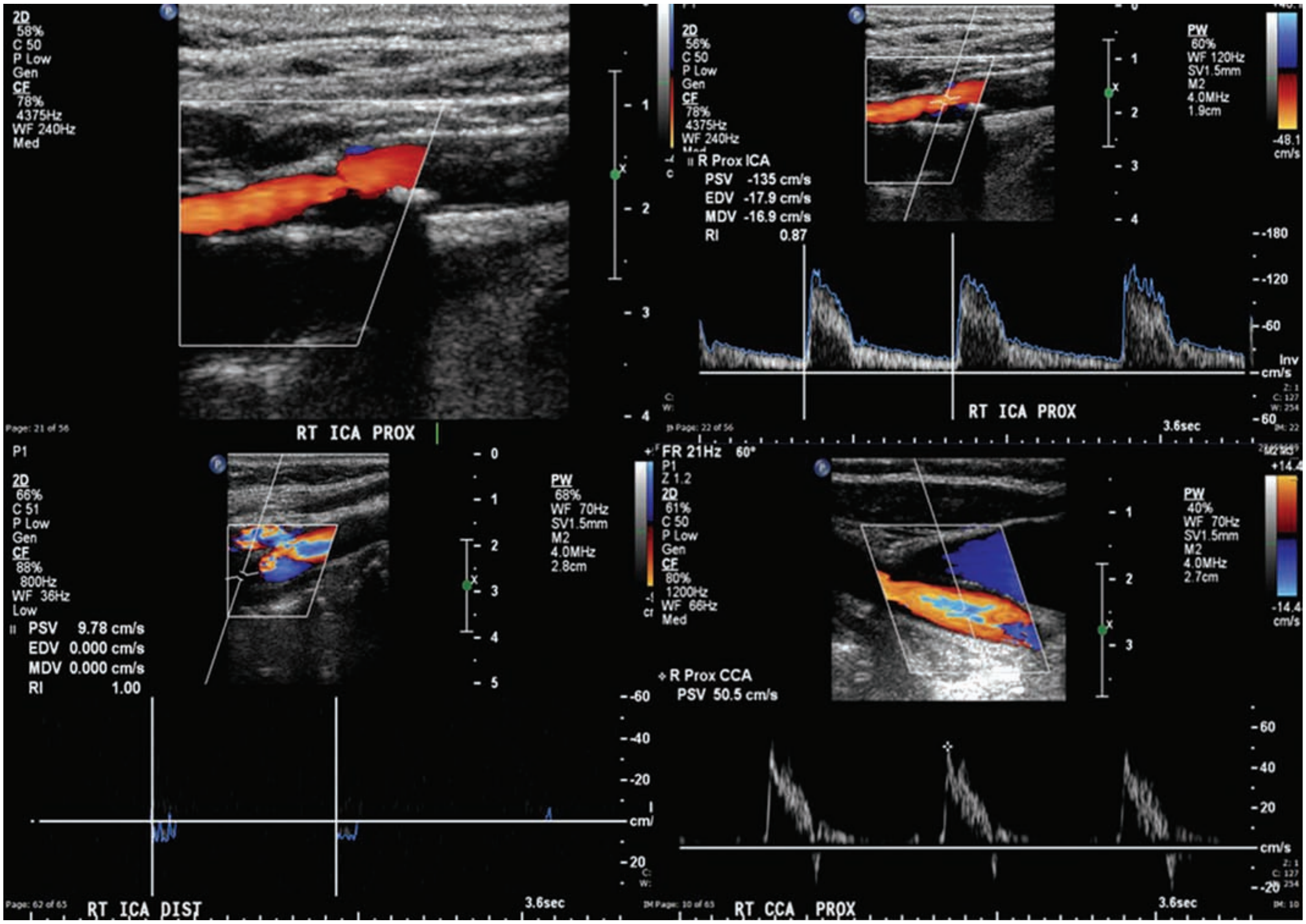

Figure 8 E-5 Right internal carotid artery (ICA) with 50% to 69% stenosis *(top)* and occlusion *(bottom)*. Flow through the right common carotid artery (CCA) is almost zero in end-diastole because it was redirected through the external carotid artery system (high-resistance arterial conduit). Normally, the Doppler spectral waveform of the CCA reflects the low distal resistance of the ICA and has flow above zero in end-diastole. *(Courtesy Dr. G. Anyfantakis.)*

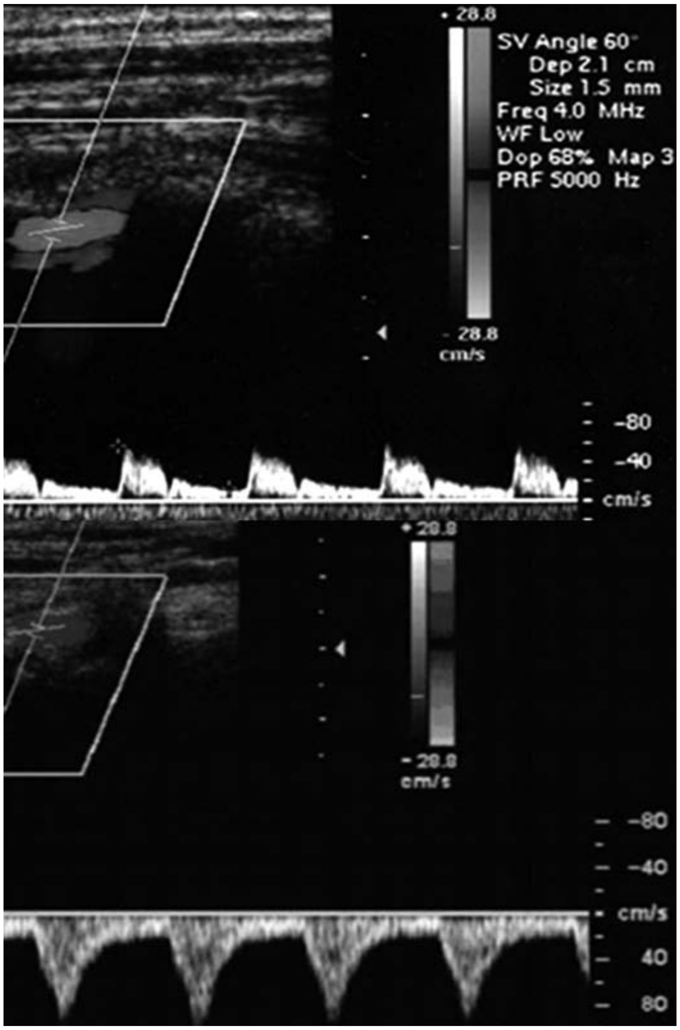

Figure 8 E-6 Normal flow in the right vertebral artery *(top)* and flow reversal in subclavian steal syndrome *(bottom)*.

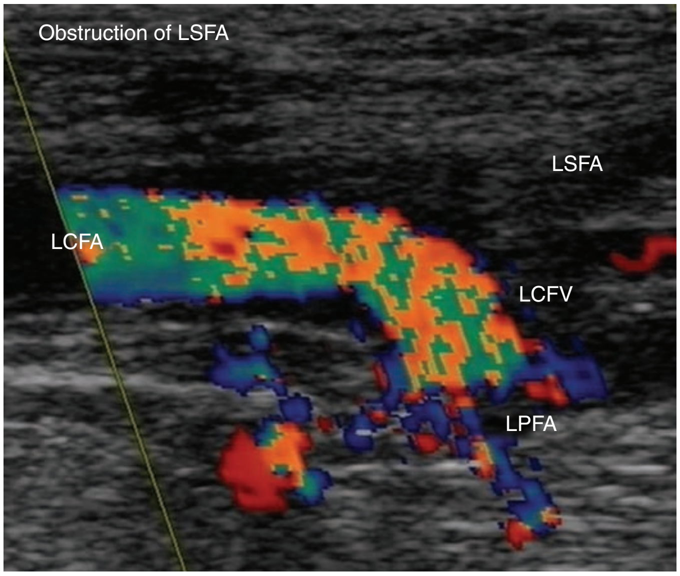

Figure 8 E-7 Acute obstruction of the left superficial femoral artery (LSFA); aliasing is depicted in the left common femoral (LCFA) and profunda (LPFA) arteries, respectively. *LCFV*, Left common femoral vein.

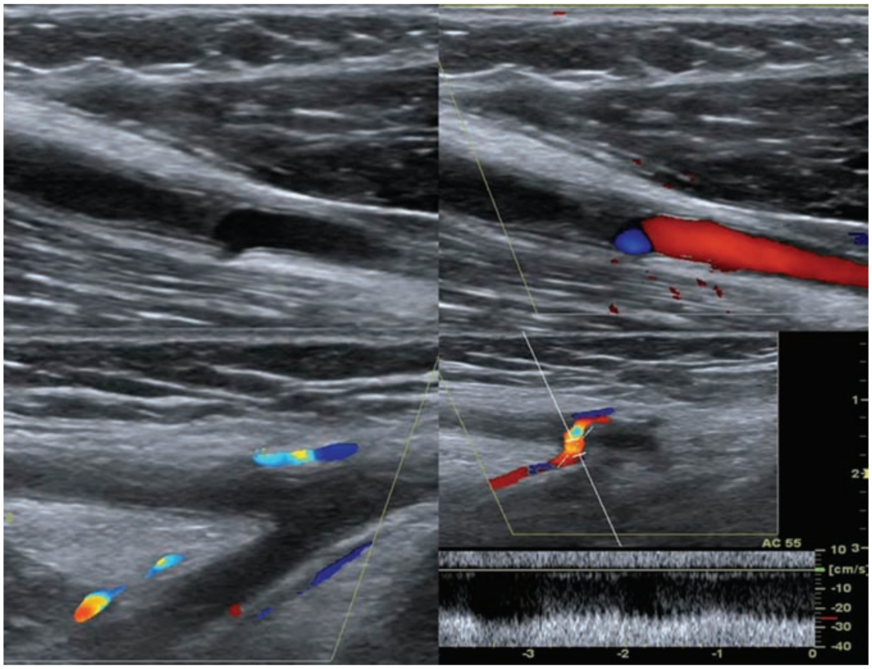

Figure 8 E-8 Chronic thrombosis of the brachial artery causing obstruction *(top)* and depiction of collaterals in the same case *(bottom)*.

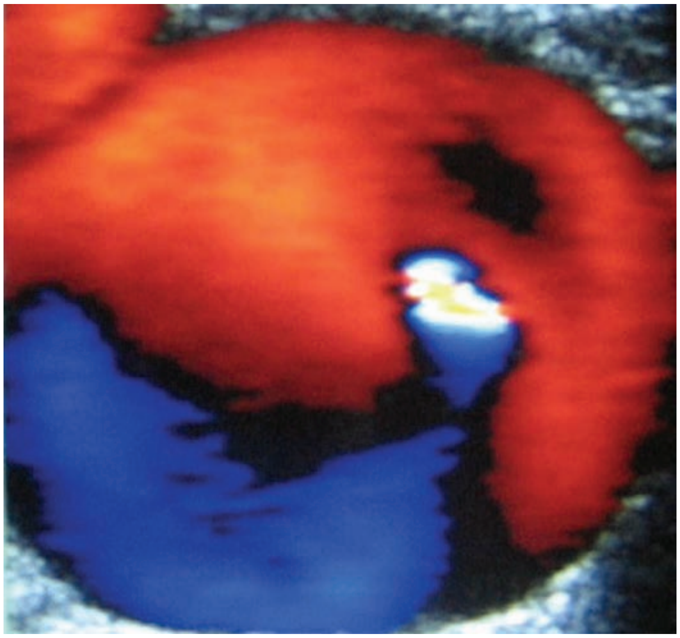

Figure 8 E-9 Demonstration of the "yin-yang" sign (color mode) in a pseudoaneurysm.

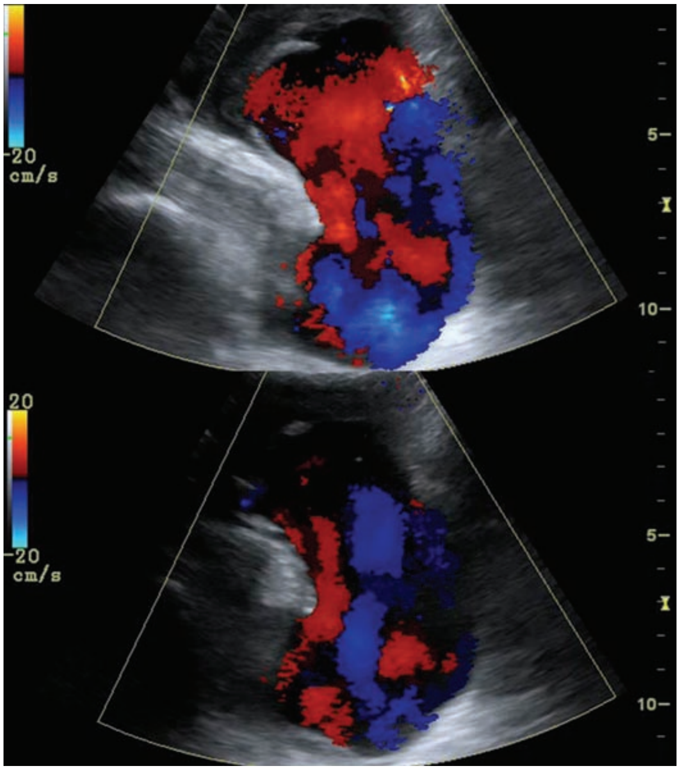

Figure 8 E-10 Whirling of flow in a common femoral artery aneurysm (oblique views).

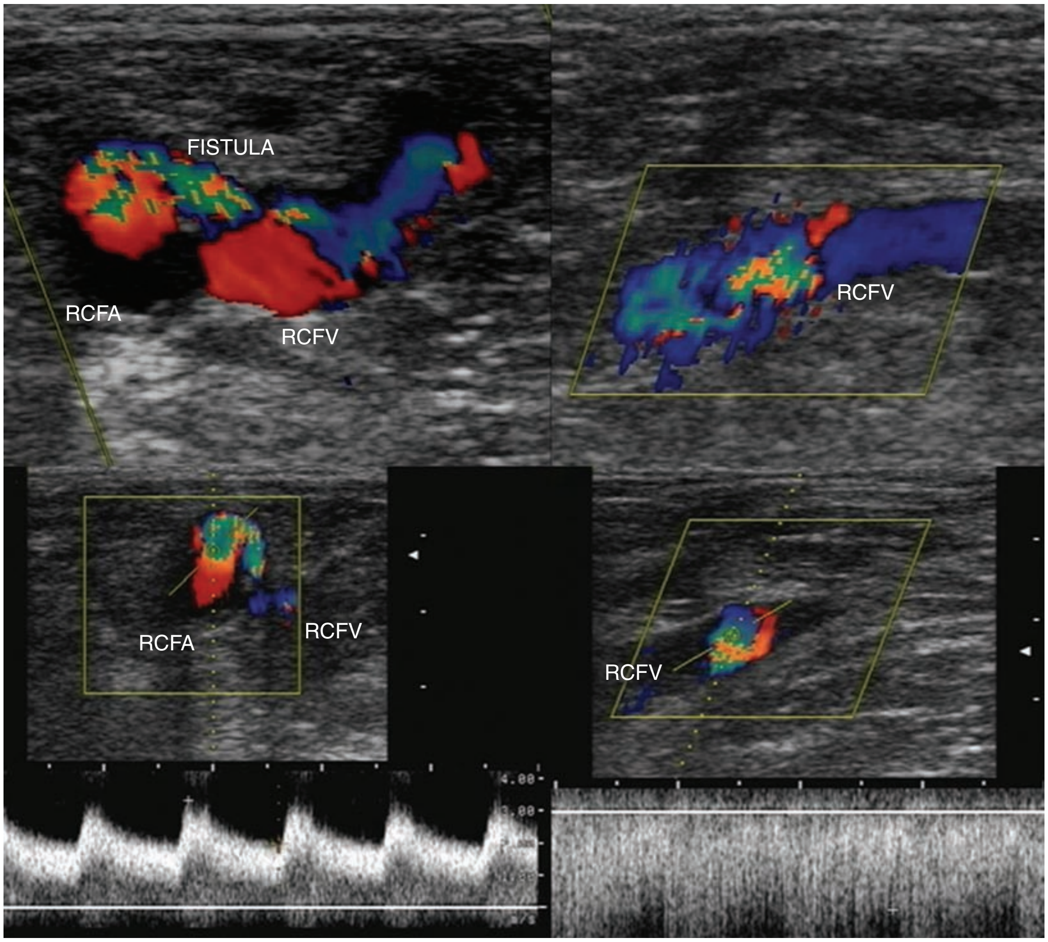

Figure 8 E-11 Arteriovenous fistula: abnormal connection of the right common femoral artery and vein (RCFA, RCFV) following blind RCFV catheterization.

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9

Ultrasonography for Deep Venous Thrombosis

GULRUKH ZAIDI | ADEY TSEGAYA | RUBIN I. COHEN

Background

Venous thromboembolism (VTE) is a spectrum of disease that encompasses both deep venous thrombosis (DVT) and pulmonary embolism (PE). It is a serious and often underrecognized condition in critically ill patients that can lead to significant morbidity and mortality. PE remains one of the leading causes of unexpected death in hospitalized patients.[1,2]

In the intensive care unit (ICU), the Virchow triad of "stasis, endothelial injury, and hypercoagulability" is a frequent occurrence, with most critically ill patients having one or more recognizable risk factors for VTE. Immobilization, mechanical ventilation, paralysis, sedation, and central venous catheters all increase the risk for DVT.[3,4]

The embolic risk for DVT is related to its location in the venous system. Ninety percent of cases of acute PE are due to emboli emanating from clots in the proximal veins of the lower extremities. The significance of upper extremity deep venous thrombosis (UEDVT) was underestimated for many years. Recently, this perception has changed, and it is now recognized that proximal UEDVT accounts for 5% to 10% of cases of VTE.[3-6] The use of chronic venous access catheters such as peripherally inserted central venous and various tunneled catheters has greatly increased, and these catheters have been associated with an increased incidence of UEDVT. In its latest guidelines for antithrombotic therapy and prevention of thrombosis, the American College of Chest Physicians for the first time recommended treatment of UEDVT involving the axillary or more proximal veins.

Classic symptoms of DVT include swelling, pain, and erythema of the involved extremity. However, the signs and symptoms of DVT in critically ill patients are often unreliable, which makes diagnosis difficult. The true incidence and prevalence of acute DVT in critically ill patients are not known. Various studies have reported incidences ranging widely from 4% to 60% as a result of differences in the patient population, methods of detection, and use of surveillance programs.[7-9]

Contrast-enhanced venography, magnetic resonance (MR) venography, and impedance plethysmography have largely been replaced by venous ultrasonography as the preferred test for diagnosis of DVT. Traditional diagnosis of DVT in the ICU requires a trained sonographer to transport an ultrasound machine to the bedside, where a full upper or lower extremity examination is performed and recorded. The study is then reviewed by a radiologist, and a report is generated. This process, though accurate, results in much delay in the management of critically ill patients, many of whom may not be candidates for empiric anticoagulation.

Because of rapid growth in the availability of portable ultrasound units, point-of-care ultrasonography performed at the bedside by critical care physicians is gaining increased popularity. A multicenter, retrospective review compared 128 bedside intensivist-performed compression ultrasound (IP-CUS) studies with a formal vascular study (FVS) performed by ultrasound technicians and interpreted by radiologists.[10] All fellows and attending physicians performing IP-CUS had received formal training at a 3-day critical care ultrasonography course. When compared with the companion FVS study ordered immediately after completion of the IP-CUS study, IP-CUS studies had a sensitivity and specificity of 86% and 96%, respectively, for ruling in DVT. The median time between ordering the test and availability of the result of an FVS was 13.8 hours.

Even though bedside ultrasonography plays a pivotal role in the diagnostic algorithms for VTE, a thorough understanding of its strengths, limitations, and clinical applications is required.

Anatomy

A review of the venous anatomy of the upper and lower extremities is necessary to identify the appropriate structures so that DVT can be recognized when performing a bedside compression ultrasound (CUS) study.

UPPER EXTREMITY VENOUS SONOGRAPHIC ANATOMY

The superficial venous system of the upper extremity consists of the cephalic and basilic veins. The cephalic vein begins at the radial aspect of the wrist and runs up the lateral surface of the arm to the shoulder. It then pierces the fascia and enters the axillary vein just distal to the clavicle. The basilic vein begins at the ulnar aspect of the wrist and runs along the medial surface of the arm. Once it crosses the teres major, it joins with the brachial veins to form the axillary vein.

The axillary vein is a deep vein of the arm that branches distally into the paired brachial veins. It runs through the axilla to the outer border of the first rib and is joined by the cephalic vein medially close to its termination. The confluence of the axillary vein and the cephalic vein forms the subclavian vein (SCV). The SCV runs from the outer border of the first rib to the sternal head of the clavicle, where it is joined by the internal jugular (IJ) vein, and together they form the brachiocephalic vein. The brachiocephalic vein drains into the superior vena cava. The IJ extends from the jugular foramen in the base of the skull to its confluence with the SCV (Figure 9-1).[11]

LOWER EXTREMITY VENOUS SONOGRAPHIC ANATOMY

The two main veins of the superficial venous system are the great and small saphenous veins. The small saphenous vein

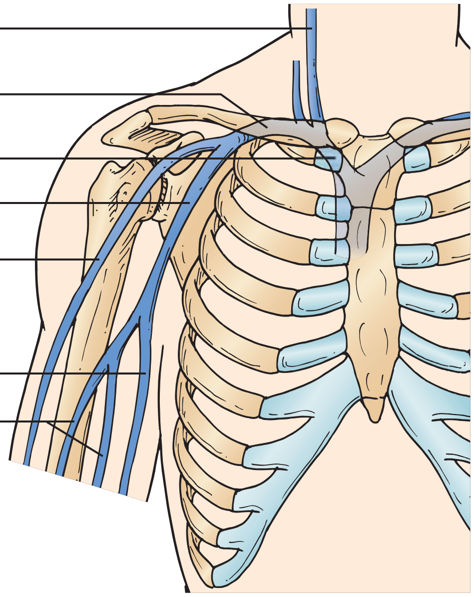

Figure 9-1 Deep veins of the upper extremity. *IJV*, Internal jugular vein.

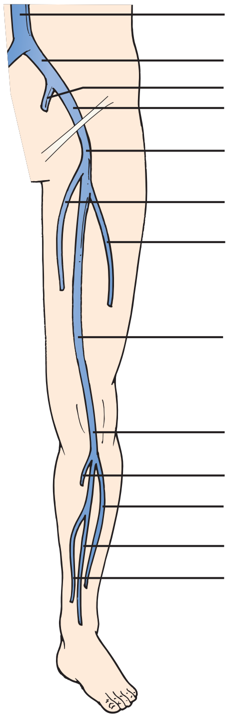

Figure 9-2 Deep veins of the lower extremity.

runs along the lateral aspect of the calf and drains into the deep venous system at the level of the popliteal vein. The great saphenous vein (GSV) runs up from the ankle along the medial aspect of the leg and, in the proximal part of thigh, traverses the fossa ovalis and drains into the common femoral vein (CFV).

The external iliac vein originates from the inferior vena cava and exits the pelvis deep to the inguinal ligament to become the CFV. The CFV is then joined on its medial aspect by the GSV. Approximately 2 cm below this point the CFV divides into the deep femoral vein (DFV) and the superficial femoral vein (SFV). The DFV can be tracked for only a short distance before it disappears into the deeper tissue away from the acoustic window. It is important to note that the SFV is part of the deep venous system and is also called the "femoral vein" to avoid confusion. The SFV travels down the anteromedial aspect of the leg to the adductor canal and then courses posteriorly into the popliteal fossa to become the popliteal vein. The popliteal vein then trifurcates into the anterior tibial, peroneal, and posterior tibial veins in the proximal part of the calf (Figure 9-2).

Basic Ultrasound Techniques

Several ultrasound techniques can be used when assessing a vessel for the presence of a clot.

COMPRESSION ULTRASONOGRAPHY

CUS uses a high-resolution ultrasound system. This allows gray-scale two-dimensional (2D) imaging of the venous segment of interest, and then manual compression is applied with the transducer.

DUPLEX ULTRASOUND

This method adds color Doppler to the 2D analysis. The energy of the returning sound waves is assigned a color. By convention, flow toward the transducer probe appears as red and flow away from the probe is visualized as blue. This is superimposed on the 2D image to allow visualization of anatomy and flow simultaneously (see Chapters 1 and 8).

TRIPLEX ULTRASOUND

This method adds spectral analysis to the 2D and color Doppler analysis (see Chapter 1). In this mode, flow velocities are displayed graphically, with time on the x-axis and velocity on the y-axis.

Traditionally, an FVS included all of the aforementioned techniques. However, studies have shown that CUS with color and pulsed wave Doppler does not increase the accuracy of the examination over CUS alone.[12-15] Therefore, in the majority of critical care studies, CUS without Doppler interrogation is used for evaluating the venous system.

TRANSDUCER SELECTION

A high-frequency linear transducer (7.5 to 10 MHz) is often ideal. For larger patients and deeper venous circuits, lower-frequency transducers can be used alternatively (see Chapter 1). Color Doppler analysis is not part of a routine CUS study but is usually helpful in identifying vascular structures, especially when scanning obese or edematous patients.

TRANSDUCER ORIENTATION AND IMAGE ACQUISITION

To begin scanning, by convention the transducer is held in a transverse plane with the marker pointing toward the patient's right. Gain should be adjusted so that the resolution and brightness of the image are uniform in both the near and far fields (Chapter 1). The depth should also be adjusted so that the structures of interest take up almost three fourths of the screen.

Once the vessels are identified, the vein is compressed on its transverse plane.

Diagnostic Criteria

A fresh, immature thrombus may not be echogenic and, because of its jelly-like consistency, may be partially compressible. Therefore the primary diagnostic criterion is lack of vessel compressibility and not visualization of a clot. Compression is applied to the vein while watching for complete apposition of the anterior and posterior walls. If complete venous compression is not attained with pressure sufficient to deform the artery, an obstructing venous thrombus is likely to be present. The angle of pressure exerted over the vessel wall is also important. Pressure must be exerted perpendicular to the venous segment; otherwise, even with appropriate pressure the vessel may not collapse.

If intraluminal echogenic material is seen on initial imaging, the sonographer should be alerted to the presence of a thrombus, and the vessel should be imaged in the longitudinal plane as well. Compression should be limited because of the possibility of dislodging the clot.

ACUTE VERSUS CHRONIC DEEP VENOUS THROMBOSIS

As discussed earlier, acute DVT has hypoechoic features, although thrombi may also appear as echogenic intraluminal structures. Chronic clots are usually hyperechoic and easily identifiable. The vessel walls surrounding a chronic clot may appear thickened with scar tissue. Chronic clots may sometimes recanalize with blood flow through the center of the clot.

Detecting the relative age of a thrombus by ultrasound requires expertise. In brief, the sonographic features of chronic thrombosis include a contracted venous segment, clot adherence, detection of hyperechoic and rather heterogeneous thrombi and partial recanalization, and the presence of venous collaterals. Ultrasound characteristics that usually favor acute thrombosis include venous distention; venous lumen partially compressible or noncompressible; and detection of hypoechoic, free-floating, and rather homogeneous thrombi. Recently, another sonographic feature has been observed in cases of acute thrombosis: a double hyperechoic line along the thrombus–venous wall interface. It was suggested that this double hyperechoic line might represent fibrin fibers coating acute clots (Figure 9-3).[16]

Ultrasound Examination Strategies in the Intensive Care Unit

Because most emboli emanate from proximal leg veins, the calf veins and distal upper extremity veins are not routinely examined in a baseline CUS study in the ICU.

PATIENT POSITIONING

Patient positioning is extremely important to optimize image acquisition. Proper positioning reduces the time required to perform the study and eases strain on the operator.

For examination of an upper extremity, the patient should be placed in a supine and, if tolerated, a Trendelenburg position. The head should be turned away from the side being examined and the arm abducted between 45 and 90 degrees. However, hyperextension of the arm should be avoided because it may impede blood flow. If possible, the neck should be slightly extended and the chin raised.

For examination of a lower extremity, the patient should be placed in a supine and, if tolerated, a reverse Trendelenburg position. The knee should be bent slightly and the hip externally rotated. To image the popliteal vein and artery the patient should ideally be in a prone position. However, this is not possible in critically ill patients, and imaging is usually performed with the knee flexed at a 45-degree angle or with the patient in a lateral decubitus position.

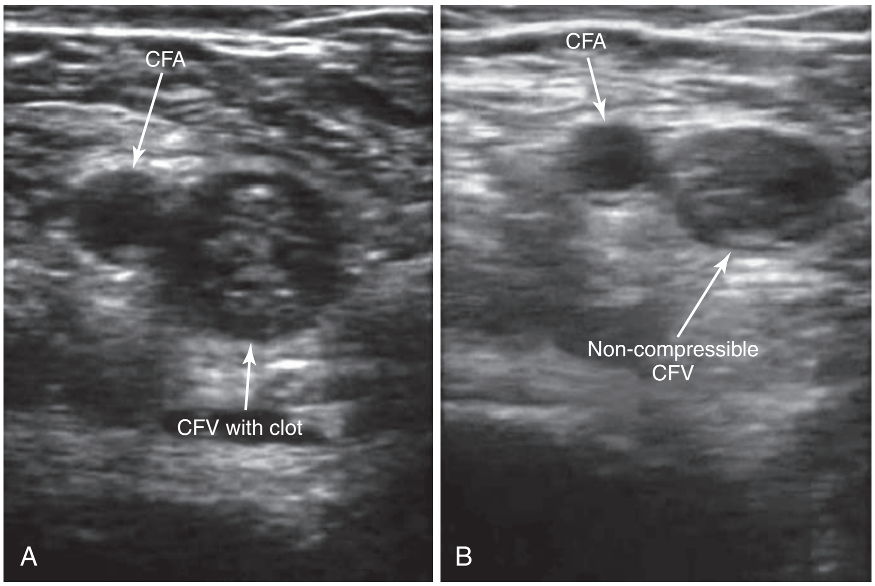

Figure 9-3 Two-dimensional ultrasound image of the common femoral vein with a clot. The image on the left is without compression and the image on the right is with compression.

UPPER EXTREMITY

For examination of an upper extremity, transverse compression of the IJ, axillary, and brachial veins should be demonstrated. To identify the paired brachial veins on either side of the brachial artery, the transducer should be placed on the medial aspect of the upper part of the arm approximately midway between the shoulder and the elbow. Compression should be applied every few centimeters along the brachial veins centrally up to the axillary vein. The basilic vein is a large superficial vein that is not paired with an artery, which allows differentiation from the deeper brachial veins. However, since the basilic vein joins with the brachial veins to form the axillary vein, a large clot burden in this vein may be clinically significant (Figure 9-4).[17]

Sequential compressions should be continued along the axillary vein to the lateral aspect of the SCV, beyond which compression is not possible because of the clavicle. Once this portion of the examination is complete, sequential compressions should be performed along the length of the IJ.

In gray-scale imaging, changes in size of the SCV with respiration and the sniff maneuver should be noted. A normal SCV should collapse at least 60%. With complete obstruction there is no response to these respiratory maneuvers, and the vein is often asymmetrically dilated when compared with the opposite side. Color Doppler techniques are helpful in examining the proximal portion of the SCV, its confluence with the IJ, and the brachiocephalic vein in mechanically ventilated ICU patients. Additionally, other advanced imaging modalities such as computed tomography or MR venography can be used.

LOWER EXTREMITY

A bedside CUS study may be limited or complete. Most of the data for CUS studies come from venous examination of the lower extremity. A complete examination is defined as sequential compressions every 2 cm from the groin crease to the distal popliteal fossa. However, previous work has shown that strategies with a limited number of compression sites have a sensitivity and specificity similar to that of a complete examination in detecting lower extremity DVT.[13,14,18]

Compressive interrogation of the vessel commences at the level of the inguinal ligament. The common femoral artery and vein should be identified and a compression maneuver performed at this level (Figure 9-5).

By sweeping the transducer below the inguinal ligament, the GSV should be seen joining the CFV medially. The CFV-GSV junction should be compressed because a thrombus at this level is associated with high risk for extension into the CFV (Figure 9-6).

Sequential compressions are then performed every 2 cm along the CFV to its bifurcation into the DFV and SFV and continued along the SFV to the adductor canal (Figure 9-7).

To image the popliteal vein, the patient's leg should be flexed at an angle of 45 degrees and the transducer placed in the popliteal fossa. The popliteal vein should be identified anterior to the popliteal artery and a compression maneuver performed. Notably, the popliteal vein is easily compressible, and even the slightest pressure may obscure it. The popliteal vein is scanned with compression maneuvers until its trifurcation into the calf veins is reached.

Important Lower Extremity Compression Points for Limited Examination in the Intensive Care Unit

- CFV at the inguinal ligament
- Junction of the CFV and GSV
- Junction of the CFV and DFV
- Popliteal vein
- Trifurcation of the popliteal vein

LIMITATIONS OF BEDSIDE COMPRESSION ULTRASOUND

- Performing a bedside CUS study can be challenging in *obese* patients. To improve image acquisition, the patient is placed in a reverse Trendelenburg position to distend the veins. The depth is increased to appropriate levels and

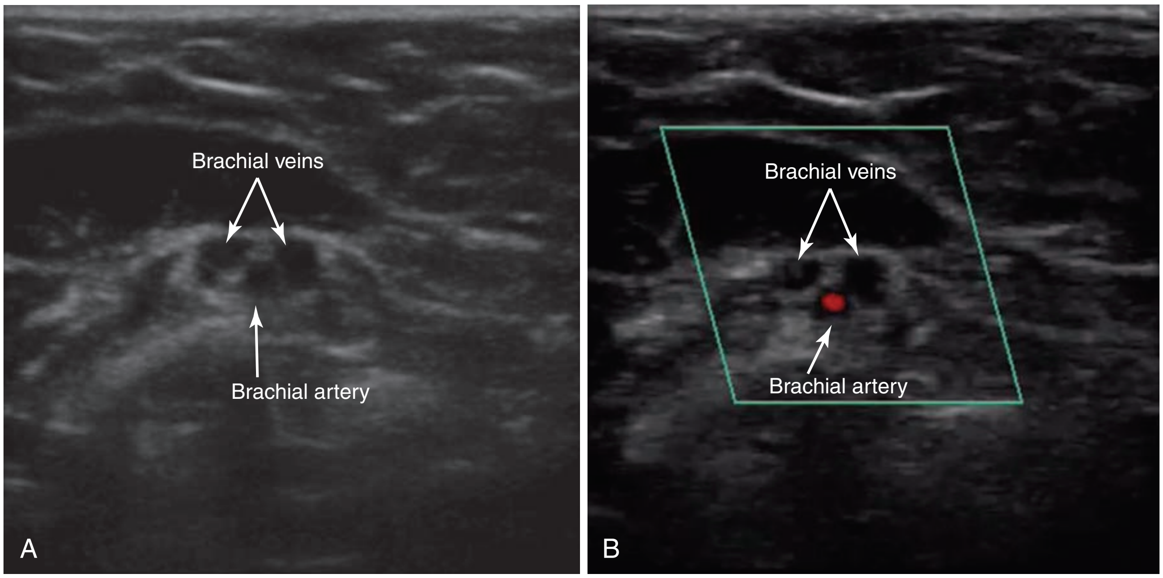

Figure 9-4 Two-dimensional ultrasound image of the paired brachial veins and artery. The image on the left is a standard gray-scale image and the image on the right is one using color Doppler, with red overlying the brachial artery.

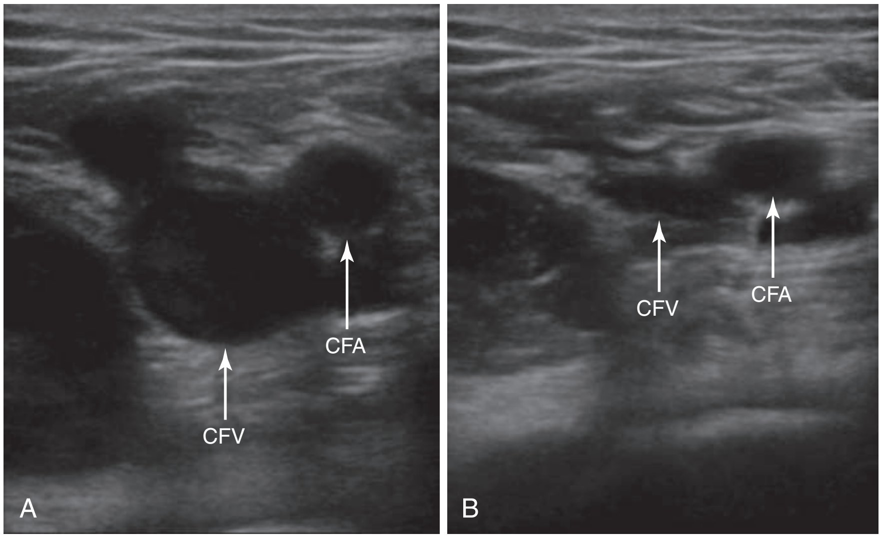

Figure 9-5 The common femoral vein with and without compression. The image on the left is without compression and the image on the right is with compression and shows complete apposition of the anterior and posterior walls of the common femoral vein. No deep venous thrombosis is present.

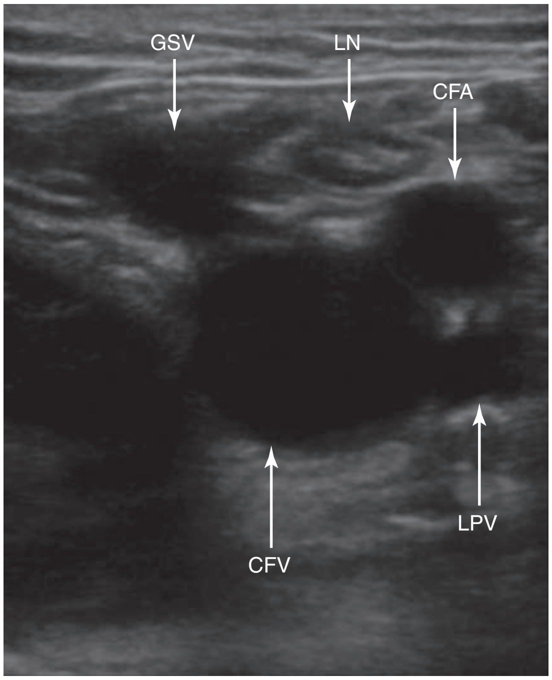

Figure 9-6 Common femoral vein at its confluence with the great saphenous vein.

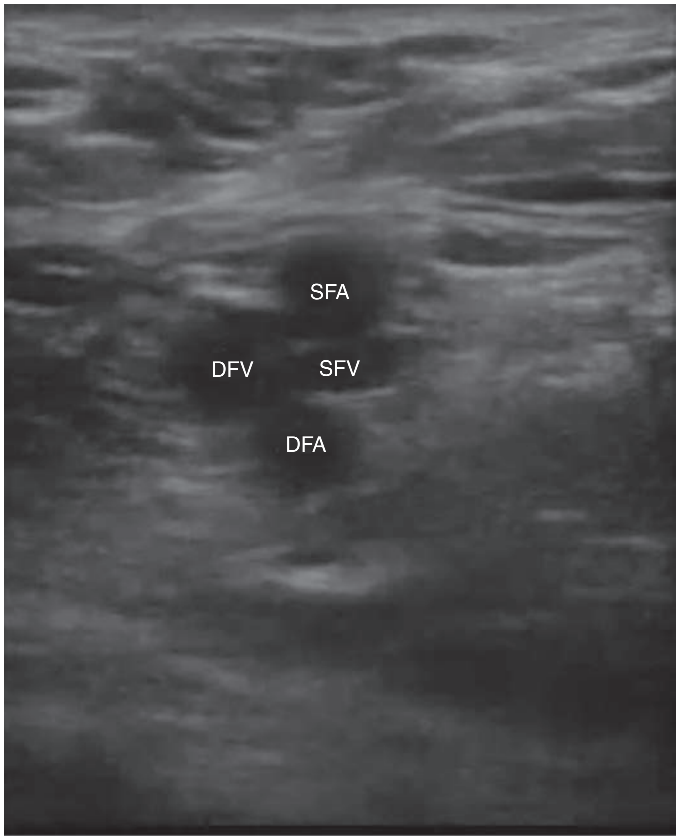

Figure 9-7 Deep and superficial femoral veins with their accompanying deep and superficial femoral arteries.

firm pressure applied to clearly visualize the deeper vessels. Identification of the companion artery will prevent misidentification of large superficial veins as deep veins in obese patients.

- The presence of *edema*, *obscuring dressings*, *local areas of tenderness*, *burns*, or *recent surgical sites* may obstruct ultrasound scanning.
- An inexperienced sonographer may sometimes *misinterpret other semisolid structures such as inguinal lymph nodes or bands of muscle* for a thrombosed vein. Similarly, fluid-filled structures such as an abscess or soft tissue cysts may resemble blood vessels. In these scenarios it is important to identify the paired artery and scan the structure of interest distally in both the transverse and longitudinal

planes. Lymph nodes, muscle bands, and cystic structures will disappear and not be accompanied by an artery.
- Because the *femoral vein* within the adductor canal is inadequately imaged, a thrombus in this area may be missed.
- In the presence of *low-flow states*, *internal echoes* or "*smoke*" may be visualized in patent veins. This is more easily seen in large veins such as the IJ, subclavian vein, and CFV. Vessel compressibility should be adequately assessed and "smoke" should not be confused with a thrombus.
- The *iliac veins* and *inferior vena cava* are not directly visualized during a lower extremity CUS study. However, excluding thrombosis in these venous segments can be facilitated by the use of color Doppler and other imaging techniques.

Pearls and Highlights

- The transducer is held in a transverse plane with the marker pointing toward the patient's right.
- Identification of the companion artery prevents misidentification of a superficial vein as a deep vein.
- Compression should be performed perpendicular to the vessel of interest.
- Lack of compressibility of the vein is diagnostic of a thrombus.
- If complete venous compression is not attained with pressure sufficient to deform the artery, an obstructing venous thrombus is likely to be present.
- The SFV is part of the deep venous system.
- If a thrombus is identified, further compression should be limited because of the possibility of dislodging the clot.
- A negative scan for lower extremity DVT does not rule out the presence of PE.
- PE remains one of the leading causes of unexpected death in hospitalized patients.
- The true incidence and prevalence of acute DVT in critically ill patients are not known.

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10

Ultrasound-Guided Central Venous Access: The Basics

AHMED LABIB | ANDREW BODENHAM

Overview

Central venous access is a core skill for anesthesiologists, intensivists, acute care physicians, and surgeons. It is indicated for fluid and drug administration, dialysis, and cardiovascular monitoring. More than 5 million central venous catheters (CVCs) are inserted annually in the United States.[1] Because central venous access often remains poorly taught and left out of training curricula, inexperienced and less skilled practitioners frequently experience significant difficulties.

Ultrasound guidance (USG) for CVC placement was introduced in the 1980s. Since then, many reports have demonstrated increased success, enhanced safety, and effectiveness of USG in comparison to anatomic landmark or audio Doppler-based techniques.[2-5]

Several national and international recommendations[6-10] have been developed that advocate the routine use of USG for placement of CVCs. Although the original practice guidelines[11] focused mainly on USG for cannulation of the internal jugular vein (IJV), USG can be used at most sites.

The first part of this chapter reviews the basics of USG, whereas the rest of the chapter focuses on specific access sites and current recommendations.

Advantages of Ultrasound-Guided Vascular Access

To appreciate the importance of ultrasound-guided vascular access (USGVA) it is necessary to understand the potential complications of attempted vascular access, which can be grouped under *immediate* and *delayed* complications. The former include inadvertent arterial or venous puncture and cannulation, hematoma, posterior vessel wall (through-and-through) puncture, pneumothorax or hemothorax, and air embolism. Other complications include multiple skin punctures, patient anxiety and discomfort, and failure of the procedure. Thoracic duct injury and nerve injury may follow CVC placement. Late complications of vascular access are local and distant infection, including catheter-related bloodstream infection (CRBSI), arterial or venous thrombosis, vessel stenosis, occlusion of the lumen or device, arteriovenous fistula formation, and tip migration.[1,6]

USGVA can potentially reduce the incidence or completely prevent many of these complications and improve the safety of the procedure.[2-5] This is due to a reduction or avoidance of primary damage caused by injury to collateral structures from the needle or secondary damage caused by misplaced guidewires, dilators, and catheters. USG enables direct visualization of the vessel or vessels of interest and surrounding structures. The depth and size of the target vessel can be measured and an optimal target vessel and site for venipuncture chosen. In trained hands, USGVA reduces the frequency of unsuccessful punctures and associated complications and facilitates first-pass cannulation.[2-5] A preprocedural scan is performed to identify abnormal anatomy, thrombosis, or valves, and a postcannulation scan is used to confirm correct placement of the guidewire and catheter in the intended vessel. Ultrasound can be used reliably for the diagnosis of pneumothorax or pleural fluid collections. The same transducer used for cannulation can be used to examine the pleura.[6] There is a potential reduction in CRBSI when USGVA is integrated within a multifaceted strategy.[3] USGVA is cost-effective because of better clinical outcomes and reduced cost of care.[2,6,11]

The Ultrasound Transducer

Application of electric current to the piezoelectric element in the transducer creates ultrasound waves (see Chapter 1). The mechanical energy generated travels and penetrates through the tissues as pulsed longitudinal waves, some of which will be absorbed or lost in the tissues whereas the remainder will be reflected back at different tissue interfaces and received at the transducer. The phenomenon of attenuation describes the loss of ultrasound energy via absorption, reflection, refraction, and scattering and can cause distortion of the image and misinterpretation of anatomic relationship. The returned energy is processed into an anatomic representation of the underlying structures (see Chapter 1).[12]

Broad-frequency transducers (5 to 15 MHz) are typically used for vascular access. Higher frequencies provide better resolution, are best suited for superficial structures, and enable identification and avoidance of adjacent vulnerable structures (e.g., small arteries and nerves). High resolution is also required for neonatal and pediatric cannulation.[9,12]

Midrange frequencies (5 to 10 MHz) are used to visualize structures 3 to 6 cm under the surface of the skin. A low-frequency probe operates below 5 MHz and is usually reserved for deeper structures; it is not commonly used for vascular access.[6,9]

The scanning surface (footprint) may be linear or curvilinear. Typical footprints vary from 20 to 50 mm in length. Smaller footprints enable access to confined anatomic locations (e.g., infraclavicular imaging or children), whereas large footprints allow the acquisition of a wider image.[6,9]

The Display

Safe, successful vascular access requires attention to the surrounding environment: ultrasound display position and transducer orientation. Operator experience and patient and equipment factors contribute to the final outcome. Adequate knowledge of the physics of USG and the mechanism of image acquisition and interpretation is essential before attempting USGVA. The operator must have the ability to interpret the displayed two-dimensional (2D) image of the vessels of interest and associated tissues, use this 2D image to perform a three-dimensional (3D) task, and possess the necessary hand-eye coordination and manual dexterity skills to manipulate the needle and transducer according to the displayed image.[9]

The display should be positioned at an appropriate height for the procedure and on the contralateral side of the patient.[6,9] The displayed image should be in the same anatomic orientation as seen from the position of the practitioner. A palpable marker on the side of the transducer corresponds to an orientation cue on the display. Touching one end of the probe and observing the associated display artifact will eliminate confusion.[12]

Typically, the operator holds the ultrasound probe with the nondominant hand in such a way that the structures beneath the left end of the probe appears on the left side of the screen and vice versa, and subsequently each side of the screen will display the ipsilateral structures.[9,12]

Image Optimization

Depth and gain control is used to improve the quality of the displayed image.[12] This typically follows a preliminary scan and identification of the structures of interest. Initially, the depth must be adequate to allow visualization of a wider anatomic field that includes the structure or structures of interest. This will identify vulnerable structures and those at risk with needle advancement, for example, the pleura and other vessels. After a preliminary scan, the depth can be reduced to focus on the target vessel and associated structures.

Sometimes the operator may want to increase or decrease the gray scale for optimization of the image. The gain control is used to reduce or amplify the ultrasound signals received and subsequently image brightness.[12] Different structures have different echogenic characteristics, and this will influence the amount of gain control required.

Relative echogenicity refers to the ability of some structures to reflect back more of the emitted ultrasound energy. Hyperechoic or echogenic structures (e.g., bones and pleura) reflect more ultrasound signal than do the surrounding tissues and appear brighter. In contrast, blood and fluid are hypoechoic.[12]

Vascular Scanning

Ultrasound-assisted vascular access refers to the use of ultrasound to verify the presence and patency of vessels whose approximate position can then be marked on the skin. This is followed by an attempted “blind” vascular puncture.[6] *Ultrasound-guided cannulation* refers to ultrasound scanning to visualize and verify a vessel and subsequently guide the tip of the needle in real time throughout the insertion process.[6]

Vascular structures have different morphologic and anatomic features. Ultrasound examination is used to distinguish veins and arteries and avoid unintentional puncture or cannulation. Veins are typically elliptic or ovoid, thin walled, and readily collapsible, whereas arteries are circular, thick walled, and less compressible.[9]

Though not routinely required for vascular access, Doppler examination can demonstrate vessel patency and the direction and nature of blood flow and enable differentiation of deeper veins from arteries. Color Doppler and spectral Doppler waveform examination require further training and can establish vessel patency, as well as differentiate between a vascular and a nonvascular hypoechoic structure.[6,9]

Various terms have been used to describe the spatial relationship between the advancing needle and probe and the target vessel. Safe and successful cannulation requires understanding of such relationships. The first step is to confirm correct orientation of the scanning probe. This is followed by visualization and verification of the target vessels and surrounding structures.[9] Thorough preliminary scanning will allow the operator to identify the most appropriate site for needle puncture and avoid anatomic misinterpretation.[6]

Ultrasound scanning of a blood vessel in its short axis generates a transverse image. Turning the position of the probe 90 degrees from the short axis generates a long-axis or longitudinal view of the same vessel. A hybrid oblique axial view has also been described and is useful with more tortuous vessels.[6]

Needle Orientation

With respect to the ultrasound beam, the needle can be advanced either in plane or out of plane. The former allows continuous visualization of the entire needle and tip throughout their complete trajectory from the surface of the skin to the target vessel, thereby enabling precise real-time control. This should improve the safety of the procedure and minimize inadvertent injury; nevertheless, it is more challenging with deeper structures (e.g., the axillary vein in the morbidly obese) and requires further training. An in-plane approach does not provide simultaneous imaging of surrounding structures, nor does it necessarily avoid transfixion of the vessel when it is at low pressure and collapsible.[6]

The more widely used out-of-plane puncture allows concomitant visualization of associated at-risk structures and simultaneous anterior-posterior and medial-lateral views of the vessel or vessels; however, the position of the needle tip is more difficult to ascertain and requires considerable experience and practice. It is easy to advance the tip of the needle across the very thin (<1 mm) ultrasound beam and misinterpret the shaft for the tip. Failure to visualize the needle tip as it penetrates through the tissues may expose the patient to avoidable harm and reduce the expected benefits of USGVA. Many operators are now combining both approaches such that the vessel is viewed in cross section (wholly or in part) and the needle introduced from the side in plane with the probe beam.[6] Irrespective of the approach taken, there are still difficulties with very collapsible veins because it is difficult to know when the tip of the needle has penetrated the anterior or posterior vein walls.[6]

Needle guides can be used to align the position of the needle in either a transverse or longitudinal view. They could be useful for less experienced operators, for whom a mechanical device to hold the needle in an appropriate orientation can be valuable.[6,9] A recent study reported better visibility, faster access, and fewer mechanical complications with an echogenic needle.[13]

Selection of the Site of Cannulation

Various factors are important when deciding on the cannulation site, including patient and operator factors, as well as the intended indication for and duration of central venous catheterization and the clinical scenario (e.g., rapid access in an emergency situation).[6,10] A preprocedural scan will help identify difficult or impossible access sites inasmuch as 10% of patients may have abnormal vascular anatomy.[6] Assessment of vessel size, position, and patency helps in identifying the most suitable site and choosing the correct size of catheter.[6] USG can influence the choice of cannulation site and the long-term outcome of the procedure:

- Vein size: Smaller veins are difficult to cannulate and more predisposed to the development of thrombosis and stenosis. As a general role, the outer diameter of the CVC should not be more than a third of the vein's caliber. A high catheter-to-vein ratio impedes blood flow and should be avoided.[6]
- Vein depth: In most individuals the IJV is less than 2 cm underneath the skin. The brachiocephalic vein and subclavian vein (SCV) are relatively deeper structures, especially in obese patients.
- Surrounding structures: The SCV lies immediately above the pleura. A more lateral infraclavicular approach allows venipuncture away from the pleura. At-risk vessels may be located in front of or behind the target vein (Figure 10-1A).
- The skin exit site should be chosen carefully because it will affect both the short- and longer-term outcome of central venous catheterization. A conveniently located exit site enables better maintenance of the CVC, is easier to dress and secure, and enhances patient compliance and nursing care. Some exit sites are associated with a higher rate of infection (e.g., femoral veins).[9]
- Anatomic and morphologic abnormalities: Mediastinal tumors and masses may cause external compression or stenosis of a great vein. An occluding thrombus or prolonged cannulation may cause blockade of the vein. Ultrasound features include demonstration of engorged collaterals and difficult-to-compress veins because of high pressure and reversed flow on Doppler examination. These sites need to be avoided since successful central guidewire and catheter insertion is unlikely. This situation is more likely to be encountered in patients requiring long-term or repeated central venous catheterization (Figure 10-1B).[6]

Ultrasound-Guided Vascular Access Techniques and Current Recommendations

INTERNAL JUGULAR VEIN CANNULATION

A substantial body of scientific evidence recommends USG over landmark techniques for cannulation of the IJV in adult and pediatric patients in both elective and acute settings.[2-6,11] USG for IJV access offers a higher success rate, typically on the first needle pass, reduced complications from collateral damage, decreased procedural time, and potential overall savings.[2-6] A procedural failure rate of 7% to 19% has been demonstrated with traditional anatomic landmark approaches. Furthermore, a success rate of less than 25% per attempt has been reported when initial blind punctures have failed.[4]

Routine USG is invaluable inasmuch as anatomic variability was observed in 36% of the population in one study.[14] Head rotation from a neutral to a lateral position can increase vein-to-artery overlap nearly threefold, and this occurs more frequently in obese patients. Precise needle control with USG reduces the risk for this complication. An ultrasound-measured IJV diameter smaller than 7 mm suggests a poor success rate, and 3% of patients had small fixed IJVs in one study. The right IJV is usually larger than the left, and USG can verify size and patency and help in determining best side for cannulation, thus improving success and minimizing complications.[11]

Patients with carotid artery disease, such as stenosis or a patch, are at particular risk, and puncture of the carotid artery with even a 21-gauge seeker needle can lead to catastrophic sequelae. High-resolution ultrasound can identify nearby at-risk structures, such as the carotid, vertebral, and subclavian arteries; thyroid gland and arteries; and lymph nodes. The subclavian, vertebral, and inferior thyroid arteries and the thyrocervical trunk cross behind the IJV low in the neck and can pose significant risk (Figure 10-2A and B).

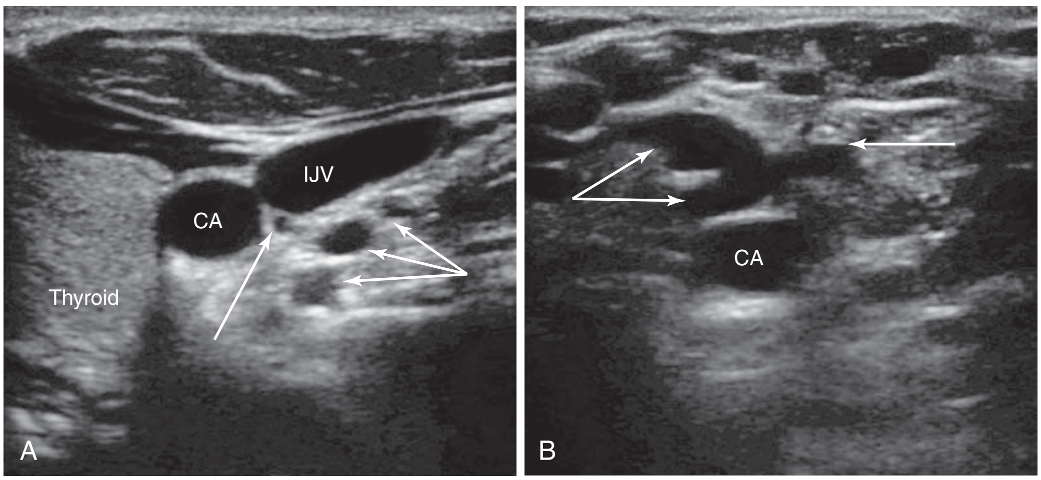

Figure 10-1 **A,** Right carotid artery, internal jugular vein (IJV), and thyroid. Note the vessels in close proximity behind the IJV *(arrows)*. These three vessels are all from the thyrocervical trunk, which arises from first part of the subclavian artery and ascends for a short distance behind the IJV before branching. Such vessels are at risk with needle transfixion of the vein. A vein is also present just below these arterial branches. **B,** Left carotid artery with a plexus of tortuous collateral veins anteriorly *(arrows)*. No obvious larger IJV is present, which has been blocked after previous long-term catheterization. The operator should move to another site of access.

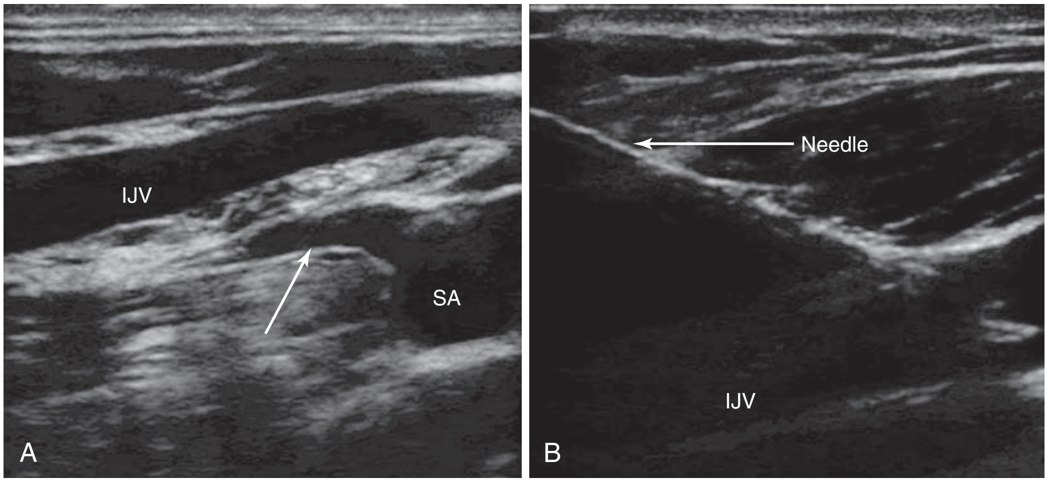

Figure 10-2 **A,** Longitudinal view of the lateral edge of the lower section of the right internal jugular vein (IJV) crossing the right subclavian artery (SA). A major branch of the artery is arising from the superior aspect of artery, the thyrocervical trunk *(arrow)*, which is about 4 mm behind the vein. The artery and branches are at risk with vein transection. **B,** In-plane needle visualization and puncture of the IJV.

Axial and lateral approaches refer to out-of-plane and in-plane transverse views of the needle during ultrasound-guided cannulation of the IJV. Precise control of the needle during the in-plane lateral approach should lessen the likelihood of arterial or pleural puncture and provide a more conveniently located exit site in the lower part of the neck. The more commonly used out-of-plane axial puncture usually results in a midneck exit site with potential difficulty in securement and dressings. The more technically challenging in-plane needle insertion via a longitudinal view should be associated with fewer complications in experienced hands.[6] In conclusion, level 1 evidence mandates the routine use of real-time USG for cannulation of the IJV by adequately trained operators.

SUBCLAVIAN VEIN CANNULATION

The SCV is the continuation of the axillary vein and runs from the apex of the axilla across the first rib in the subclavian groove and is separated from the axillary artery by the insertion of the anterior scalene muscle. It joins the IJV behind the sternoclavicular junction to form the brachiocephalic vein. Throughout most of its course the SCV lies behind the clavicle, which impedes ultrasound visualization; however, a supraclavicular and infraclavicular lateral approach can be used for USG. The SCV is close to the pleura, subclavian artery, and brachial plexus (Figure 10-3). Because of currently insufficient evidence, routine use of USG for SCV cannulation is not mandated despite its perceived advantages.[9,10]

Landmark-based techniques for SCV cannulation are associated with up to 12% complication rates.[9] There is increasing experience and interest in ultrasound scanning for SCV cannulation. Fragou et al[15] used a parasternal approach to SCV cannulation and reported a higher success rate, faster access, and fewer needle passes and complications. USG via a suprasternal approach facilitated success on the first needle pass in more than 98% of attempts with no reported major complications.[16]

Many clinicians are probably actually accessing the axillary vein rather than the SCV, which starts at the level of the first rib. The axillary vein lies entirely outside the rib cage, and a slightly

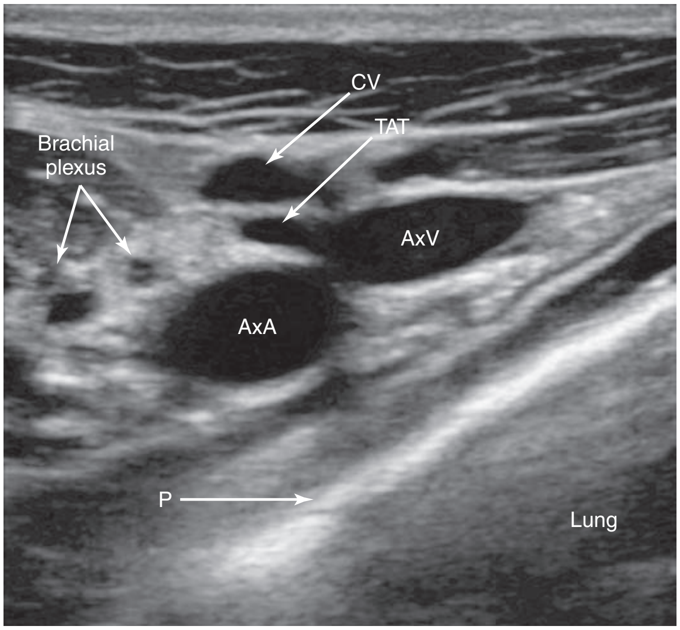

Figure 10-3 Lateral infraclavicular approach to the right axillary vein. Note the right axillary artery (AxA) and vein (AxV) with the thoracoacromial trunk (TAT) branch in front, the cephalic vein (CV), and the pleura (P).

more lateral infraclavicular approach allows easy visualization with ultrasound and a greater distance between the pleura and vein and can largely avoid pleural or lung damage.[17]

A recent analysis confirmed the safety and effectiveness of this approach.[18] Real-time needle visualization and depiction of the axillary artery and brachial plexus can avoid injury to these structures. The cephalic vein and thoracoacromial branch of the axillary artery (see Figure 10-3) may lie anterior to the axillary vein and can be avoided.[18]

FEMORAL VEIN CANNULATION

The common femoral vessels lie within the femoral sheath in the femoral triangle formed by the inguinal ligament, adductor

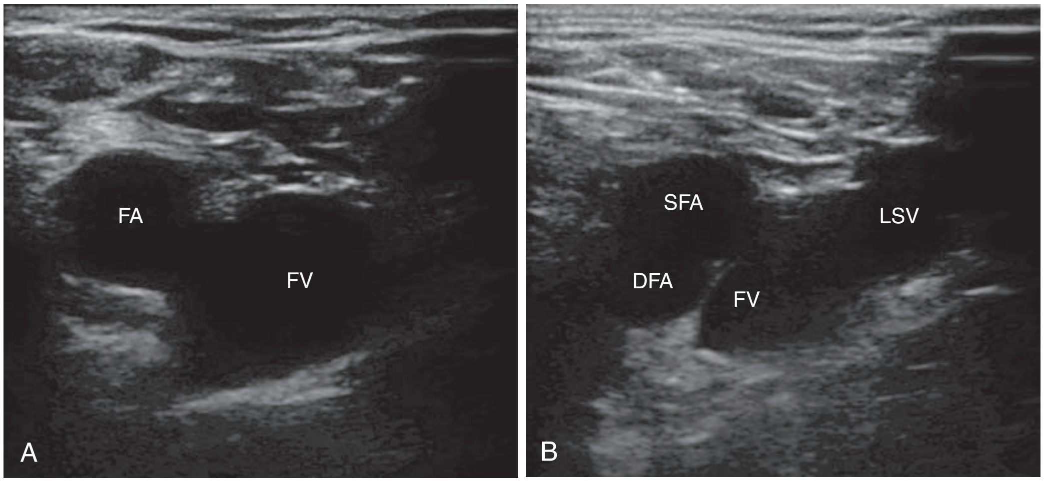

Figure 10-4 **A,** Femoral vessels at the level of the inguinal ligament with side-by-side orientation. **B,** Vessels just below the inguinal ligament with overlap: superficial (SFA) and deep (DFA) femoral arteries. Note the long saphenous vein (LSV) as it joins the femoral vein (FV).

longus, and sartorius muscle. Many patients will not have the classic textbook description of the femoral artery and vein running side by side, and significant overlap has been observed in adults and children.[9] Ultrasound imaging identifies the common femoral vein (FV) with the great saphenous vein joining it and the superficial and deep branches of the common femoral artery. With USG, vessel patency, depth, and overlap can be verified (see Figure 10-4A,B).

The FV is the preferred route of access for many cardiac procedures in both children and emergency scenarios.[9] Attempted FV cannulation does not interfere with cardiopulmonary resuscitation, breathing tubes, and monitoring cables and avoids the risk for pneumothorax and hemothorax.[9] However, vascular complications may follow FV access and include bleeding, arterial puncture, hematoma, thrombosis, and formation of an arteriovenous fistula and pseudoaneurysm. Rare but serious complications include bowel and bladder perforation and peritoneal or retroperitoneal bleeding following high puncture sites.[9]

These complications are less likely when USG is used. FV catheters are predisposed to contamination because of their close proximity to the perineal area. Both prolonged cannulation and repeated needle passes increase this risk; the latter can be minimized by USG, and it should be used routinely for FV catheterization.[6,10]

Pearls and Highlights

- Competency in ultrasound image acquisition, interpretation, and management is a prerequisite before undertaking practical procedures. The operator must be able to appreciate the difference between the virtual 3D patient anatomy and the 2D displayed ultrasound image. Skill in needle visualization, guidance, and navigation in real time requires considerable training.
- Doppler shift differentiates vascular from nonvascular structures. Color Doppler and spectral Doppler waveform examination are used to differentiate arterial from venous flow.
- Accurate interpretation of the ultrasound image, identification of the target vessel, and continual visualization of the tip of the needle are fundamental to the safety and success of the procedure.
- USGVA improves patient safety by reducing mechanical and possibly infectious complications, efficacy of the procedure by reducing the number of attempts and duration, and maximizes patient satisfaction.

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11

Ultrasound-Guided Vascular Access: Trends and Perspectives

ARIEL L. SHILOH | LEWIS A. EISEN | MICHAEL BLAIVAS | DIMITRIOS KARAKITSOS

Ultrasound-guided vascular access (UGVA) was introduced in the preceding chapter. This chapter highlights a few tips for novices as well as additional techniques and innovations that would assist skilled operators in definitively identifying the target vessel and improving catheterization in the intensive care unit (ICU).

Many randomized controlled trials and meta-analyses have associated UGVA with a considerable reduction in complications and increased first-attempt success when compared with standard landmark techniques.[1-3] As 1 of their 11 practices to improve patient care, the Agency for Healthcare Research and Quality (AHRQ) recommends the use of ultrasound for placement of a central venous catheter (CVC).[4] The National Institute for Clinical Excellence (NICE), as part of their NICE technology guidelines, advocated the routine use of UGVA.[5] Most recently, an international, evidence-based consensus statement was developed to assist clinicians in performing UGVA and as a reference for future clinical research. The group advised that ultrasound guidance can be used not only for central venous cannulation but also for peripheral and arterial cannulation. In addition to guidance, the group recommended the use of ultrasound to check for immediate and life-threatening complications, as well as catheter positioning.[6]

Patient and Technical Considerations

The implementation of a simple three-step UGVA technique (pre-procedural scanning, real-time ultrasound-guided cannulation, post-procedural scanning) maximizes success rates and decreases complications in the intensive care unit (ICU).[6] A pre-procedural scan is recommended to guide the selection of an optimal target vessel.[4-6] Usual criteria for the selection of an optimal vein are:

Normal venous patency (venous collapse during breathing or compression without signs of thrombosis)

Easy accessibility (relatively short distance from the skin surface to the vessel wall)

Adequate size (vessel size less than three times the caliber of catheter may carry a greater risk for thrombosis)[7]

Absence of anatomical variation

Intended purpose of cannulation (i.e., neck surgery often requires infraclavicular vascular access)

Intended duration for catheter placement (i.e., a cancer patient receiving chemotherapy often requires long-term vascular access)

Complication rates after the implementation of landmark techniques differ between sites (Chapter 10). The internal jugular vein carries the highest risk of accidental arterial puncture and hematoma, the subclavian carries the highest risk for pneumothorax, hemothorax, and catheter malposition, while the femoral vein carries the highest risk for thrombosis and infection (Table 11-1). The subclavian vein is considered advantageous in the ICU (compared to the internal jugular or the femoral vein) as it carries the lowest infection risk. However, recent studies show that Chlorhexidine gluconate -impregnated sponge dressing when used with the standard care decreases the incidence of major catheter-related infections from 1.4 to 0.6 per 1000 catheter-days.[8] The American Society of Anesthesiologists Task Force on Central Venous Access recommends the use of a central line insertion work and safety checklist and bundling of required equipment to minimize errors, risk of infection, and complications.[9] These measures have shown reduction (up to 66%) in central line-associated bloodstream infections.[10]

Preprocedural Tips

A few practical tips when performing an ultrasound-guided central venous cannulation for the first time include:

- The implementation of a strict sterilization process including use of a sterile probe cover and gel (Figure 11-1)
- Avoid applying extreme probe pressure on the vessel as normal veins are collapsible vessels
- Optimize the two-dimensional image: center the image on the screen and adjust depth, gain and focus, while obtaining the proper orientation of anatomy with standardization of the dot on the left (Chapter 1).
- When a clear two-dimensional image of the vein is obtained check its patency by applying probe pressure to exclude thrombosis (Video 11-1).

Notably, a thorough preprocedural scan at a prospective region of interest (ROI) should be performed because of the frequent finding of venous and arterial asymmetry between symmetric sites. In that sense, anatomic diversities may exist as well in occasional patients (e.g., duplicated femoral vein). Venous compressibility and patency should be examined because exclusion of thrombosis is mandatory (Chapter 9). The latter is more commonly observed at the common femoral vein site than at other cannulation sites, and ultrasound monitoring of a central line may reveal cases of catheter-related thrombosis (Figure 11-2). Occasionally, trauma to the venous wall, trapped air, hematomas, arteriovenous fistulas, or injuries to nonvascular adjacent structures may be identified after a "clumsy" blind attempt or multiple blind penetrations, which could produce local trauma (Figure 11-3). Estimating vessel size is equally important, as previously mentioned. The size of the internal jugular vein can be evaluated before and after a Valsalva maneuver, which may make a relatively small-caliber vessel that is seemingly difficult to catheterize become robust and easy to puncture.[11] Moreover, the diameter of the internal jugular vein

TABLE 11-1 Complication rates in different central veins

Complication	Internal jugular	Subclavian	Femoral
Arterial puncture %	10.6	5.4	6.25
Hematoma %	8.4	5.4	–
Pneumothorax %	2.4	4.9	–
Hemothorax %	1.7	4.4	–
Malposition %	–	11	–
Infection rate per 1000 catheter-days	8.6	4	15.3
Thrombosis rate per 1000 catheter-days	1.2 – 3	0 – 13	8 – 34

*Results associated with the landmark/blind method (Lamperti M, Bodenham AR, Pittiruti M, et al: International evidence-based recommendations on ultrasound-guided vascular access, *Intensive Care Med* 38(7):1105-1117, 2012.)

Figure 11-1 A standard central venous access kit and ultrasound probe baring a sterile cover.

is usually found to be larger when the vessel is depicted in the lower neck area (scanning caudally toward the clavicle) than in the upper neck area (scanning cranially toward the mandible). When planning on catheterizing the internal jugular or subclavian vein, the pleura should be assessed for a sliding lung while identifying the vasculature.

Visualization of the vasculature is most often done with B-mode ultrasound. When compared with B-mode, use of the color Doppler mode for vascular access has been associated with a longer learning curve, longer insertion time, and higher cost.[12] Although in the vast majority of cases the absence of Doppler capability does not preclude safe catheterization, it can be of assistance when identification of the target vasculature is difficult. Color Doppler and pulsed wave Doppler are useful techniques that facilitate the differentiation between arterial and venous pulsation. The use of ultrasound for vascular access has been shown to decrease the need for correction of coagulopathy before insertion of the catheter. In the hands of experienced operators, when favorable vasculature is visualized, UGVA has been demonstrated to be safe and successful, with a low rate of complications.[13,14]

Variations in Technique

One-person (two-hand) and two-person (three-hand) techniques have been described for USGV. In the one-person technique, the operator controls the transducer with the nondominant hand and the needle with the dominant hand. An assistant, also in full sterile barrier precautions, is required to hold the probe for the two-person technique. The one-person technique is reported to be learned easily and is associated with improved first-pass and overall success of CVC placement when compared with the two-person technique.[2,11] When first learning the technique, many operators find the two-person technique easier. Eventually, most operators gravitate toward the one-person technique.

The ergonomics of UGVA is equally important. Ideally, the ultrasound machine should be placed on the contralateral side of the ROI while the operator stands at the cannulation site (Figures 11-4 and 11-5). Usually, the dominant hand of the operator holds the needle and the nondominant hand holds the transducer. Hence, the latter can be flexed slightly while resting on the body surface of the patient to stabilize the elbow in a comfortable position. Because the elbow of the operator remains stable, it is easier for the operator's wrist to relax and sweep the transducer accurately while the needle is moved forward gently under the transducer in real time.

Variations on needle insertion have been described (Chapter 10). Real-time, dynamic visual guidance (free-hand access) throughout catheterization is always superior to marking a spot with ultrasound and then trying to locate a vessel without guidance (Figures 11-6 and 11-7).[2,11,12, 13-16] As described previously, longitudinal visualization of the vessel allows improved and continuous visualization of the advancing needle tip but requires a more skilled operator, especially when attempting to catheterize small-caliber vessels. The transverse approach, though easier to learn, has been associated with an increased incidence of posterior wall perforation, probably because operators are often mistaking the shaft of the needle for the tip since it is easy to advance the tip of the needle past the ultrasound beam.

When using a transverse approach, we advocate using the "creeping" technique, in which the tip of the needle is visualized continuously, by using the following steps:

1. Localize the target vessel.
2. Measure the distance from the surface of the skin to the wall of the vessel.
3. Superficially insert the needle posterior to the transducer, to the same distance measured in step 2, at a 45-degree angle.
4. Tilt the transducer toward the needle to identify the tip of the needle.
5. Advance the needle into the vessel while simultaneously advancing and tilting the transducer forward in a slow creeping motion and keeping the tip of the needle visualized at all times.
6. The tip of the needle should be seen indenting and advancing through the anterior vessel wall.

When using a longitudinal approach, the main technical difficulty is depicting a "steady" image of the target vein while advancing the needle. Performing synchronous manipulations (e.g., moving the needle while adjusting the ROI to depict the target vein) has been recommended. However, these manipulations may be dangerous, especially when performed by novice

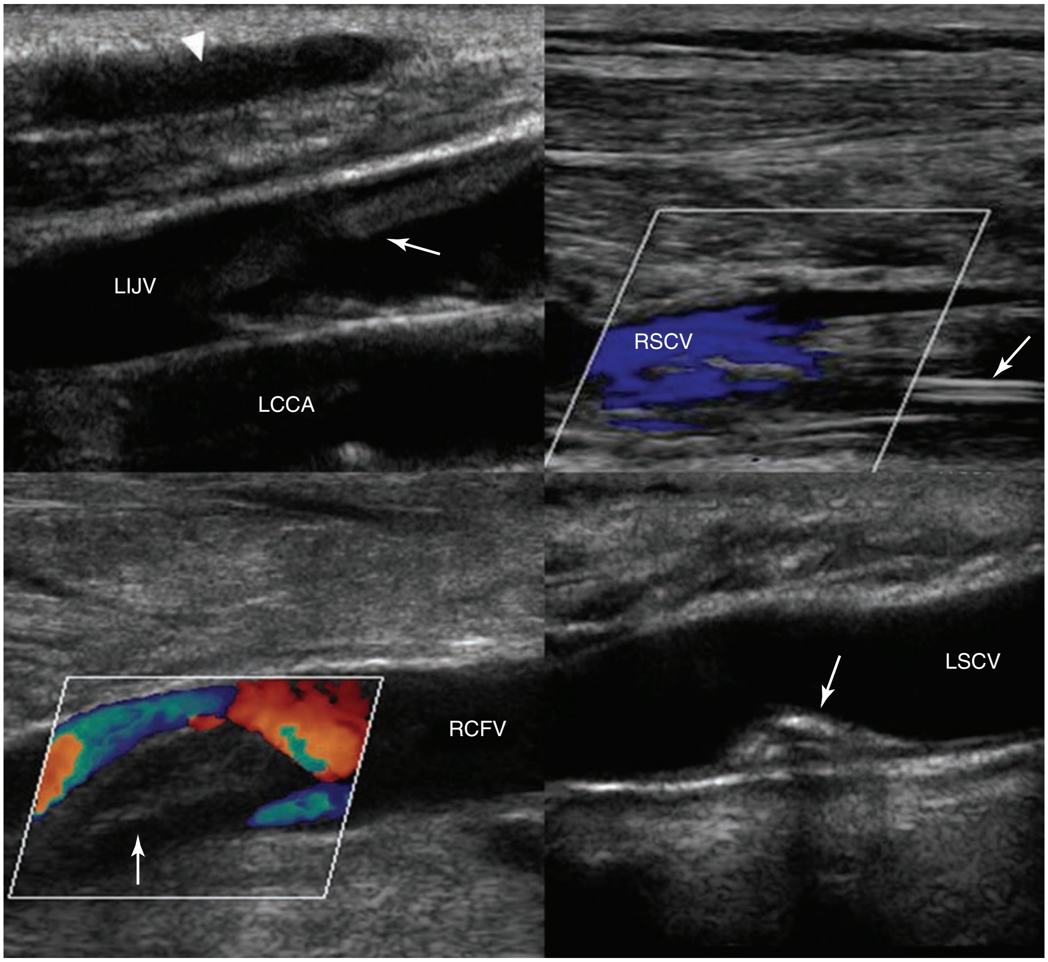

Figure 11-2 *(Top)* Depiction of a superficial hematoma *(arrowhead)* and a fresh floating thrombus in the left internal jugular vein (LIJV), which is overlying the left common carotid artery (LCCA), on a longitudinal plane *(left)*. A longitudinal view of the right subclavian vein (RSCV) shows partial flow from central line–associated thrombosis *(arrow)*. *(Bottom)* Fresh thrombus *(arrow)* obstructing flow in the right common femoral vein (RCFV) on a longitudinal plane *(left)*. A longitudinal view of the left subclavian vein (LSCV) shows a calcified remnant of a thrombus (following treatment with an anticoagulant) attached to its posterior wall that is not obstructing the vessel's lumen *(right)*.

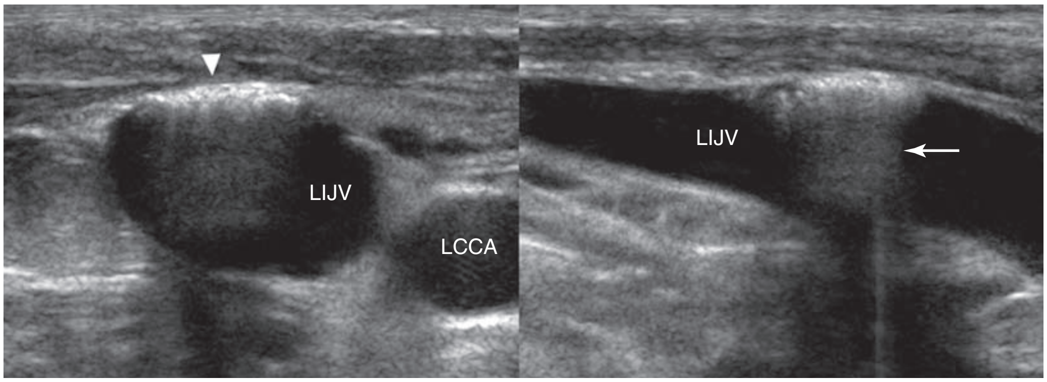

Figure 11-3 Sequelae of a blind attempt at cannulation of the left internal jugular vein (LIJV). *LCCA*, left common carotid artery. Transverse *(left)* and longitudinal *(right)* views show trauma to the anterior wall *(arrowhead)* of the LIJV with trapped air that is causing enhanced posterior acoustic shadowing *(arrow)*.

Figure 11-4 Demonstration of proper equipment setup for cannulation of the internal jugular vein. The ultrasound machine is placed downstream of the operator in a direct line of sight.

Figure 11-5 Demonstration of proper equipment setup for cannulation of the internal jugular vein. The ultrasound machine is placed downstream of the operator in a direct line of sight.

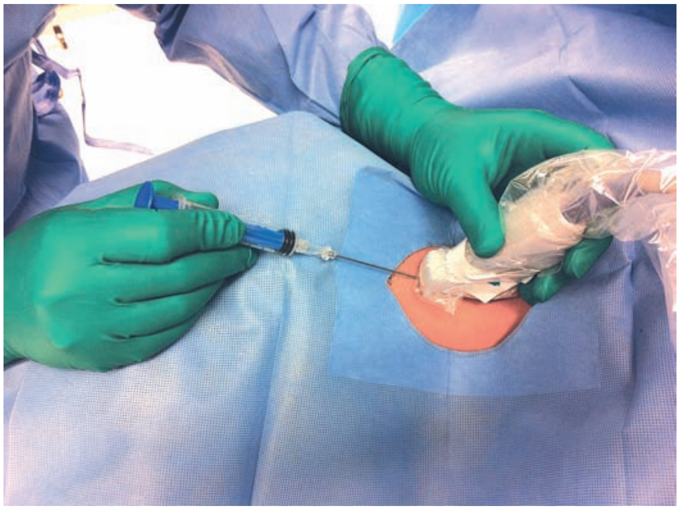

Figure 11-6 Free hand access dynamic cannulation on the longitudinal axis requires fine coordination of movements (note that the plane and trajectory of the needle follows the plane of the probe).

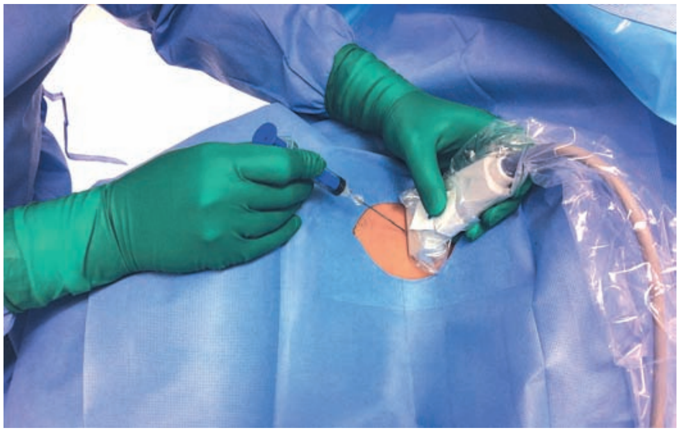

Figure 11-7 Free-hand access dynamic cannulation on the transverse axis (the angle of the penetrating needle is around 45 degrees) is technically less demanding, although the visualization of the needle may be indeed more problematic, compared to the longitudinal axis approach.

users. For example, when a desirable ROI is found after continuous manipulations, the needle, which is moving synchronously, thereafter may well have followed an out-of-plane course. Hence, it is safer to first identify a desirable image of the target vein and then advance the needle in real time while keeping that image intact. Finally, estimating the depth of the target vein from the skin surface is important because the distance may sometimes be greater than anticipated for various reasons (e.g., anatomic variations, trauma, obesity) and necessitate adjustments of the insertion angle and thereby increase the technical difficulty of the procedure.

Intraprocedural and Postprocedural Tips

For the most part, evaluation of target vessels is limited to the insertion point and what can be visualized immediately proximal and distal to the insertion site. Although a well-chosen site increases the success of catheter deployment and positioning, it does not guarantee success. When inserting a CVC into the internal jugular or subclavian vein, the rib cage obscures further evaluation of the vessel downstream. [13-16] Fragou et al demonstrated that the contralateral vasculature could be visualized by an assistant while advancing the guidewire to assess for potentially misdirected catheter deployment.[17] If the guidewire is seen in the contralateral vasculature, attempts could be made to redirect the wire. In addition, the guidewire should always be visualized within the vein before any dilation is performed to prevent potential catastrophic arterial damage (Figure 11-8).

After the procedure the pleura should once again be visualized and assessed for lung sliding to ensure that pneumothorax is not present (Chapter 19). If difficulty was encountered despite using UGVA, such as an inability to thread the guidewire or unexpected resistance in catheter deployment, the vasculature should be scanned for the potential development of a hematoma, pseudoaneurysm, or arteriovenous fistula (Chapter 8).

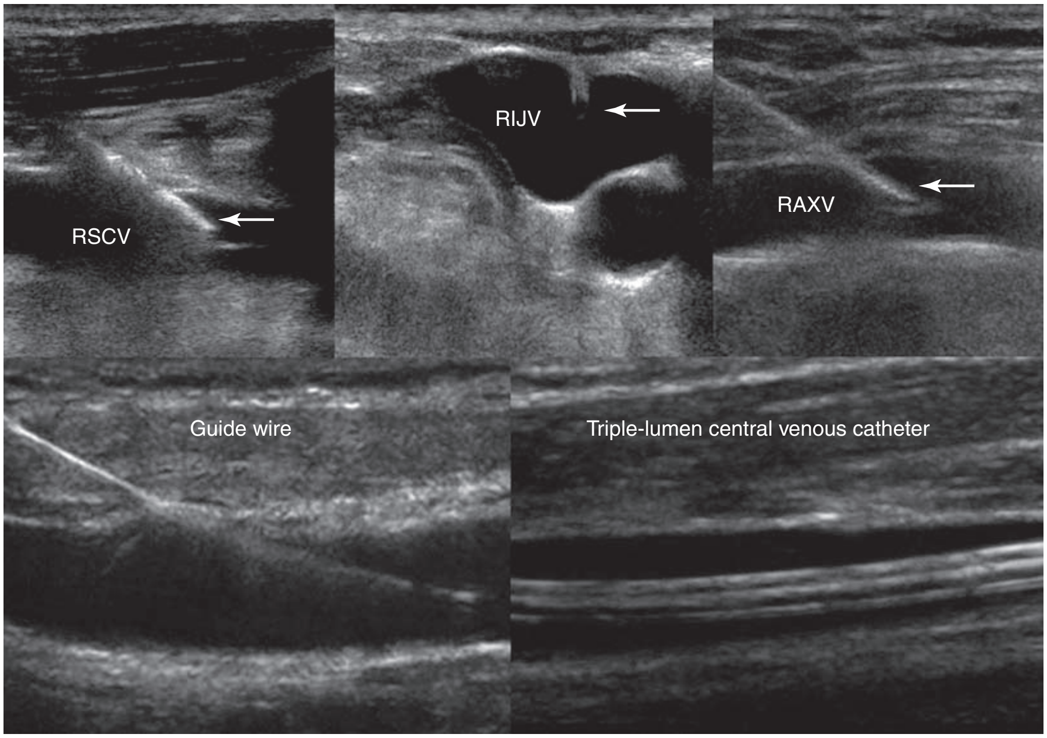

Figure 11-8 *(Top)* Real-time visualization of an echogenic vascular cannula, regardless of the angle of its insertion, in the right subclavian (RSCV), internal jugular (RIJV), and axillary (RAXV) veins. *(Bottom)* Depiction of the guidewire *(left)* and the triple-lumen central venous catheter *(right)* following successful central venous cannulation of the RIJV.

Simulation Training and Echogenic Technology

In recent years, implementation of simulation-based training for CVC insertion has been increasing. Such training has resulted in a significant reduction in mechanical and infectious complications and an increase in ultrasound use.[18] At the present time, simulation mannequins and vascular task trainers, compatible with ultrasound, can be used to improve the skills of novice and less experienced operators.

Optimal image acquisition can be affected and deteriorated by subcutaneous air, obesity, trauma, and mechanical ventilation in the ICU. Such factors often make continuous visualization of the tip of the needle a challenge. The use of echogenic vascular cannulas, which have the potential to improve image acquisition and thus needle visualization, has been shown to improve success rates in technically difficult cases of vascular access.[19,20] Etched reflectors on the tip of the vascular cannula improve visualization of the needle independent of the angle of insertion, in a method analogous to a bicycle reflector (see Figure 11-8). Recent, preliminary data have demonstrated improved continuous needle visibility and decreased access times and technical complexity of UGVA when using echogenic needle technology in either a longitudinal or transverse approach.[19,20]

Pearls and Highlights

- As 1 of their 11 practices to improve patient care, the AHRQ recommends the use of ultrasound for CVC placement.
- The American Society of Anesthesiologists Task Force on Central Venous Access recommends the use of a central line insertion work and safety checklist and bundling of required equipment to minimize errors, risk of infection, and complications
- The implementation of a simple three-step UGVA technique (pre-procedural scanning, real-time ultrasound-guided cannulation, post-procedural scanning) maximizes success rates and decreases complications in the ICU
- A thorough preprocedural scan can familiarize the operator with the sonographic anatomy of the cannulation site (e.g., detection of possible anatomic diversity, venous and arterial asymmetry between symmetric sites) while excluding preexisting thrombosis, which is mandatory.
- Ultrasound monitoring of central lines aids in early identification of catheter-associated thrombosis.
- Postprocedural scanning can confirm flawless deployment of the guidewire or catheter (or both) in the vein, avoiding thus the pitfall of dilating an artery, and can facilitate repositioning when the guidewire or catheter is malpositioned.
- Simulation-based UGVA training is a new educational tool that can improve the skills of novice users.
- The use of echogenic vascular cannulas, which enhance real-time visualization of the tip of the needle regardless of its angle of insertion, could prove to be advantageous in technically difficult catheterization scenarios in the ICU.

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For a full list of references, please visit www.expertconsult.com.

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12

How to Choose the Most Appropriate Ultrasound-Guided Approach for Central Line Insertion: Introducing the Rapid Central Venous Assessment Protocol

MAURO PITTIRUTI | ANTONIO LAGRECA

Overview

Standard central venous access performed with the "blind" technique was historically based on the puncture of two central veins (the subclavian vein and the internal jugular vein),[1] but ultrasound (US) guidance has expanded the spectrum to at least four sites: the internal jugular vein, the brachiocephalic (or "innominate") vein, the subclavian vein, and the axillary vein. In many patients, two additional, centrally located venous segments can be cannulated: the external jugular vein (in its final tract close to the junction of the subclavian vein) and the cephalic vein (in its final, infraclavicular tract close to the junction of the axillary vein).

The list just presented is limited to the veins available for placement of central venous catheters (CVCs) *in the neck/thoracic area*. However, other peripheral veins can be used for US-guided cannulation and placement of a peripherally inserted central catheter *in the upper part of the arm* (the cephalic vein, the brachial veins, the basilic vein, and the axillary vein in its distal tract). Other peripheral veins located *in the groin area* (the femoral and saphenous veins) can be accessed for placing "central" venous catheters.

The shift from a "heads-or-tails" choice (subclavian vs. jugular) to a wide spectrum of choices (internal jugular, brachiocephalic, subclavian, axillary, etc.) is the real "Copernican" revolution of the US era. Whereas in the last century the physician was bound to choose between the subclavian and jugular sites on the basis of personal preference, instinct, or experience, selection of the most appropriate vein to cannulate can be determined today on a rational basis by means of US technology.[2]

The Rapid Central Vein Assessment

US guidance is an evidence-based methodology that significantly reduces the complications related to insertion of CVCs.[3-5] However, the benefit of using US is not limited to real-time US-guided venipuncture. The GAVeCeLT (Italian Group for Venous Access Devices) recommended the use of US during CVC insertion for six different purposes: (1) US evaluation of all veins available, (2) choice of the vein on the basis of rational US-based criteria, (3) real-time US-guided venipuncture, (4) US-based control of guidewire/catheter orientation during the procedure, (5) US-based control of pleura-pulmonary integrity after axillary or subclavian vein puncture, and (6) transthoracic echocardiography for verification of the position of the tip of the catheter at the end of the procedure.

Of particular relevance is the application of US for rapid assessment of the central veins in an effort not only to exclude veins that appear morphologically abnormal (thrombosis, external compression, anatomic variations) but also to evaluate the possible options and choose the best approach. This can easily be performed by following the rapid central vein assessment (RaCeVA) protocol, which has been standardized by our group and is currently taught in our GAVeCeLT courses on US-guided central venous access.

This six-step protocol suggests the following preprocedural complete venous scan (before deciding on the most appropriate approach):

- The transducer is positioned in a transverse plane at the midneck region (Figure 12-1A). This allows evaluation of the internal jugular vein and carotid artery (short axis; Figure 12-1B). This is an ideal position for an internal jugular vein, US-guided approach using either an "in-plane" or an "out-of-plane" technique.
- By sliding the transducer down the neck toward the sternum (Figure 12-2A), it is possible to evaluate the internal jugular vein in its lower tract (in the short axis) and visualize the subclavian artery (long axis; Figure 12-2B).
- By tilting the transducer to achieve an almost frontal plane (Figure 12-3A), the brachiocephalic vein can be visualized (long axis; Figure 12-3B). This is an ideal position for "in-plane" cannulation of the brachiocephalic vein.
- By sliding the transducer laterally, behind the clavicle (Figure 12-4A), the subclavian vein and external jugular vein (long axis; Figure 12-4B) can be visualized, and the subclavian artery can be detected at an even more lateral plane (short axis). In this position the subclavian or the external jugular vein can be cannulated via an "in-plane" approach.
- Next, the transducer is positioned below the distal third of the clavicle (Figure 12-5A) for proper visualization of the axillary vein and artery (short axis) and the cephalic vein (long axis; Figure 12-5B). In this position the axillary vein can be cannulated via an "out-of-plane" approach.
- By rotating the transducer anticlockwise (Figure 12-6A), the axillary vein is visualized (long axis; Figure 12-6B). In this position the vein can be cannulated via an "in-plane" technique.

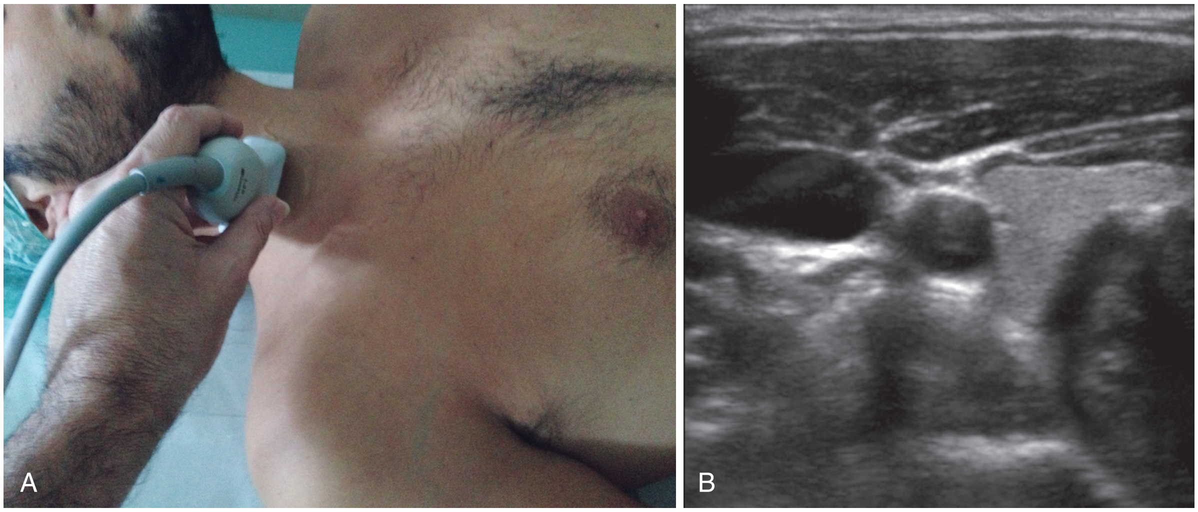

Figure 12-1 First step in the rapid central vein vascular assessment protocol. **A,** Probe positioned at the midneck. **B,** Visualization of the internal jugular vein and carotid artery.

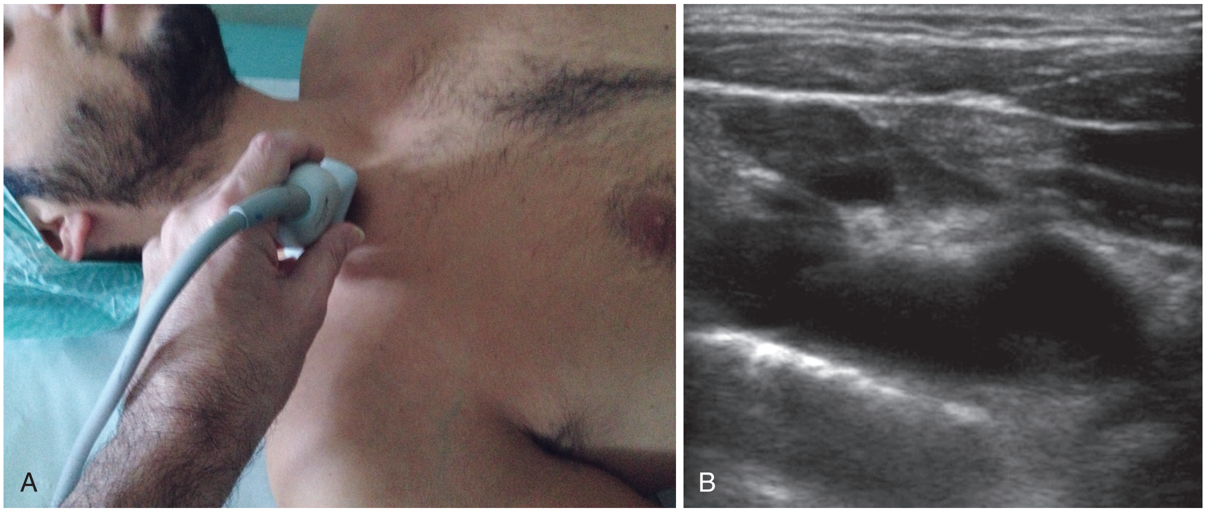

Figure 12-2 Second step. **A,** Probe sliding down to the sternum. **B,** Visualization of the lower tract of the internal jugular vein and the subclavian artery.

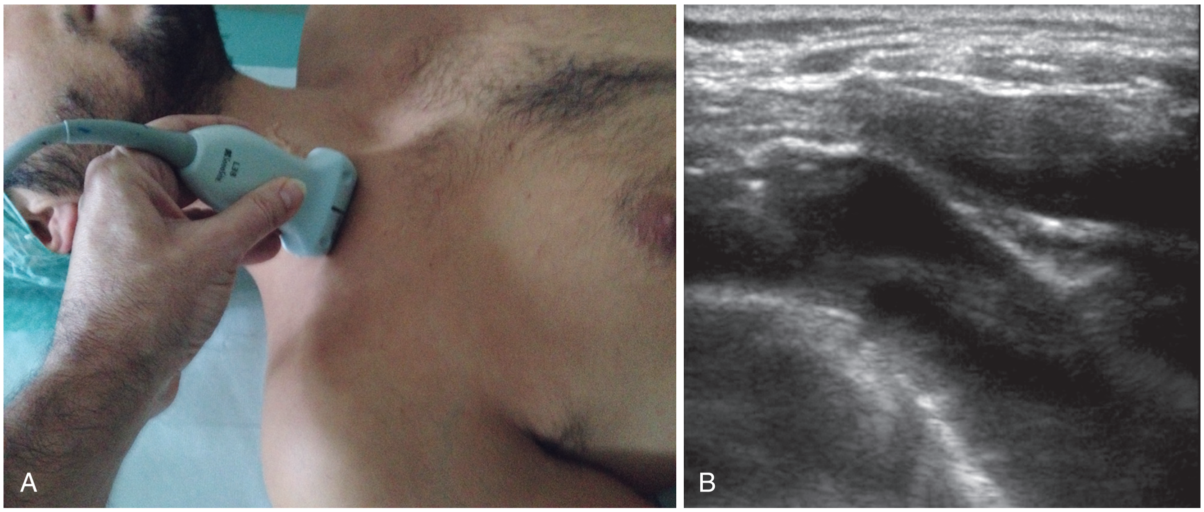

Figure 12-3 Third step. **A,** Tilting the probe to an almost frontal plane. **B,** Visualization of the brachiocephalic vein.

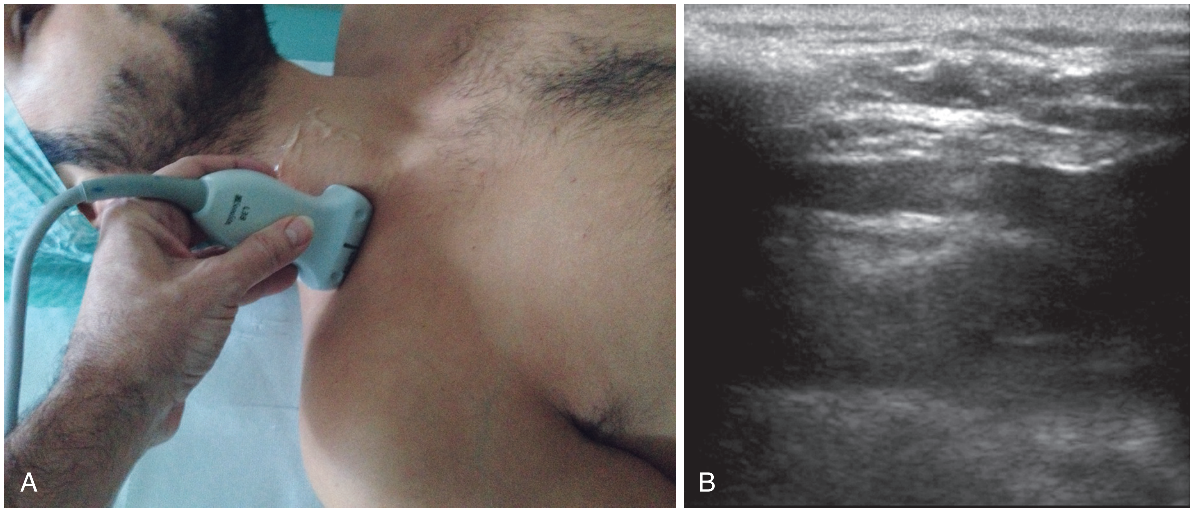

Figure 12-4 Fourth step. **A,** Sliding the probe laterally above the clavicle. **B,** Visualization of the subclavian vein and external jugular vein.

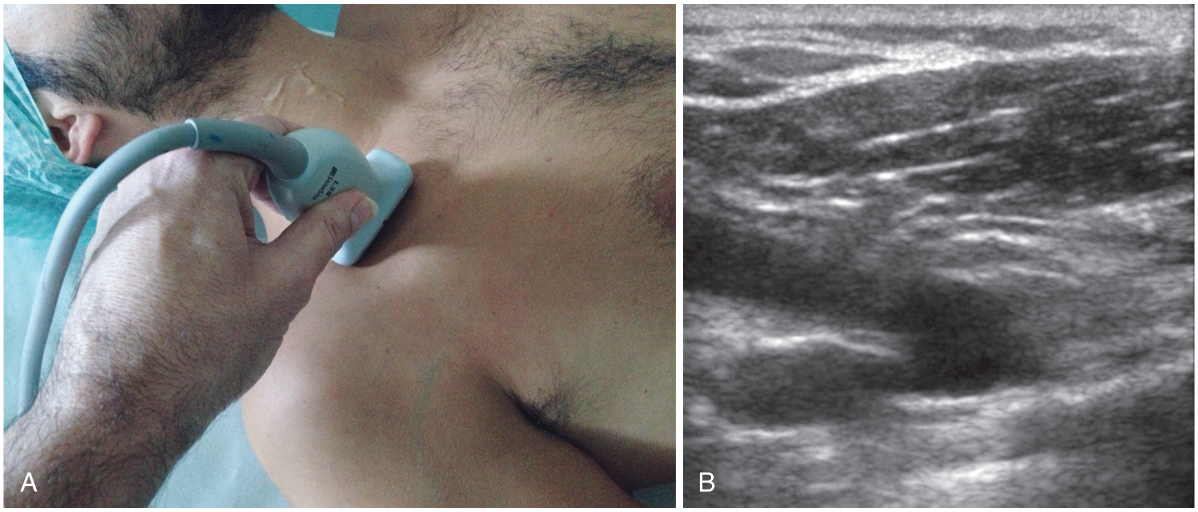

Figure 12-5 Fifth step. **A,** Probe below the lateral third of the clavicle. **B,** Visualization of the axillary vein, the axillary artery, and the cephalic vein.

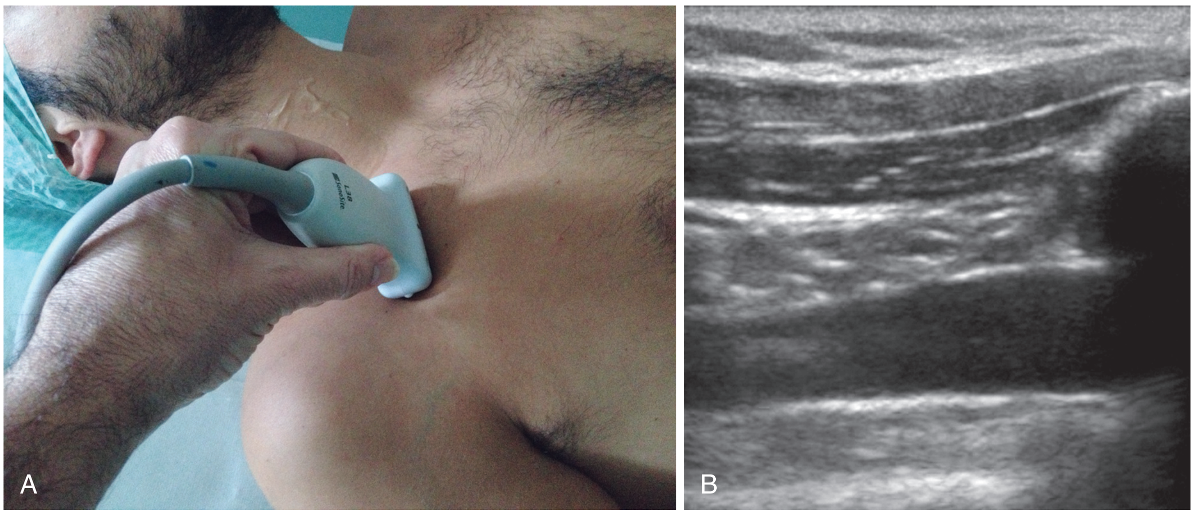

Figure 12-6 Sixth step. **A,** Rotating the probe below the clavicle. **B,** Visualization of the axillary vein in the long axis.

Criteria for Choosing the Appropriate Vein According to the Rapid Central Vein Vascular Assessment Protocol

The scan of the neck and supraclavicular and infraclavicular areas (which is performed rapidly by expert operators) just described enables the operator to make a rational decision about which vein to cannulate by applying the following criteria:

- Diameter of the vein. Usually, the largest vein in this area is the brachiocephalic vein. The other three major veins are variable in size. The cephalic vein and the external jugular vein are normally small in adults, although in children and neonates these veins appear to have a relatively larger size than the adjacent venous segments. As a general rule, veins that are too small are difficult to cannulate. When the diameter of the vein is less than three times the caliber of the catheter, the risk for thrombosis might be increased.
- Depth of the vein from the surface of the skin. The axillary vein, for example, may be easy or difficult to cannulate, depending on its depth.
- Possible venous collapse during breathing. This is typically an issue with the internal jugular and axillary veins.
- Compression of the vein by strong arterial pulsation (e.g., compression of the internal jugular vein by the carotid pulse).
- Proximity of the vein to structures that may increase the risk for mechanical complications (e.g., the pleura being constantly "adherent" to the inferior wall of the subclavian vein).
- Easy management of the exit site. For example, when dealing with nontunneled catheters, an exit site in the infraclavicular area is favored over one located in the midneck region because the former is associated with easier nursing care and decreased risk for dislocation and infection.

Pearls and Highlights

- The benefit of US is not limited to real-time US-guided venipuncture. US has an even more important role in allowing the operator to choose the safest and easiest approach for central venous access.
- Application of the RaCeVA protocol (which has been introduced by the Italian Group for Venous Access Devices) facilitates systematic scanning of all possible venous targets and enables the operator to make a rational decision about which vein to cannulate by applying specific criteria. Moreover, it is a teaching tool for the different US-guided approaches that may be used to cannulate a central vein.[6]
- The RaCeVA protocol can be performed rapidly (40 seconds for each side) by expert operators and is easy to teach and learn. It can be used in any patient (adults, children, and neonates) and represents a cost-effective solution that may increase patient safety.[7]

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13

Pediatric Ultrasound-Guided Vascular Access

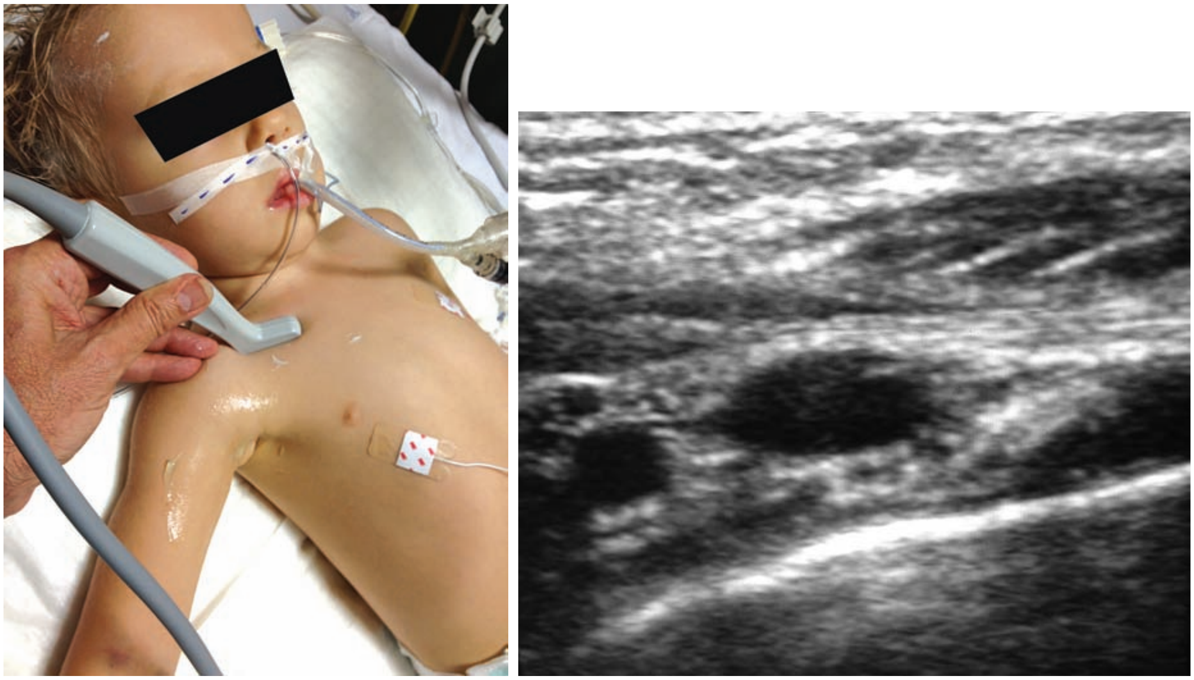
MAHMOUD ELBARBARY | MAURO PITTIRUTI | MASSIMO LAMPERTI

General Considerations and Ultrasound Evaluation of Peripheral and Central Veins in Pediatric Patients (Preprocedural Scanning)

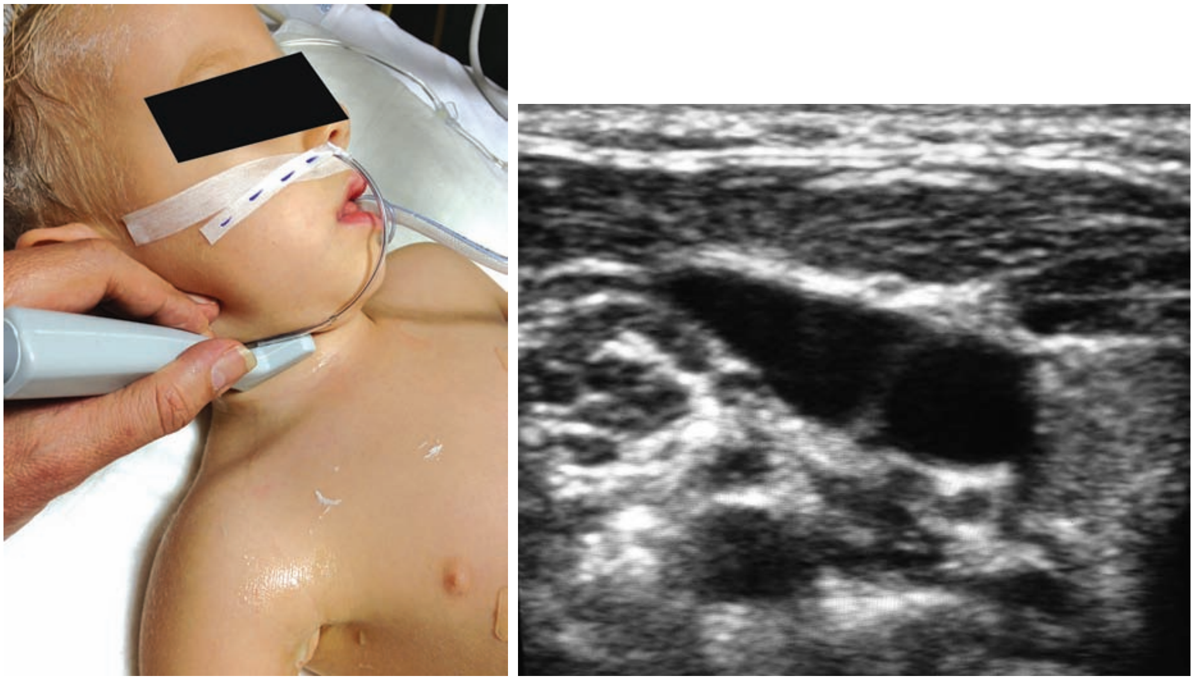
Ultrasound offers the advantage of preprocedural evaluation of all possible venipuncture sites as detailed in previous chapters. This is an essential feature of the ultrasound method when applied in the pediatric intensive care unit (PICU).[1-4] A thorough ultrasound examination allows the identification of vessels that may be difficult to puncture (e.g., small vessel diameter, especially in relation to the size of the catheter used; vessels collapsing during breathing; vessels in close proximity to arteries or the pleura; or the presence of thrombosis, hematomas, strictures, or anatomic variations). Ideally, the external diameter of the catheter should not exceed a third of the internal diameter of the vein (e.g., a 3-Fr catheter should be inserted into a vein with an internal diameter of 3 mm [≥9 Fr = 3 mm] as measured by ultrasound, a 4-Fr catheter would require a 4-mm vein, and so on).[3] In the PICU, preprocedural scanning may optimize the choice of catheter type (e.g., peripherally inserted central catheter [PICC] vs. a centrally inserted venous catheter) or puncture site (venous segments of the superior vs. the inferior vena cava network) and thus facilitate real-time ultrasound-guided catheterization of the vessel.

Implementation of the holistic approach (HOLA) to ultrasound scanning facilitates fast and detailed exploration of all venous circuits in pediatric patients[3] (see Chapters 1 and 47). Preprocedural scanning starts with examination of the *superficial and deep veins of both arms*. When central venous access is needed, the forearm veins can be ignored and the evaluation may start directly at the antecubital area, where the *cephalic vein* is generally visible on the radial border. The *brachial artery* is located medially, and one or more *brachial veins* are usually identified adjacent to the artery. Approximately halfway between the elbow and axilla the veins can be more carefully evaluated for possible cannulation. The most easily accessible vein at this level is the *basilic vein*, which lies superficial and medial to the brachial veins. As the basilic vein approaches the axillary area, it progressively merges with the brachial veins to form the *axillary vein*. *In the PICU, cannulation of the basilic vein is a preferable option because this vein is larger and located more distantly in relation to the artery and the median nerve than the brachial veins are.* The cephalic vein is usually a poor choice for cannulation because it is superficial, small, and tortuous.[5] However, all upper extremity veins should be evaluated sonographically in terms of (1) internal diameter, (2) depth (distance from the surface of the skin), (3) regularity of trajectory (a tortuous vein or a vessel with a sudden bend is a bad choice for cannulation), (4) proximity to other anatomic structures that may be accidentally punctured (e.g., brachial artery, median nerve), and (5) any preexistent abnormalities (e.g., thrombosis, anatomic variations). Two-dimensional, color Doppler, and compression ultrasonography techniques can all be applied to investigate the aforementioned parameters.[2] When the patient is hypovolemic or the veins are smaller than expected, the sonographic examination should be repeated after placement of a tourniquet (quite tightened and placed at the axilla). The minimum size of venous catheter available for ultrasound-guided insertion is 3 Fr. When no arm vein reaches a diameter of 3 mm, cannulation should not be attempted in this area. *Interestingly, neonates and small infants rarely have deep arm veins larger than 2 mm. Occasionally, some infants might have an axillary vein with a diameter of 3 mm or larger (at the level of the axilla).*

Preprocedural scanning continues by exploration of the *infraclavicular* area to visualize the *axillary vessels* in both the transverse and longitudinal planes (Figures 13-1 and 13-2). In this area the *cephalic vein* can be also evaluated at its union with the axillary vein. In children, both the axillary and cephalic veins can be cannulated quite easily at this level. In neonates and infants, these veins are usually too small for cannulation, although exceptions might occur, as mentioned in previous paragraphs. Scanning of the *supraclavicular* area starts at the middle of the neck by sweeping the transducer in a transverse plane over the *internal jugular vein* (IJV) and the common carotid artery (Figures 13-3 and 13-4). At this level the IJV is evaluated in terms of diameter, extent of collapse during breathing, position relative to the artery, presence of valves, and possible abnormalities (e.g., thrombosis, hypoplasia). By sweeping the transducer downstream (along the IJV trajectory) toward the lower neck region, the subclavian artery can be visualized as a major arterial segment that lies deeper than the IJV and in transverse alignment with the IJV trajectory. Next, the transducer reaches the suprasternal notch, where it can be tilted in a frontal orientation to scan the anterior mediastinum, at which point the *brachiocephalic vein* (almost longitudinal plane) is visualized (Figures 13-5 and 13-6). *In neonates, the brachiocephalic vein is often the easiest and safest vein to cannulate because of its large diameter.* By sweeping the transducer laterally (above the superior clavicular border) the *subclavian vein* (longitudinal plane) is visualized (Figures 13-7 and 13-8). In this area, especially in neonates and infants, the *deep tract of the external jugular vein* (longitudinal axis) becomes visible as a compressible structure that lies posterosuperior and parallel to the subclavian vein. Hence external jugular venipuncture may be easier and safer than subclavian venipuncture in view of the close proximity of the latter to the

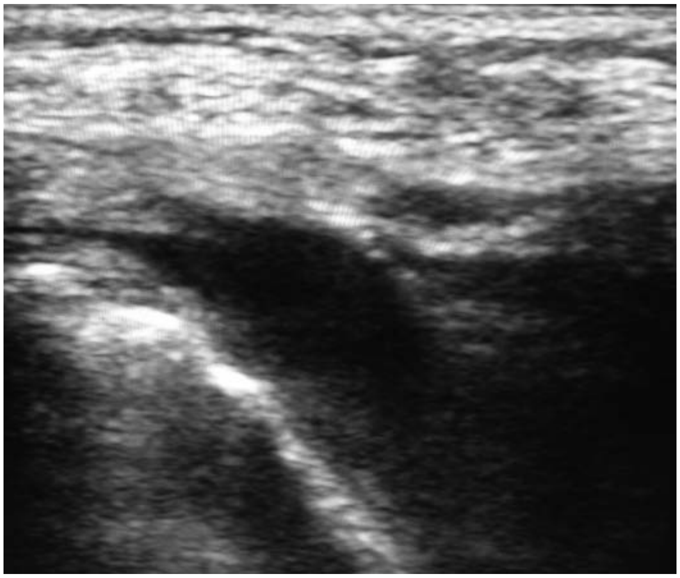


Figures 13-1 and 13-2 Visualization of the axillary vessels in the infraclavicular area.

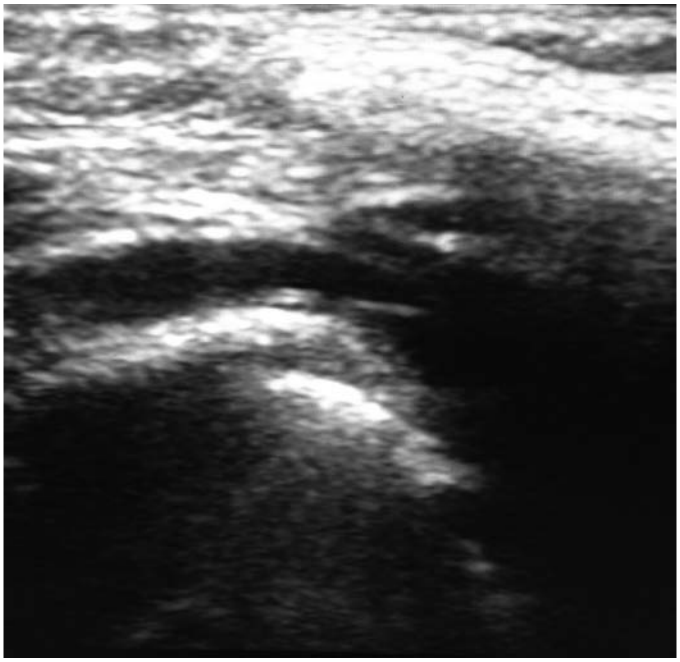


Figures 13-3 and 13-4 Visualization of the internal jugular vein and the carotid artery at the midneck region.

pleura. Once again, preprocedural scanning should evaluate all the aforementioned venous circuits (which are accessed in the neck area) in terms of diameter, distance from the surface of the skin, possible abnormalities, and other parameters as mentioned in previous paragraphs. Finally, the lower extremity is scanned accordingly only in the upper part of the thigh and the groin area. The most suitable veins for cannulation are usually the femoral and saphenous veins. Nevertheless, both veins can indeed be very small in underweight neonates and thus not suitable for cannulation. Ultrasound-based evaluation of all peripheral and central veins, which represent potential catheterization "targets," is performed bilaterally. In expert hands a complete ultrasound examination may require just 2 minutes. Next, the same strictly aseptic, real-time ultrasound-guided method used in adults is also applied in children to obtain central venous access; however, various technical differences do exist.



Figures 13-5 and 13-6 Visualization of the brachiocephalic vein in the anterior mediastinum.



Figures 13-7 and 13-8 Visualization of the subclavian vein above the clavicle.

Instrumentation and Kits Used for Ultrasound-Guided Catheterization in Neonates and Children

TRANSDUCER

Neonates and infants ideally require a high-frequency linear transducer (10 to 20 MHz), which will offer the best resolution at a depth of 2 cm from the surface of the skin. In older children, lower-frequency transducer with small footprints may occasionally be used (e.g., microconvex). Transducers bearing small footprints are preferred in pediatric patients. The shape of the transducer is also relevant (e.g., the neck of a neonate is particularly short and thus the supraclavicular venous segments are best explored with a "hockey stick"–shaped transducer).[1,3,5]

NEEDLE

In pediatric patients, both peripheral and central veins should be punctured only with 21-gauge echogenic needles (appropriately sharpened). Needle length is in the range of 3.5 to 6 cm, although the central veins of a neonate should preferably be punctured with the smallest available needles.[2]

GUIDEWIRE

J-shaped guidewires should not be used in pediatric patients for either peripheral or central cannulation.[6] The guidewire must have a straight floppy tip so that it is less atraumatic and thus easily guided in the lumen of the vessel. When 21-gauge needles are used, 0.018-inch guidewires are needed. Nitinol (nickel plus titanium) is currently regarded as the material of choice for small-gauge guidewires.[3] In neonates, use of separate 22- to 24-gauge cannulas and baby wires instead of the central line introducer kit is helpful (Figure 13-9).

MICROINTRODUCER AND DILATOR

All ultrasound-guided insertions of central venous catheters in pediatric patients should be performed according to the indirect or "modified" Seldinger technique. This implies the use of a microintroducer and dilator of appropriate length (5 to 7 cm) and stiffness to facilitate smooth transition of the introducer, dilator, and guidewire. The microintroducer and dilator are inserted over the guidewire; next, the dilator and guidewire are simultaneously removed and the catheter is threaded into the introducer (most introducers are removed by a peel-away mechanism).[3,5]

CATHETER

Polyurethane and silicone catheters are commonly used in neonates, infants, and children for both central and peripheral cannulation. Polyethylene catheters are too rigid and are therefore considered only for arterial cannulation. There are no differences between polyurethane and silicon catheters in terms of infection or thrombosis risk according to the current literature. Silicon catheters are more fragile than polyurethane catheters and prone to accidental rupture and dislocation. Power-injectable polyurethane is rapidly becoming the best option in terms of material since it is highly biocompatible, resistant to mechanical trauma, and less prone to obstruction.

Figure 13-9 Kit for neonatal venous access.

Moreover, it allows high-flow (2 to 5 mL/sec) and high-pressure (e.g., contrast agents) infusions. The most usual catheters inserted under ultrasound guidance in children are 3-Fr single-lumen, 4-Fr single- or double-lumen, and 5-Fr single- or double-lumen catheters. When small catheters are used, it is advisable to choose a power-injectable polyurethane catheter to maintain high infusion flow.[3-5]

Technique of Ultrasound-Guided Central Venous Catheterization in Neonates and Small Infants (Younger Than 3 Months)

The IJV is generally preferred over the subclavian vein as a cannulation site in neonates and small infants,[7-9] mainly because of the higher incidence of pneumothorax and subclavian artery puncture associated with the latter. In contrast, IJV cannulation has traditionally been linked with a low incidence of mechanical complications in pediatric patients. However, carotid artery puncture still represents a major complication, especially when an out-of-plane technique is used for ultrasound-guided IJV cannulation. No preferred puncture site for IJV cannulation exists because this is largely individualized.[3,5,10] However, the transducer is usually angled at 25 degrees, and a focal length of 15 mm from the skin surface should be used. Real-time ultrasound-guided IJV cannulation should be performed with a hands-free technique.[10] Needle guides are generally avoided, since the ideal entrance point for the needle is not certain because of the soft tissue variability observed in pediatric cases. The patient is usually placed in a slight Trendelenburg position (to increase the cross-sectional diameter of the vein), and the head is rotated 45 or 90 degrees to maintain the patient's neck and thorax in the same plane. Other possible central venous access targets are the brachiocephalic or subclavian veins.[11-13] Patients are placed in a slight Trendelenburg position with a rolled towel positioned under the shoulders. The head is rotated 30 degrees away from the venipuncture side, and the ipsilateral arm is gently pulled toward the knee. To puncture the brachiocephalic vein, the transducer is placed perpendicular to the skin on the neck's side, and cross-sectional images of the IJV are obtained. Next, the trajectory of the IJV is followed until the junction of the subclavian vein and IJV is reached. At this level, by sweeping the transducer medially and caudally, longitudinal images of the subclavian and brachiocephalic veins are obtained. When operators aim to puncture the subclavian vein, the transducer is usually positioned over the clavicle to visualize its distal segment, which is traveling in the infraclavicular area, while pertinent transducer adjustments (e.g., tilting) are performed to depict an optimal longitudinal image of the vein at this level. The brachiocephalic and subclavian veins are commonly used for placement of central venous catheters in small infants and neonates.[11-13]

Technique of Ultrasound-Guided Central Venous Catheterization in Infants and Small Children (3 Months to 6 Years Old)

The IJV remains the most frequently used access site for central venous catheterization in infants and children.[14,15]

No data suggest a higher rate of infection with IJV cannulation than with subclavian or brachiocephalic vein cannulation.[2] IJV cannulation is generally avoided in patients with a tracheostomy or anatomic neck abnormalities. In the latter cases, brachiocephalic or subclavian vein cannulation is preferred. Cannulation of the brachiocephalic vein allows better fixation of the central venous catheter in the upper part of the thorax, the catheter can easily be tunneled, and thus the risk for infectious complications is minimized. Less frequent cannulation sites for obtaining central venous access are the femoral[16] and axillary veins. The femoral vein is usually the preferred site for central venous cannulation in the emergency department because the coagulation state of the child is often unknown and a prompt fluid resuscitation may be necessary. The transducer is generally placed over the groin area and a transverse image of the femoral vein (and adjacent artery) is obtained; catheterization is commonly performed by the application of a fast-track, out-of-plane technique, especially when the child is hemodynamically unstable. As soon as the child is stabilized and transferred to the PICU, the central venous catheter should be removed from the femoral site and placed elsewhere to minimize the risk for infectious and mechanical complications.[17] The axillary vein is an alternative option for central venous cannulation despite the fact that it is oftentimes small with a variable diameter during the respiratory cycle in pediatric patients.[10] This may facilitate slow venous flow in a catheterized axillary vein, which could lead to the generation of thrombosis. Hence any central venous catheter in the axillary vein should be monitored regularly in the PICU. The catheter should be removed immediately in the event that a reduced vein-catheter diameter ratio of less than 70% is detected sonographically.

Technique of Ultrasound-Guided Insertion of Peripheral Lines in Pediatric Patients

In terms of position of the tip of the catheter, venous access devices (VADs) can be classified as central (the tip is positioned in proximity to the junction of the superior vena cava and right atrium) or peripheral (the tip is positioned anywhere else in the venous system).[3] Central VADs can be used for blood sampling, hemodynamic monitoring (e.g., central venous pressure, oxygen saturation of mixed venous blood), hemodialysis, and infusion of any kind of solution (including vesicant and phlebitogenic solutions). Peripheral VADs are not ideal for monitoring or blood sampling and can be used only for infusion of drugs with a pH of 5 to 9 and low osmolarity.

SHORT VENOUS ACCESS DEVICES

Short cannulas (2 to 5 cm long) are made of Teflon or polyurethane or silicon. These cannulas can be inserted under ultrasound guidance (by commonly using an out-of-plane technique) into any superficial vein of the upper or lower extremity. Usual cannulation sites are the basilic vein or the superficial tract of the external jugular vein. Short VADs should remain in place for a short period because of the risk for dislocation. Recently, longer cannulas (8 to 10 cm) have been introduced for insertion of peripheral lines via the Seldinger technique.

MIDLINE VENOUS ACCESS DEVICES

Midline cannulas (10 to 25 cm long) are commonly inserted into arm veins. These cannulas are not long enough to be considered as central venous catheters. When cannulating small infants, midline VADs may be considered as central lines because their tip could be well positioned adjacent to the cavoatrial junction. Midline cannulas are made of polyurethane or silicon and are inserted via the modified Seldinger technique.

INFERIOR VENA CAVA ACCESS DEVICES

When the tip of a peripherally inserted catheter is positioned in the inferior vena cava (preferably below the confluence of the renal veins), the catheter can be used as a central line for drug infusion; however, it obviously cannot be used for hemodynamic monitoring purposes.[10] Inferior vena cava VADs are placed through the femoral or saphenous veins under ultrasound guidance according to the direct or indirect Seldinger technique. These catheters are made of polyurethane or silicon and have one or two lumens and appropriate length.

Peripherally Inserted Central Venous Catheters in Children

PICCs provide a relatively long-term vascular access option in pediatric patients. PICCs are VADs of adequate length (their tip is positioned adjacent to the cavoatrial junction, although their entry sites are located peripherally) that they can be used for the administration of total parenteral nutrition, prolonged intravenous antibiotic treatment, or chemotherapy.[4,10] Home treatment of pediatric patients is facilitated since insertion of a PICC carries the benefit of lower infection rates and more convenient entry sites than is the case with other cannulas of shorter length inserted through arm veins. When placing a PICC, the operator can use a peel-away sheath, particularly with a small single-lumen catheter (e.g., 2 Fr) at the entry site. Implementation of the modified Seldinger technique is more appropriate with larger catheters. Ultrasound is used to guide access to peripheral veins at the site of entry of the PICC. The latter can be advanced under fluoroscopic or ultrasound guidance, whereas the position of the tip of the catheter can be confirmed sonographically by injection of contrast agents or agitated saline.

Pearls and Highlights

- Select a high-frequency transducer with a small footprint when attempting to cannulate a pediatric patient.
- During preprocedural scanning, two-dimensional, color Doppler, and compression ultrasound techniques are usually applied to identify a patent target vein and adjacent structures (e.g., artery, nerve) in the region of interest.
- Preprocedural scanning according to the HOLA ultrasound concept facilitates detailed and fast exploration of all venous circuits.
- The same strictly aseptic, real-time ultrasound-guided method used in adults is applied in children to obtain central venous access. However, various technical differences do exist.
- Power-injectable polyurethane catheters are rapidly becoming the best option in terms of material because of

their high biocompatibility and resistance to mechanical trauma. These catheters are less prone to obstruction and allow high-flow (2 to 5 mL/sec) and high-pressure (e.g., contrast agents) infusions.

- Neonates and small infants rarely have deep arm veins larger than 2 mm.
- The brachiocephalic and subclavian veins are commonly used for placement of central venous catheters in small infants and neonates.
- The IJV remains the most frequently used access site for central venous catheterization in infants and children.
- The femoral vein is generally the preferred site for central venous cannulation in the emergency department because the coagulation state of the child is often unknown and prompt fluid resuscitation may be necessary
- In pediatric patients, short, midline, and inferior vena cava VADs are usually considered as peripheral lines, whereas PICCs provide a relatively long-term vascular access option.

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14

Ultrasound-Guided Peripheral Intravenous Access

SHEA C. GREGG | CHARLES A. ADAMS

Ultrasound guidance to obtain vascular access has become increasingly more popular over the past decade. Advances in ultrasound technology have enhanced its ability to detect and interrogate smaller vascular structures for cannulation purposes. Given the potential complications that can develop when accessing central veins, practitioners have turned to ultrasound-guided peripheral access. Although no invasive procedure is without risks, the relative array of complications potentially produced by peripheral, non–centrally extending venous lines tend to be significantly less severe than those from central venous access.[1] This chapter outlines the indications, risks, and benefits of ultrasound-guided, noncentral peripheral intravenous (IV) access.

The standard limitations described with landmark-based IV catheter placement can be overcome given the advances in visualization brought to the bedside with ultrasound. With regard to operators, emergency physicians, anesthesiologists, nursing staff, intensivists, and their respective trainees have reported peripheral IV cannulation success rates of higher than 85%.[2-7] With regard to risk for infection, Maki et al reported that peripheral IV catheters in general maintain lower infection rates than do any other forms of IV access.[1] Additionally, when complications did occur, they tended to not be as morbid as those associated with central venous catheters.

Despite such a successful track record of placement and safety, limited data exist on the role of ultrasound-guided peripheral IV access in patients in the intensive care unit (ICU). One of the reasons for this is that many medications should not be administered through peripheral access given their potentially damaging effects on veins (e.g., certain vasopressors, total parenteral nutrition [TPN]). In another report, medications such as vancomycin or phenytoin were suggested to be associated with increased rates of thrombophlebitis.[8] Aside from these relative contraindications, a question remains: in patients who do not need central venous access, are ultrasound-guided peripheral IV techniques reliable enough to allow increased avoidance or removal of central lines in the critically ill? Gregg et al were able to achieve ultrasound-guided peripheral venous access in 99% of patients who failed standard landmark attempts at placement.[7] Among the diverse group of trauma, postsurgical, and cardiac intensive care patients, 34 central lines were avoided and 40 were removed as a result of adequate peripheral access. In a small randomized controlled trial, Kerforne et al also demonstrated increased success rates of ultrasound-guided peripheral IV access over the landmark technique in critical care patients who were deemed to have difficult access.[9] Despite reports of relatively low complication rates with ultrasound-guided peripheral IV access in the ICU,[7] no trials have directly compared rates of infection or thrombophlebitis with the use of ultrasound-guided versus landmark techniques.

Different techniques for placing peripheral IV catheters have been described. One-person operation of the ultrasound transducer while placing the IV line has the benefit of allowing the entire procedure to be performed by a single party. However, applying appropriate skin tension when limited to a single hand to perform the insertion has the potential to be awkward. This has led to reports of a two-person technique that involves an ultrasound operator and an IV operator working together throughout the placement procedure. Chinnock et al showed that the number of operators placing the IV line was not predictive of successful placement,[10] and a variety of other studies describing either a one- or two-person technique have shown successful placement more than 85% of the time.[2-7] Another variation in equipment described includes the use of guidewire assistance. Guidewire-assisted vascular access devices have traditionally been used when attempting arterial access; however, given their ease of use, successful single-operator cannulation rates higher than 95% can be achieved.[7-11] The limitation of catheters with wires that are preloaded onto the device is that the IV lines tend to come in limited diameters. To overcome this shortcoming, Sandhu and Sidhu described a technique that allows upsizing an access catheter to a larger-bore one by means of exchanging the device over a free wire.[4] It is this author's preference to use wire-assisted devices for single-operator placement of peripheral IV lines when larger-bore access is not necessary.

In summary, ultrasound-guided peripheral IV lines are an attractive access option since they have been shown to have low procedure-related morbidity while avoiding the possible complications associated with central venous catheters. Future challenges for this approach to IV access include the widespread availability of ultrasound and standardized education of all levels of practitioner.

Pearls and Pitfalls

PEARLS

Anatomy

- Any of the named veins in the arm can be candidates for access. However, the *radial vein* in the midforearm region tends to be the best access point. It is usually deep enough that it is not routinely accessed because of limited visualization with landmark techniques, yet it is easily detected with ultrasound.

Technical tips

- Get comfortable. Performing the procedure while sitting down is preferable.
- Have multiple catheters available in the event of unsuccessful cannulation.

IMAGING CASE

The Line "Holiday"

A 40-year-old man underwent total pancreatectomy for chronic pancreatitis. His postoperative complications included hemorrhagic shock, multisystem organ failure, and an enterocutaneous fistula. The patient eventually recovered, successfully completed rehabilitation, and was being maintained on outpatient TPN. He was seen multiple times with recurrent bacteremia as a result of peripherally inserted central venous catheter infections. The intravenous nurse was unable to gain access through landmark techniques, and a new central line was suggested. Given the patient's ongoing fevers and chills and evidence of persistent bacteremia, ultrasound was used to assess the patency of other peripheral veins. Multiple veins were visualized with tourniquet placement, and two peripheral IV lines were placed for administration of antibiotic. The central line was removed and the patient's bacteremia cleared. When readmitted to the hospital after some time for line infections, additional IV lines were placed without complication. The patient's enterocutaneous fistula was eventually repaired surgically 1.5 years following his first operation, and TPN was stopped.

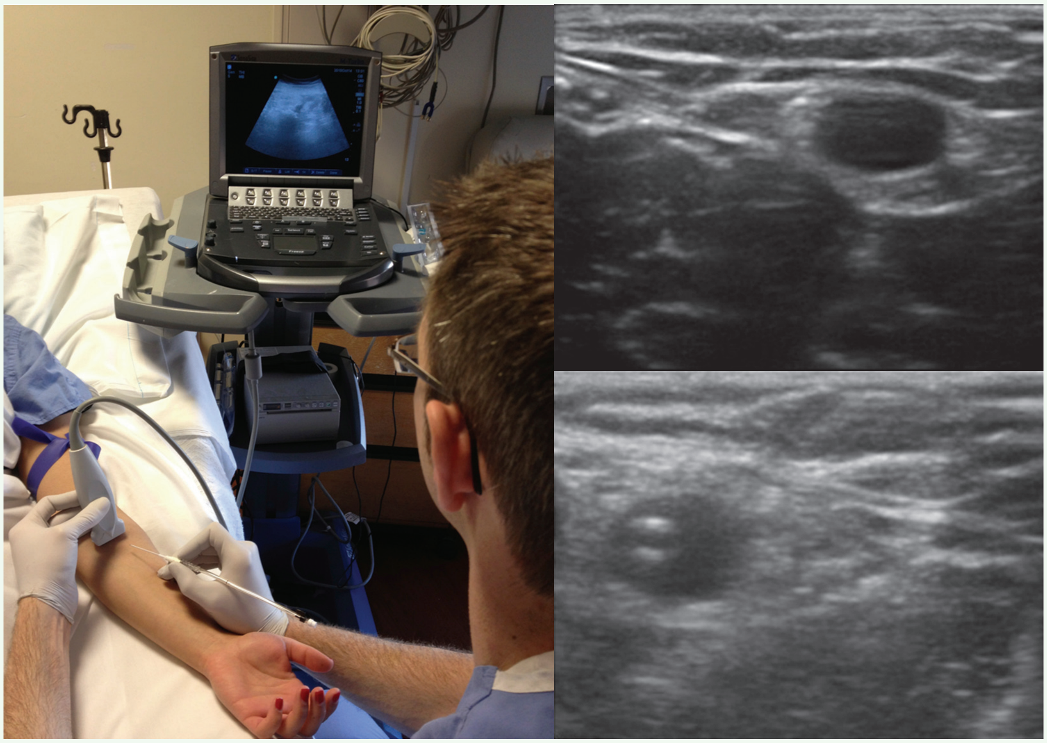

Figure 14-1 *Left panel*, Demonstration of an ultrasound-guided intravenous technique involving the use of a wire-assisted catheter. *Right panel*, Compressible basilic vein (*top*) and a basilic vein with an intravenous catheter within its lumen (*bottom*).

- Tape the forearm to the bed in a supinated position.
- Place a tourniquet above the biceps to occlude superficial blood return.
- Have all dressing supplies ready to apply.
- Prepare the skin with chlorhexidine—use it as ultrasound medium. A clear plastic adhesive dressing may be applied to the transducer to protect it.
- Ensure that the vessel collapses—if not, be concerned for thrombosis or that the vessel may be an artery. IV catheters may be placed above areas with short segments of thrombosis of the superficial veins. Tributaries may keep these proximal areas patent.
- Use high-frequency transducers with the depth set to around 2 cm to achieve the best resolution of superficial veins.
- Apply an elastic tourniquet to augment the vein's diameter.
- Use gentle pressure on the skin when scanning to avoid inadvertent collapse or nonvisualization of veins, or both.
- Consider using a catheter with a guidewire to assist in the placement process. If unavailable, a standard IV catheter can be used.
- Use a catheter of appropriate length to allow proper seating within the vein. Catheters that are minimally 1.75 inches in length tend to be long enough to reach the deeper veins of the forearm.
- Once the vein is accessed and the wire has passed into the vein, gently rotate the catheter over the wire while it is being advanced into the vein. It should slide smoothly over the wire and not meet any resistance.
- Confirm placement by attaching a saline-filled syringe with extension tubing to the catheter and flushing. Turbulence can be seen within the vein on ultrasound during flushing.
- Suturing the IV line in place is not necessary; the IV line may be taped or a clear plastic dressing may be applied.
- Maintain patency with IV fluids running at a low rate.

PITFALLS

- Veins smaller than 2 mm in diameter tend to be difficult to cannulate or detect by ultrasound, and long-term patency may be limited.
- Cannulating the venae comitantes of an artery is not usually successful given their tortuosity. Try to cannulate veins away from the arteries.
- Avoid pulsatile vessels.
- The deeper the basilic vein runs, the longer the catheter will be needed to span the distance of the subcutaneous tissue. Try to access it closer to the elbow to ensure enough intravessel catheter length.
- Veins on the dorsal surface of the hand tend to be difficult to visualize with ultrasound because of limited subcutaneous tissue in this area. Consider the landmark technique when attempting to access these veins.

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15

Ultrasound-Guided Placement of Peripherally Inserted Central Venous Catheters

GIANCARLO SCOPPETTUOLO | MAURO PITTIRUTI

Overview

The concept of achieving central venous access by cannulation of a peripheral arm vein is old, although only in the last decade has the peripherally inserted central catheter (PICC) emerged as a safe and cost-effective option. In the last century, PICCs were positioned by catheterization of visible or palpable superficial veins in the antecubital area (mostly the cephalic or the antecubital vein) or less often at the forearm or the upper part of the arm. Obviously, this "blind" cannulation could not provide any information about the actual diameter or trajectory of the vein. Hence, the rate of insertion failure, malpositioning, and catheter-related venous thrombosis was exceedingly high. Since the exit site of PICCs was usually located in the antecubital area, it was vulnerable to infections (because of extraluminal contamination) and local thrombophlebitis (because of catheter instability). Moreover, this exit site was rather uncomfortable for the patient and thus resulted in poor compliance with the device.

At the beginning of this century, the widespread use of ultrasound for guiding vascular access has dramatically changed the technique of insertion of PICCs.[1-6] Currently, PICCs are inserted by ultrasound-guided puncture and cannulation of the deep upper arm veins (most often the basilic or brachial vein) via the modified Seldinger technique (venipuncture with a small-gauge needle, insertion of a thin guidewire through the needle, removal of the needle, insertion of a microintroducer-dilator over the guidewire, removal of the wire and dilator, insertion of the catheter through the introducer). This technique facilitates catheterization of large-bore veins of known diameter and trajectory while allowing positioning of the exit site in the upper part of the arm (halfway between the elbow and the axilla). As a final result, the rate of insertion failure is minimal, insertion-related complications are almost negligible, the exit site is handled easily by patients and nursing stuff (easy dressing and securement, good patient comfort), and the rate of late complications (infection, catheter-related venous thrombosis, dislocation) is low.

In other words, the 21st century ultrasound-guided PICC is a different venous access device than the 20th century PICC in terms of indications, insertion technique, expected rate of failure, and insertion-related complications, as well as the incidence of late complications.

Ultrasound Anatomy of the Arm Veins

PICCs are usually inserted in the deep veins of the arm, which allows an exit site in the middle third of the upper part of the arm. Sometimes the only veins available for cannulation (in terms of diameter) are quite close to the axilla. In such cases the catheter can be tunneled downward to obtain a more favorable exit site. The deep veins of the forearm should not be considered for PICC insertion; however, these veins can be used for ultrasound-guided insertion of peripheral lines. The most frequently accessed vein is the *basilic vein*, which runs in the groove between the humerus and the biceps muscle. This vein usually has a large diameter (4 to 6 mm) and is located rather superficially (10 to 25 mm from the surface of the skin) and relatively distant from arteries and major nerves. The *brachial veins* are an alternative option. Their number may range between two and four, and they generally travel close to the brachial artery and the median nerve (which is typically located adjacent to the artery; see Chapter 51). The brachial veins are smaller (with diameters ranging from 1 to 4 mm) and usually travel medially and deeper than the basilic vein; however, *anatomic variations are numerous.* When visualized sonographically in a transverse plane, the artery and the two adjacent basilic veins appear to have a "Mickey Mouse"–like configuration. Because of their diameter and proximity to structures such as the brachial artery and the median nerve, the basilic veins are not a primary option for catheterization.

As the basilic vein travels upstream, it appears to be located progressively closer to the neurovascular brachial bundle, whereas close to the axilla it merges with the brachial veins to form the axillary vein. If the other deep arm veins are too small for cannulation (e.g., children, hypovolemic or malnourished adults), the *axillary vein* can be considered as an alternative option. However, catheterization of the axillary vein often implies tunneling the catheter to place the exit site far away from the puncture site. In obese (especially morbidly obese) patients, the basilic vein and the brachial veins may be located too deep (>30 mm from the skin surface). In such cases, PICCs can be inserted by cannulating the *cephalic vein*. The latter usually courses along the lateral side of the upper part of the arm quite superficially (above the muscular fascia) and displays a nonlinear trajectory, and it merges with the axillary vein in the infraclavicular area (10 to 20 mm before the transition of the axillary vein to the subclavian vein). Generally, this vein is not appropriate for PICC insertion, but in obese patients it is a relatively deep and "stable" vein that is easily accessible.

Sonographic visualization of all arm veins in a transverse plane is relatively easy and facilitates a "panoramic" view of all adjacent anatomic structures (e.g., nerves, arteries, muscles) in a region of interest (ROI). The importance of this "panoramic" view is analyzed elsewhere according to the holistic approach ultrasound concept (Chapters 1 and 51). When transducer compression is applied to an ROI, a vessel that pulsates is an artery, whereas a vessel that does not pulsate and is noncollapsible is most likely a thrombosed vein (Chapter 9).

Ultrasound-guided puncture is most commonly performed via an "out-of-plane" approach (the needle trajectory does not lie in the transducer plane). Even though transducers can be equipped with a needle holder to facilitate puncture, the "freehand" technique is usually favored by many experts because it is more versatile and effective. However, needle holders may be useful as a teaching tool.

Since PICCs are "central" lines, their tip should be positioned adjacent to the cavoatrial junction.[7] A gross preprocedural evaluation of the length of catheter that ensures correct tip positioning can be performed by empiric methods (distance from the exit site to the midclavicular point plus the distance from the midclavicular point to the third intercostal space on the right parasternal line). Appropriate verification of tip position should be obtained intraprocedurally (fluoroscopy or intracavitary electrocardiography) or postprocedurally (chest radiography or echocardiography).

The Safe Insertion Protocol for Peripherally Inserted Central Catheters

Safe PICC insertion depends on many factors: successful puncture and cannulation of the vein via a real-time ultrasound-guided aseptic technique, appropriate positioning of the tip of the catheter, and securement of the catheter at the exit site. Therefore the key to uneventful insertion and successful clinical performance of the device is the adoption of evidence-based, cost-effective strategies to minimize the incidence of complications. The GAVeCeLT (Italian Group for Central Venous Access) has developed a set of recommendations that summarize the most important steps for insertion of PICCs based on current international guidelines.[7-13] This set of recommendations (the safe insertion of PICCs [SIP] protocol) includes eight steps:

1. *Hand washing, aseptic technique, and maximal barrier protection.* According to the international guidelines,[12,13] "maximal barrier protection" includes sterile gloves, nonsterile mask, nonsterile hat, sterile gown, and a vast body drape over the patient. Chlorhexidine 2% in an alcohol solution (70% isopropyl alcohol) should be preferred for skin preparation before PICC insertion.
2. *Bilateral ultrasound scans of all neck and arm veins.* Preprocedural bilateral scans of the deepest arm veins (basilic, brachial; Figure 15-1) and neck veins (axillary, subclavian, internal jugular, brachiocephalic; Figure 15-2) should be performed. Such scanning is essential to rule out major vascular and other pertinent anatomic abnormalities or variations and preexisting venous thrombosis and thus facilitate a rational choice of the most appropriate vein for catheterization. The deep arm veins should be evaluated with and without a tourniquet.
3. *Choice of the appropriate vein at the mid to upper part of the arm.* It is recommended that a vein be chosen that is

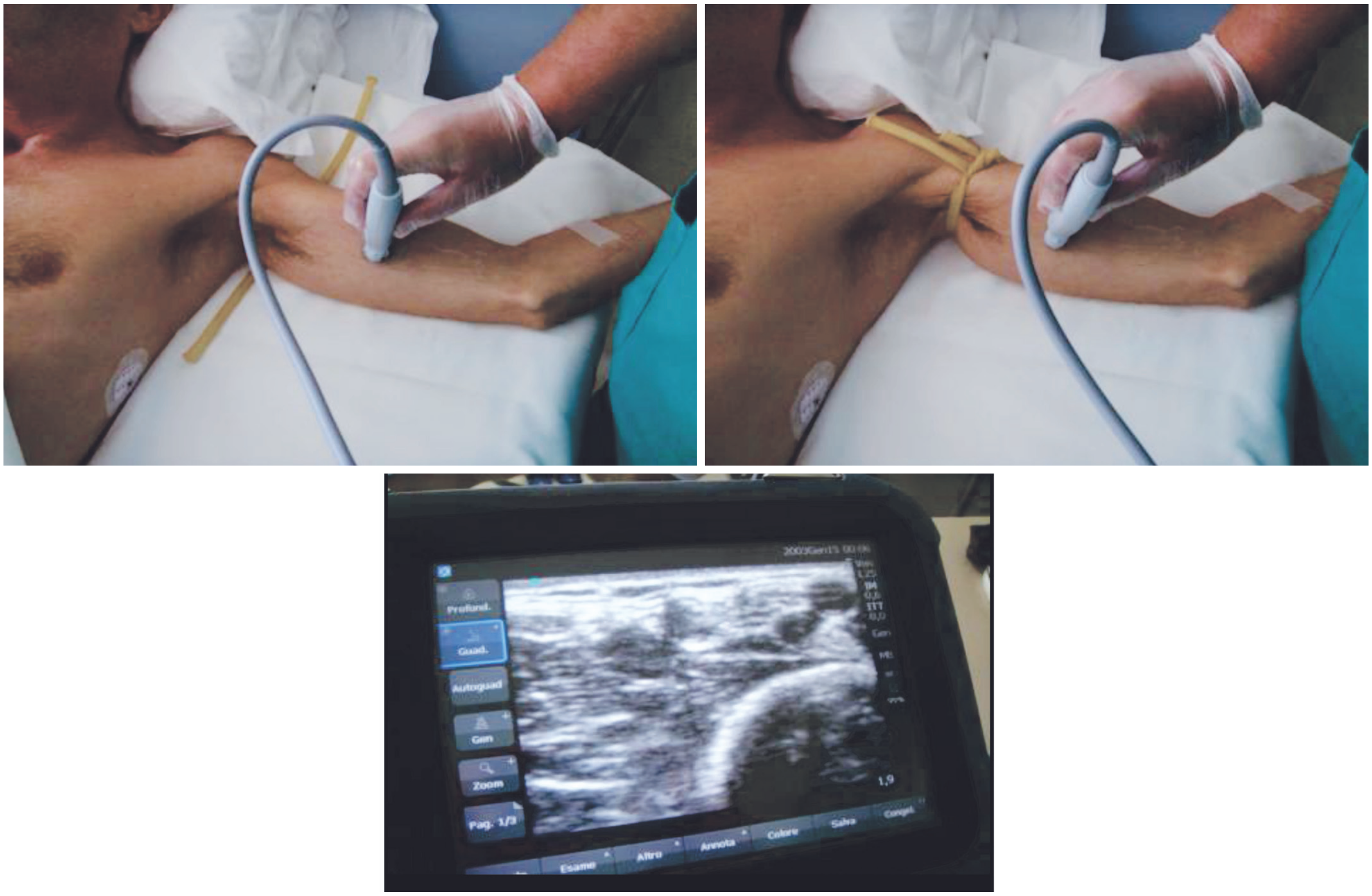

Figure 15-1 Ultrasound scan of the arm veins, with and without a tourniquet.

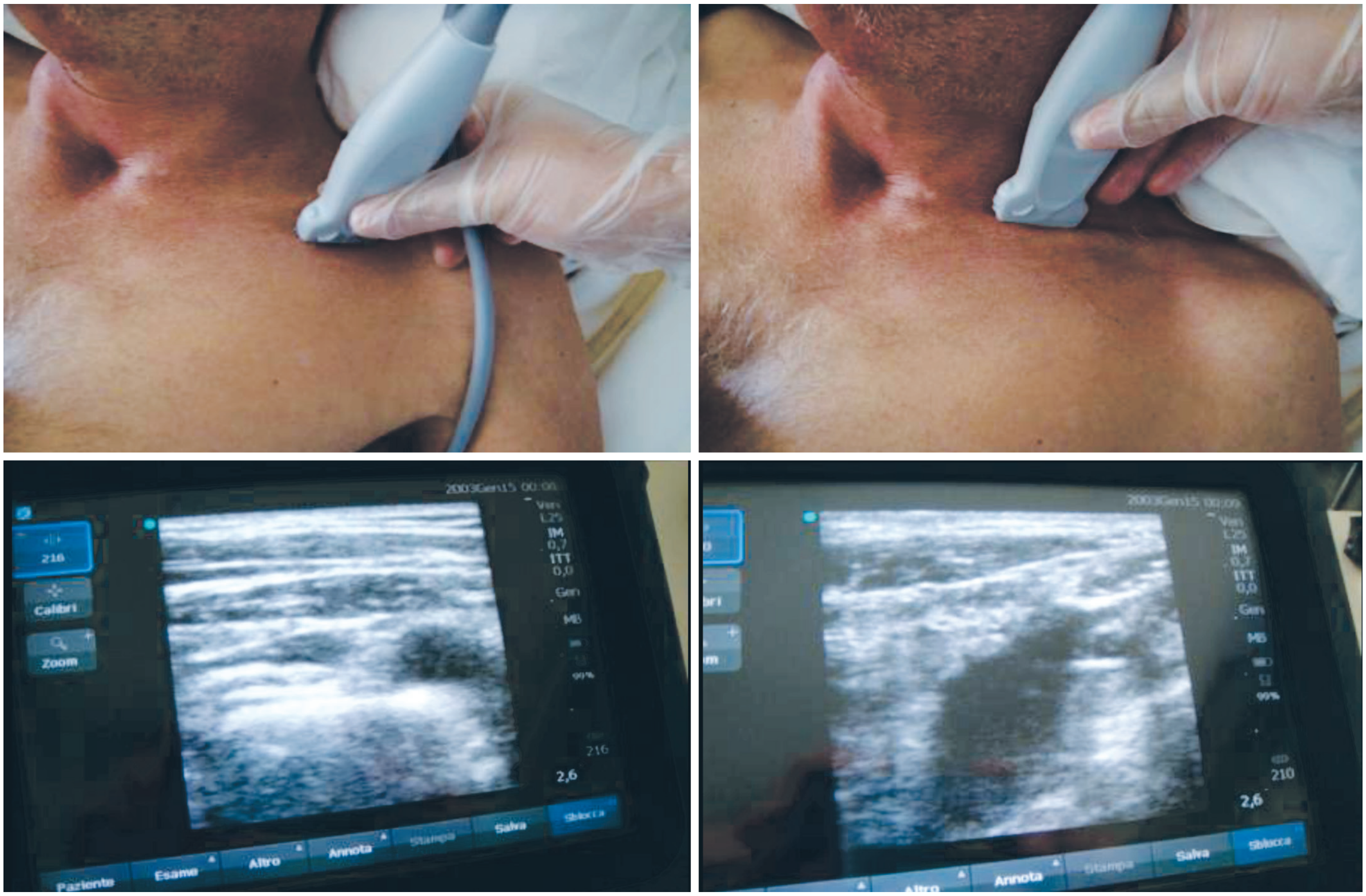

Figure 15-2 Ultrasound scan of the axillary and brachiocephalic veins.

located not deeper than 30 mm from the surface of the skin. To minimize the risk for venous thrombosis, catheters should be inserted in veins whose diameter is at least three times larger than the catheter's size. Thus vein diameter (in millimeters) should be as large or larger than the external diameter of the catheter in French (Fr) units. For example, a 3-Fr catheter should be placed in a vein 3 mm or larger (equals 9 Fr), a 4-Fr catheter should be placed in a vein 4 mm or larger (equals 12 Fr), and so on.

4. *Clear identification of the median nerve and brachial artery.* The most effective method to avoid accidental nerve injury is direct visualization of the nerve before and during venipuncture. Although the most important nerve in the arm is the median nerve (adjacent to the brachial artery), the lateral cutaneous nerve of the arm (adjacent to the basilic vein) should be also evaluated. The most effective method to avoid accidental arterial puncture is to identify and visualize the brachial artery before and during any venipuncture.
5. *Ultrasound-guided venipuncture.* Real-time ultrasound-guided venipuncture of a deep vein (basilic or brachial) is the recommended choice for PICC insertion (Figures 15-3 and 15-4).[10] A microintroducer kit is mandatory, preferably with a small-gauge (21-gauge) echogenic needle and a 0.018-inch soft straight-tipped nitinol guidewire. With the possible exception of very "high" punctures close to the axilla, a tourniquet should be used to facilitate the venipuncture.
6. *Ultrasound scan of the internal jugular vein during introduction of the PICC.* While inserting the catheter into the introducer, the ipsilateral internal jugular vein should be compressed by the ultrasound probe to facilitate passage of the catheter from the subclavian vein into the brachiocephalic vein. After the maneuver, evidence of absence of the catheter in the internal jugular veins on both sides should be obtained by ultrasonography (Figure 15-5).
7. *Intracavitary electrocardiographic method for assessing tip position* (Figure 15-6). The intracavitary electrocardiographic method is an inexpensive, effective, simple, and safe methodology for real-time intraprocedural assessment of catheter tip positioning.[14-16] Correct tip positioning (in the proximity of the cavoatrial junction) reduces the risk for catheter malfunction, fibrin sleeves, and catheter-related "central" venous thrombosis. This intraprocedural method aids in evading the cost and risk associated with PICC repositioning. Fluoroscopy, though intraprocedural, is not cost-effective, and a chest radiograph is inevitably a postprocedural method.
8. *Securing the PICC with a sutureless device.* The PICC should be secured at the exit site with a sutureless device (Figure 15-7) to decrease the risk for infection, dislocation, and local thrombosis.

Consistent and complete adoption of the SIP protocol reduces the incidence rate of mechanical complications such as insertion failure, repeated punctures, nerve injury, and arterial

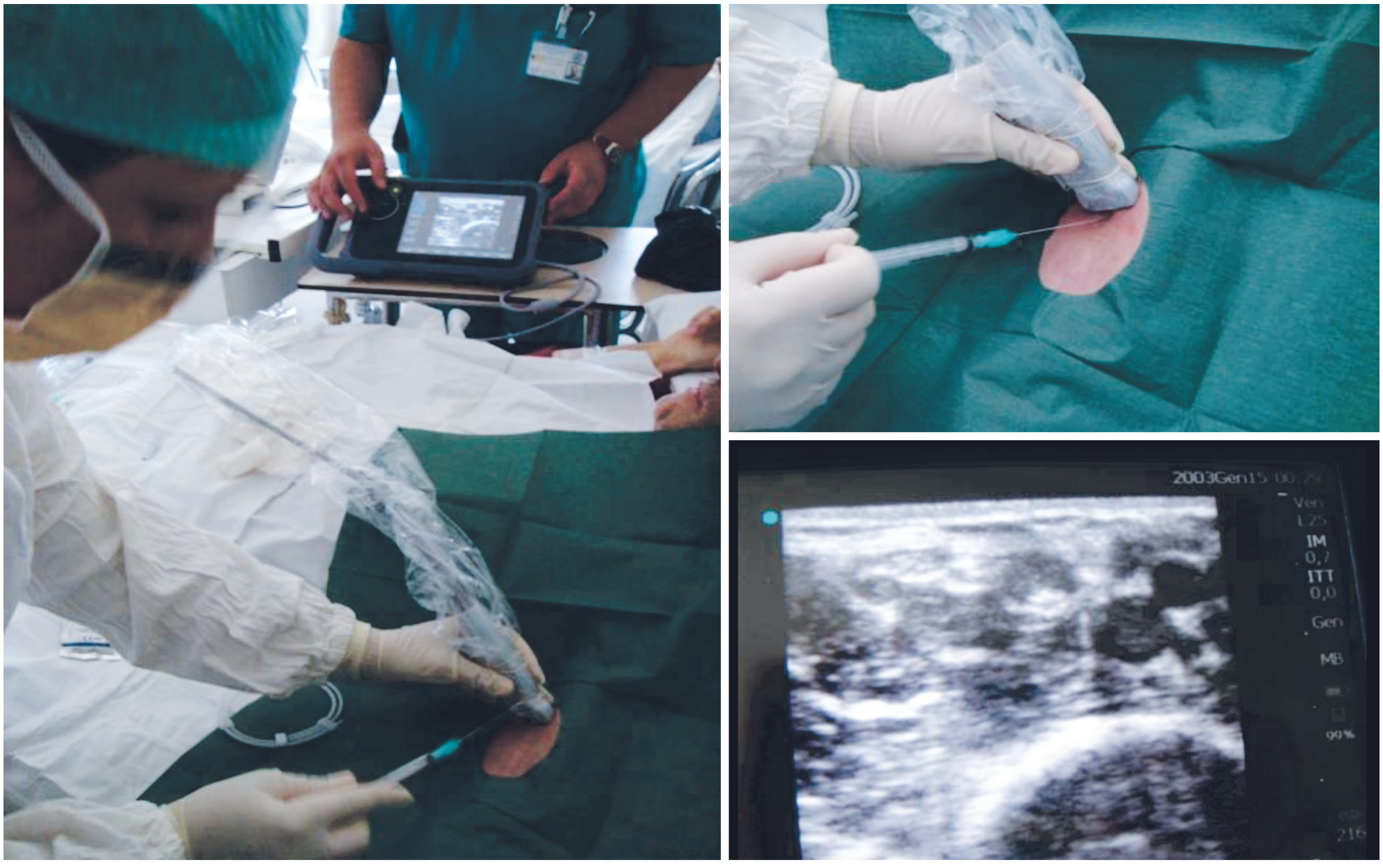

Figure 15-3 Real-time ultrasound-guided puncture of the basilic vein.

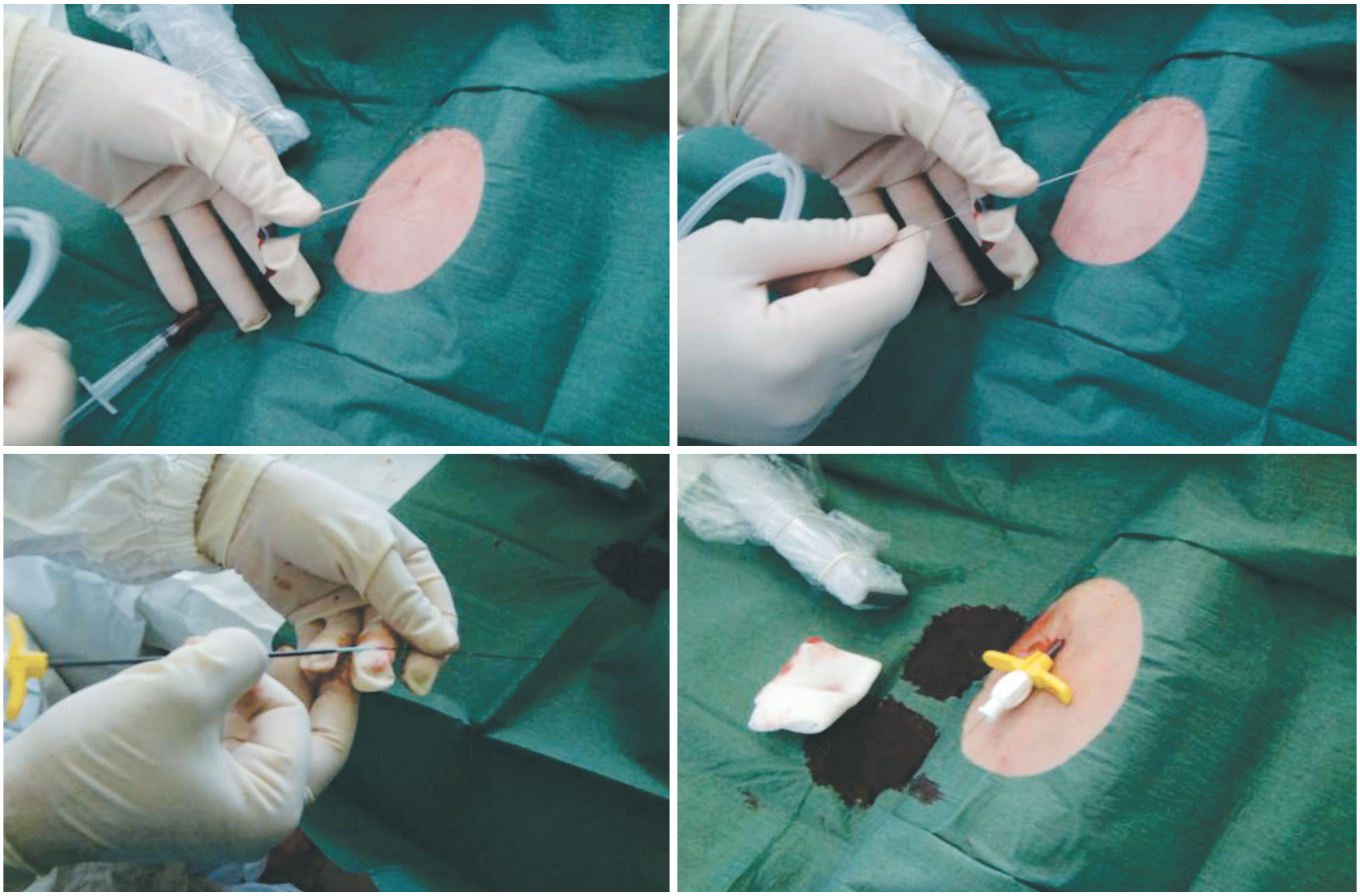

Figure 15-4 Modified Seldinger technique.

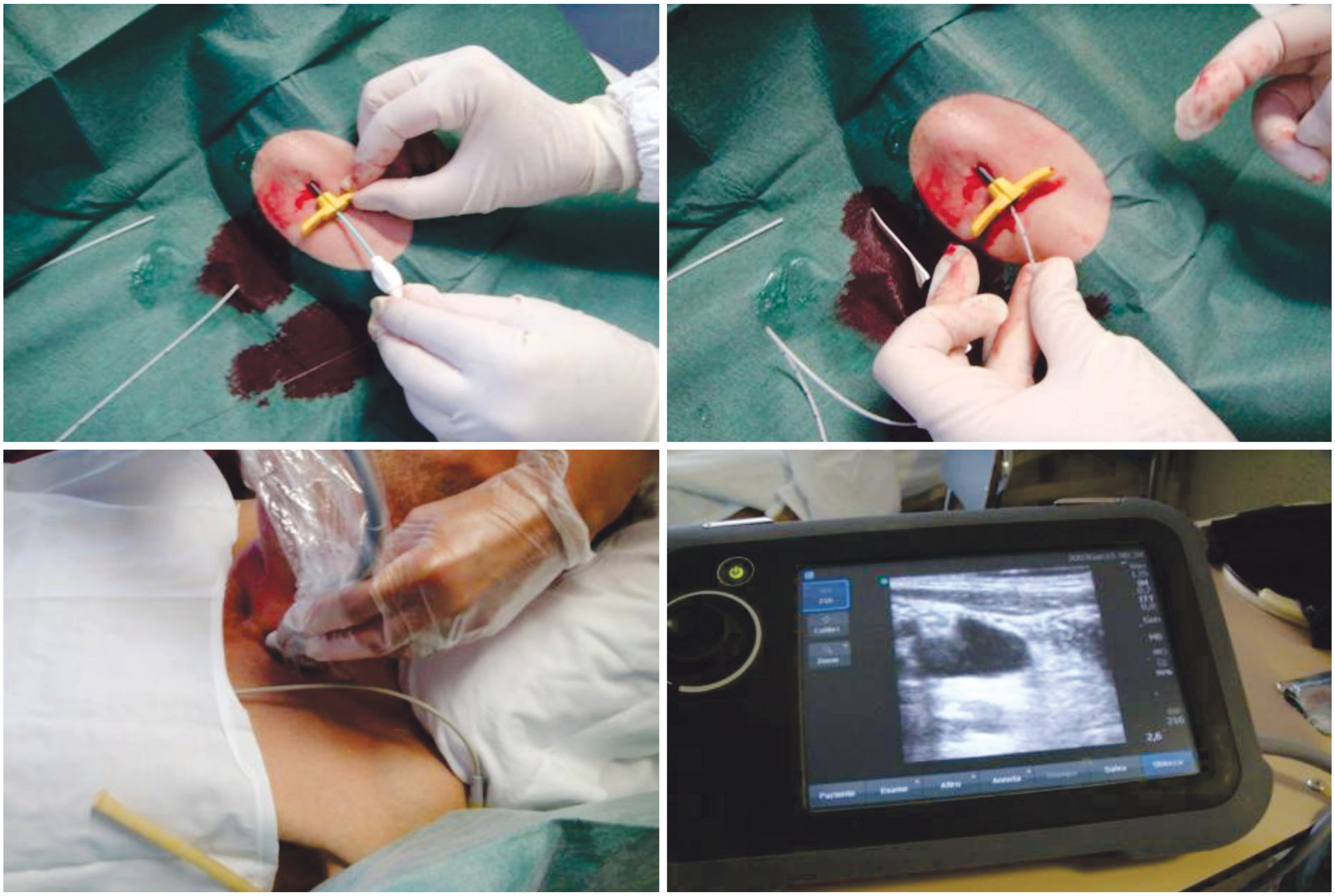

Figure 15-5 Ultrasound inspection of the internal jugular vein while advancing the catheter.

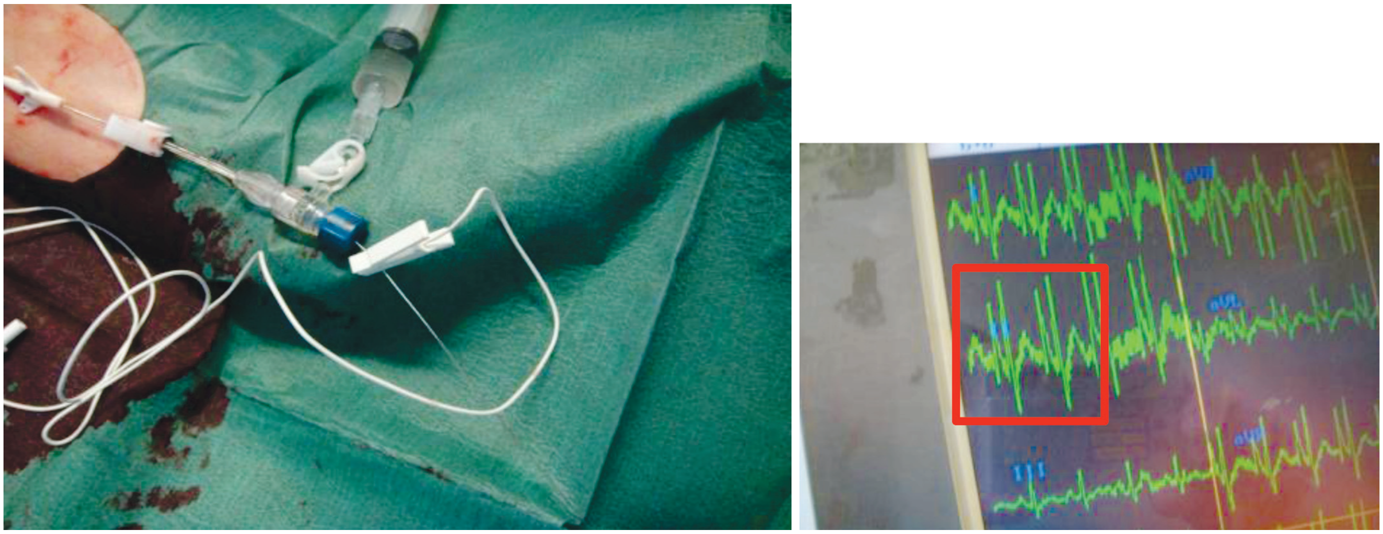

Figure 15-6 Intracavitary electrocardiographic technique. The maximum height of the P wave corresponds to the position of the tip at the cavoatrial junction.

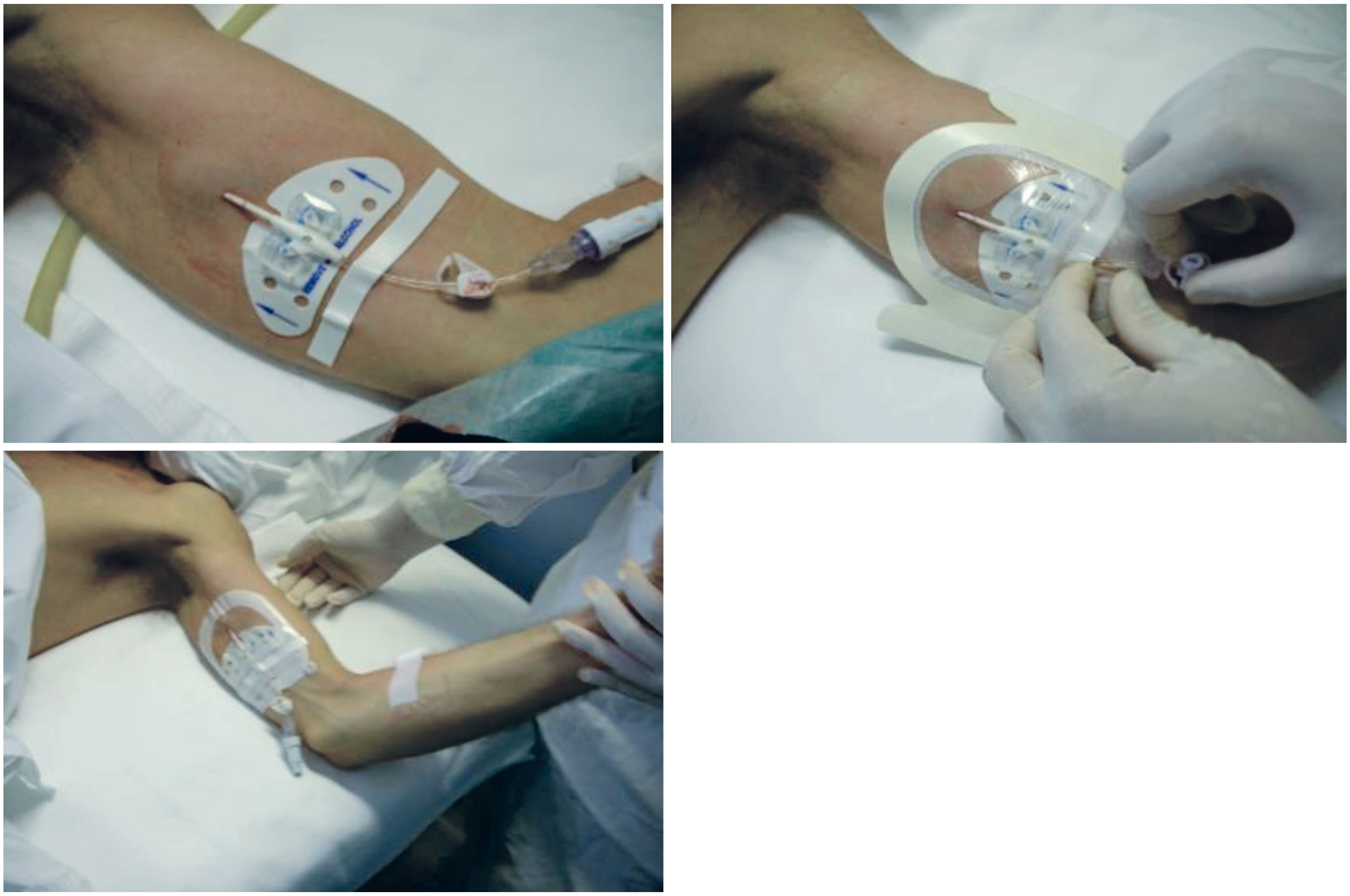

Figure 15-7 Securement with a sutureless device.

injury (steps 3, 4, and 5); minimizes malpositioning (steps 6 and 7); and decreases the risk for venous thrombosis (steps 3, 5, and 7), dislocations (step 8), and infections (step 1).[9]

Pearls and Highlights

- The 21st century ultrasound-guided PICC is a different venous access device than the 20th century PICC in terms of indications, complications, and overall clinical performance.
- Routine features of ultrasound-guided PICC insertion are preprocedural visualization of the vein (transverse plane) and implementation of an out-of-plane, "freehand" puncture technique.
- The most commonly accessed veins for PICC insertion are the basilic and brachial veins; however, other arm veins (axillary and cephalic) might be considered.
- Critical issues when choosing a vein for PICC insertion are vein diameter (at least three times larger than the size of the catheter) and depth from the skin surface (veins located deeper than 30 mm should be avoided), as well as the location of the exit site (preferably in the middle third of the upper part of the arm).
- The SIP protocol outlines the main steps in PICC insertion, such as preprocedural evaluation of veins, real-time ultrasound-guided venipuncture, intraprocedural or post-procedural verification of optimal catheter tip positioning by various methods, use of appropriate aseptic techniques and microintroducer kits, and sutureless securement of the catheter at the end of the procedure.

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16

Ultrasound-Guided Arterial Catheterization

ARIEL L. SHILOH | RICHARD H. SAVEL | LEWIS A. EISEN

Overview

Arterial catheterization is a frequent and essential procedure that is used in the intensive care unit (ICU) for accurate hemodynamic monitoring and repeated sampling of blood for analysis.[1] Blind or palpated catheter insertion can be difficult because pulsations and landmarks are often obscured by edema, obesity, hypotension, hypovolemia, and small-caliber vasculature. Repeated attempts at catheterization are often less successful because of arterial spasm. In addition, the external landmarks used for catheter placement are not necessarily predictive of the underlying anatomy. This is especially true of the femoral vasculature, for which it has been reported that a portion of the common femoral artery overlaps the common femoral vein up to 65% of the time.[2-5]

Recent studies and meta-analyses have shown the utility of ultrasound for guiding arterial catheterization, with increased success and decreased complication rates similar to those found with the use of ultrasound for central venous catheter placement.[6-10] A meta-analysis by Shiloh et al demonstrated a 71% improvement in first-attempt success and a number needed to treat of six when using ultrasound guidance for radial artery catheterization.[9] Ultrasound-guided arterial catheterization has been shown to be beneficial in pediatric and adult populations in the ICU, surgical, and interventional settings. B-mode (two-dimensional) ultrasound is most often used for arterial catheterization and has been shown to be superior to Doppler ultrasound techniques. Real-time visual guidance is superior to marking a spot with ultrasound and then trying to locate a vessel without guidance.[11-15]

Procedure and Instrumentation

A high-frequency (7.5- to 10-MHz) transducer is best suited for arterial catheterization because it provides appropriate resolution and penetration. Sterile sheathes and sterile conducting gel are required for the procedure.

B-mode (two-dimensional) ultrasound is used for arterial catheterization. Arteries appear hypoechoic on B-mode in contrast to the adjacent soft tissue (isoechoic). A key step in ultrasound-guided arterial catheterization is identification of the target artery and the adjacent vein. *Pulsatility* distinguishes arteries from veins. Partial arterial compression will accentuate pulsations that may be difficult to visualize in smaller-caliber vessels or hypotensive patients.[16] As opposed to veins, arteries should not be fully compressible with mild pressure from the transducer. As a rule, the artery should begin to indent when the vein is completely collapsed by pressure from the transducer. In addition, color power Doppler and pulsed wave Doppler can be used to distinguish arterial and venous pulsation.

Color Doppler can be used to distinguish the flow of blood in relation to the transducer. Blood cells moving toward the transducer produce a positive Doppler shift, and by convention the latter is represented as red color flow on color mode. A negative Doppler shift, produced by blood cells moving away from the probe, is represented by blue color flow accordingly. As blood velocity increases, so does the Doppler frequency. Lighter shades of red or blue indicate higher velocity, whereas deeper shades indicate lower velocity. Absent flow or low-flow states fail to produce a Doppler shift and are represented as black. For color flow to be present there must be flow in the direction of the ultrasound beam. The angle of insonation (the angle between the direction of flow and the ultrasound beam) is the key factor when using color Doppler (see Chapters 1 and 8). Doppler frequency increases as the ultrasound beam becomes more aligned with the direction of flow (parallel to the vessel). If the flow is perpendicular to the beam, no relative motion will be detected. It is dependent on the operator to appropriately angle the transducer in a fashion that will create flow toward the transducer as arterial or red-shifted. In addition to being red-shifted, arterial flow will be visualized as pulsatile and of higher velocity than venous flow. Venous flow will be blue-shifted and demonstrate continuous flow when compared with arterial flow. Similarly, pulsed wave Doppler can be used to measure changing blood velocity at a single point. A flow waveform of frequency shift (velocity) over time is created. Arterial flow demonstrates pulsatility, representative of the cardiac cycle, with a systolic peak and diastolic nadir. Venous flow is represented by continuous, low-velocity flow. It is important to not rely on Doppler techniques alone, because pulsatile venous Doppler flow can be demonstrated in patients with elevated right atrial and central venous pressure.[17,18]

Before the procedure a preliminary scan of prospective sites should be performed to identify the most appropriate vessel for catheterization. Frequently, there is asymmetry in the size of the arteries between the two sides of the body. Common locations for arterial catheterization include the radial, femoral (Figure 16-1), brachial, axillary, and dorsalis pedis arteries. After determining the target artery, the site is prepared in sterile fashion with full barrier precautions. An assistant applies sterile conducting gel to the uncovered probe and holds it vertically. The sterile operator inserts a hand into the sheath, holds the probe, and inverts the sheath over the probe and cable. Additional sterile ultrasound gel is then applied to the sterile probe.

If using a one-person technique, the operator controls the needle with the dominant hand and the transducer with the nondominant hand. When using a two-person technique, an assistant in full sterile barrier precautions controls the transducer. When compared with the two-person technique, the

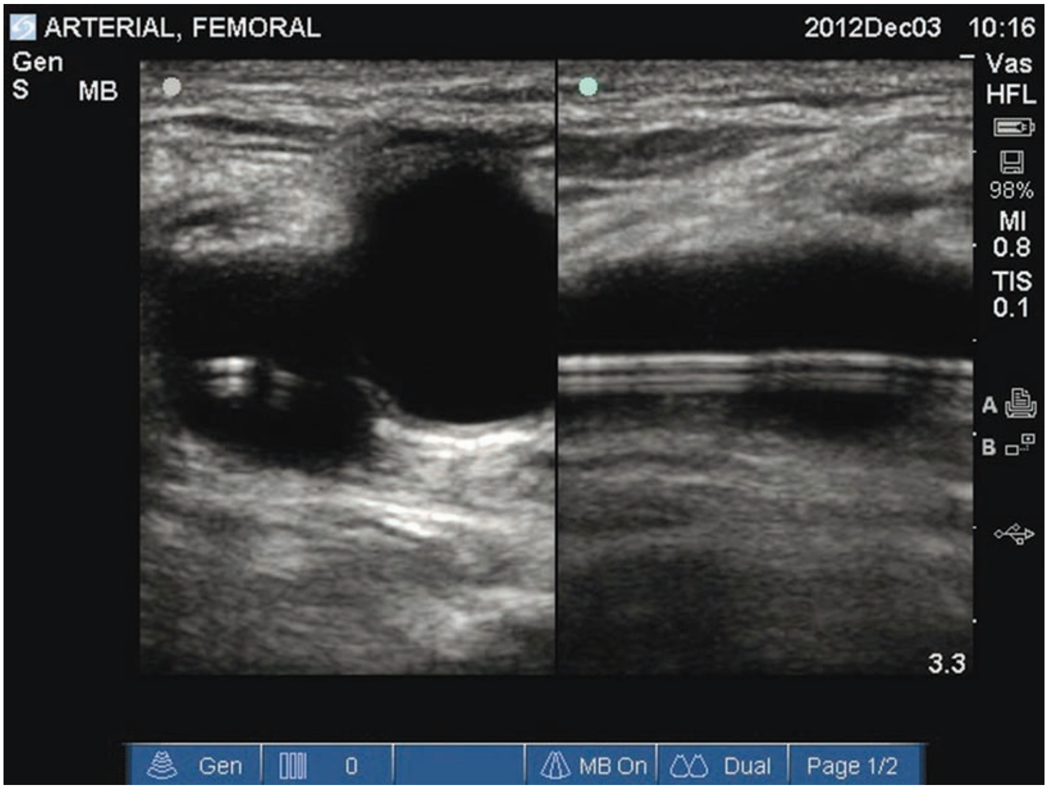

Figure 16-1 Transverse and longitudinal views of the femoral artery. A femoral arterial catheter can be visualized within the lumen of the vessel.

one-person technique has been reported to be learned easily and has improved first-pass and overall success for central venous catheterization.[11,15]

The artery is localized and centered on the screen in the transverse plane. Transverse and longitudinal views can both be used for catheterization. The transverse view allows easier visualization and catheterization of smaller (radial, dorsalis pedis) and tortuous arteries. The longitudinal view allows the direct visualization of the needle at all times, which may reduce perforation of the posterior vessel wall, but it also limits visualization of the surrounding structures because of a smaller plane of view. The longitudinal view is obtained by rotating the probe 90 degrees after localizing the artery in the transverse view while keeping the artery within the region of interest at all times.[19]

Local anesthetic is injected under ultrasound guidance slightly distal to the probe, and a subcutaneous wheal is visualized as an enlarging hypoechoic area. The introducer needle is advanced through the skin at a 45-degree angle slightly distal to the probe and advanced in the plane of the probe until it is visualized penetrating the artery. Shallower angles may be indicated for superficial arteries. Once the artery is entered with the introducer needle, the ultrasound probe is placed on the field, which frees the operator's nondominant hand. The catheterization is completed by following the modified Seldinger technique, and the catheter should be secured and dressed in standard fashion.

Site-Specific Tips

RADIAL ARTERY

In the transverse view the radial artery and accompanying veins are well visualized. The veins that are often accidentally catheterized when using the palpation technique can be compressed with light pressure from the transducer. When catheterizing the radial artery, an ultrasound-guided Allen test using Doppler signal can be performed to ensure good flow to the hand.[16] Ultrasound evidence demonstrates that the dimensions of the radial artery are unaltered when the wrist is extended up to 45 degrees. Extension beyond 60 degrees results in a decrease in radial artery diameter, thereby rendering catheterization more difficult.[20]

FEMORAL ARTERY

Though often used to delineate the inguinal ligament, the inguinal crease, a common puncture site for femoral artery catheterization, is an unreliable landmark for the underlying vascular anatomy. Use of the inguinal crease alone as a landmark coupled with an oblique puncture angle above the inguinal ligament may possibly lead to intraabdominal or peritoneal puncture.[4] Ultrasound guidance can be used to exclude intraperitoneal structures and avoid catastrophic complications.

Large amounts of overlap may occur between the common femoral artery and vein. Life-threatening complications of arterial catheterization, such as hematomas, arterial pseudoaneurysms, and arteriovenous fistulas, can be avoided, detected, and promptly treated when using ultrasound as detailed elsewhere (Chapter 8).

Hematomas

Because of mixing of liquid and coagulated blood, acute hematomas may be visualized on ultrasound as solid or mixed echogenic structures. With time, liquefactive necrosis of the hematoma results in a cystic structure, until ultimately a hypoechoic structure (with a possible hematocrit sign) is produced.[21]

Pseudoaneurysms

When compared with palpation-guided puncture, use of ultrasound-guided puncture for endovascular interventions was found to decrease rates of pseudoaneurysm formation.[22] Ultrasound is the method of choice for detection of pseudoaneurysms (Chapter 8). Findings include a communicating collection adjacent to the femoral artery. Turbulent internal blood flow and flow through the communicating channel can be detected with Doppler ultrasound. Ultrasound-guided percutaneous thrombin injection and ultrasound-guided compression are initial therapies for femoral pseudoaneurysms.[23] Potential embolic complications can be reduced by avoiding needle puncture through visualized atheromas.

Arteriovenous Fistulas

Arteriovenous fistulas are defined by a direct connection between an artery and vein (see Chapter 8). Color and pulsed wave Doppler are diagnostic and demonstrate flow in the tract between the vascular structures. The jet of arterial flow into the vein causes turbulent flow and, in severe cases, an arterial waveform within the vein.[21]

AXILLARY ARTERY

Nerve injury can be prevented by visualization and identification of the branches of the brachial plexus when catheterizing the axillary artery. Ultrasound guidance can be used to catheterize the artery via the traditional approach through the axillary fossa or via a transpectoral approach through the chest wall. Because of its cleaner and drier location, the transpectoral approach may potentially reduce the incidence of catheter infection.[24]

DORSALIS PEDIS

Even though the complication rates of dorsalis pedis and radial artery catheterization are similar, the success rate is much lower when placing dorsalis pedis catheters via palpation techniques, probably because of the relatively small caliber and tortuous course of the dorsalis pedis artery.[25] Ultrasound guidance would probably improve the success rate of catheterization.

IMAGING CASE: DIFFICULT ARTERIAL CANNULATION

A 68-year-old obese man with a past history of coronary artery disease and heart failure was admitted to the ICU after a motor vehicle accident. The patient had a history of difficult vascular access and extensive atherosclerosis. The resident on call attempted to place an arterial line in his right brachial artery because both wrists were fractured and radial artery access was not possible. A patent brachial artery (Figure 16-2) was visualized in both the transverse and longitudinal planes. The vessel was located relatively deep because of obesity and concomitant subcutaneous edema (arrow). Moreover, the vessel was atherosclerotic (arrowhead).

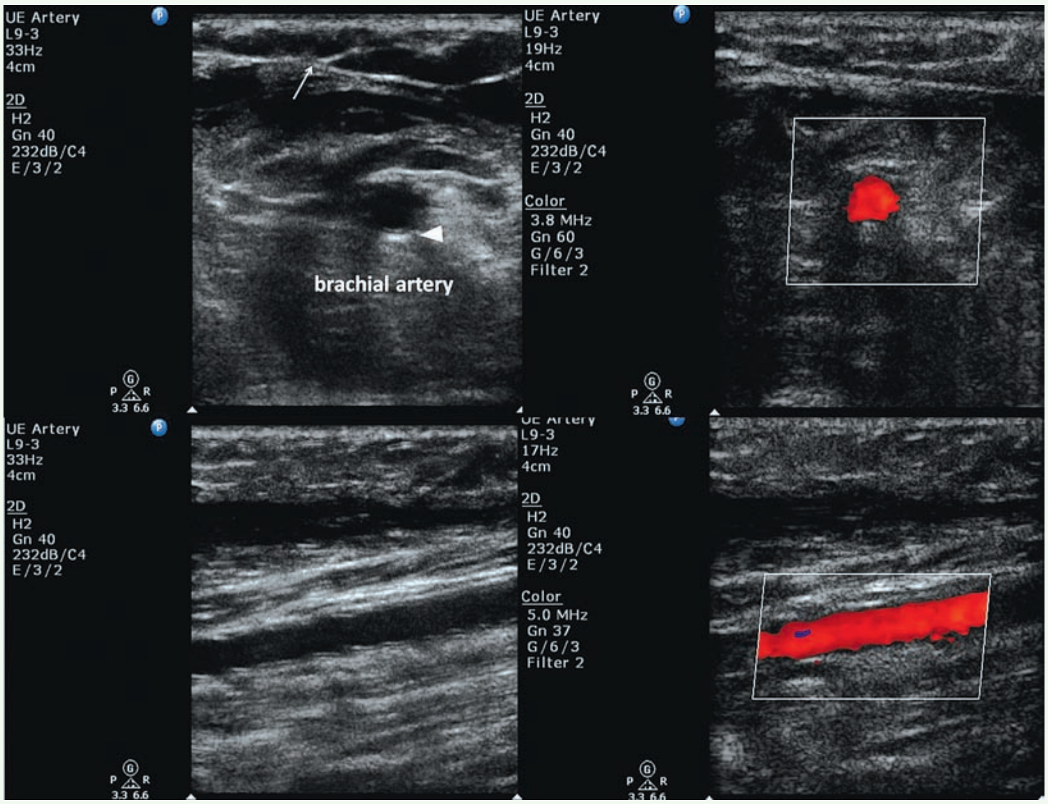

Figure 16-2 *Courtesy Dr. D. Karakitsos.*

Continued on following page

IMAGING CASE: DIFFICULT ARTERIAL CANNULATION (Continued)

The resident was not confident in using continuous real-time guidance, and after marking the vessel site he attempted a couple of blind, unsuccessful cannulations. Shortly thereafter, the on-call attending physician asked him to perform real-time cannulation in the longitudinal axis by using an echogenic vascular cannula (Figure 16-3). On revisualization (see Figure 16-3) the vessel was noted to be located even deeper and had a smaller diameter than seen in previous scans (see Figure 16-2). Color Doppler demonstrated increased flow velocity patterns. The combination of color Doppler and B-mode findings were consistent with postcatheterization vasospasm, a common complication during insertion of an arterial line (also note that the image in Figure 16-3 is rather blurred when compared with Figure 16-2 because of previous unsuccessful attempts to cannulate the vessel). Finally, real-time ultrasound-guided cannulation was performed successfully. The needle can be seen advancing toward the target vessel and cannulating the lumen in successive images in Figure 16-3. Please note that the artifact (arrow) in the bottom right panel demonstrates the use of agitated saline and movement of the needle tip to confirm cannulation within the vessel lumen.

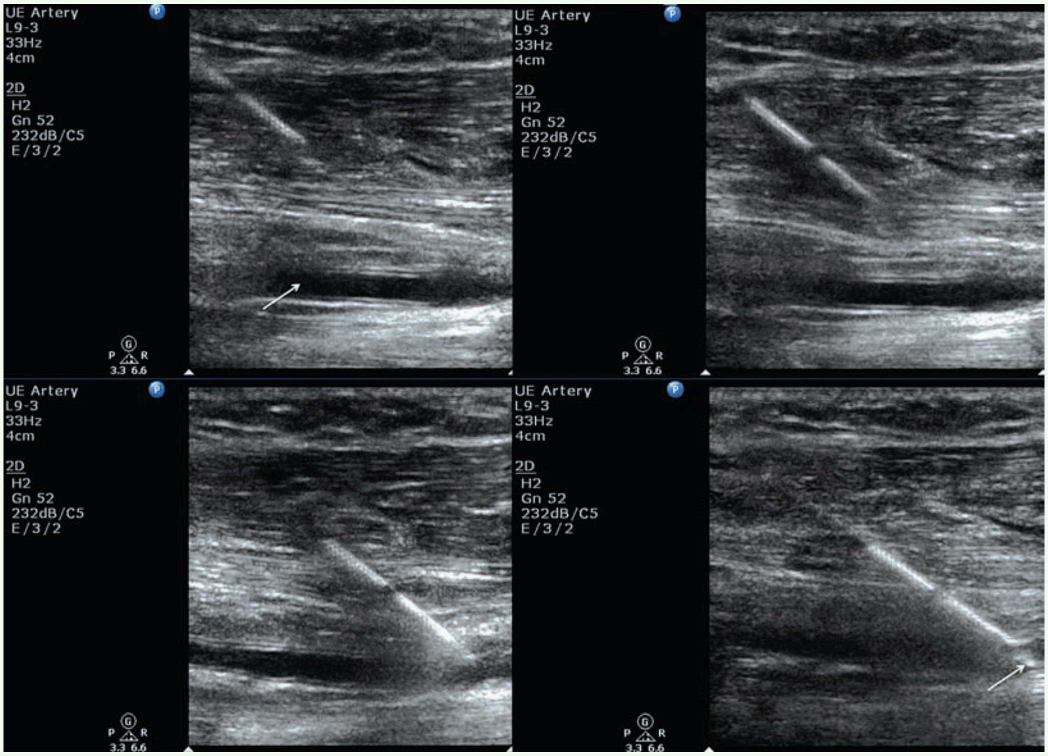

Figure 16-3 *Courtesy Dr. D. Karakitsos.*

Pearls and Highlights

- Blind or palpated catheter insertion can be difficult because pulsation and landmarks are often obscured by edema, obesity, hypotension, hypovolemia, and small-caliber vasculature.
- Recent studies and meta-analyses have shown the utility of ultrasound for guiding arterial catheterization, with increased success and decreased complication rates similar to those found with the use of ultrasound for central venous catheter placement.
- Ultrasound-guided arterial catheterization increases first-pass success rates by 71% over landmark techniques.

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17

Intravascular Ultrasound

HAIYUN WU | YU WANG

(CONSULTANT-LEVEL EXAMINATION)

Overview

Since its advent in 1977, percutaneous coronary intervention (PCI) has become a dominant treatment modality for ischemic coronary artery disease, especially unstable angina and acute myocardial infarction. During the last 2 decades, intravascular ultrasound (IVUS), a catheter-based technique that provides tomographic images perpendicular to the length of the coronary arteries, has been used widely in clinical research and has contributed to technologic improvements in interventional cardiology because it provides invaluable information on the coronary vascular lumen and wall. IVUS uses high-frequency catheter-based transducers to visualize all basic components of the vessel: the cross-sectional luminal size, shape, and vessel wall, as well as the various layers of the wall such as the intima, media, and adventitia and perivascular structures. IVUS examination of the carotid arteries may enable the morphologic characteristics of the carotid lesions to be assessed and thus treatment to be optimized. IVUS evaluation of the venous circulation is still limited. However, the method has been used to study arteriovenous malformations and mainly to demonstrate inferior vena cava compression or thrombosis, as well as to guide stent and filter placement.[1]

Clinical Applications of Intravascular Ultrasound for Percutaneous Coronary Interventions

In the bare metal stent (BMS) era, the major use of IVUS has been for optimization of stent deployment, particularly for complex lesions such as bifurcations, left main lesions, in-stent restenosis, and saphenous vein graft lesions. A challenging problem after BMS implantation was in-stent restenosis, and IVUS predictors of this phenomenon include smaller minimal stent area (MSA), stent underexpansion, stent edge dissection, incomplete stent apposition, and incomplete lesion coverage.[2] IVUS is superior to coronary angiography in assessing vessel size, calcium content, and lesion severity.[3] Therefore IVUS can be used before PCI to assess reference lumen dimensions and lesion length for appropriate stent sizing and to identify superficial calcium, which may lead to prestent rotational atherectomy. Poststent IVUS assessment may detect complications of PCI and suboptimal stent deployment.[4]

Previous studies have shown a beneficial effect of IVUS guidance on postprocedural angiographic results and stent restenosis during long-term follow-up as a result of a larger MSA with a higher postdilation balloon pressure.[2,3,5] Stent under expansion (identified by IVUS) can be treated with appropriate postballoon dilation. IVUS allows more aggressive intervention with a larger-diameter balloon with confidence in terms of safety; thus BMS implantation under IVUS guidance can provide a bigger MSA and more favorable clinical outcomes than angiographically guided PCI can. Although studies have differed regarding the best cutoff value for MSA (ranging from 6.5 to 9.0 mm^2), larger post-PCI areas consistently predict lower rates of restenosis.[6,7] In a registry of 1706 patients, the risk for restenosis with BMSs decreased 19% for every 1-mm^2 increase in MSA.[8]

Routine use of IVUS for BMS implantation is still controversial. Several meta-analyses have shown that when compared with angiographically guided PCI, IVUS-guided PCI results in an improvement in acute postinterventional results (larger minimal luminal diameter) and a lower frequency of repeated revascularization, angiographic restenosis, and main adverse coronary event rates, but no difference in the incidence of death or myocardial infarction during the follow-up period.[9-11]

The advent of drug-eluting stents (DESs) has markedly reduced the rate of in-stent restenosis. However, rapid implementation of DESs in standard practice also led to expansion of the indications for PCI to high-risk patients and complex lesions, and in-stent restenosis still occurs in 3% to 20% of patients, depending on patient and lesion characteristics and DES type.[12] Indeed, several retrospective investigations have showed the potential of IVUS in optimizing stent deployment, even in the DES era. In a study of 449 patients (543 lesions) who completed 6-month angiographic follow-up after the implantation of sirolimus-eluting stents, the postprocedural minimum stent lumen area and stent length on IVUS emerged as the only predictors of stent restenosis.[13] In another study, unselected patients undergoing DES implantation under IVUS guidance were identified and compared with those undergoing angiographically guided PCI,[14] and it was suggested that IVUS-guided DES implantation may significantly decrease rates of definite stent thrombosis at 30 days and 12 months. However, the few randomized controlled trials evaluating IVUS guidance for PCI with DESs showed that IVUS-guided PCI with DESs may not influence rates of restenosis. One published randomized trial, HOME DES (Long-Term Health Outcome and Mortality Evaluation after Invasive Coronary Treatment Using Drug Eluting Stents With or Without IVUS Guidance), randomized 210 patients to an IVUS-guided PCI strategy versus an angiographically guided strategy.[15] In this study the IVUS-guided strategy led to more frequent postdilation, higher balloon inflation pressure, and larger balloon size, but it did not result in lower rates of target vessel revascularization or major adverse cardiac events.

The reduced risk for in-stent restenosis in patients undergoing DES implantation is offset by concerns about stent thrombosis.[16] A study featuring a propensity-matched analysis in 884 patients treated with DESs showed a significant reduction in the stent thrombosis rate at both 30 days (0.5% vs. 1.4%, $P = .046$) and 12 months (0.7% vs. 2.0%, $P = .014$) in the IVUS-guided PCI group.[14]

IVUS may play a potential role in the assessment of coronary lesions classified as intermediate based on angiography, especially those located in the left main coronary artery (Figure 17-1). Management of intermediate lesions remains a therapeutic dilemma for interventional cardiologists. Even experienced interventional cardiologists cannot accurately assess the hemodynamic significance of intermediate or moderate lesions with stenosis of between 40% and 70% via angiography.[17] In this case, fractional flow reserve (FFR) is considered the "gold standard" for assessment of lesions, but several studies have reported fairly good correlation between IVUS-derived anatomic data and ischemia by physiologic assessment. FFR can be predicted accurately by using established equations and accurate three-dimensional IVUS imaging,[18] and several studies have suggested that with non–left main lesions, a minimal lumen area (MLA) of 4.0 mm^2 or greater can accurately identify nonischemic lesions for which PCI can be safely deferred, whereas an MLA of less than 4.0 mm^2 does not accurately predict a hemodynamically significant lesion and should not be used to justify revascularization. Because accurate assessment of intermediate left main lesions is important to optimize outcomes, IVUS has been widely used for the assessment of intermediate left main coronary artery lesions.[19] In a study of 55 patients with moderate left main stenosis, an MLA cutoff value of 5.9 mm^2 (sensitivity of 93% and specificity of 95%) and a minimal lumen diameter of 2.8 mm (sensitivity of 93% and specificity of 98%) best correlated with an FFR of less than 0.75.[20] In a recent study of 354 patients with intermediate left main stenoses, an MLA value greater than 6.0 mm^2 identified patients at low risk for adverse events with deferred revascularization.[21]

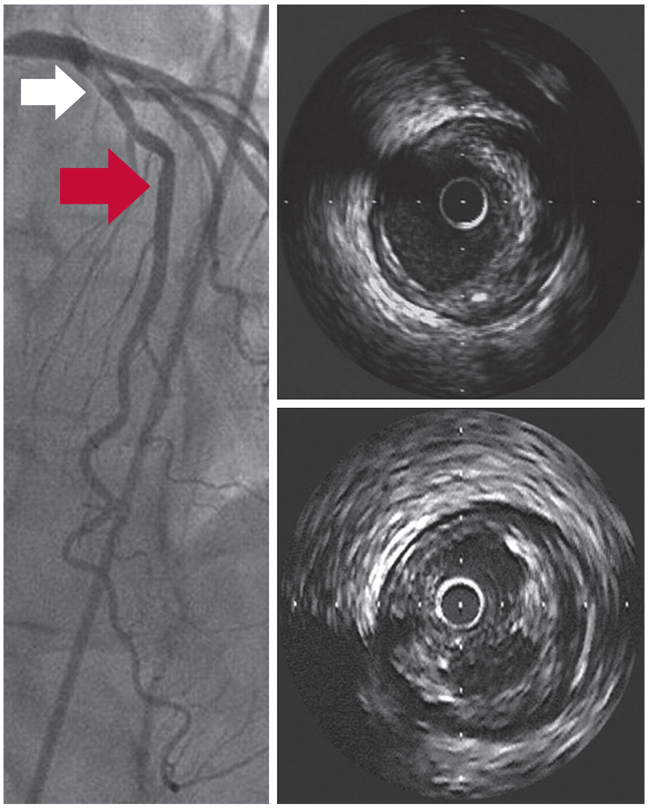

Figure 17-1 A cross-sectional tomographic image obtained by intravascular ultrasound examination (top right) within the proximal segment (white arrow on angiogram) revealed substantial atheroma within the arterial wall. The bottom right segment illustrates a tomographic image of atheroma containing significant ulceration (5 o'clock) at the site of the red arrow on the angiogram.

Intravascular Ultrasound for Carotid Revascularization

Carotid artery stenosis is the cause of about 20% to 25% of strokes.[22] Carotid stenosis of 75% to 94% is associated with a risk for stroke of 18.5% in asymptomatic patients and 27% in symptomatic patients.[23] Large-scale randomized trials have established the benefit of carotid endarterectomy over medical management in patients with symptomatic and, to a lesser degree, asymptomatic carotid artery disease. In the last decade, carotid artery stenting has been increasingly advocated as less invasive treatment than surgery.[24]

In contrast to the large amount of literature evaluating the potential of IVUS guidance for PCI, to date, published studies evaluating the utility of IVUS for carotid artery stenting are limited. Unlike the coronary artery, the extracranial carotid artery can be examined directly by B-mode and Doppler ultrasound. Current guidelines recommend duplex ultrasonography as the initial diagnostic test to detect hemodynamically significant carotid stenosis in asymptomatic patients with known or suspected carotid stenosis.[25]

However, several observational studies have suggested that preoperative IVUS evaluation of the internal carotid artery may provide useful information on the characteristics of the lesions and aid in stent selection, and it may be used to assess postprocedural results.[26-28] IVUS may be used to assess the quality of performance during open surgical procedures.[29] Finally, virtual histology IVUS allows improved characterization of plaque composition and may play a potential role in the preoperative or intraoperative evaluation of the lesion to be treated by identifying patients with unstable plaque and, consequently, at high risk for intraoperative cerebral embolism.[30]

Pearls and Highlights

- IVUS guides coronary stent deployment efficiently, particularly for complex lesions such as bifurcations, left main lesions, and saphenous vein graft lesions.
- It may be used as a complementary tool for assessing intermediate coronary lesion severity (left main artery).
- Color flow IVUS facilitates real-time dynamic assessment of carotid plaque morphology and aids in stent selection. Its use in the evaluation of veins is still limited; however, it has been used to guide inferior vena cava stent and filter placement.

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18

Ultrasound-Guided Placement of Inferior Vena Cava Filters

RAM GURAJALA | AMANJIT GILL

(CONSULTANT-LEVEL EXAMINATION)

Venous thromboembolism (VTE) is a major problem in patients in the intensive care unit (ICU), as previously analyzed (Chapter 9). VTE will develop in approximately 12% of ICU patients despite appropriate prophylaxis.[1] Furthermore, pulmonary embolism (PE) is common and underrecognized in critically ill patients.[2]

Inferior vena cava (IVC) filter placement is indicated in a small group of patients with VTE who have a contraindication to anticoagulation (in whom it results in complications, fails, or is insufficient) or following massive PE with residual deep vein thrombosis (DVT). The only prospective randomized trial of the use of IVC filters demonstrated that even though patients with IVC filters have a lower rate of PE than do those who undergo anticoagulation, they also have an increased rate of subsequent DVT without a difference in mortality or post-phlebitic syndrome.[3,4]

IVC filters are most commonly placed in an interventional radiology (IR) suite equipped with fluoroscopic guidance. Fluoroscopically guided filter placement has the advantage that IVC venography can be performed, which can ensure that the IVC is patent (Figure 18-1) without any duplication (Figure 18-2) or anatomic variant and is of appropriate size for placement of the filter. It is recommended that anticoagulation be initiated once the contraindication resolves.[5]

Many ICU patients require IVC filters to prevent PE and death since they usually have contraindications to anticoagulation. Concerns over transportation-related risks have led some investigators to evaluate ultrasound-guided IVC filter placement at the bedside in an attempt to limit transport-associated complications in critical care patients. Papson et al reported 230 unexpected events occurring during the transport of ICU patients, 30 (8.9%) of which were considered serious.[6]

Abdominal ultrasound has been used to guide IVC filter placement. However, failure to visualize the IVC adequately limits the use of abdominal ultrasound guidance.[7] Intravascular ultrasound (IVUS) offers the ability to accurately measure IVC diameter and visualize tributaries in great clarity. A review of the current literature regarding IVUS guidance for IVC filter placement revealed 1 animal study and 13 retrospective human case series. Only three of these studies included more than 50 patients. The largest case series, by Rosenthal et al, reported a 93.1% technical success rate of placing retrievable IVC filters (97 Gunther Tulip and 90 Celect) under IVUS guidance at the bedside, with 6 Tulip filters being misplaced in the iliac veins and 12% tilted.[8] When compared with the 3.4% tilt rate described in 100 patients in the prospective Celect filter registry, it is clear that fluoroscopic guidance allows more accurate placement of retrievable IVC filters.[9]

Although a bedside technique has its advantages, observational studies have reported an increased incidence of filter malposition.[8] It is well known that malpositioned filters can result in poorer cross-sectional protection of the IVC (Figure 18-3), and lead to PE despite the filter's presence and can increase the challenge at the time of retrieval. Another disadvantage of IVUS-guided placement is that no venogram is performed, thereby missing any anatomic variants, in which case the filter may not be protective (e.g., circumaortic left renal vein, duplicated IVC). If managed carefully, the cost related to transport, monitoring equipment, and nursing staff will be negligible in comparison to bedside placement of the filters. Adherence to

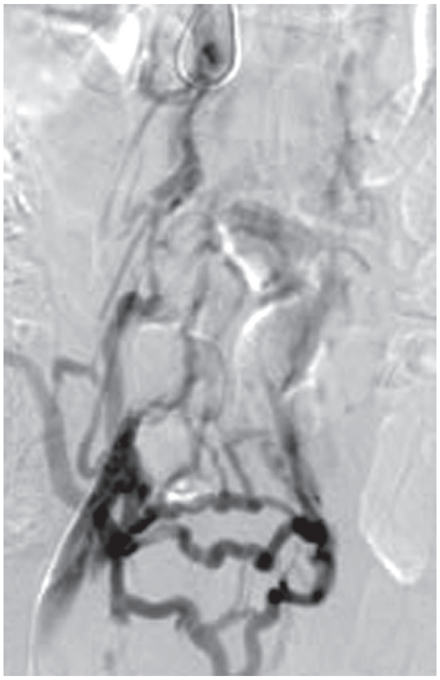

Figure 18-1 Occluded inferior vena cava (injection of contrast material into the right common femoral vein) with visualization of multiple pelvic collateral veins.

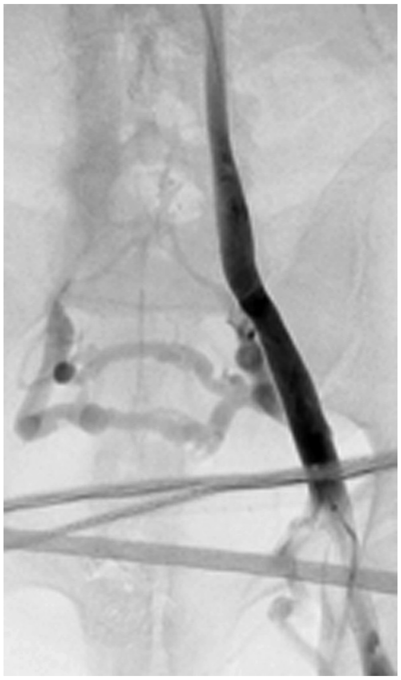

Figure 18-2 Duplicated inferior vena cava (injection of contrast material into the left external iliac vein).

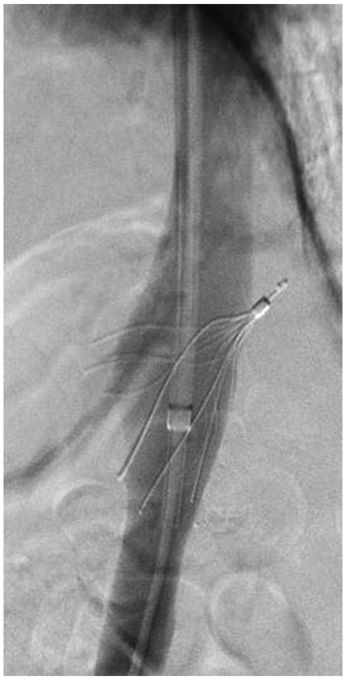

Figure 18-3 Vena cavagram performed during removal of a Gunther Tulip IVC filter. Marked tilting and projection of the retrieval hook outside the lumen of the inferior vena cava are seen.

guidelines for the transportation of critically ill patients, when implemented, can dramatically reduce the morbidity associated with the transportation of such patients.[10] Further evidence based on a randomized trial of bedside IVUS-guided placement versus the commonly used fluoroscopically guided placement in an IR suite is warranted.

Technique of Bedside Intravascular Ultrasound–Guided Inferior Vena Cava Filter Placement

Evaluation of the available cross-sectional anatomy is recommended to look for IVC patency and venous variants before considering bedside IVC filter placement.

EQUIPMENT

A portable ultrasound unit with a 7-MHz linear probe, portable IVUS unit with a 12.5-MHz IVUS catheter, sterile tray, and the filter deployment kit are needed.

TECHNIQUE

Single venous access:

- Perform ultrasound of the femoral veins to ensure their patency.
- Access a patent femoral vein (the right femoral vein is preferred because of less tortuosity).
- Place a 7-Fr sheath in the femoral vein.
- Advance the IVUS catheter into the IVC and image the renal veins (Figure 18-4).
- Place the IVUS catheter at the level of the renal veins.
- Mark the outside of the catheter at the hub of the sheath.
- Pull the catheter back 1 cm plus the length from the hub to the skin entry site and remark the outside of the catheter.
- Remove the IVUS catheter and measure the distance from the IVUS transducer to the final catheter marking. This is the distance that the tip of the filter should be inserted from the skin entry site.
- Mark the outside of the delivery sheath at the same distance just measured.
- Exchange the existing sheath over a wire for the delivery sheath.
- Place the filter into the delivery sheath according to the manufacturer's instructions. With the filter deployment system connected to the delivery sheath, the tip of the filter should be at the desired location.
- Deploy the filter according to the manufacturer's instructions.
- Reinsert the IVUS catheter to ensure that the apex of the filter is in the midportion of the IVC and the tip is below the renal veins (Figure 18-5).

Modification with two venous accesses:

- In addition to the steps just outlined, a second venous access can be obtained for placement of an IVUS catheter at the level of the renal veins.
- With the IVUS in place, the sheath and filter can be advanced, the tip of the filter placed 1 cm below the renal veins under direct visualization, and the filter deployed.
- The monitoring IVUS catheter should be withdrawn below the filter before deployment and then readvanced to image the filter after deployment.

Never attempt to place an IVC filter from a jugular, subclavian, or arm approach, because crossing the right atrium without fluoroscopic guidance is not recommended.

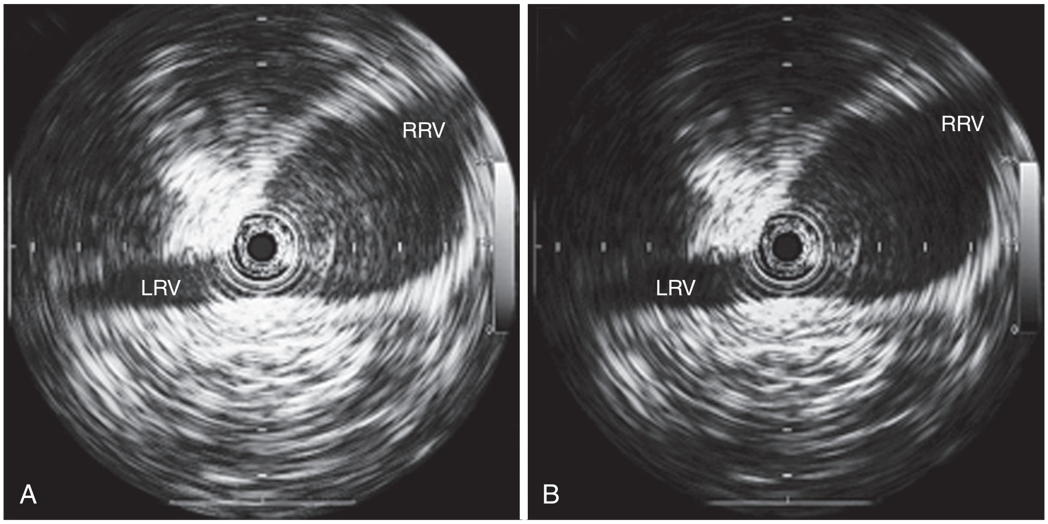

Figure 18-4 Visualization of the right and left renal veins opening into the inferior vena cava. The most central ring represents the intravascular ultrasound catheter. *(Reproduced with permission from the Journal of Endovascular Therapy8. ©Copyright (2009). International Society of Endovascular Specialists. Tulip G: Select IVC filters in multiple-trauma patients,* J Endovasc Ther *16:494-499, 2009.)*

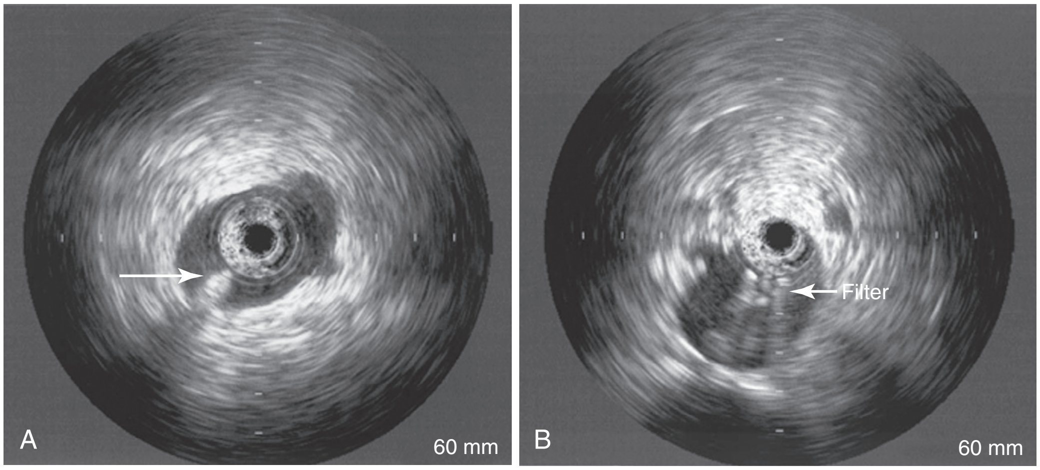

Figure 18-5 Intravascular ultrasound after deployment of the filter for confirmation of the position of the tip of the filter and adequate deployment of the filter legs. *(From Bedside intravascular ultrasound-guided vena cava filter placement. Wellons ED, Matsuura JH, Shuler FW, Franklin JS, Rosenthal D, from the Department of Vascular Surgery, Atlanta Medical Center. Presented at the Twenty-seventh Annual Meeting of the Southern Association for Vascular Surgery, Tucson, Ariz, Jan 15-18, 2003,* J Vasc Surg *38:455-458, 2003. Copyright © 2003 by The Society for Vascular Surgery.)*

The sheaths are then removed and hemostasis achieved with manual compression for 5 to 10 minutes.

A follow-up anteroposterior abdominal radiograph is obtained to confirm the location and assess tilt. Consider obtaining an ultrasound image of the access vein on postprocedure day 1 because occlusion of the access vein can occur as a result of the femoral access. When the anatomy of the IVC is thought to not be suited for bedside filter placement (unexplained large tributaries, small or large size of the IVC), the patient should be moved to the IR fluoroscopy suite for placement of the filter.

Since the technical success rate is significantly lower and the procedure-related adverse event rate is significantly higher with IVUS-guided placement than with fluoroscopically guided placement and since the adverse event rate in the periprocedural period is not significantly different, we advocate that transportation of patients to IR for fluoroscopically placed filters be continued in ICU patients with rigorous institution of transport protocols.

Pearls and Highlights

- VTE and its management are a major problem in critically ill patients.
- Based on strict guidelines, IVC filter placement is indicated in only a small group of patients with VTE.
- It is recommended that anticoagulation be initiated as soon as the contraindication resolves.
- IVC filters are most commonly placed in an IR suite equipped with fluoroscopic guidance, which has the advantage of real-time assessment of the procedure and associated difficulties.

- A bedside technique under IVUS guidance has advantages but also more procedure-related complications such as filter malposition, which can lead to PE and increase the challenge at the time of retrieval.
- With appropriate checklists and adherence to transportation guidelines, significant complications associated with moving patients to the IR suite can be minimized and allow more accurate IVC filter placement, which should minimize any long-term sequelae of filter malposition.
- Further evidence based on a randomized trial of bedside IVUS-guided placement versus the commonly used fluoroscopically guided placement in an IR suite is warranted.

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SECTION IV

General Chest Ultrasound

19

Lung Ultrasound: The Basics

SAHAR AHMAD | LEWIS A. EISEN

General chest ultrasound (lung ultrasound and echocardiography) is a core element of the holistic approach to critical care ultrasound presented in Chapter 1. Lung ultrasound and echocardiography are illustrated in Chapters 19 to 24 and 26 to 34, respectively; moreover, features of hemodynamic monitoring in the intensive care unit (ICU) are presented in Chapters 36 to 40.

Overview

The lung and its pathologic states are amenable to ultrasound analysis by virtue of the interplay between air and fluid within the thorax, the varying proportions of which suggest distinctive processes. In fact, bedside lung ultrasound has proved to be more informative than portable chest radiography in supine, critically ill patients for detecting and qualifying pulmonary pathology, including pneumothorax, infiltrates, pulmonary edema, and pleural effusion. Although some technical limitations are inherent in ICU patients, the accessibility of real-time ultrasound for immediate goal-directed imaging and interpretation is a valuable tool in the approach to respiratory dysfunction in the ICU.

The Normal Lung

A low-frequency transducer, 3.5 to 5.0 MHz, is positioned in longitudinal orientation over the chest wall in an intercostal space with the probe marker held cranially by convention. Gain and depth settings are adjusted to focus attention at the space between the rib shadows. The pleural line (Figure 19-1), a bright hyperechoic horizontal linear structure, is visualized between the rib shadows. A dynamic sign perceived as shimmering of the parietal and visceral pleura in contact is referred to as *lung sliding* and is part of the normal aeration pattern. Confirmation of lung sliding can be pursued with the use of *M-mode*. Directing the ultrasound beam between the rib shadows to transect the pleural line allows analysis of motion over time in the single-dimensional interface at that location. In the presence of normal pleural interaction, the resulting screen after initiating M-mode will display a pattern referred to as the *seashore sign* (Figure 19-2). Horizontal lines superficial to the pleural surface indicate a lack of motion of the chest wall structures with respiration. Deep to this is a bright hyperechoic horizontal line (representing the pleural surface), and immediately deep to the pleural line is a granular pattern indicating a normal aeration pattern in an inflating and deflating lung.

Evaluation of the lung parenchyma is based on the presence of different artifact patterns, all of which emanate from the pleural line. The *A-line* (Figure 19-3) is a reverberation of the pleural line, and given an adequate depth setting, several of these parallel lines can be seen at regular intervals. When visualized in the presence of lung sliding, an A-line–dominant pattern is said to occur and is suggestive of normal lung

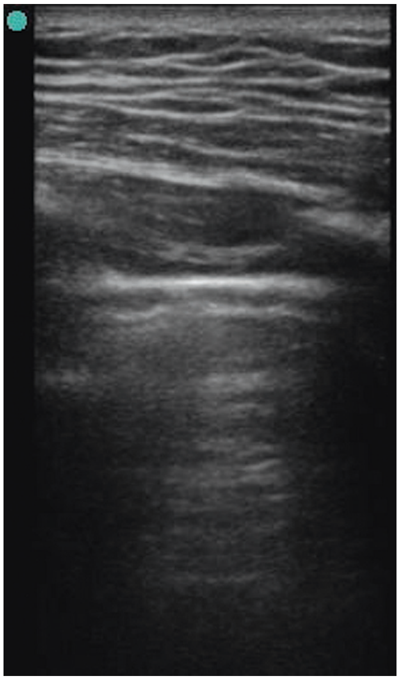

Figure 19-1 Pleural line.

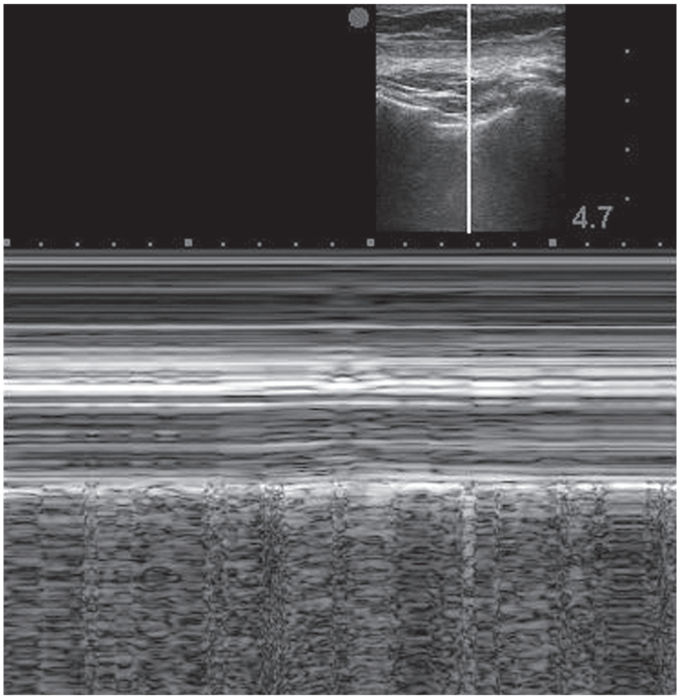

Figure 19-2 Seashore sign.

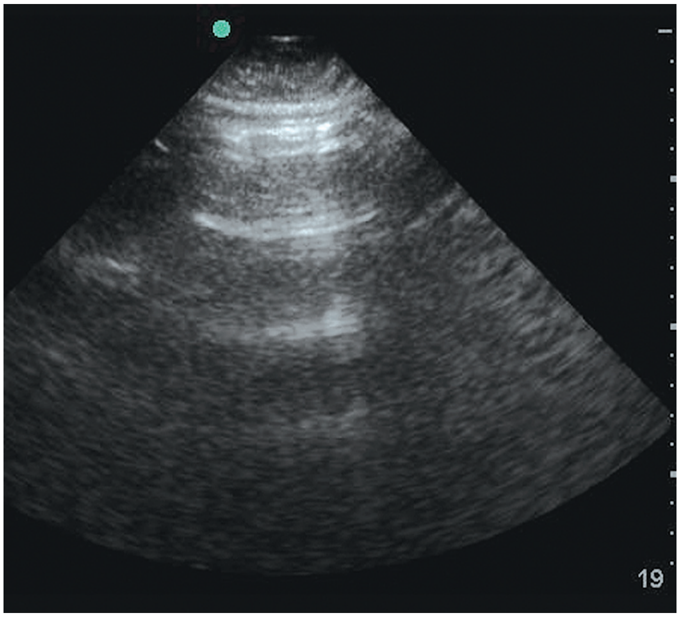

Figure 19-3 Pleural line with A-lines.

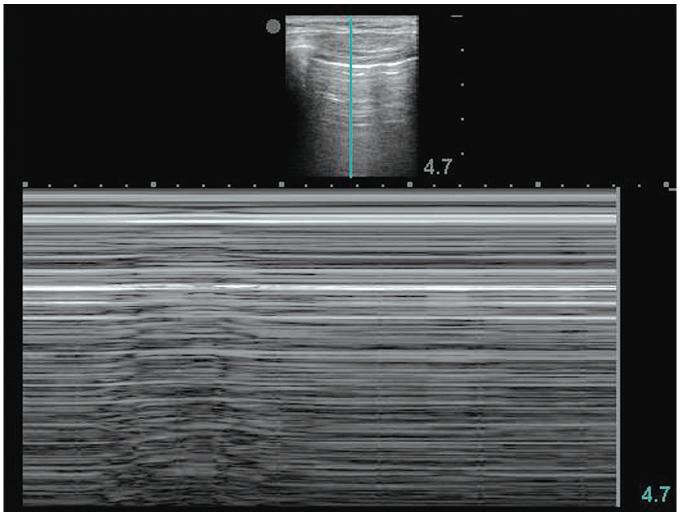

Figure 19-4 Barcode (stratosphere) sign.

parenchyma. In addition, an A-line–dominant pattern is noted to correlate with low pulmonary capillary wedge pressure and hence represents a low likelihood for pulmonary edema.[1]

Evaluation for Pneumothorax

A sonographic diagnosis of pneumothorax begins with clinical suspicion. Chest trauma in a young, otherwise healthy patient, sudden alterations in ventilator airway pressure, and postprocedure hypoxemia are all settings in which a lack of normal lung ultrasound findings along with compatible vital signs and findings on physical examination would yield a diagnosis of pneumothorax with certitude. Depending on the clinical stability of the patient, action may be warranted based only on the ultrasound findings.

Either low- or high-frequency transducers can be used, although with older machines, use of a low-frequency transducer in a thin patient may produce insufficient near-field detail. In our practice a high-frequency (vascular) transducer is routinely used for evaluation of pneumothorax and is preferred in thin subjects. In a supine patient, examination of the anterior chest wall at six to eight positions in each hemithorax and identification of lung sliding at each point would essentially rule out pneumothorax. In contrast, the absence of lung sliding (representing parietal pleura without visceral pleura to slide against) or the presence of a nonspecific air artifact without the normal aeration pattern is suggestive of pneumothorax. Confirmation of lung sliding can be verified with M-mode. The area under investigation, between the ribs shadows, is centered on the screen. M-mode is initiated after aligning the vertical line through the area in question while holding the probe as still as possible to avoid motion artifact. The "barcode sign" (or "stratosphere sign") (Figure 19-4) is the appearance of parallel horizontal lines extending through the entire field of view and indicates lack of normal motion of an inflated lung.

If lung sliding is absent and the barcode sign is noted on M-mode, any condition separating the two viscera from their physiologic juxtaposition or impeding their normal movement should be suspected. Causes include massive pneumonia, effusion, atelectasis, apnea, severe acute obstructive lung disease, and previous pleurodesis or pleurectomy. Even though lack of lung sliding is not specific for pneumothorax, the *presence of lung sliding effectively rules out pneumothorax at the intercostal locations under the applied ultrasound probe*.[2]

A *lung point* is a less commonly found but highly specific finding that rules in pneumothorax.[2,3] The operator would see findings compatible with pneumothorax (absent lung sliding) juxtaposed to aerated lung (lung sliding, A- or B-lines) and moving with each respiratory cycle. This finding not only makes the diagnosis but also, since a lung point defines the margin of the pneumothorax, helps quantify the size of the pneumothorax within the chest cavity. It can also be helpful for procedural guidance in evacuating a pneumothorax. A lung point can be viewed in M-mode (Figure 19-5), with the screen fluctuating over time between the seashore and barcode (or stratosphere) patterns with the transducer stationary. The position on the hemithorax at which the lung point is noted is further informative. Extensive pneumothorax with retraction

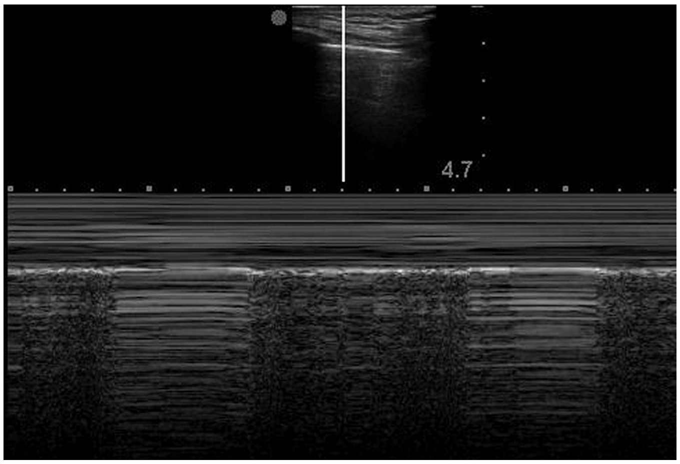

Figure 19-5 Lung point, M-mode.

of the majority of lung would produce a lung point very posteriorly or not produce one at all because of lack of lung reaching the chest wall in any location. A small pneumothorax would generate a lung point at an anterior and caudal location. In general, the more lateral and posterior a lung point is noted, the larger and more clinically relevant the pneumothorax.[2]

Evaluation for Pulmonary Edema (Interstitial Syndrome)

Lung ultrasound can contribute to the diagnosis of pulmonary edema when supported by a suggestive clinical scenario. A normal, A-line–dominant pattern, as described earlier, has been associated with low pulmonary artery occlusion pressure and is likely to represent a "dry" lung. Several authors have described a correlation between extravascular lung water and a specific air artifact pattern known as the *B-line* pattern.[1,4]

A B-line, or *comet tail* (Figure 19-6), is a horizontal hyperechoic beam emanating from the inferior margin of the pleural line and extending through to the deep edge of the screen. The B-line fans out, obliterates visualization of A-lines, and moves with the motion of the pleural line. Vertical lines that do not meet these criteria are artifacts of no clinical value. When diffusely identified, a B-line pattern correlates with thickened interlobular septa or ground-glass areas on computed tomography (CT). Though not reproduced in the literature, two distinct B-line patterns have been described, each correlating with a specific pulmonary parenchymal process. The first pattern consists of multiple B-lines discernible on screen, separated by 3 mm at a smooth pleural line. Sometimes referred to as B3-lines, this pattern is thought to correlate with subpleural ground-glass lesions, as would be the case with pulmonary edema, whether cardiogenic or related to acute respiratory distress syndrome (ARDS). In the case of ARDS, a mixed pattern of B-lines anteriorly and consolidation at gravity-dependent regions of the lung is expected. The second pattern consists of fewer visible B-lines, separated by approximately 7 mm at a ragged pleural line. These B7-lines are thought to correspond to thickened subpleural interlobular septa, as would be the case with interstitial lung disease.[5]

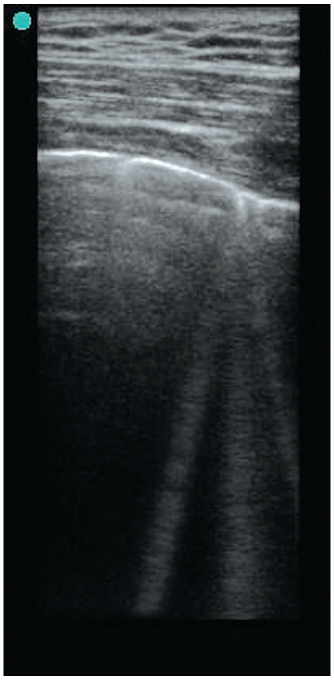

Figure 19-6 Pleural line with B-lines.

A single B-line in isolation or a B-line pattern confined to the last intercostal space is unlikely to be indicative of any pathology.[5] The lung bases, which have a greater mass of lung parenchyma, will often display a B-line pattern, and therefore an upper lung field examination is more informative in directed evaluation for pulmonary edema.

Several comet tail artifacts can mimic B-lines. The latter are identifiable by several key features: arising and fanning out from the inferior edge of the pleural line, not fading and extending to the deep edge of the ultrasound screen, obliterating A-lines as they proceed, and moving in synchronization with lung sliding. E-lines, often seen in emphysema, are aligned comet tail artifacts arising from layers superficial to the pleural line and indicate a thin air layer formed within two parietal layers. The commonly found Z-line is another comet tail artifact that does arise from the pleural surface; however, it is ill defined, is of variable echogenic appearance, and fades quickly without obscuring A-lines.

Evaluation for Consolidation (Alveolar Syndrome)

ATELECTASIS AND INFILTRATE

Consolidated lung offers numerous neighboring fluid-filled alveoli for the ultrasound beam to reflect off, thereby giving rise to a tissue-like appearance on the ultrasound screen. The term *hepatization* is applied when the lung's density and pattern resemble that of the liver. Distinguishing infiltrate from atelectasis can be difficult. The finding of sonographic air bronchograms suggests an infiltrative process with alveolar consolidation. Sonographic air bronchograms (Figure 19-7) are tubular bright artifactual structures within a tissue, such as occurs with consolidation, that correspond to air bronchograms on radiographs. On M-mode these structures can be further characterized as dynamic or static. Static bronchograms produce straight lines,

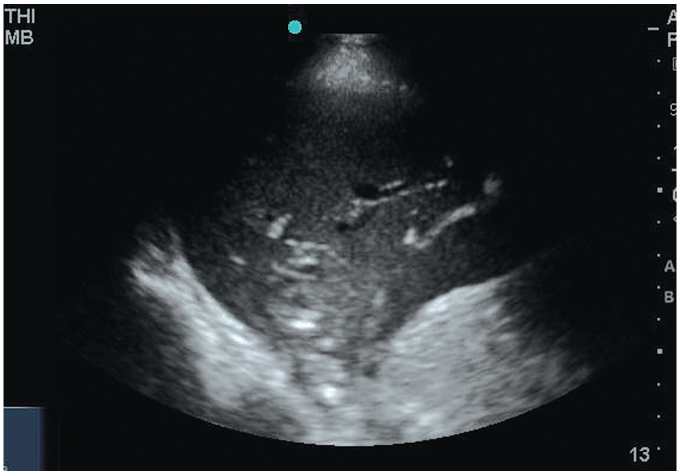

Figure 19-7 Air bronchogram.

whereas dynamic bronchograms produce a sinusoidal pattern. Although static air bronchograms can occasionally be seen in atelectatic lung, dynamic air bronchograms effectively differentiate pulmonary consolidation from atelectasis.[6,7]

Evaluation for Pleural Effusion

Pleural effusion is not uncommon in critically ill patients and can contribute to respiratory insufficiency or suggest the source of clinical decompensation. Ultrasound of the pleura and its pathology is highly informative and discussed in a separate chapter.

Goal-Directed Applications

APPROACH TO ACUTELY HYPOXEMIC PATIENTS

An acutely hypoxemic patient in the critical care unit has a wide range of differential diagnoses. The list of potential causes can be narrowed quickly with a directed application of chest ultrasound. The systematic approach to hypoxemia, along with sample protocols, is discussed in a separate chapter.

APPROACH TO VENTILATOR-DEPENDENT PATIENTS

In a patient in whom weaning from ventilator support is difficult, ultrasound can be used to evaluate for diaphragmatic dysfunction.[8] The low-frequency transducer is applied in conventional fashion to the lateral chest wall of a supine, intubated patient. The diaphragm is identified and the patient is directed to perform a sniff maneuver. Diaphragmatic motion is visualized in real time, similar to the fluoroscopic test, and its strength and function can be evaluated. In a mildly sedated or delirious patient who cannot produce a sniff on command, the ventilator can be transiently occluded at end-expiration and diaphragmatic motion at inspiratory effort observed. In a passively ventilated patient, paradoxic movement of the diaphragm can be detected. If the diaphragm is not well visualized, movement of the superior edge of the liver or spleen can be used as a surrogate for motion of the diaphragm. Diaphragmatic thickness is informative of function and can be assessed by ultrasound.[8] Conventionally, the patient is positioned upright and the diaphragm is identified at the zone of apposition, where it is easily visualized surrounded by tissue. Measurements are taken in either M-mode or two-dimensional scanning at a range of lung volumes extending from residual volume to total lung capacity. In a critically ill patient, semirecumbent positioning can be used.[9] If mechanically ventilated, measurements can be made at the points of end-inspiration and end-expiration by using brief hold maneuvers on the ventilator, if needed, to capture a still image.

OTHER APPLICATIONS

Additional applications of lung ultrasound are recognized. After lung recruitment measures, ultrasound can be used to assess the degree of re-aeration of the lung regions in question.[10] Adequate positioning of the endotracheal tube above the carina after intubation is suggested by identification of bilateral pleural sliding or motion of B-lines in concert with manual ventilation or ventilator-delivered breaths. Pneumothorax can be ruled out after procedures such as central line placement or thoracentesis immediately and with greater accuracy than with the standard chest radiograph.

Limitations

Sonographic assessment of critical care patients has multiple challenges, as mentioned in Chapter 1. Unlike ambulatory patients, the critically ill are commonly confined to the supine position and are often sedated and unable to follow commands, thus requiring operators to adapt their technique. The anterior and lateral chest wall is usually readily available for placement of the transducer, and these regions are often adequately informative. With support from staff, patients could be transiently repositioned for rapid assessment of the posterior chest wall as needed.

Rooms in the ICU are often overcrowded with life-sustaining devices such as ventilators, dialysis machines, and wiring for hemodynamic monitors and pacemakers. Making room for the sonographer is not always an easy feat. Room reorganization and manipulation of equipment should be done with care and with support of the critical care nursing staff. Postoperative patients, especially after sternotomy or abdominal surgery, will have bandages for the sonographer to contend with, and access to the chest wall can be limited. The presence of subcutaneous edema can obscure the ultrasound view and result in suboptimal information. Trauma patients may have subcutaneous emphysema, which will prevent adequate visualization of the pleural surface. Obese patients may also have suboptimal ultrasound windows.

Case

An intubated, supine ICU patient undergoes portable chest x-ray imaging in the setting of new fever. The resulting film shows a hazy opacity at the left lung base. It is not certain from this study whether pneumonia is present, which should be treated with antibiotics; effusion, which may need to be sampled; or simple atelectasis, which warrants a further search for the source of the fever. A chest CT scan is not feasible at this time because of patient instability and transport limitations.

Goal-directed bedside lung ultrasound is performed and reveals a hepatized lung with dynamic air bronchograms at the site of the questioned opacity. A diagnosis of pneumonia is confirmed, and appropriate management is pursued immediately.

Case

A patient is evaluated by the ICU service for severe respiratory distress caused by an acute exacerbation of chronic obstructive pulmonary disease requiring emergency intubation. Unequal breath sounds are noted immediately after intubation, and the ventilator is reading elevated airway pressure. It is unclear whether this is the result of the obstructive airway disease, pneumothorax, right mainstem intubation, or atelectasis. Portable chest radiography is ordered, but the patient continues to desaturate.

Bedside lung ultrasound performed bilaterally at the anterior chest wall reveals lung sliding on the right and absence of lung sliding or lung pulse on the left. Under ultrasound guidance the endotracheal tube is repositioned immediately, which resulted in recovery from the lung sliding and lung pulse at the left anterior chest wall, as well as normalization of ventilator airway pressure.

Pearls and Highlights

- A high-frequency probe often produces clearer images of pleural lines, lung sliding, and A- and B-lines at the anterior chest wall in thin patients.
- A lung point rules in pneumothorax, whereas the absence of lung sliding could have several causes.
- The presence of lung sliding rules out pneumothorax, but only at the intercostal space under examination.
- Given the high sensitivity of lung ultrasound for detection of pneumothorax as compared with supine chest radiography, scanning for lung sliding before and after placement of a central venous catheter is advised.
- Dynamic air bronchograms, when identified on M-mode, rule out atelectasis and suggest consolidation.

GLOSSARY

A-line: Sonographic reverberations of the pleural line. These hyperechoic horizontal lines appear at regular intervals deep to the pleural line and between the rib shadows.

B-line: Also called a lung rocket, this hyperechoic vertical sonographic artifact arises from the inferior aspect of the pleural line and extends to the edge of the screen without fading. B-lines obscure A-lines and move with lung sliding.

Barcode sign: Also called the stratosphere sign, this is an M-mode pattern of uninterrupted horizontal lines only, indicative of a lack of normal aeration.

Comet tail: A general term for hyperechoic vertical sonographic artifacts that may be present during lung ultrasound. B-lines are a type of comet tail.

Dynamic and static air bronchogram: Sonographic air bronchograms are tubular bright artifactual structures within a tissue, such as lung consolidation; they correspond to air bronchograms on radiographs. On M-mode, static bronchograms will produce straight lines, whereas dynamic bronchograms produce a sinusoidal pattern.

Hepatization: A term applied when the lung's appearance on lung ultrasound resembles that of the liver.

Lung point: A dynamic sign, this is the cyclic appearance of findings associated with aerated lung (lung sliding, A- or B- lines) creeping into and then out of view with each respiratory cycle.

Lung pulse: Similar to lung sliding, this dynamic sign is perceived as shimmering of the pleural line in concert with the heartbeat and is commonly seen at the left anterior chest wall.

Lung sliding: A dynamic sign perceived as shimmering of the pleural line in association with respiration.

Seashore sign: This sign is an M-mode pattern of uninterrupted horizontal lines superficial to the pleural surface with a granular pattern deep to this level; it indicates a normal aeration pattern in an inflating and deflating lung.

Stratosphere sign: See barcode sign.

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20

Pleural Ultrasound

KIMMOI WONG LAMA | ASTHA CHICHRA | RUBIN I. COHEN | MANGALA NARASIMHAN

Overview

Pleural ultrasound is influenced particularly by the presence of ribs and aerated lung. Ribs provide a shadowing artifact that completely blocks the transmission of ultrasound waves. Aerated lung is a powerful reflector of ultrasound waves and creates a typical artifact pattern. The pleura is well visualized by ultrasound, given that it is a boundary between two tissue densities (the lung and subcutaneous tissue) that have different acoustic impedance.

Proper equipment setup is important to maximize diagnostic yield, increase image detail, and improve accuracy. Usually, two-dimensional imaging is adequate for a pleural sonographic examination, and color Doppler techniques are not generally required. A microconvex transducer (3.5 to 8 MHz) is ideal for pleural ultrasound examination because it allows the deeper structures to be visualized and has a small footprint such that it can easily fit between the intercostal spaces.[1] In addition, high-frequency transducers can be used to allow more detailed imaging of the pleural surface.

In addition to transducer selection, proper orientation of the transducer is important when imaging the pleura and pulmonary structures. Imaging of the pleura should be performed in the longitudinal plane, and the marker of the transducer should always be directed to the head of the patient. By standard convention, imaging of the pleura will require the marker to be in the top left corner of the ultrasound screen.[2] The operator is able to perform various adjustments to optimize the quality of acquired images as detailed in previous chapters.

Identification of Anatomic Structures

When performing a basic lung ultrasound examination, the thorax is usually divided in three zones:

- The anterior zone is defined medially by the sternum, superiorly by the clavicle, laterally by the anterior axillary line, and inferiorly by the diaphragm.
- The posterior zone extends from the posterior axillary line to the posterior midline.
- The lateral zone is located between the anterior and posterior zones.

The ribs are easily identified because they cast an acoustic shadow. The examiner should move the transducer on a longitudinal plane to identify the pleura and lung tissue through the intercostal spaces while scrolling through the ribs (Figure 20-1).[2]

Ultrasound examination of the pleura is easy to perform. A normal pleural line is located 0.5 cm below the ribs and appears as a bright line interposed between the chest wall and the air artifact generated by the lung. The costal pleura can be almost completely examined when scanning the chest zone by zone in a longitudinal method. The diaphragm is easily visualized in the lateral zone with a longitudinal scanning method. The presence of a pleural effusion makes it easier to appreciate the diaphragm.

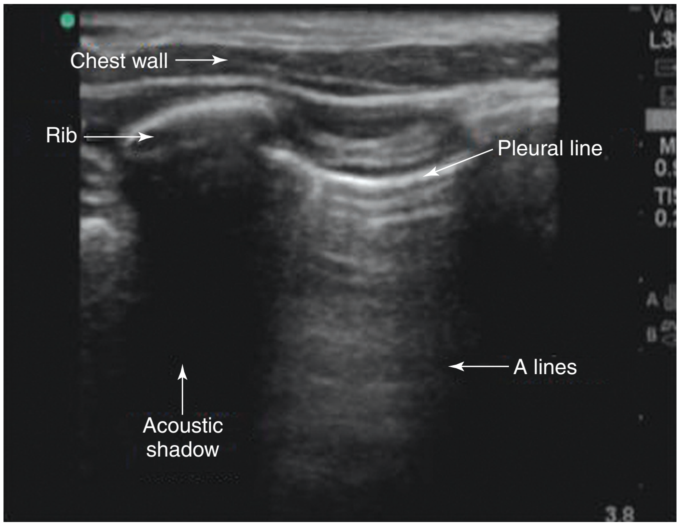

Figure 20-1 Normal pleural line. A longitudinal view of the chest wall displays normal anatomic boundaries.

Lung Sliding

The pleura appear as a moving bright line on lung ultrasonography. When using a high-frequency transducer the visceral and parietal pleura can be visualized as separate linear structures that are closely apposed. Movement of the pleural line against a fixed chest wall is known as lung sliding. Visualization of lung sliding implies that the two pleural surfaces are mobile and in apposition with each other and that no air is opposed between them at the point of the transducer. It is very important to distinguish pleural sliding from chest wall movement.[1,2] An alternative method of assessing lung sliding is M-mode. Pleural sliding gives a characteristic seashore sign (Figure 20-2). The presence of lung sliding implies with 100% certainty that no pneumothorax is present at the point of the probe.[3]

Lung Pulse

Careful observation of the pleura reveals a subtle shimmering movement of the pleural line that coincides with cardiac pulsation; this is known as lung pulse. The finding of lung pulse is usually more prominent in the left hemithorax and in the lower

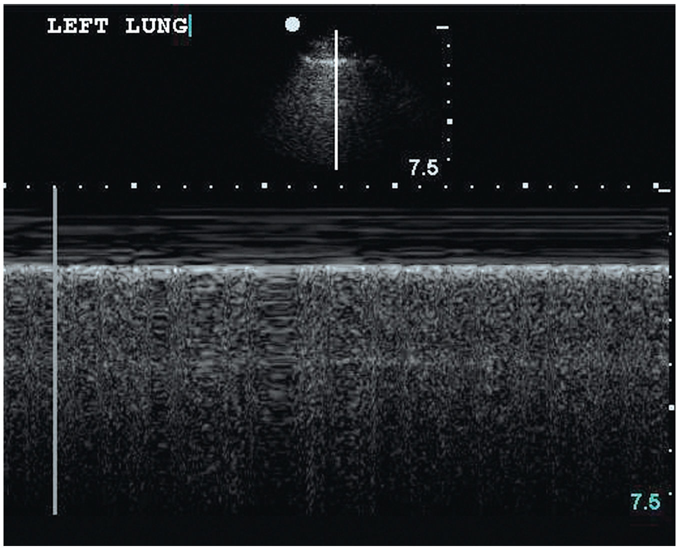

Figure 20-2 Seashore sign. M-mode demonstrates an alternative method of assessing lung sliding.

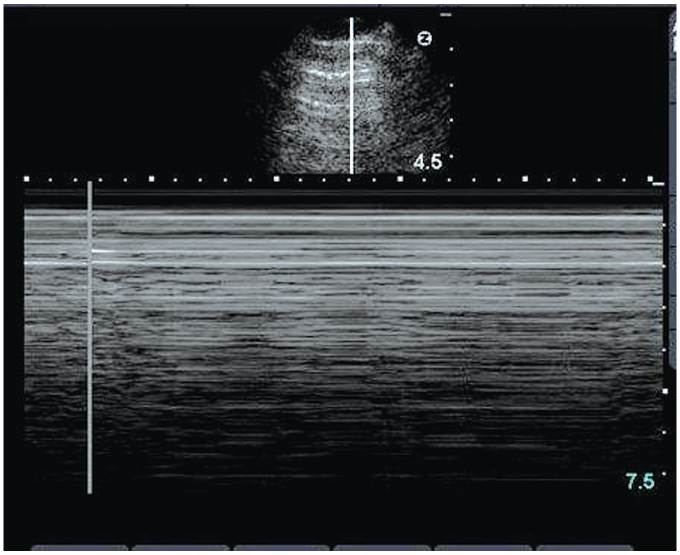

Figure 20-3 Stratosphere sign. This finding is consistent with pneumothorax. Note the absence of the typical seashore sign, which corresponds to lung sliding.

aspects of the thorax.[2] The presence of lung pulse indicates apposition of the parietal and visceral pleural surfaces at the point of the transducer; therefore the finding of lung pulse reliably excludes the presence of pneumothorax.

Pneumothorax

The ability to rule out pneumothorax quickly is a critical application of pleural ultrasonography, which is noninvasive procedure that has greater specificity than and equal sensitivity as chest radiography in diagnosing pneumothorax.[4] It is also excellent for detecting residual pneumothorax after drainage.[5] At the point on the chest where the pneumothorax is present there will be neither lung sliding and nor a seashore sign. Because the air rises to nondependent areas in the pleural cavity, ultrasound examination should begin in this area of the chest.[2] The presence of lung sliding rules out pneumothorax. However, the opposite is not true, and the examiner should keep in mind that the absence of lung sliding is not specific for pneumothorax only. Lung sliding may be absent in other conditions such as atelectasis, pleural thickening, extensive pulmonary fibrosis, and pleural symphysis.[1] Other findings that suggest the presence of pneumothorax are lung point, "barcode" sign (Figure 20-3), and B-lines (lung rockets), as detailed in Chapter 19.[2,6,7] Hence the use of lung ultrasound after every procedure that carries high risk for pneumothorax, such as attempts at central venous catheterization, thoracentesis, or bronchoscopy with transbronchial biopsy, is a prudent strategy.

Pleural Effusions

Identification of a pleural effusion is a straightforward application of pleural ultrasound. The latter easily detects fluid collections throughout the body as anechoic or hypoechoic structures.[8] Ultrasound is superior to chest radiography in detecting pleural effusions. A free-flowing pleural effusion usually accumulates in the most dependent areas of the chest, and its position can change with changes in the patient's posture or positioning in the bed. It is important to study the entire chest to detect pleural effusions that may be loculated and will not collect in dependent areas of the chest.[2]

The position of the patient is a major limitation of performing pleural ultrasound in the intensive care unit because patients are often supine, have limited mobility, and may be undergoing mechanical ventilation. However, the operator can overcome these limitations by placing the transducer in the posterior axillary line and pushing on the bed while angling the transducer toward the center of the body. This facilitates visualization of small dependent effusions and coexisting lung parenchymal abnormalities.

There are three cardinal rules for diagnosing a pleural effusion:

1. Identification of the anatomic boundaries of a pleural effusion:
   a. The chest wall.
   b. The diaphragm and subdiaphragmatic organs: liver (right side), spleen (left side), and the kidneys.
   c. Lung should be identified and distinguished from the pleural effusion.
2. Identifying the relatively anechoic space that will constitute the pleural effusion in the context of the boundaries just listed (Figure 20-4).
3. Dynamic changes:
   a. A *flapping lung* refers to the undulating movement of the compressed lung within the pleural effusion (*jellyfish sign*). The lung may not be compressed and a flapping lung may be absent with small effusions.
   b. The *curtain sign* refers to aerated lung that moves into the scanning field and partially obscures the pleural effusion and adjacent compressed air during inspiration.
   c. The *sinusoid sign* reflects the respiratory motion of the visceral pleura on M-mode as it moves toward and away from the chest wall with each breath. It represents movement of the pleural surface within the fluid-filled pleural space.[2]

In addition, the size of a pleural effusion can be determined with pleural ultrasound. The easiest way to quantify the pleural

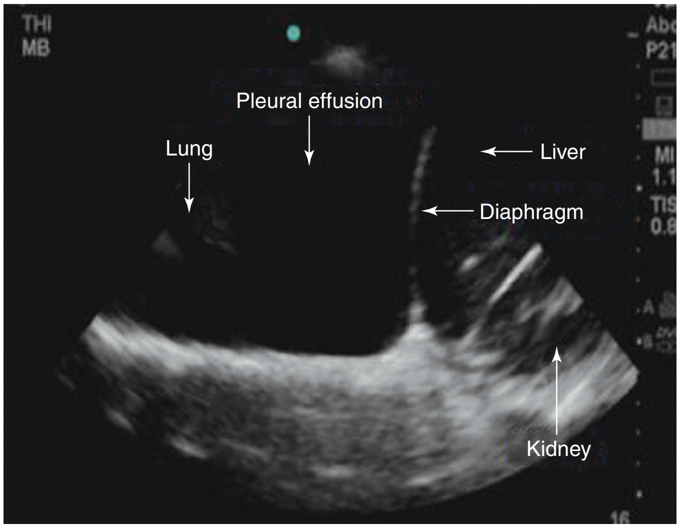

Figure 20-4 Pleural effusion. A typical anechoic fluid collection within normal anatomic boundaries is seen.

effusion is to determine whether it is small, moderate, or large.[8] Complex patterns within pleural effusions such as loculations, septations, and stranding patterns, which are commonly found in patients with complicated parapneumonic effusions and empyemas, can be featured by pleural ultrasound (Figure 20-5).

TYPES OF PLEURAL EFFUSION

The echogenicity of the pleural effusion has clinical significance. The appearance of the fluid aids in determining the cause of the pleural effusion. Pleural fluid is usually anechoic but may have floating echogenic debris. An anechoic effusion can be either transudative or exudative. Homogeneously echogenic effusions consisting of diffuse internal echoes with a uniform gray appearance are usually exudative.[9] Heterogeneously echogenic effusions (including debris, strands, fronds, or septations) may indicate a complicated parapneumonic effusion or empyema (see Figure 20-5). Heterogeneously echogenic effusions are identifiable by the presence of the following sonographic signs:

1. *Hematocrit sign*: usually seen with highly cellular effusions, it appears as a bilayer in which the most dependent part of the effusion is largely echogenic, where cells collect as a result of gravity.
2. *Plankton sign*: swirling debris that is agitated by the cardiac or respiratory cycle within a pleural effusion.
3. *Undulating movements*: strands or fronds that are agitated by cardiac or respiratory motion within the pleural effusion.[2]

Solid Pleural Abnormalities

Pleural ultrasound can detect solid pleural abnormalities. The latter can be malignant (e.g., a mesothelioma) or benign (e.g., lipomas) and appear as single or multiple lesions. When multiple pleural nodules are detected in the context of a malignant pleural effusion, they are highly indicative of pleural metastasis (Figure 20-6). Pleural ultrasound will guide experienced examiners in localizing and detecting these lesions and targeting pleural biopsy.

Pleuroparenchymal Disorders

Ultrasound examination of the surface of the pleural line could aid in differentiating between acute cardiogenic pulmonary edema (APE) and acute respiratory distress syndrome (ARDS). Pleural line abnormalities are usually present in ARDS (Chapter 22) and consist of a reduction or even absence of pleural sliding, thickening, and an irregular appearance of the pleural line. In APE, the pleural line is usually regular and smooth with normal lung sliding (Figure 20-7).[10]

Diagnostic and Interventional Applications of Pleural Ultrasound

1. *Thoracentesis.* Ultrasound guidance improves the yield and reduces the complication rate of thoracentesis.[11] Ultrasound allows superior localization and identification of the pleural space. Additionally, it enables safe

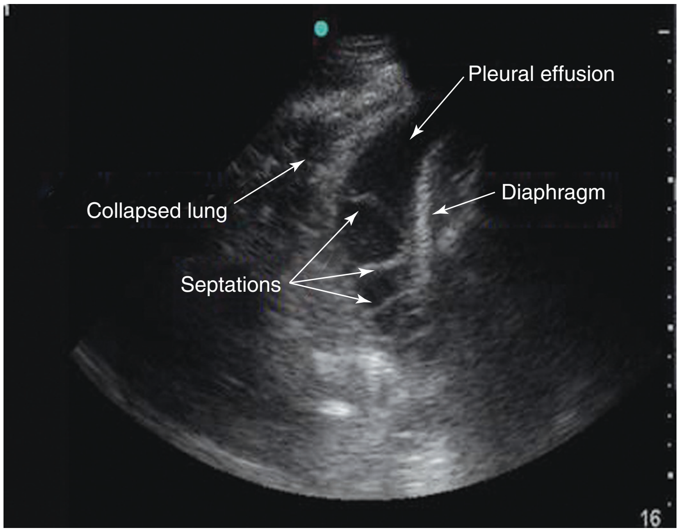

Figure 20-5 Complex pleural effusion with multiple septations.

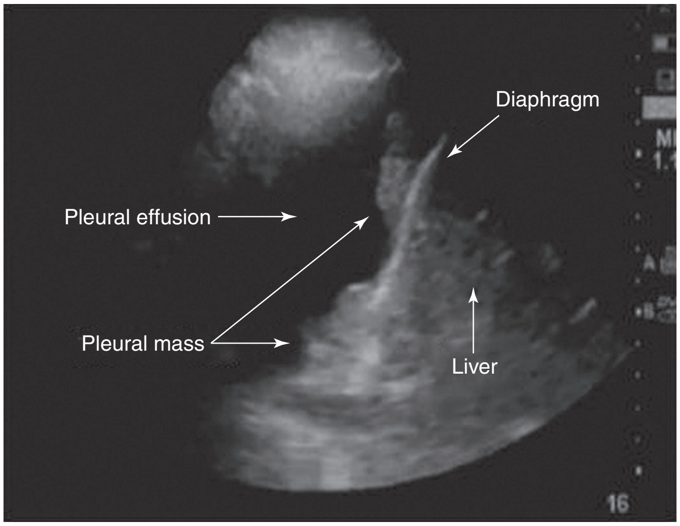

Figure 20-6 Solid pleural abnormalities. Multiple pleural masses are present over the diaphragm.

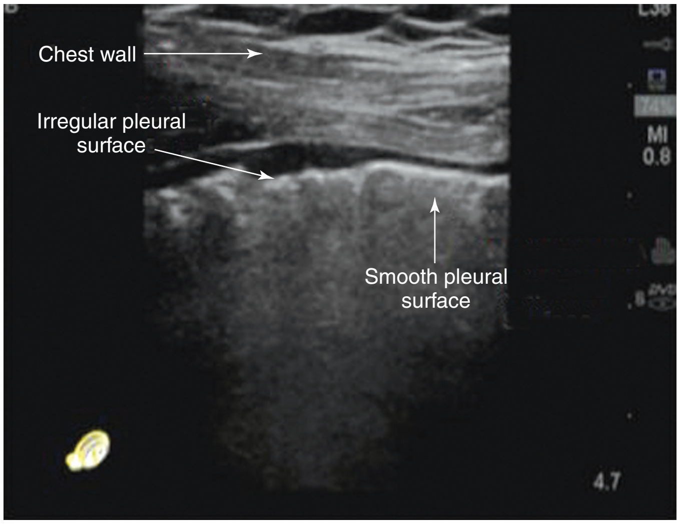

Figure 20-7 Evaluation of the pleural surface. Note its irregularity.

identification of pleural effusions in mechanically ventilated patients, in whom localization of the effusion and body positioning can be challenging.[12]

2. *Pleural biopsy.* Biopsy of solid pleural findings that require further sampling to determine the diagnosis can be performed under direct visualization.
3. *Chest tube placement.* Ultrasound-guided placement of chest tubes and pigtail catheters for drainage of various pleural pathologic conditions has been proved to be safe and effective in draining both simple and complicated pleural effusions.[13]
4. *Mechanical septal lysis.* After placement of a chest tube, the latter can be effectively manipulated (its movement can be directed toward the transducer) to facilitate visualization of septations within a complex pleural space. Lysis of septations and better drainage of a complicated pleural space can therefore be achieved.

Pitfalls and Limitations

Pleural imaging is challenging in morbidly obese and very muscular patients, as well as in those with extensive soft tissue edema, which may degrade image quality. The examiner may not be able to visualize the pleural surface adequately, and such situations may require expert-level operators.[8]

Pearls and Highlights

- Imaging of the pleura should be performed in a longitudinal plane, and the marker of the transducer should be directed toward the head of the patient.
- Movement of the pleural line against a fixed chest wall is known as lung sliding. Its presence effectively rules out pneumothorax (at the point of the transducer).
- The presence of lung pulse indicates apposition of the parietal and visceral pleural (at the point of the transducer). Its presence also rules out pneumothorax.
- Pleural ultrasonography should be used after every procedure that carries a high risk for pneumothorax, such as attempts at central venous catheterization, thoracentesis, or bronchoscopy with transbronchial biopsy.
- A free-flowing pleural effusion usually accumulates in the most dependent areas of the chest.
- There are three cardinal rules for the sonographic diagnosis of a pleural effusion: identification of its anatomic boundaries, detection of the relatively anechoic space that will constitute the pleural effusion in the context of these boundaries, and visualization of dynamic signs (jellyfish, curtain, and sinusoid).
- Ultrasound guidance improves the yield and reduces the complication rate of thoracentesis.

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21

Lung Ultrasound in Trauma

GIOVANNI VOLPICELLI | MATTIA TULLIO | ALESSANDRO LAMORTE

Overview

The great potential of ultrasound in the study of lung parenchyma lies in its ability to detect alterations in parenchymal density resulting from loss of alveolar air with or without increase of interstitial fluids.[1] Moreover, pleural disorders can be studied by direct visualization or indirect detection of abnormal fluids or air collected in the pleural space. Ultrasound abilities are based not only on the capacity to visualize real images of disorders (e.g., direct visualization of pleural effusion or lung consolidations) but also on analyzing various artifacts. The latter are generated by the acoustic interface created between parietal pleura and lung parenchyma and enable the detection of pneumothorax and various interstitial disorders. In trauma patients, bedside lung ultrasound readily identifies life-threatening disorders, such as hemothorax and/or pneumothorax, thus facilitating prompt treatment.[2,3] In trauma patients who present without any life-threatening conditions, lung ultrasound can detect lesions that appear radio-occult on radiography (e.g., lung blast), thus optimizing the selection of patients undergoing whole-body computed tomography (CT) scans.[4]

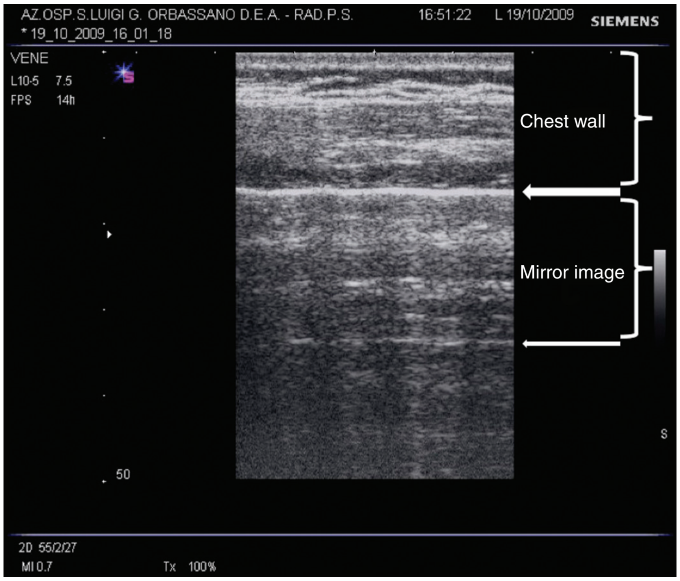

Figure 21-1 Oblique scan of a normally aerated lung. The image above the pleural line *(thick arrow)* is a real anatomic reconstruction of the chest wall. From the pleural line to the A-line *(thin arrow)*, the image represents a reflection of the chest wall (mirror effect) that moves synchronously with respiration.

The Technique

In a trauma scenario, the lung can be examined by any transducer, from high-frequency transducers well-suited for surface scanning to *microconvex* transducers that facilitate scanning between the tiny acoustic bone windows of the thoracic cage. Convex transducers represent the optimal mixture between a large spatial visualization and penetration depth achieved by low frequencies. Apart from lung scanning, microconvex transducers enable the examination of the abdomen, heart, veins, and so on, which is a time-saving feature in trauma cases.[5]

Trauma patients usually lie supine and cannot be moved; hence emergency lung ultrasound can access the chest through its anterior and lateral areas. Scanning these areas is sufficient in most cases, but sometimes it is necessary to sweep the transducer above the diaphragm or toward the posterior aspect of chest. Initially, scanning is performed on longitudinal planes because the latter allow identification of the pleural line between two adjacent ribs.[6] By slightly rotating the transducer along intercostal spaces, oblique views are obtained that allow visualization of a larger portion of the pleura and of the underlying lung parenchyma.

The Normal Pattern

Scanning a normally aerated lung permits visualization of the entire chest wall from skin to parietal pleura. The alveolar air creates an interface with the pleura and the soft tissues of the chest wall because of differences in acoustic impedance (air is an acoustic barrier). Hence visualization of the lung parenchyma below the pleural line is not feasible. The image corresponding to the normal lung is made by artifacts that represent chest wall's reflections below the pleural line ("mirror effect" of the lung) (Figure 21-1).[1] *A-lines* are horizontal lines visualized at constant intervals in the zone of artifacts and represent multiple reflections of the pleural line.[7]

Lung ultrasound is a dynamic technique that allows detection of lung movements against the chest wall. The normal lung is characterized by two movements. *Lung sliding* is a horizontal movement against the chest wall that is observed during normal respiratory efforts. *Lung pulse* is observed because of the transmission of cardiac beats to lung parenchyma against the chest wall and can only be visualized when patients with normal lungs, for some reason, stop breathing. Pulsation is horizontal or vertical, depending on the lung zone that is scanned.

Pneumothorax

Air in the interpleural space cannot be visualized because it limits the penetration of the ultrasound beam. In case of pneumothorax, the static ultrasonographic lung image is similar to that of the normally aerated lung that adheres to the parietal pleura (Figure 21-2). The only difference is dynamic, because air

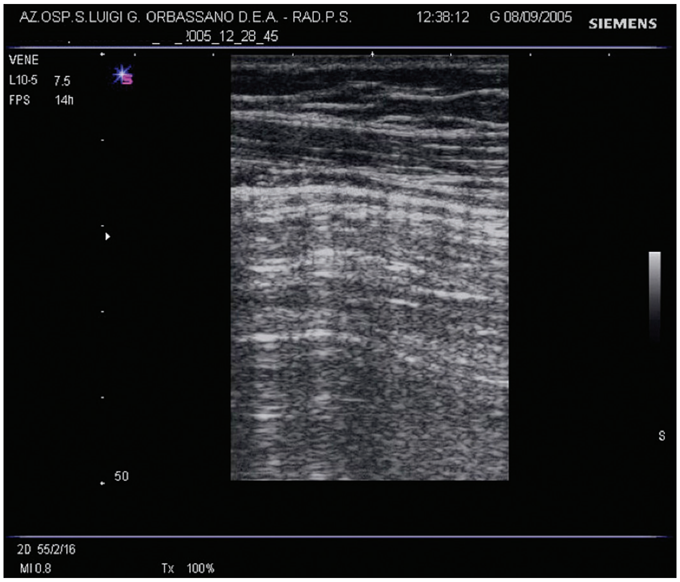

Figure 21-2 Oblique scan in pneumothorax. The still image of the lung is not distinguishable from the normal pattern (mirror effect) of Figure 21-1. Dynamic analysis allows appreciation of absence of any movement of the mirror image against the chest wall.

between the two pleural layers does not allow visualization of any lung movement.

ULTRASONOGRAPHIC SIGNS

Lung sliding: Although visualization of lung sliding rules out pneumothorax (high negative predictive value), its absence has no sufficient diagnostic accuracy to rule in pneumothorax.[8] This is mainly because lung sliding can be equally observed in other disorders, such as atelectasis, acute respiratory distress syndrome (ARDS), or selective intubation. Hence, in case of absent sliding, operators should always check for other basic ultrasound signs.[5,9]

B lines: Changes in normal air/fluid balance in lung zones (loss of air) generates vertical laser-like artifacts (B-lines).[10] B-lines blur, or even completely erase, the "mirror effect."[1] Depiction of multiple and diffuse B-lines indicates loss of the lung's aeration and increase of interstitial fluids.[11] However, presence of air in the pleural space prevents B-line visualization.[10] Thus even one isolated B-line rules out the diagnosis of pneumothorax. Absence of B-lines is not only observed in pneumothorax. In case of absence of lung sliding and B lines, other signs also should be evaluated to definitively rule in pneumothorax.

Lung point: A partially collapsed lung resulting from pneumothorax usually exhibits a chest point where the lung adheres again to the parietal pleura. This is visualized in a single lung ultrasound scan as the fleeting appearance of a lung pattern (sliding and/or pulse and/or B-lines) replacing a pneumothorax pattern (the "mirror image" of a still lung without B-lines). This sign is known as the "lung point" and is 100% specific for the diagnosis of pneumothorax.[12] Although highly specific, the lung point has low sensitivity because it cannot be visualized in totally collapsed lungs.

Lung pulse: In case of absence of lung sliding, B-lines, and lung point, operators should check for the lung pulse. This sign can only be visualized when the two pleural layers adhere.[13] Even in case of a pattern highly suggestive of pneumothorax, for instance, absence of sliding and B-lines, visualization of the slightest lung pulse rules out the diagnosis of pneumothorax.

TECHNICAL ISSUES AND PITFALLS

Air in the pleural space is usually mobile and tends to gather in the most dependent chest areas because of gravity. Searching for air in a supine trauma patient starts by scanning the anterior-inferior areas of the chest,[9] keeping in mind that patient positioning may be highly variable in prehospital scenarios. Also, lung ultrasound techniques may be variable depending on the patient's status (e.g., clinically stable or unstable, cardiac arrest). In acute emergency cases, the examination for lung sliding, B-lines, and lung pulse in the most dependent chest areas (bilaterally) is sufficient. In case of absence of these three signs, pneumothorax can be diagnosed, and the patient can be treated accordingly.[9] In stable patients, detection of pneumothorax in the most dependent chest areas should be confirmed by checking the lateral chest areas for the lung point sign.[6]

Sometimes, air cannot move freely inside the pleural cavity because the two pleural layers may adhere or simply because the amount of air is too small to move against gravity inside a virtual cavity.[14] The former condition may be observed in trauma patients, because lung contusions may cause pleural adherences.[15] Hence small amounts of air may not be located in the most dependent chest areas, and scanning the entire chest surface may be necessary. A condition of *loculated pneumothorax* produces an image of two simultaneously moving lung points from the two sides of the same ultrasound scan *(double lung point sign)*.[9,14]

Another possible source of error is subcutaneous emphysema, which is commonly found in trauma patients. Air in the subcutaneous tissue prevents visualization of the pleural line (Figure 21-3). When the pleural line is not visible, no safe diagnostic conclusions can be drawn. However, ultrasonographic and/or physical signs of subcutaneous emphysema in the setting of a chest trauma of an otherwise healthy patient are indicative of pneumothorax and/or rupture of the upper airways.[9]

Lung Contusion

Lung parenchymal contusion (lung blast) is commonly observed after blunt chest trauma.[2,4] Unlike pneumothorax, this condition rarely requires urgent intervention. However, diagnosis of contusion is important because it influences prognosis, while enabling correct diagnostic approaches to respiratory dysfunction. Radiology dramatically underestimates lung contusion in the emergency setting because its classic signs may take several hours to appear. Lung ultrasound detects even the earliest signs of lung blasts.[4] Contused lung parenchyma is initially characterized by the presence of a hemorrhagic area resulting from trauma. Over time, progression toward interstitial edema with infiltrates and air loss is common, thus producing regions of increased density within the lung parenchyma. Lung ultrasound detects alterations in regional lung parenchymal density; however, differentiating abnormalities that produce similar sonoanatomic images is not always feasible. Ultrasonographic findings of lung areas in the setting of a blunt chest trauma, with increased density and disappearance of the "mirror effect" resulting from B-lines and consolidations, are highly suggestive of lung contusions. The first

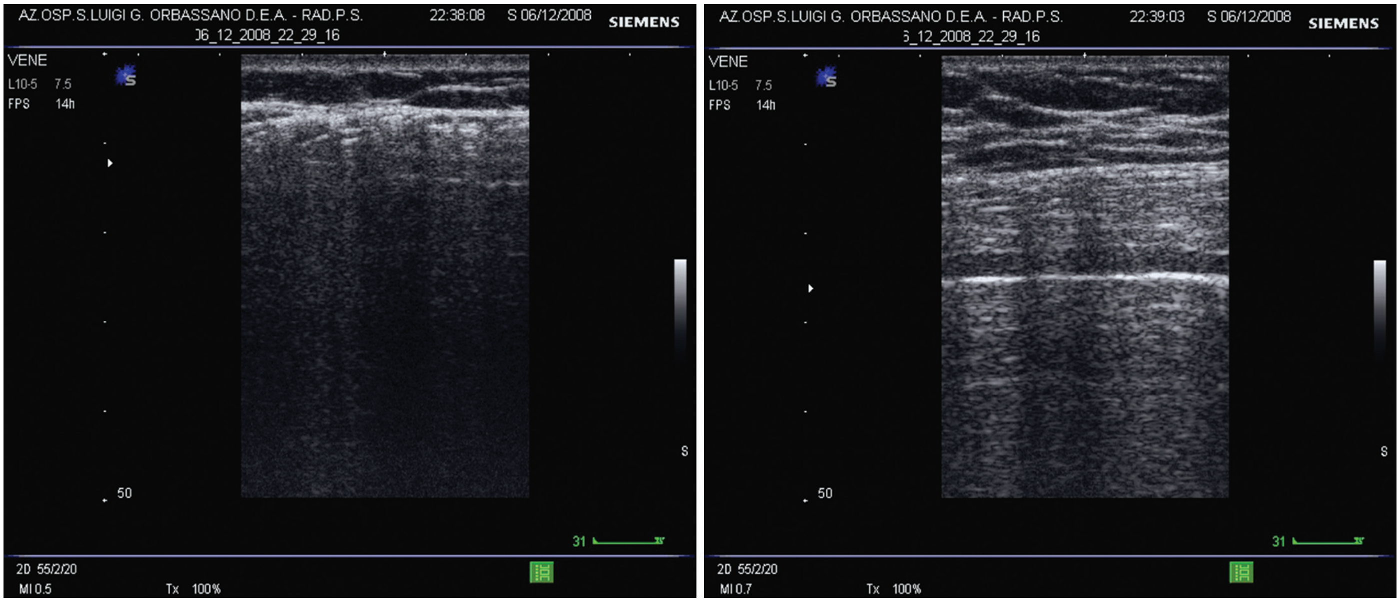

Figure 21-3 Bilateral lung scans in left-sided subcutaneous emphysema resulting from blunt thoracic trauma. The pattern of the left lung (*left*) does not show the pleural line. Comparison with the pattern of the contralateral lung (*right*) allows appreciation of a regular pleural line and highlights the difference.

step of aeration loss is the *interstitial pattern*, which is depicted as multiple B-lines, often with some irregularity of the pleural line, whereas increased density and echogenicity may reflect the severity of the condition. The *consolidation pattern* represents the final step in the loss of aeration. Its ultrasonographic patterns are variable, ranging from the anechoic blurred "fluid alveologram" to the "tissue-like" image with (or without) hyperechoic punctiform or linear elements corresponding to air bronchograms (Figure 21-4). The above patterns represent lung areas with different densities, and they may coexist in the same patient and/or in the same scan (Figure 21-5).

Figure 21-4 Lung scan showing tissue-like evolution of contusion (*C*) resulting from blunt chest trauma. Echotexture of the consolidation is similar to the liver (*L*) and shows some air-bronchograms (*thin arrow*). Between the liver and the consolidated lung, the echoic line represents the diaphragm (*D*).

Hemothorax

The use of ultrasonography in the diagnosis of effusion has been routinely applied for many decades and is based on reproduction of a real image of the disorder.[16,17] Unlike air, fluids within the pleural space create acoustic windows that permit ultrasound beam penetration. Pleural effusion is a dependent collection usually visualized as an anechoic space between the two pleura layers, with a cyclic variation of the interpleural distance during respiration.[2] The ideal technique consists of scanning the most dependent chest areas, which are the lateral-basal lung areas, bilaterally, in a supine patient. The main sonoanatomic landmark is the image of the diaphragm and the abdominal solid organs, liver or spleen, immediately below it. When effusion is absent, the ultrasonographic image of a lung pattern will intermittently overlap and hide, moving like a curtain, the image of the diaphragm and the underlying abdominal organ. Alternatively, a fixed image of a consolidated lung with a tissue-like pattern may be visualized over the diaphragm. In trauma patients, depiction of an anechoic space between the two pleural layers is highly indicative of hemorrhagic effusion.[18] Ultrasound may also diagnose the nature of the effusion. In general, while the anechoic pattern cannot be differentiated, visualization of internal echoes (e.g., mobile particles) is highly suggestive of hemothorax (Figure 21-6).[16]

Pearls and Highlights

- Bedside lung ultrasound is superior to conventional radiography in diagnosing common sequelae of blunt chest trauma, such as hemothorax, pneumothorax, and lung blasts.
- Pneumothorax is diagnosed by the combined evaluation of four ultrasonographic signs: lung sliding, B-lines, lung point, and lung pulse. Lung sliding, B-lines, and lung pulse have high negative predictive value, whereas lung point is used to confirm the diagnosis.

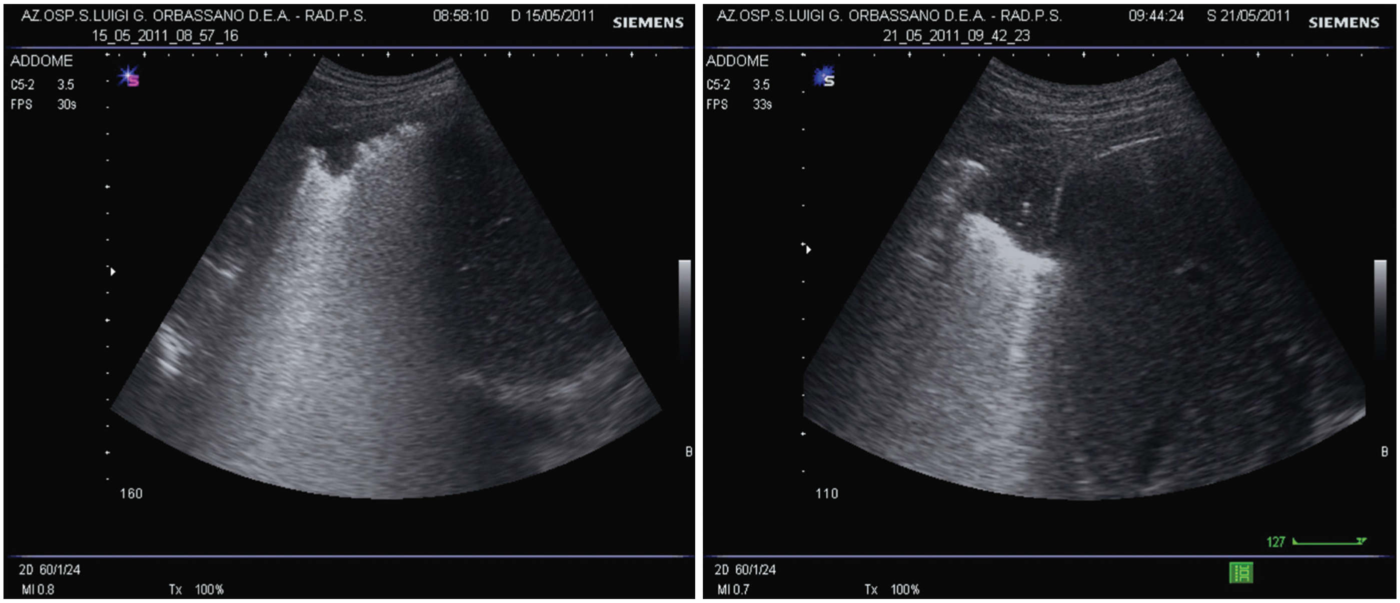

Figure 21-5 A case of blunt chest trauma. *Left*, Examination upon arrival in the emergency department revealed a basal right lung contusion. The pattern shows an alternation of B-lines with a subpleural anechoic consolidation. *Right*, The same lung area scanned after 6 days shows evolution of the lung blast to a tissue-like pattern with lentil-sized air bronchograms.

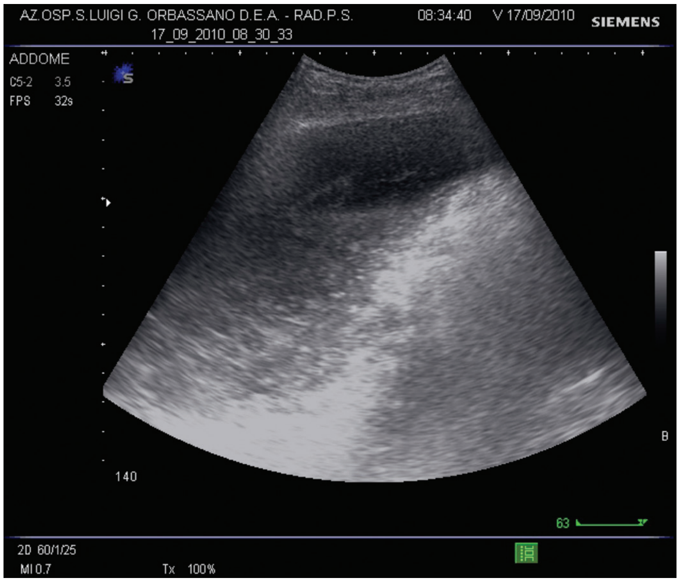

Figure 21-6 The lung ultrasound pattern in hemorrhagic pleural effusion resulting from blunt chest trauma. The image is only partly anechoic but shows some internal echoes in the lower part, resulting from interactions of the clots and cells with the ultrasound beam.

- In unstable patients (e.g., cardiac arrest), a "fast-track" technique is applied to diagnose pneumothorax, consisting of checking for B-lines, lung sliding, and lung pulse in the most dependent chest areas (anterior-inferior chest in the supine patient, bilaterally). Absence of these three signs indicates need for immediate drainage. In stable patients, the technique should be extended to the lateral chest by searching for the lung point.
- Subcutaneous emphysema and loculated pneumothorax are possible source of pitfalls when lung ultrasound is used to diagnose pneumothorax.
- Hemorrhagic lung areas, alterations in regional lung parenchymal density, and changes in aeration are common features of lung blasts monitored by ultrasound. Evolution toward interstitial and/or consolidation ultrasonographic patterns is usually observed.
- Hemorrhagic effusion is a dependent collection of blood in the pleural space that can be ultrasonographically detected as an anechoic space between the two pleural layers, with occasional internal echoes, in the most dependent chest areas above the diaphragm.

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22

Lung Ultrasound in Acute Respiratory Distress Syndrome (ARDS)

FRANCESCO CORRADI | CLAUDIA BRUSASCO | MARCELO GAMA DE ABREU | PAOLO PELOSI

Overview

Acute respiratory distress syndrome (ARDS) is a clinical entity characterized by acute inflammatory lung injury, increased pulmonary vascular permeability and lung weight, as well as loss of aerated lung tissue. The clinical hallmarks of ARDS are hypoxemia, bilateral opacities detected by chest radiograph or computed tomography (CT) scan, decreased lung compliance, and increased dead space. ARDS has different etiologies, among which the most common ones are sepsis, aspiration, pneumonia, trauma, major surgery, and multiple transfusions.[1]

A new definition of ARDS has been recently proposed based on the presence of the following criteria[2]:

1. *Timing:* Acute onset within 1 week of a known clinical insult or new or worsening respiratory symptoms
2. *Chest imaging:* Bilateral opacities detected by chest radiograph or CT scan
3. *Origin of edema:* Respiratory failure not explained by cardiac failure or fluid overload. Objective assessment by echocardiography or quantification of pulmonary capillary wedge pressure (PCWP) to exclude hydrostatic edema
4. *Oxygenation:* partial pressure of arterial oxygen (Pao_2)/fraction of inspired oxygen (Fio_2) ≤ 300

Moreover, ARDS is classified in three mutually exclusive severity stages depending on the values of Pao_2/Fio_2: mild ([$200 < Pao_2/Fio_2 \geq 300$ with positive end-expiratory pressure (PEEP) or continuous positive airway pressure (CPAP) > 5 cm H_2O]), moderate ($100 < Pao_2/Fio_2 \geq 200$ with PEEP > 5 cm H_2O), and severe ($Pao_2/Fio_2 \leq 100$ with PEEP ≥ 5 cm H_2O).

Past studies using chest CT scans have elucidated that, unlike acute cardiogenic pulmonary edema (ACPE), ARDS is characterized by inhomogeneous pulmonary injury, with some areas of the lungs severely affected, some mildly involved, and others completely healthy.[3,4] However, CT cannot be used on a daily basis because of the high amount of ionizing radiation exposure, the high cost, and the difficulty in transporting patients to the CT scanner. Hence the diagnosis of ARDS may be challenging, especially during its acute phase, because it is not always feasible to perform a CT scan or invasive hemodynamic measurements (e.g., evaluation of PCWP using a pulmonary artery catheter) and because of the tenuous respiratory function and hemodynamic instability of patients. In addition, images from a simple portable chest radiograph are inaccurate in distinguishing an ARDS pattern from ACPE. Recently, lung ultrasound has emerged as a noninvasive, radiation-free, bedside technique with high sensibility in the detection of different lung and pleural disorders, as analyzed in preceding chapters.[5]

Lung Ultrasound B-lines and Extravascular Lung Water

Healthy aerated lungs are featured by an anechoic echotexture. Diseased lungs are characterized by varying amounts of reduced aeration and edema that correspond to progressively dense and/or hyperechoic sonographic patterns (Figure 22-1). The latter is observed mainly due to the increased number and thickness of artifacts (B-lines or comet-tails). B-lines are generated because of subpleural interlobular septal thickening resulting from hydrostatic or "lesional" edema, pulmonary inflammatory edema, and/or fibrosis.[6] Previous work demonstrated that the number of B-lines is proportional to the amount of extravascular lung water, thus being a sensitive sign of alveolar-interstitial syndrome.[7-10] A simple visual score based on the sum of the number of B-lines (in each scanning intercostal space) correlates with chest radiograph visual scores,[6,7] lung weight and density (quantitative CT),[10] PCWP evaluated by the thermodilution method using the invasive pulse-induced contour cardiac output (PiCCO) system (Pulsion Medical Systems, Munich, Germany),[8] and also with lung weight assessed by gravimetry in experimental animals.[11]

Ultrasonographic Signs of Acute Respiratory Distress Syndrome

The main signs that can be recognized by lung ultrasound in cases of suspected ARDS are

1. *B-lines:* Vertical artifact, also called "comet-tail artifact," extending to the edge of the screen, moving within pleural line synchronously with inspiration and effacing A-lines. In ARDS, B-lines should be bilateral and, in number, greater than 3 or more, to confluence in a completely "*white lung.*" In the anterior lung fields, B-lines are not homogeneously distributed, whereas in the posterior lung fields, the B-lines are more compact and homogeneous, producing the image of a global white lung (see Figure 22-1).
2. *Spared areas:* Areas of normal lung that are observed in at least one intercostal space, surrounded by areas of B-lines or white lung (usually in the anterior lung fields) (Figure 22-2).
3. *Consolidations:* Areas of hyperechoic echotexture with punctiform elements or "hepatization," with presence of static or dynamic air bronchograms.[12] In ARDS, consolidations may be located in the posterior lung fields, especially at the bases (Figure 22-3).
4. *Pleural line abnormalities:* Thickening is greater than 2 mm, and there is irregularity of the pleural line as well as evidence of small subpleural consolidations (Figure 22-4). In ARDS,

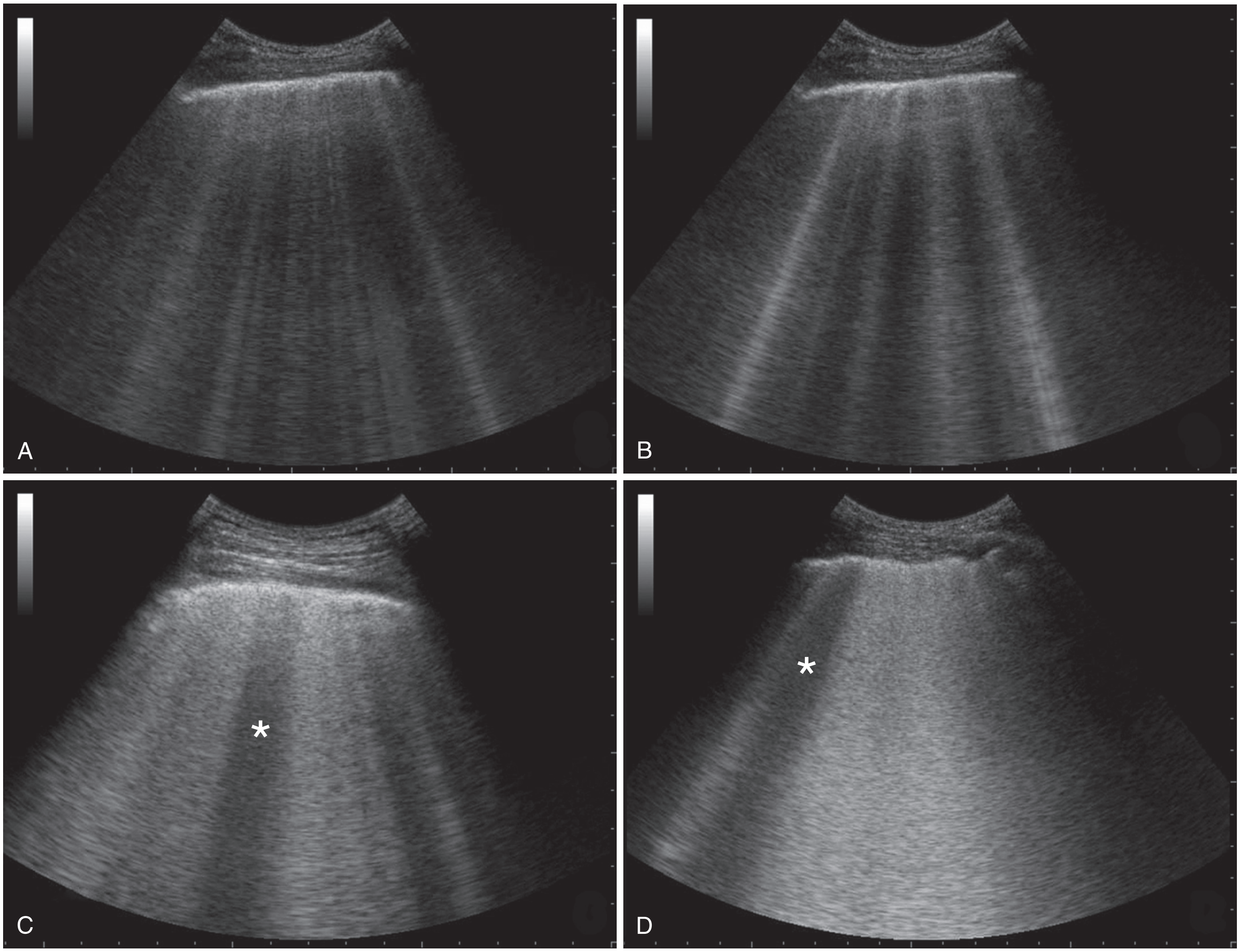

Figure 22-1 Various stages of increasing severity in alveolar-interstitial syndrome: interstitial syndrome (panel **A**), alveolar-interstitial syndrome (panel **B**), more severe alveolar interstitial syndrome with spared area *(star)* and thickening of pleural line (panel **C**) and alveolar-interstitial syndrome with ground-glass attenuation, irregular pleural line and spared area *(star)* (panel **D**).

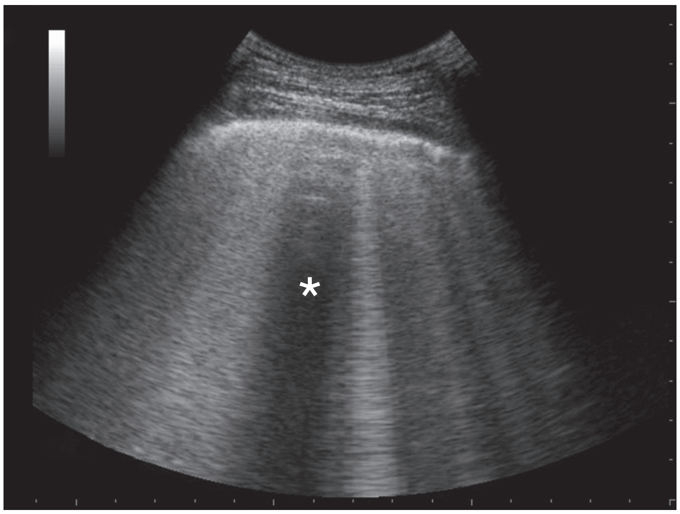

Figure 22-2 Visualization of spared area *(star)* and thickened pleural line in an acute respiratory distress syndrome (ARDS) case.

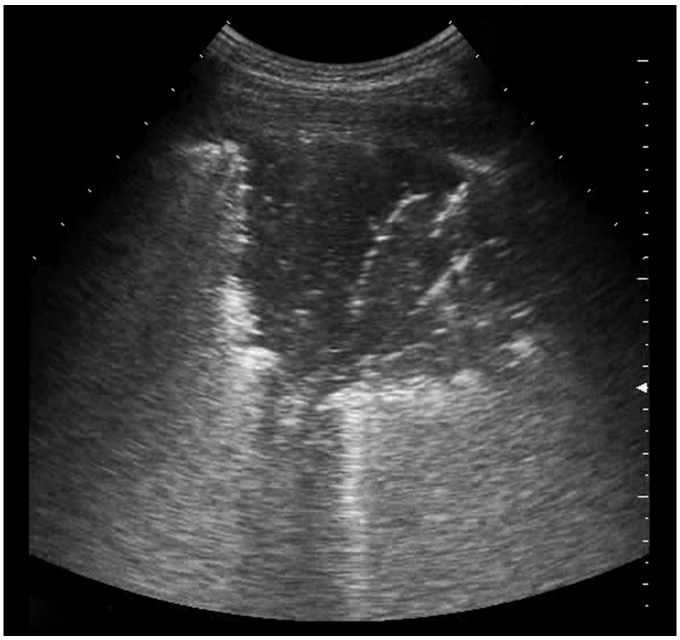

Figure 22-3 Visualization of a pulmonary consolidation and associated air bronchogram in a patient with acute respiratory distress syndrome (ARDS).

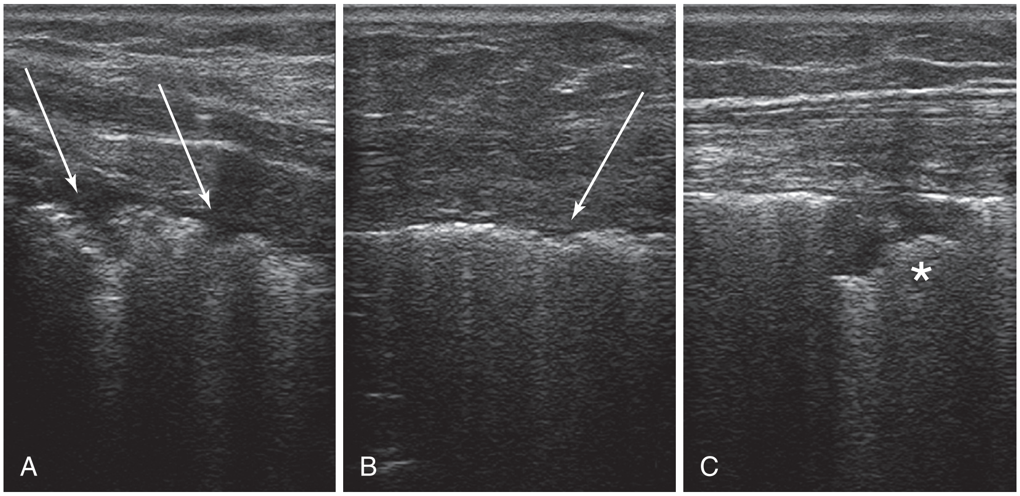

Figure 22-4 Ultrasound scans of the anterior (upper) lung region, by using a high-frequency transducer, depict a thickened irregular pleural line (panels **A** and **B,** *arrows*) and subpleural consolidation and in a patient with acute respiratory distress syndrome (ARDS) case (**C**).

the pleural line is always involved, and this leads to a reduction of *lung sliding.* In white lung areas, lung sliding might be absent and the pleural line may appear to move according to the heartbeat *(lung pulse sign).*

5. *Pleural effusion:* Anechoic and homogeneous pleural areas with no evidence of gas inside, limited by the diaphragm and pleura. If pleural effusion is likely to create a mechanical compression, the lower lung lobe can be visualized as collapsed and floating. Pleural effusion is rarely observed in ARDS. However, this is equally dependent on the primary cause of ARDS (e.g., pancreatitis, lower respiratory tract infection).

Acute Respiratory Distress Syndrome versus Acute Cardiogenic Pulmonary Edema: Differential Diagnosis by Lung Ultrasound

The role of lung ultrasound in the diagnosis of alveolar-interstitial syndrome has been well known since 1997.[6] The nonspecific lung ultrasound pattern (B-lines and white lung), which is predominant in the alveolar-interstitial syndrome, is also observed in other abnormalities characterized by an increase of extravascular lung water with thickening of alveolar septa (e.g., ACPE). In 2008, Copetti et al[13] analyzed lung ultrasound images of 58 consecutive patients affected by ARDS or ACPE and described different pleuropulmonary sonographic patterns to differentiate alveolar-interstitial syndromes. This report suggested that the classic pleuroparenchymal patterns described by CT are similar to the pleuroparenchymal patterns detected by ultrasound in both disorders. In ACPE, a pattern of homogeneous hydrostatic edema with interstitial thickness and subsequent extravasations of fluid in the alveoli, in the absence of impaired alveolar-capillary membrane, can be equally well identified by both CT and ultrasound. However, in ARDS, the integrity of the alveolar-capillary membrane is compromised, and this causes an early, diffuse, heterogeneous alveolar flooding. Hence a homogeneous white lung pattern, which is usually observed in both anterior and posterior lung fields along with evidence of pleural effusion, is predominant in ACPE (Table 22-1). In ARDS, the white lung pattern is rather heterogeneous in the anterior fields of the lung (spared areas), whereas it tends to appear more homogeneous with bilateral pleural line modifications and consolidated areas in the posterior lung fields; however, this is also dependent on the ARDS stage (see Table 22-1).

TABLE 22-1 Lung Ultrasound Findings in ARDS versus ACPE

	ARDS			ACPE		
		Se %	Sp %		Se %	Sp %
B-lines	++ Heterogeneous/ homogeneous	100	0	++ Homogeneous	100	0
Spared areas	11	100	100	2	0	0
Consolidations	11	83.3	100	2	0	0
Pleural line abnormalities	11	100	45	2	25	0
Lung pulse	11	50	100	2	0	50
Pleural effusion	+/−	66.6	5	11	95	33.3

ACPE, Acute cardiogenic pulmonary edema; *ARDS*, acute respiratory distress syndrome; *Se*, sensitivity; *Sp*, specificity.

The Integration of Lung Ultrasound in Acute Respiratory Distress Syndrome Management

The therapeutic management of ARDS depends on its underlying etiology as well as its morphology and severity.

LUNG MORPHOLOGY: DIFFUSE OR FOCAL LOSS OF AERATION?

Lung ultrasound can be very useful to assess lung morphology. Indeed, ARDS can be classified as *focal* or *diffuse* based on the distribution of aeration loss as detected by ultrasound.[14] A focal ARDS pattern is ultrasonographically evident by the presence of normally aerated anteriolateral lung fields (A-line profile and normal lung sliding) and by loss of aeration in the posterolateral lung fields (multiple B-lines and areas of consolidation). A diffuse ARDS pattern is ultrasonographically identified by a global loss of aeration (multiple B-lines and areas of consolidation) in all pertinent lung fields (upper, lower, anterior/posterior, and lateral). The identification of a focal loss of aeration points toward a more careful application of mechanical ventilation because high PEEP might generate a hyperinflation of healthy lung regions, thus increasing the risk of lung stress and strain. In contrast, a diffuse loss of aeration usually permits the application of higher levels of PEEP to optimize global lung recruitment.[15,16] Of note, 70% of ARDS cases present with a focal lung morphology pattern, and 25% of cases with a diffuse pattern. Hence it is essential to identify the two different aeration patterns and adjust accordingly the applied mechanical ventilation strategies.[17]

LUNG RE-AERATION SCORE

Recently, Bouhemad et al[18] have validated an ultrasound score to assess lung aeration. The score classifies four main lung aeration conditions: (1) a normal aerated lung with A-lines and lung sliding, (2) the interstitial syndrome with B-lines at intervals of 7 mm, (3) the alveolar-interstitial syndrome with B-lines at intervals of 3 mm or less, and finally (4) the alveolar consolidation. The score analyses 12 lung areas. The summation of the results obtained from each area provides an idea of the global lung aeration and correlates well with lung aeration patterns determined by quantitative CT. An ultrasound score less than 5 was associated with re-aeration and therapy success, whereas an ultrasound score less than 10 was associated with exacerbation of aeration loss and therapy failure. The ultrasound re-aeration score seems to be a reliable method to monitor ARDS patients daily.[19] This ultrasound monitoring also facilitates the prompt detection of the results (e.g., improvement of lung aerations) of ongoing therapy (e.g., protective ventilation, antimicrobial therapy, drainage of pleural effusion). The ultrasound lung re-aeration score is further analyzed in Chapter 23.

Technical Issues

Lung ultrasound should examine the entire lung fields, bilaterally, when evaluating patients with alveolar-interstitial syndrome. However, intensive care unit (ICU) patients are usually in a supine position, and thus posterior lung fields (sometimes even lateral fields) may not be easily accessible compared with the anterior ones. It is useful to adopt a systematic scanning protocol by dividing the lung into six regions (upper and lower—anterior, lateral, and posterior regions), which are further outlined by the anterior and posterior axillary lines (see Chapter 1). Lung ultrasound parenchymal scanning (see Figure 22-1) is usually performed by means of low-frequency convex transducers (which permit analysis of deeper structures), whereas high-frequency transducers can better visualize and thus analyze more superficial structures, such as abnormalities of the pleural line (see Figure 22-4). Finally, microconvex transducers are extremely useful because of their small footprints, when scanning between intercostal spaces (see Chapter 1).

CASE

A patient was admitted in our unit because of respiratory failure requiring emergent intubation on the grounds of endocarditis with severe mitral valve regurgitation. A chest radiograph revealed a bilateral white lung pattern that was consistent with the diagnosis of alveolar-interstitial syndrome. Based on his history, ACPE was suspected. However, bedside ultrasound revealed the presence of a marked irregularity of the pleural line, a focused pattern of subpleural consolidation (spared areas), and posterior basal atelectasis without pleural effusion. The findings were consistent with ARDS. The latter was confirmed by depiction of a PCWP of 12 via a pulmonary artery catheter. The early use of lung ultrasound allowed the discontinuation of diuretic therapy, prompt initiation of antibiotic therapy, lung protective ventilation with optimal PEEP, and facilitated the recruitment of atelectatic regions of lung parenchyma, as confirmed by an amelioration of the re-aeration score.

Pearls and Highlights

- Lung ultrasound lung is an invaluable tool in the diagnosis and management of mechanically ventilated ARDS patients.
- Usual ultrasonographic findings in patients with ARDS may include B-lines, spared areas of normal lung parenchyma, consolidated areas, pleural line abnormalities, and pleural effusions.
- In ACPE, a homogeneous white lung pattern is usually observed in both anterior and posterior lung fields along with pleural effusion.
- In ARDS, the white lung pattern is usually heterogeneous in the anterior lung fields and more homogeneous in the posterior ones, but pleural effusion is uncommon. However, with ARDS, ultrasonographic patterns depend much on the primary etiology and stage.
- ARDS can be classified as focal or diffuse based on the distribution of aeration loss as detected by ultrasound. This is an important discrimination because it may facilitate the optimization of mechanical ventilation strategies.

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23

Lung Ultrasound in Mechanically Ventilated Patients

OWEN MOONEY | ANDREW W. KIRKPATRICK | LAWRENCE M. GILLMAN

Overview

Mechanically ventilated patients often have contraindications to transport outside a monitored setting. Ultrasound is an alternative to traditional imaging techniques in the critical care environment because of its portability, absence of radiation, and real-time image acquisition. This chapter will highlight the utility of bedside ultrasound in the day-to-day management of mechanically ventilated patients.

Recruitment/Positive End-Expiratory Pressure (PEEP)

Recruitment maneuvers play an integral role in the management of patients with severe lung injury. Key to the success of a recruitment maneuver is identification of patients with potentially recruitable lung units. However, the amount of potentially recruitable lung varies widely within this patient population, from negligible to upward of 50% of lung weight.[1] Identifying who will and will not benefit from such maneuvers is crucial because there are risks to maintaining these high airway pressures, even if done transiently, including hemodynamic effects, pneumothoraces, and unintended airway trauma.

High-resolution computed tomography (CT) of the chest and evaluation of static pressure-volume loops on modern ventilators have been used to assess the effectiveness of lung recruitment. However, each of these has potential limitations because the improvements in oxygenation may not be immediately evident.[2] Point-of-care lung ultrasound offers a noninvasive, portable, easily reproducible method of identifying potential recruitable lung parenchyma. The normal and abnormal ultrasonographic appearance of lung parenchyma has been well described in previous chapters. The degree of lung aeration can easily be identified at the bedside. This bedside assessment can be categorized into four discrete ultrasonographic patterns.[3] These patterns include (1) horizontal A-lines, representing normal lung aeration; (2) multiple vertical B-lines that are regularly spaced, representing a moderate loss of lung aeration; (3) coalescence of closely spaced B-lines, representing severe loss of lung aeration; and finally, (4) gross collapse. With this simple classification, researchers have developed a prediction model to better define how much an individual patient may benefit from attempts at lung recruitment (Table 23-1). The lung re-aeration score is simply a tool that helps quantify the amount of lung recruited (in milliliters) postrecruitment. This scoring system has been validated against traditional pressure-volume loop analysis.[3] Each lung is systematically examined in six lung regions (upper anterior, posterior, and lateral; lower anterior, posterior, and lateral). The prerecruitment degree of lung aeration is then categorized as normal (N), moderate loss of aeration (B1), severe loss of aeration (B2), or completely consolidated (C) in each of these regions. A score of 1, 3, or 5 is then assigned to the change in the appearance of the lung postrecruitment. For example, an area of lung that went from being completely consolidated (C) to normal (N) would be assigned 5 points, whereas an area of lung that went from completely consolidated (C) to moderate loss of aeration (B1) would be assigned 3 points. The lung aeration score is calculated by the sum of scores from each of the six lung regions. A lung aeration score of +8 predicts a recruitable lung volume of greater than 600 mL, with the application of moderate amounts of PEEP.[4] Identification of patients who will minimally benefit (lung aeration score <8) from such maneuvers is tantamount in avoiding unnecessary and potential harmful attempts at future recruitment.

The "lung pulse" has also been advocated to identify potentially recruitable lung units.[5] Sliding of the pleura with respiration in normal lungs prevents ultrasonographic perception of cardiac oscillation. When visualized lung is atelectatic, the motion of the patient's beating heart is transmitted through the collapsed lung and perceived as cyclic motion, termed the lung pulse. Abolishment of this sign and the resumption of normal lung sliding postrecruitment maneuver can be an early sign of successful reexpansion of collapsed lung.[5]

The duration and level of peak airway pressure attained during recruitment is variable between studies and institutions. This may be because each collapsed lung unit has a unique time constant, and a "one-size-fits-all protocol" may not be appropriate to all patients. The use of real-time lung ultrasound allows the operator direct visualization of the lung during recruitment, thus yielding real-time feedback and allowing customization of both the peak pressure and duration of the maneuver (Figure 23-1, Video 23-1).[3,4,6]

After successful recruitment of atelectatic lung, it is important to ensure that the recruited lung does not derecruit after the sustained high airway pressure is removed. Arbitrarily increasing the PEEP postrecruitment maneuver without confirmation that reexpansion of collapsed lung was successful can have detrimental effects on other areas of the lung. When the increased PEEP is not transmitted to the atelectatic lung, the parts of the lung that were nonatelectatic are now exposed to higher end-expiratory pressures, potentially resulting in overdistention and worsening V/Q mismatch. In theory, direct visualization of the lung would be of benefit for the setting of "best" PEEP, but further research is needed to validate its use routinely.

TABLE 23-1 Ultrasound Lung Re-aeration Score

QUANTIFICATION OF RE-AERATION			QUANTIFICATION OF LOSS OF AERATION		
1 point	3 points	5 points	1 point	3 points	5 points
B1→N	B2→N	C→N	N→C	N→B2	N→B1
B2→B1	C→B1			B1→C	B1→B2
C→B2					B2→C

Modified from Bouhemad B, Brisson H, Le-Guen M, et al: Bedside ultrasound assessment of positive end-expiratory pressure-induced lung recruitment, Am J Respir Crit Care Med *183(3):341-347, 2001.*

B1, Multiple, well-defined, either regularly spaced 7 mm apart or irregularly spaced B-lines (moderate loss of lung aeration); B2, multiple coalescent B-lines (severe loss of lung aeration); C, lung consolidation; N, normal pattern (normal lung aeration).

Note: The ultrasound re-aeration score is calculated as follows: In a first step, ultrasound lung aeration (N, B1, B2, and C) is assessed in each of 12 lung regions, examined before and after application of positive end-expiratory pressure of 15 cm H_2O. In a second step, the ultrasound lung re-aeration score is calculated as the sum of each score characterizing each lung region and examined according to the scale shown in the table above.

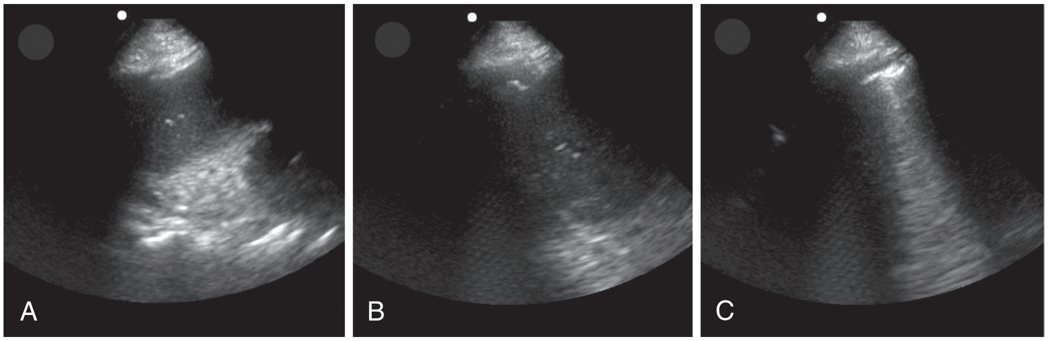

Figure 23-1 Point-of-care lung ultrasonogram during a recruitment maneuver. Lung tissue can be seen to progress from initial lung atelectasis **(A)** to improving atelectasis **(B)** and eventually visualization of the pleural interface and comet-tail artifacts **(C)** as the atelectatic lung expands.

Screening for Complications of Mechanical Ventilation

As well described in Chapter 21, lung ultrasound is both a sensitive and specific method of identifying pneumothoraces. Critically ill patients undergoing mechanical ventilation are at high risk of developing a pneumothorax from invasive procedures (e.g., central line placement, thoracentesis) or simply from the mode of ventilation.[7] This is a very dangerous occurrence because mortality has been reported as being up to 91% if a tension pneumothorax occurs on a ventilator. In patients with a high clinical suspicion of pneumothorax, awaiting a chest radiograph or CT scan to confirm or refute its presence can delay intervention, which may have detrimental effects on the patient. However, blind needle decompression or chest tube placement in these critically ill patients with tenuous respiratory status, although sometimes lifesaving, can have severe consequences if the diagnosis is incorrect. As well, even the complication rate of tube thoracostomy tubes is much greater than clinicians typically perceive. The speed and accuracy of diagnosis without having to transport the patient outside a monitored setting makes ultrasound an attractive alternative to other methods used to identify a pneumothorax.

The Difficult-to-Wean Patient

Prolonged mechanical ventilation has been associated with a number of serious complications.[8] Patients who are difficult to wean from mechanical ventilation make up 20% to 30% of intubated patients in an intensive care unit (ICU).[9] The etiology of liberation failure is complex and multifactorial. It is important to undertake a systematic evaluation of these difficult-to-wean patients in order to identify potentially reversible causes that may be impairing weaning. Point-of-care ultrasound can be an effective tool in the evaluation of such patients.

EVALUATION OF THE PLEURAL SPACE

Pleural effusions can compromise chest wall compliance and lead to compressive atelectasis. This can ultimately lead to prolongation of mechanical ventilation, especially in those patients whose respiratory status is tenuous.[10] Ultrasonography has both diagnostic and therapeutic implications in the management of pleural effusions. First, identifying the volume of effusion can help predict the potential benefit of fluid removal. Balik, et al[11] have developed simple formulas to aid in the quantification of pleural fluid:

$$V\ (\text{mL}) = 20 \times \text{Sep}\ (\text{mm})$$

where V is equal to the calculated volume of the effusion in milliliters and Sep is the maximal distance between the visceral and parietal pleura measured in the posterior axillary line of the patient at an angle of approximately 15 degrees from supine.

Ultrasound also allows dynamic visualization of the pleural space, intercostal spaces, and hemidiaphragms, which helps to ensure safe entrance into an appropriate location.[12] Real-time visualization of the needle/introducer tip can help in minimizing complications through inadvertent puncture of lung parenchyma or other structures.

EVALUATION OF DIAPHRAGMATIC WEAKNESS/ EXCURSION

Ventilator-induced diaphragmatic dysfunction is a common complication of mechanical ventilation[9,13] and likely contributes to patients' failure to liberate from the ventilator. Measurement of diaphragm function with nerve conduction studies and fluoroscopic evaluation is complex and impractical. In recent years, lung ultrasound has been evaluated as a noninvasive bedside method of assessing diaphragmatic function.[14] Diaphragmatic excursion, measured by M-mode ultrasonography, can be used adjunctively with the rapid-shallow breathing index (RSBI) to aid in the identification of those patients at high risk of postextubation distress[15] as well as in the workup of patients who require prolonged mechanical ventilation.

With the patient in the supine position, a low-frequency ultrasound probe is placed in the anterior axillary line. Time motion (M) mode is used to measure diaphragmatic movement during inspiration and expiration. An excursion distance of less than 10 mm or paradoxic diaphragmatic movement is suggestive of diaphragmatic dysfunction (Figure 23-2).[13] This evaluation can provide static measurements for diagnostic purposes and dynamic measurements, which can be helpful for following the progression or regression of the patient.

Evaluation of Lung Parenchyma

Lung ultrasound allows the operator to distinguish different forms of parenchymal lung problems. As outlined in previous chapters, the identification of B-lines can be indicative of loss of lung aeration or interstitial and alveolar edema,[2,16,17] whereas "hepatitization" of lung tissue along with "dynamic air bronchograms" is suggestive of dense consolidation and may prompt consideration of therapeutic bronchoscopy to reexpand these consolidated areas to facilitate ventilator weaning.[18,19]

The lung re-aeration score, as described above, can also have a role in identifying those patients who are at high risk of postextubation failure.[16] Because the lung re-aeration score is useful in quantifying the amount of volume gained with a recruitment maneuver, it can also help quantify the amount of volume lost with reduction in ventilatory support. The lungs are examined systematically before and then during a spontaneous breathing trial. A lung re-aeration score of greater than 17 (see Table 23-1) during a spontaneous breathing trial suggests significant derecruitment and is predictive of postextubation distress, whereas a lung re-aeration score (LAS) less than 12 may predict successful extubation.[16]

Evaluation of the Abdomen

Intraabdominal pathology within the ICU is often overlooked as a potential contributor to prolonged mechanical ventilation. Peritoneal fluid within the intraabdominal cavity can have negative effects on the compliance of the respiratory system, especially if it induces intraabdominal hypertension (IAH). IAH in the setting of acute respiratory distress syndrome (ARDS) further exacerbates lung edema and increases the degree of atelectasis, especially in cases of extrapulmonary ARDS. Short of surgical decompression, severe IAH can often be successfully ameliorated through the use of ultrasound-guided paracentesis if fluid is present that can be safely drained. Again, in this respect, ultrasound serves both diagnostic and therapeutic purposes in identifying intraabdominal fluid that can be safely percutaneously accessed. Dynamic ultrasonography during a peritoneal tap can ensure that vital structures are not accidentally punctured.

Evaluation of Cardiac Function

Mechanical ventilation has a number of beneficial effects on the physiology of the weakened heart.[19] Positive pressure ventilation

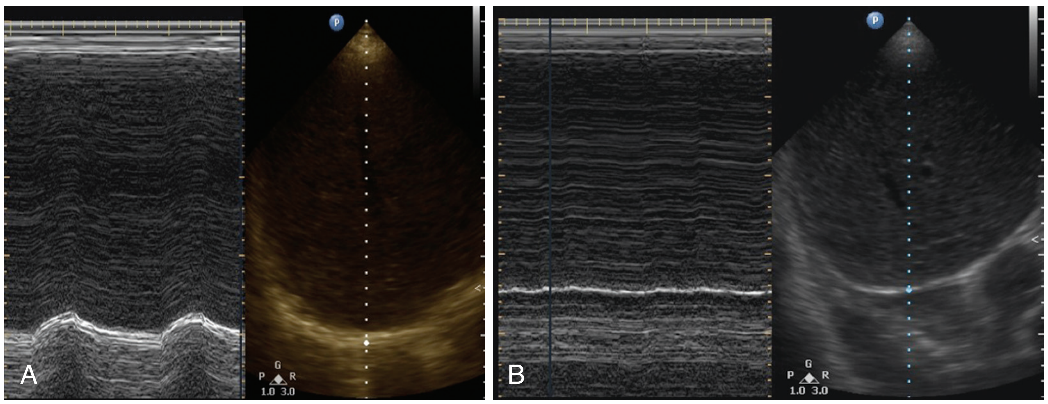

Figure 23-2 Point-of-care lung ultrasonogram of diaphragmatic excursion in a patient with normal diaphragmatic excursion **(A)** and diaphragmatic paralysis **(B).** Time motion (M) mode can be seen in the *left* panel, with the corresponding B-mode image on the *right. (Courtesy Dr. Dimitrios Karakitsos.)*

decreases preload by increasing intrathoracic pressure, thus reducing venous return to the right heart. The elevation in intrathoracic pressure also augments afterload by reducing the transmural pressure gradient of the left heart. With removal of mechanical ventilation, both preload and afterload are increased, along with an increase in oxygen consumption caused largely by the increased work of breathing placed on the respiratory muscles.[9] Subclinical myocardial ischemia is an underappreciated cause of the difficult-to-wean patient. In these patients, ultrasound can be used to dynamically assess the effects of weaning ventilation on the cardiac function of the heart. This "stress test" can potentially reveal patients who will develop myocardial ischemia with weaning.

Lung Ultrasound with Alternative Forms of Ventilation

Advances in technology and critical care medicine have brought along alternative forms of mechanical ventilation, termed nonconventional mechanical ventilation. One such form of ventilation is high-frequency oscillatory ventilation (HFOV). First used in the 1960s, this alternative form of ventilation uses constantly maintained, high mean airway pressures to prevent derecruitment. Recent advances in lung protective ventilation in the treatment of ARDS have increased the use of HFOV in this subset of patients.[20] Although it still remains mainly a rescue therapy, the results of ongoing studies of early acute lung injury/ARDS may make its use more mainstream.

Although theoretically reducing volutrauma and atelectrauma, the high mean airway pressures of HFOV result in a substantial risk of barotrauma. However, making the diagnosis of a pneumothorax during HFOV can be extremely challenging. Classic physical examination findings of asymmetric breath sounds are limited by the background noise of the ventilator and the lack of true breath sounds with HFOV. The greatest strength of lung ultrasound in this situation lies in its ability to rule out rather than rule in a pneumothorax. The visualization of comet-tail artifacts or normal lung sliding implies the apposition of the parietal and visceral pleura and essentially rules out a pneumothorax at that probe position with close to 100% negative predictive value.[21-23]

There have been some theoretic concerns that because of the extremely small and rapid tidal breaths used during HFOV (3-12 per second), lung sliding may be absent or undetectable even in the absence of pneumothoraces. Only a single case study has reported on the use of lung ultrasound in this patient population.[7] In that case, normal lung sliding was visualized on one hemithorax in a patient on HFOV and was absent on the opposite side (Figure 23-3, Videos 23-2 and 23-3), where a pneumothorax was later confirmed by detection of a lung point (Figure 23-4, Video 23-4). However, depending on the power and frequency settings (which determine tidal volumes), lung sliding may still be subtle or undetectable, and its absence should not be relied upon as the sole sign for diagnosis of pneumothorax. There have been no reports of lung ultrasound in other alternative forms of ventilation, but it seems like an ideal method for the evaluation for pneumothoraces in the prone positioned patient.

Lung ultrasound represents an ideal tool for rapid, repeated, and noninvasive evaluation of the critically ill, mechanically ventilated patient. From the initiation of the mechanical ventilation to guiding recruitment and evaluating for complications and assessment of weaning, its role extends throughout a patient's ICU stay.

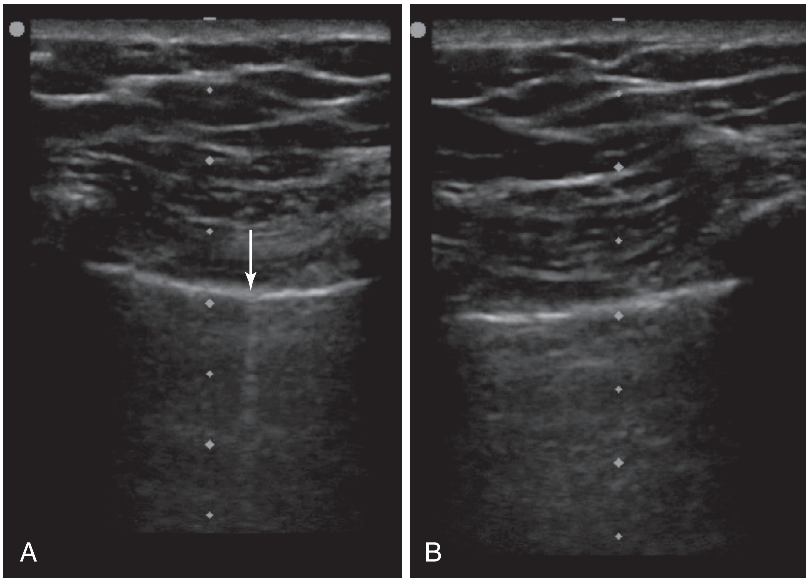

Figure 23-3 Point-of-care lung ultrasonogram of the right lung **(A)** of a patient receiving high-frequency oscillatory ventilation (HFOV), confirming the absence of a pneumothorax by the presence of lung sliding (not shown) and comet-tail artifacts *(arrow),* and of the left lung **(B),** suggesting the presence of a pneumothorax by the absence of lung sliding and comet-tail artifacts. *(Republished with permission of the* Journal of Ultrasound in Medicine: *From Gillman LM, Kirkpatrick AW: Lung sonography as a bedside tool for the diagnosis of a pneumothorax in a patient receiving high-frequency oscillatory ventilation,* J Ultrasound Med *29:997-1000, 2010. Permission conveyed through the Copyright Clearance Center.)*

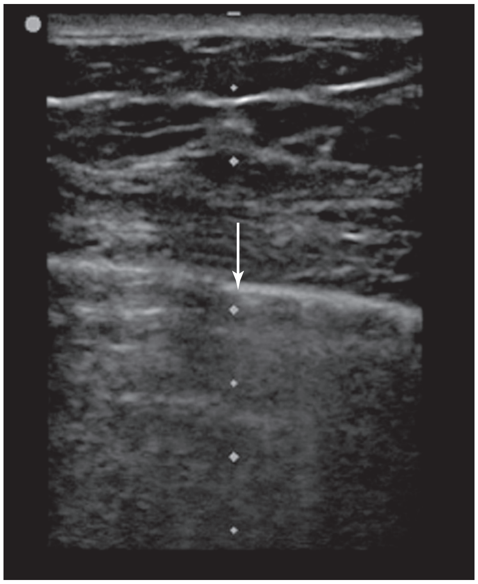

Figure 23-4 Point-of-care lung sonogram of the left lung of a patient receiving high-frequency oscillatory ventilation (HFOV), confirming the presence of a pneumothorax by the presence of a lung point *(arrow)*. *(Republished with permission of the* Journal of Ultrasound in Medicine: *From Gillman LM, Kirkpatrick AW: Lung sonography as a bedside tool for the diagnosis of a pneumothorax in a patient receiving high-frequency oscillatory ventilation,* J Ultrasound Med *29:997-1000, 2010. Permission conveyed through the Copyright Clearance Center.)*

Pearls and Highlights

- Through direct visualization of the lung, ultrasound can be used to identify patients with recruitable lung parenchyma and in real time can guide and personalize recruitment maneuvers.
- Ultrasound can be incorporated into a comprehensive approach to the difficult-to-wean patient by systematically evaluating for and potentially guiding treatment of parenchymal, pleural, intraabdominal, and cardiac disease, and of diaphragmatic dysfunction.
- Lung ultrasound can potentially be used in the identification of pneumothoraces as a complication of nonconventional modes of ventilation such as HFOV.

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24

Lung Ultrasound: Protocols in Acute Dyspnea

CARLA VENEGAS | LEWIS A. EISEN | ARIEL L. SHILOH

Overview

Lung ultrasound is becoming a standard diagnostic and therapeutic tool in the management of intensive care unit (ICU) patients, as analyzed extensively in this section of the book. It helps the clinician to rapidly evaluate thoracic pathologies and guide many bedside procedures. Thoracic ultrasound and the findings that follow are described in detail in previous chapters. This chapter aims to offer protocols and review specific profiles that will assist in the evaluation of acute dyspnea.

Instrumentation and Technique

Use of a microconvex transducer with a 4- to 8-MHz frequency range is recommended. In general, the microconvex transducer is used for the evaluation of the lung and the pleural space, but a high-frequency probe also can be used for the specific diagnosis of a pneumothorax when using ultrasound for vascular access. The intubated patient is almost always examined in the semirecumbent or supine position (Figure 24-1).

For the ultrasound examination, the thorax can be divided into three anatomic areas: anterior, lateral, and posterior, delineated by the anterior and posterior axillary lines. Each of these areas is divided in half, forming upper and lower sections. These divisions form six anatomic regions: upper and lower sections of the anterior, lateral, and posterior chest wall.

The technique is as follows:

1. Expose the thorax and place ultrasound gel on the six regions of the chest.
2. Start the examination with the transducer in the first intercostal space in the upper anterior region of the chest, with the ultrasound marker pointing toward the head of the patient.
3. Continue the examination by sliding the ultrasound probe in a longitudinal direction, from the head toward the toes of the patient.
4. Visualization is performed in each intercostal space, concentrating on the image between the two rib shadows, and should last for at least one complete respiratory cycle.
5. Repeat the process in the lateral and posterior chest walls in the same manner.
6. The following lung findings are evaluated:
   a. A-lines
   b. B-lines
   c. Sliding lung
   d. Pleural effusions
   e. Consolidation
7. In addition to lung findings, the following can be evaluated to supplement the examination:
   a. Left ventricular function and size
   b. Right ventricular function and size
   c. Lower extremity vasculature for thrombosis

In 2008, Daniel Lichtenstein evaluated the potential of lung ultrasound in diagnosing acute dyspnea.[1] Ultrasonography was performed on patients with acute respiratory failure, comparing lung ultrasonography results on initial presentation with the final diagnosis by the ICU team. The study developed the *BLUE Protocol* (*B*edside *L*ung *U*ltrasound in *E*mergency Protocol) as a diagnostic tool (Figure 24-2). The following patterns and profiles were established:

1. Predominance of A-lines in the presence of lung sliding indicated an exacerbation of asthma or chronic obstructive pulmonary disease (COPD) (89% sensitivity and 97% specificity).
2. Multiple, anterior diffuse B-lines in the presence of lung sliding indicated pulmonary edema (97% sensitivity and 95% specificity).
3. Normal anterior profile in the presence of a deep venous thrombosis indicated pulmonary embolism (81% sensitivity and 99% specificity).
4. Anterior absence of lung sliding in the presence of A-lines and lung point indicated pneumothorax (81% sensitivity and 100% specificity).
5. Anterior alveolar consolidations, anterior diffuse B-lines with abolished lung sliding, anterior asymmetric interstitial patterns, posterior consolidations, or effusions in the absence of anterior diffuse B- lines indicated pneumonia (89% sensitivity and 94% specificity).

The use of these profiles provided an accurate diagnosis in 90.5% of cases of acute respiratory failure.[1] We recommend looking for the following signs and findings to organize a diagnostic approach while evaluating a patient with acute dyspnea:

1. Localize and observe the relationship between the lung surface, the pleural line, and the upper and lower rib. The lack of normal relationship may indicate subcutaneous emphysema.
2. Then look for the presence of lung sliding. Abolished lung sliding is indicative of pneumothorax if accompanied by the "lung point sign."
3. In the presence of lung sliding, then look for the A-lines, which indicate presence of air. It can be physiologic or pathologic. For further analysis, it is recommended to perform an ultrasound venous examination. The interpretation of the findings can be as follows:
   a. Presence of A-lines and a thrombosed vein suggest pulmonary embolism.
   b. Presence of A-lines and the absence of deep vein thrombosis suggest pneumonia in the presence of a posterior lateral alveolar/pleural syndrome (PLAPS) or COPD/asthma in the absence of PLAPS.

Figure 24-1 Patient positioning. The intubated patient is almost always examined in supine position. Check all six anatomic regions: upper and lower sections of the anterior, lateral, and posterior chest wall.

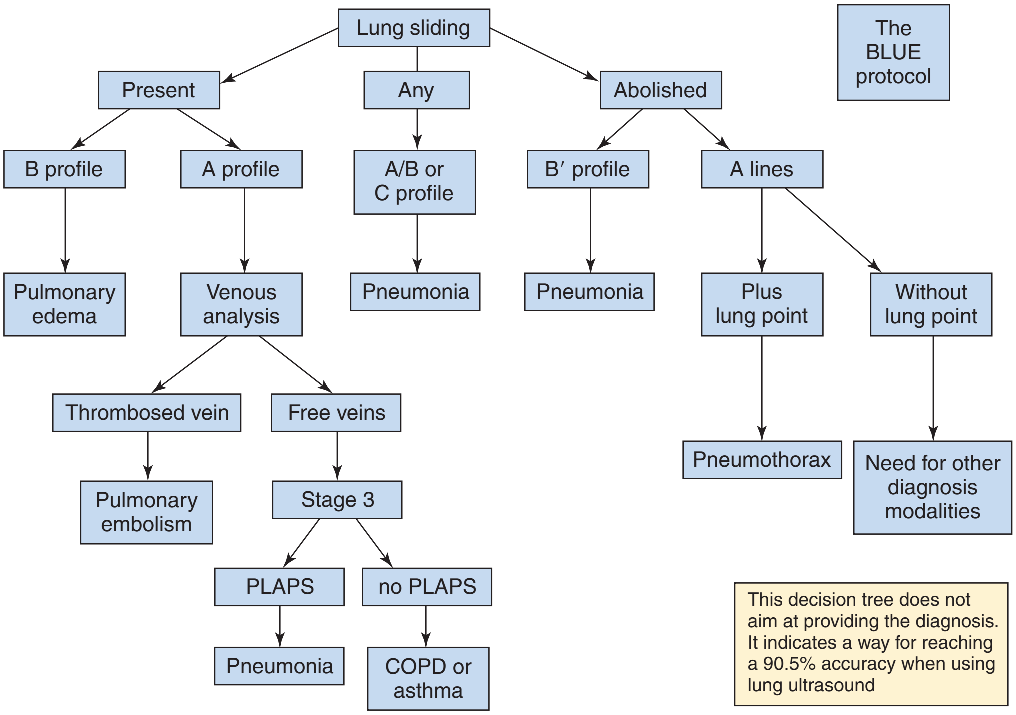

Figure 24-2 The BLUE Protocol: A decision tree using lung ultrasonography to guide diagnosis of severe dyspnea. *(From Lichtenstein D, Mezière G: Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE Protocol.* Chest 134(1):117-125, 2008.)

4. Then check for the presence of B-lines. The presence of one B-line is enough for ruling out the diagnosis of pneumothorax where the transducer is applied. The presence of B-lines and other accompanying signs need further analysis for correct interpretation.
   a. Diffuse, bilateral B-lines (at least in four points of the anterior chest wall) may indicate cardiogenic or noncardiogenic pulmonary edema. Performing echocardiography may be helpful in this case.
   b. Focal B-lines may indicate interstitial syndrome.
5. The last step is to look for the "sinusoid sign" to identify the presence of any kind of pleural effusion. This sign diagnoses pleural effusion, regardless of its echogenicity, and indicates the possibility of using a small needle for withdrawing fluid.

How to Interpret the Thoracic Ultrasound Findings in the Workup for Dyspnea

Acute dyspnea is a common challenging scenario that requires an appropriate diagnosis and early medical therapy. Management of critically ill patients very frequently requires imaging tools that are essential for optimizing diagnostic and therapeutic procedures.[2] In this section, we will explore the statistical analysis that supports the thoracic ultrasound findings in the diagnosis and management of acute dyspnea.

Gavi et al[3] studied the concordance of the pre-ultrasound physician diagnoses versus the ultrasonic diagnoses while approaching acute dyspnea. They found that the ultrasound diagnoses are more often in concordance with final diagnoses (66%)

than the pre-ultrasound physician diagnoses (50%), and in about 30% of the cases, the ultrasound findings may correctly change the initial therapeutic management. During this study, the diagnostic ultrasound was performed in a very short period of time, ranging from 60 to 270 seconds.[3] After recognizing ultrasound as a fast and useful diagnostic tool in the evaluation of acute dyspnea, the following are the most common abnormal findings in the thoracic ultrasonography.

Alveolar-interstitial syndrome: Using a standard ultrasound probe, it is possible to differentiate a thickened interlobular septum representing interstitial edema (seen as multiple B-lines at least 7 mm apart) from a ground-glass area representing an alveolar edema (observed as multiple B-lines 3 mm or less apart). In a European study, Gargani et al found that in patients with acute dyspnea, the presence of pulmonary congestion (sonographically seen as B-lines) is significantly correlated to N-terminal pro-brain natriuretic peptide (NT-proBNP) values ($r = .69$, $P < .0001$, sensitivity 97%, specificity 92.6%), and this finding is highly accurate in predicting the cardiac origin of dyspnea.[4] In another study published by Stefanidis et al,[5] lung ultrasound showed high sensitivity and specificity values (ranging from >80% for the lower lung fields up to >90% for the upper lung fields) in detection and localization of the alveolar-interstitial syndrome in the critically ill.

Pleural effusions: In a prospective study comparing the diagnostic accuracy of both bedside chest radiography and lung ultrasound versus thoracic computed tomography (CT), Lichtenstein et al[6] showed that lung ultrasound had a diagnostic accuracy of 93% for pleural effusion, 97% for alveolar consolidation, and 95% for alveolar-interstitial syndrome versus 47%, 75%, and 72%, respectively, with bedside chest radiography. Interobserver agreement for the ultrasound findings was satisfactory: 0.74, 0.77, and 0.73 for detection of alveolar-interstitial syndrome, alveolar consolidation, and pleural effusion, respectively.

Pneumonia: Lung consolidations are described as the presence of B-lines with absent lung sliding. It appears as poorly defined hypoechoic lung tissue structure. Also, with ultrasound it is possible to visualize air bronchograms within consolidated lung. Lung ultrasound has been shown to provide the possibility of assessing quantitatively the lung re-aeration resulting from antimicrobial therapy in critically ill patients with ventilator-associated pneumonia.[2] Although more studies are needed in this field, a tight correlation was found between pulmonary re-aeration measured by lung CT and the change in the "ultrasound score."

Pneumothorax: There are two different signs that can suggest the presence of a pneumothorax. First, there is the lack of sliding lung resulting from a parietal–pleura air interface. This sign has a sensitivity of 92% when compared with the gold standard CT scan of the chest. Always look for loculated posterior, mediastinal, and apical pneumothoraces. Second, the presence of a lung point, described as the place where it is possible to observe an anterior movement of the pleura and a posterior displacement of the lung, is a specific sign of pneumothorax. This sign is seen when alternating lung sliding and abolished lung sliding are at the same location. In general, the sensitivity and specificity of lung ultrasound for diagnosing pneumothorax were 86% and 97%, respectively, whereas conventional chest radiography had sensitivity and specificity of 28% and 100%, respectively.[7] In his study, Dulchavsky et al[7] demonstrated that bedside lung ultrasound is more efficient than bedside chest radiography for diagnosing pneumothorax in emergency conditions.

In conclusion, ultrasound is becoming a standard tool in critical care. It is noninvasive, easily repeatable at the bedside, and provides an accurate evaluation of the respiratory status of patients with acute dyspnea. Bedside lung ultrasound is highly sensitive, specific, and reproducible for the detection of several thoracic disorders and thus is an essential tool for the diagnosis and management of acute respiratory failure.

Pearls and Pitfalls

- Lung ultrasound is an operator-dependent imaging modality. Focused, supervised training is needed to ensure that the operator correctly interprets the ultrasonographic findings. Inadequate training may increase the risk of misinterpretation and complications.
- For obese patients and multiple trauma patients with subcutaneous emphysema, the visualization of lung parenchyma might be difficult.
- The use of established lung ultrasound profiles provides correct diagnoses in 90.5% of acute dyspnea cases.
- The ultrasonographic diagnosis of pneumothorax is considered one of the most difficult parts of training.[8] When possible, the use of higher emission frequencies (up to 12 MHz) facilitates the recognition of lung sliding abolition. The diagnosis is even more difficult in the presence of partial pneumothorax. The patient should lie strictly supine to allow location of pleural gas effusion in nondependent lung regions.
- Although ultrasound is among the most useful tests for the evaluation of acute dyspnea, it should always be interpreted in the context of the clinical information and other tests.

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25

Endobronchial Ultrasound

SEPTIMIU MURGU | HENRI COLT

(CONSULTANT-LEVEL EXAMINATION)

Overview

Convex probe endobronchial ultrasound-guided transbronchial needle aspiration is used for diagnosing (and staging) intrathoracic lymphadenopathy in lung cancer,[1] other intrathoracic tumors,[2] and lymphadenopathy from extrathoracic malignancies.[3] The aspiration yield for benign causes of intrathoracic lymphadenopathy is less than with cancer, mostly because of lack of tissue architecture in cytology specimens, but sarcoidosis, and bacterial, mycobacterial, and fungal infections can be diagnosed.[4-6] High-frequency endobronchial ultrasound (EBUS), using a radial scanning probe, is used to diagnose peripheral pulmonary nodules[7] and to define airway wall structures in tracheal stenosis, tracheobronchomalacia, excessive dynamic airway collapse, and tumor invasion.[8-10]

Extraluminal vascular structures (superior vena cava, azygos vein, main pulmonary artery and its branches, ascending and descending aorta, aortic arch, pulmonary veins, and left atrium) are visualized using convex probe EBUS (see Figure 25-5 in the imaging case box). Bronchoscopists can assess volume status, pericardial fluid, or the presence of pulmonary embolism.[11,12] Thoughtful resource use for intensive care unit (ICU) admissions[13] warrants that EBUS should be considered in critically ill patients with suspected lung, mediastinal, cardiovascular, and hemodynamic disorders. This chapter illustrates potential applications of EBUS and EBUS–transbronchial needle aspiration (TBNA) in patients admitted to the ICU or undergoing general anesthesia. Moreover, we suggest algorithms built on the strengths of EBUS diagnostic abilities, its minimally invasive nature, and its proven safety profile for the noncritically ill patient setting (based on our own institutional experience).

Intrathoracic Lymphadenopathy

Many patients admitted to the ICU demonstrate enlarged intrathoracic lymph nodes on computed tomography (CT) scans performed for a variety of reasons. Sampling lymph nodes could assist in management. For example, patients with hypoxemic respiratory failure and parenchymal or interstitial infiltrates may have associated lymphadenopathy of variable significance. Although a patient with pneumonia likely has reactive lymphadenopathy, needle aspiration could reveal the actual organism. Patients with sarcoidosis and anthracosis have characteristic findings on EBUS-TBNA specimens (granulomatous reaction and anthracotic histiocytes, respectively).[4,14]

EBUS-TBNA can make the diagnosis of primary lung cancer or extrathoracic malignancy, metastatic to mediastinal, and hilar lymph nodes. It allows staging or restaging of patients with known or suspected malignancy.[1-3] This information is used to redefine level of care, ICU priority scores, and guide treatment. A patient with cancer on mechanical ventilation, for example, may be at risk for transbronchial or transthoracic lung biopsies. EBUS-TBNA can make a diagnosis of progressive disease, infections, or granulomatoid reaction (Figure 25-1).

Extrinsic Central Airway Obstruction, Pulmonary Artery Compression, and Superior Vena Cava Syndrome

Extrinsic compression is often amenable to interventional procedures, such as airway stent insertion,[15] so that patients with respiratory failure on mechanical ventilation may be weaned from ventilators.[16] Bronchoscopy and EBUS-TBNA are performed for the dual purpose of diagnosing the central airway obstruction (CAO) (Figure 25-2) and making a cytohistologic diagnosis by sampling impinging masses. Doppler mode is useful to assess the vascularity of the mass and suggests tumor engorgement with potential worsening airway obstruction in the supine position or hypervolemic state. A rapid diagnosis allows prompt referral for stent insertion and systemic therapy. A patient with a large mediastinal cyst could even be drained[17] rather than be referred for open surgery.

Main pulmonary arteries (PA) and the superior vena cava (SVC) can be compressed by mediastinal tumors. This may cause pulmonary hypertension and SVC syndrome, respectively. Hypoxemia and hypercarbia can lead to worsening of PA pressures and cause acute cor pulmonale. Fluid overload and the supine position lead to increased tumor volume and worsened SVC compression, potentially precipitating SVC syndrome and its consequences on hemodynamics and upper airway patency. Convex probe EBUS convex with Doppler mode allows tumor measurement and visualization of the PA, SVC compression, and intratumoral vascularity.

Expiratory Central Airway Collapse, Tracheal Stenosis, and Airway Wall Tumor Invasion

Expiratory central airway collapse (ECAC) is a reported cause of hypercarbic respiratory failure as well as inability to wean from mechanical ventilation. Diagnosis can be made with white light bronchoscopy (WLB), but assessment of airway wall structures requires visualization in cross section (Figure 25-3). A high-frequency (20 MHz) radial probe, used through a bronchoscope with a working channel of 2.8 mm, allows identification of hypoechoic and hyperechoic layers of the airway wall and identifies cartilage abnormalities in diffuse malacia, excessive dynamic

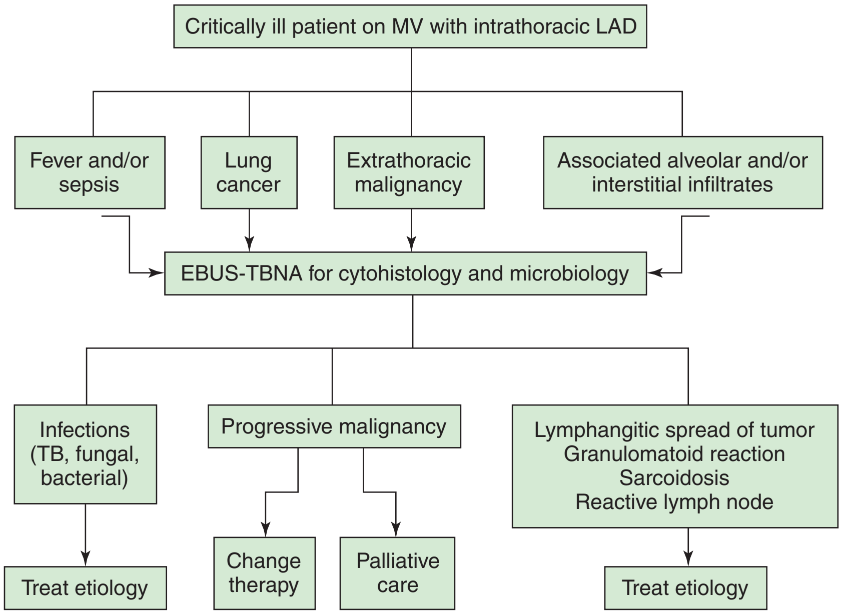

Figure 25-1 Proposed algorithm for using (convex probe) endobronchial ultrasound (EBUS) in critically ill patients with intrathoracic lymphadenopathy. A No. 8.5 to 9 endotracheal tube (ETT) is used to facilitate passage of the EBUS bronchoscope (outer diameter [OD], 6.9 mm) and prevent auto–peak end-expiratory pressure (PEEP). *LAD,* Lymphadenopathy; *MV,* mechanical ventilation; *TB,* tuberculosis; *TBNA,* transbronchial needle aspiration.

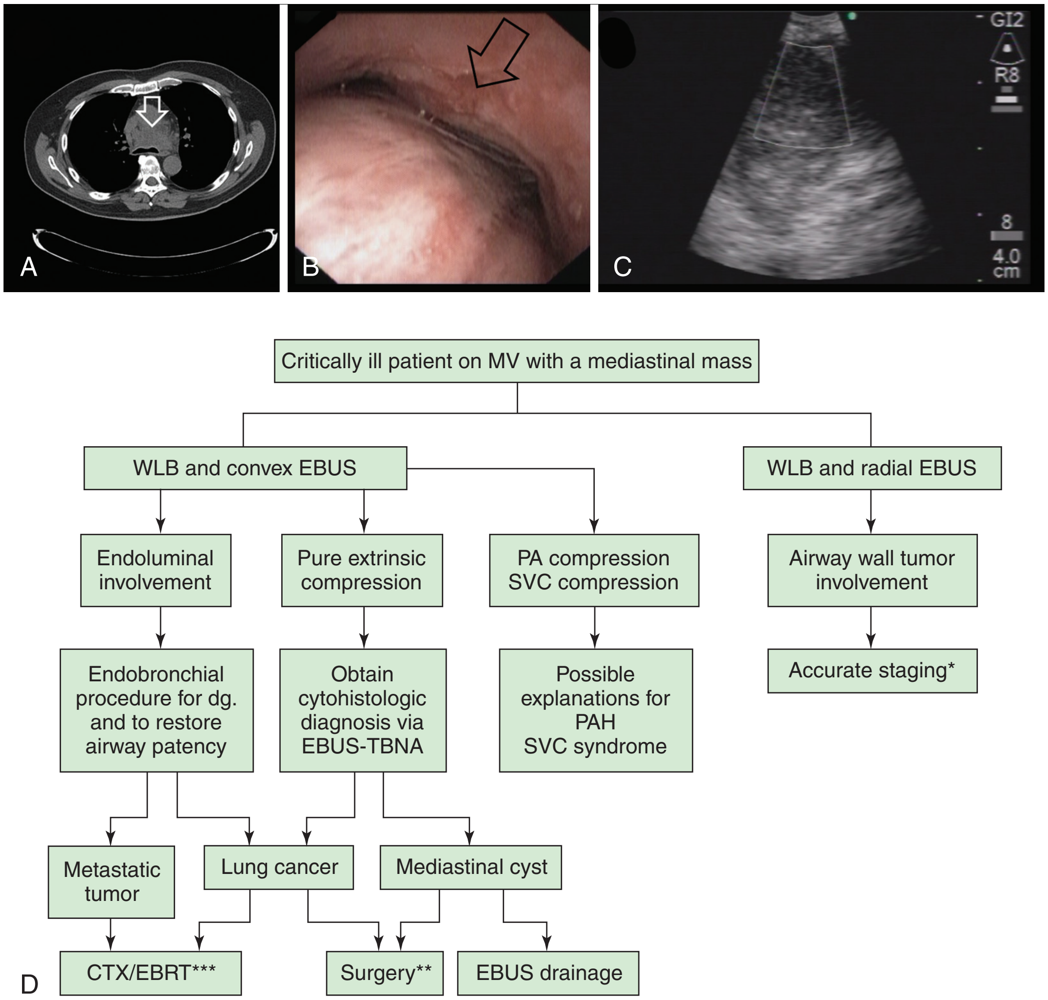

Figure 25-2 Potential role of endobronchial ultrasound (EBUS) in critically ill patients with mediastinal masses (*arrows*). **A,** Large pretracheal mass compressing the lower trachea and main carina. **B,** Near-complete obstruction in the lower trachea and proximal mainstem bronchi because of extrinsic compression and excessive dynamic airway collapse. **C,** Large (3 cm in anteroposterior diameter), heterogeneous mass confirmed to be small cell lung cancer (SCLC) on rapid on-site cytology examination (ROSE). **D,** Proposed use of EBUS and white light bronchoscopy (WLB) in patients with mediastinal masses requiring mechanical ventilation. *CTX,* Chemotherapy; *EBRT,* external beam radiotherapy; *MV,* mechanical ventilation; *PA,* pulmonary artery; *PAH,* pulmonary arterial hypertension; *SVC,* superior vena cava; *TBNA,* transbronchial needle aspiration;
*Tracheal wall invasion by a primary lung tumor defines a T4 and thus at least stage IIIB lung cancer.
** Surgical treatment is considered for cases of large mediastinal cysts compressing the airway and not treatable by other minimally invasive techniques. For lung cancer, surgery is considered if the tumor is deemed resectable after complete staging AND if the patient is operable.
***In general, CTX and EBRT are offered once patient's functional status improves after liberation from mechanical ventilation.

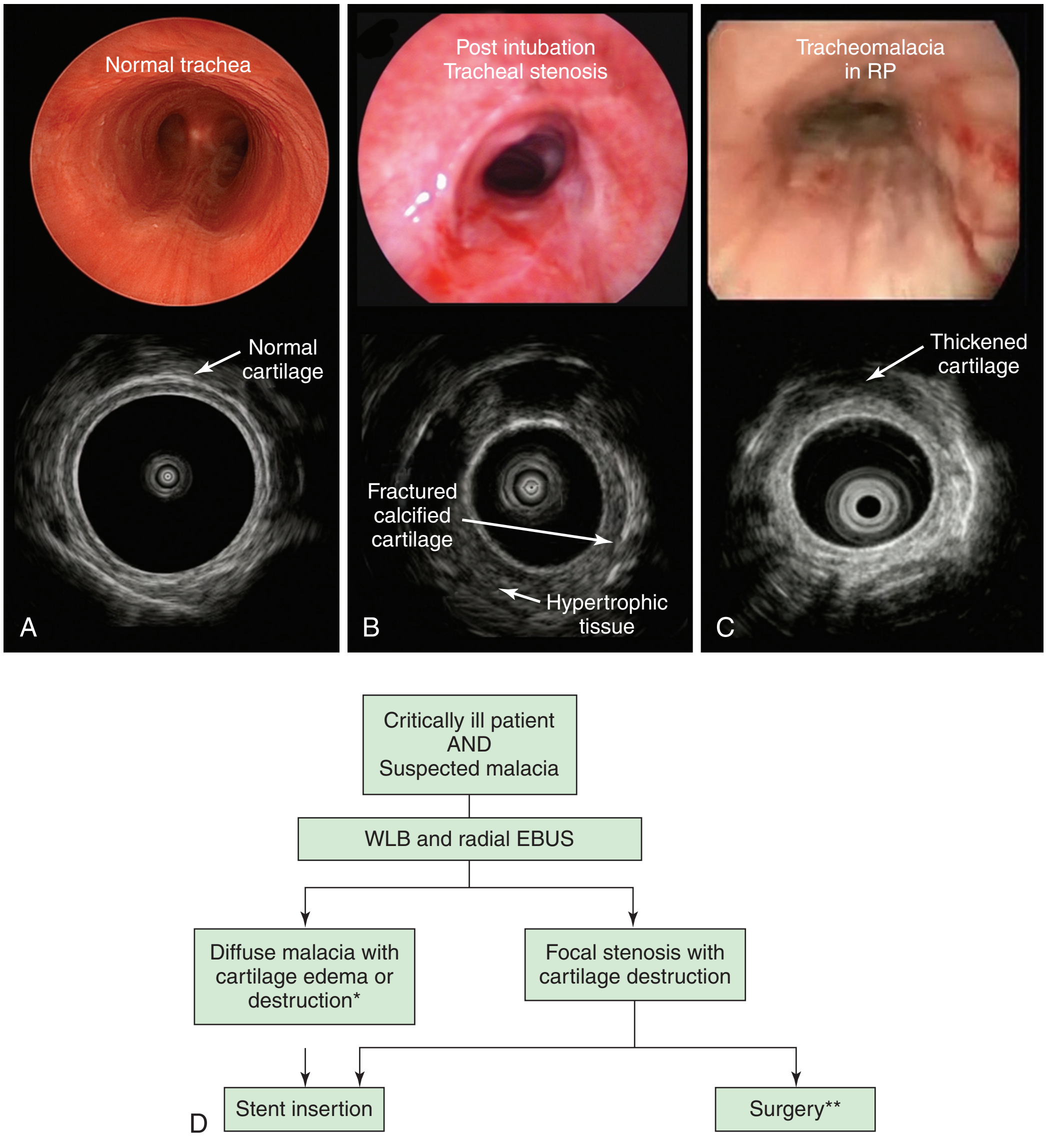

Figure 25-3 Potential role of high-frequency endobronchial ultrasound (EBUS) (radial probe) in critically ill patients with suspected malacia. **A,** Normal tracheal lumen on white light bronchoscopy (WLB) and on EBUS; the sonographic image (*bottom*) showed a thin, intact cartilaginous wall. **B,** WLB and EBUS in posttracheostomy tracheal stenosis; although WLB shows circumferential airway lumen narrowing, only ultrasonographic imaging reveals extent of hypertrophic stenotic tissues and disruption of cartilage. **C,** WLB shows diffuse circumferential tracheomalacia and mucosal edema in a patient with relapsing polychondritis (RP); EBUS shows cartilage thickening. **D,** Proposed algorithm for use of radial EBUS in conjunction with WLB in patients with suspected malacia. In diffuse malacia resulting from cartilage abnormality, stent insertion may be warranted.
*Surgery for diffuse expiratory central airway collapse (ECAC) is offered to patients with cartilage weakness and crescent-type malacia, but not to those with diffuse cartilage collapse as seen in RP. In patients with tracheal stenosis, laser-assisted mechanical dilation has a high recurrence rate if cartilage is disrupted. These patients benefit from surgical referral for sleeve resection.
**Nonsurgical candidates may benefit from restoring airway patency with indwelling airway stents.

airway collapse (EDAC), and tracheal stenosis.[8-10] Cartilage integrity in ECAC, its fracture in posttracheostomy or postintubation stenosis, its invasion by extraluminal tumor, and precise identification of cross-sectional extent of hypertrophic stenotic tissues in tracheal stenosis can impact management. For instance, a patient with ECAC-related respiratory failure might have excessive dynamic airway collapse on WLB but no evidence of cartilage abnormality. This should prompt a search for causes of obstructive ventilatory impairment resulting from small airway disease/parenchymal changes.[18] On the other hand, a patient with diffuse malacia, from relapsing polychondritis, for example,[10] may warrant stent placement to restore airway patency (see Figure 25-3). A patient with cartilage invasion by primary lung tumor might warrant systemic chemoradiotherapy, whereas in tracheal stenosis, if the cartilage is destroyed, the risk of recurrence is high after laser-assisted or balloon dilation. EBUS findings might accelerate appropriate referrals in each of these instances (see Figure 25-3).

Peripheral Pulmonary Nodules

In critically ill patients, peripheral pulmonary nodules may be caused by primary or metastatic malignancy, or fungal (i.e., coccidioidomycosis, invasive pulmonary aspergillosis, cryptococcus, histoplasmosis), mycobacterial (i.e., tuberculosis), or bacterial septic emboli. They are also seen in patients admitted to the ICU with diagnoses of autoimmune disease, granulomatosis with polyangiitis, or rheumatoid arthritis. If tissue diagnosis is needed, patients on mechanical ventilation are at high risk for pneumothorax (PTX) from transbronchial lung biopsy or CT-guided fine-needle aspiration (FNA). Furthermore, there are dangers transporting critically ill patients outside the ICU. Radial probe EBUS has a diagnostic yield of 50% to 80%, depending on the clinician's ability to visualize the nodule, the size of the nodule, presence of air bronchus sign on CT scan, the nodule's distance from the hilum, and the position of the probe in relation to the nodule.[19] Compared with CT-guided FNA, lower rates of PTX and bleeding are described.[7]

Pulmonary Embolism

Central pulmonary embolism (PE) (defined as thrombus in the pulmonary trunk or a main or a lobar PA) is diagnosed using contrast-enhanced chest computed tomography (chest CT angiogram). Acute PE with hemodynamic instability, contrast allergy, or severe renal dysfunction may occur and often preclude intravenous contrast administration. Bedside transthoracic echocardiography (TTE) has low sensitivity for confirming PE, although it might reveal right ventricular dysfunction. Pulmonary angiograms or ventilation-perfusion scans require transport to radiology, which is risky in unstable patients. Because the majority of patients who succumb from PE die within 2 hours from the onset of symptoms (and those who do survive may succumb from recurrent PE), a firm diagnosis is warranted. Visualization of pulmonary arteries by using convex probe EBUS is possible because depth of penetration is approximately 5 cm. Vessels run adjacent to the central airways and there is no interposition of ventilated lung parenchyma between airways and vessels.[12] In a prospective, multicenter pilot study of 32 patients with CT angiogram-confirmed, hemodynamically stable PE, CT angiogram documented 101 PEs, of which 97 (96%) were also detected by EBUS.[12] EBUS missed only 4 emboli (1 in a middle lobe and 3 in a left upper lobe artery). There were no EBUS-related complications. The entire main pulmonary trunk, main PAs, the lower lobe arteries, and at least 10 mm of the upper lobe and middle lobe arteries can be examined in just a few minutes (Figure 25-4A and B, see Figure 25-1D). Whether EBUS might worsen hemodynamic instability because of increased intrathoracic pressures during bronchoscopy is unknown. A large endotracheal tube (No. 8.5-9) should probably be used to avoid expiratory flow limitation, which might lead to intrinsic peak end-expiratory pressure (PEEP) and worsening hypotension. Future research in hemodynamically unstable patients may be hampered by the fact that diagnostic bronchoscopy is generally contraindicated in patients with ongoing cardiac ischemia or severe refractory hypoxemia, both of which can occur in the setting of acute massive PE.

Pericardial Effusion

EBUS allows visualization of the middle mediastinum and images pericardial effusion around the left atrium (see Figure 25-4). Although most pericardial disorders are diagnosed by TTE or transesophageal echocardiography (TEE), in case of acute hemodynamic instability during general anesthesia or in the ICU, EBUS could be useful because it allows assessment of pulmonary vessels, SVC, and portions of the pericardium. If TTE is suboptimal (obesity, chest deformity, hyperinflation while on positive-pressure ventilation, emphysema, subcutaneous edema or emphysema, lack of patient cooperation, inability to rotate the patient for optimal scanning, presence of surgical dressings) and TEE is not readily available, EBUS can be used to visualize posterior cardiac structures in great detail. A patient with hypotension in whom tamponade is suspected might thus warrant EBUS when TTE is nondiagnostic and/or not readily available. We have seen patients in whom pericardial effusion around the left atrium is clearly identified (see Figure 25-4C and D). In theory, when tamponade physiology affects the left atrium (LA), the respiratory variation in LA chamber size and diastolic collapse could be detected. The single scanning plane and limited chamber visualization, however, limit the benefit of EBUS in patients with pericardial disease. Relevant to patients in the operating room under general anesthesia or in the ICU on positive-pressure ventilation is that a reversed sequence of intrathoracic pressure occurs during the respiratory cycle. Intrathoracic pressure is higher during inspiration, and therefore venous return is smaller. Further experience is needed to better understand anatomic structures in scanning planes before EBUS can be recommended for cardiac assessment.

Volume Status

The assessment of fluid responsiveness is relevant to managing patients with acute hypotension. If patients on mechanical ventilation have no significant respiratory variation in the inferior vena cava (IVC) or SVC diameter, it is unlikely that cardiac output will increase with volume expansion, which could actually be harmful. Whereas the diameter of the IVC at the junction with right atrium is measured using the subcostal view on TTE, the SVC diameter measurement is usually performed by TEE.[20] Measurement of IVC diameter is less predictive than SVC diameter because the former is unreliable in patients with high intraabdominal pressures, whereas the latter directly reflects the relationship between central blood volume and intrathoracic pressures. Maximal and minimal SVC diameter (measured at the top of the right atrium) are observed during respiration.[20] Studies using TEE demonstrate that the collapsibility index of the SVC, defined as [(maximum diameter on expiration − minimum diameter on inspiration)/(maximum diameter on expiration)], is highly predictive of fluid responsiveness. Results show that in septic patients on mechanical ventilation, an SVC collapsibility index above 36% predicted an increase in cardiac index after volume expansion of more than 11%, (specificity 100% and sensitivity 90%).[20] We observed that cyclic increase in intrathoracic pressure can induce partial or complete collapse of the vessel seen by EBUS, when the SVC is visualized with the scope in the lower trachea/proximal right main bronchus and oriented anterolaterally toward the right (see Figure 25-4E and F). Using the signal from the ventilator, airway pressures are displayed on the screen of the ultrasound monitor, allowing accurate timing of SVC cyclic changes during the respiratory cycle. Interpretation should be evaluated in the context of the patient's clinical condition, radiographic findings, degree of hypoxemia, urine output, and fluid balance (see Figure 25-4G).

Conclusions

EBUS is an exciting imaging technique for visualizing mediastinal lymph nodes, major vessels, tumors, and airway structural changes. Its role in critically ill patients in the ICU or operating theater is promising.

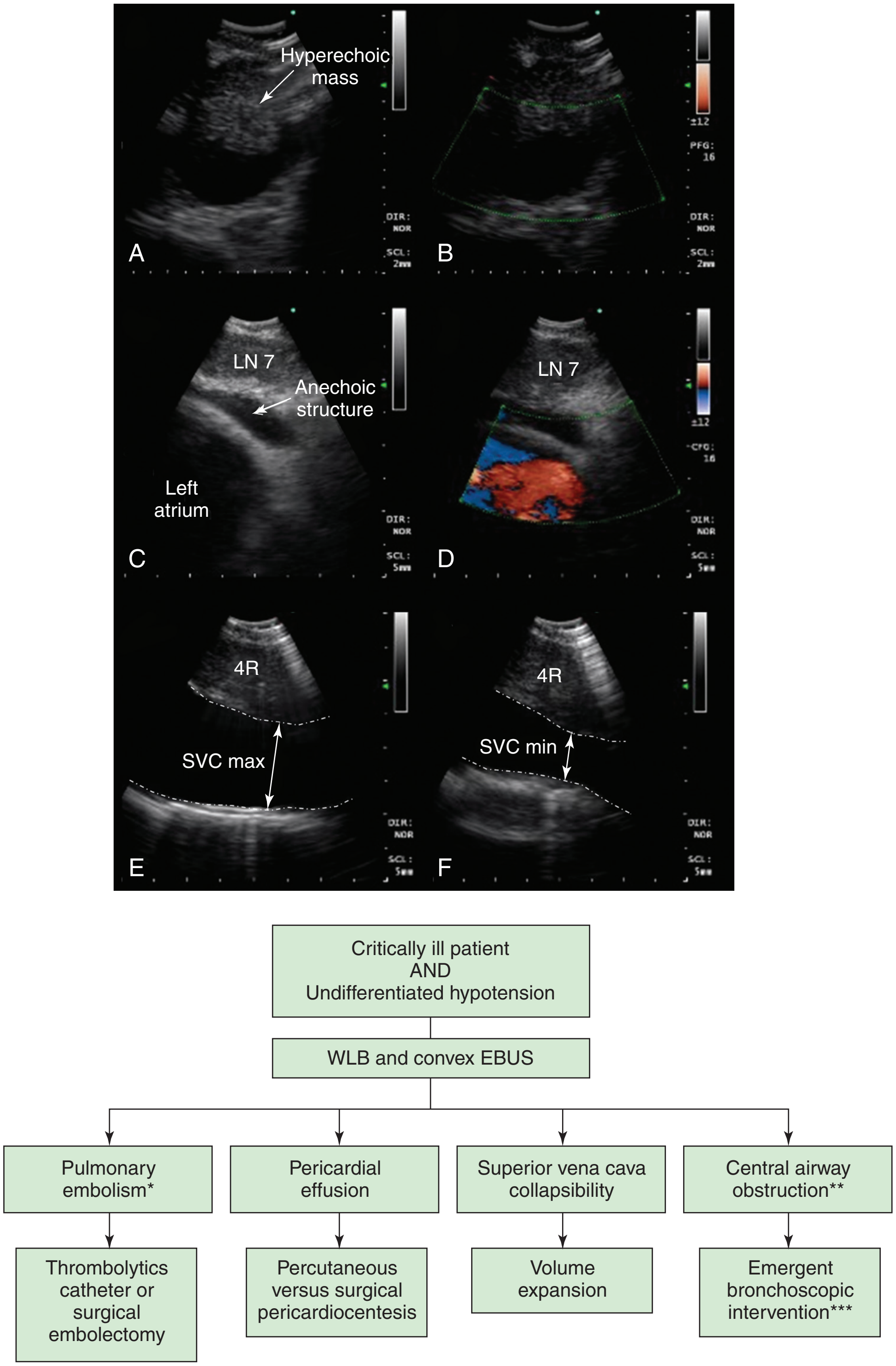

Figure 25-4 Potential role of convex probe endobronchial (EBUS) in undifferentiated hypotension. (Images A and B, C and D, and E and F represent different patients.) **A,** Hyperechogenic mass inside a tubular anechoic structure resembling EBUS description of a thrombus inside a pulmonary artery. **B,** In this case, however, the structure imaged was a subcarinal node, and Doppler mode showed that the anechoic signal was not a vessel. EBUS–transbronchial needle aspiration (TBNA) showed recurrent squamous cell carcinoma. **C,** Anechoic layer surrounding the heart in a patient undergoing EBUS-TBNA for subcarinal lymphadenopathy (LAD) (lymph node *[LN] 7*). **D,** Doppler mode confirms presence of fluid around the left atrium (fluid is Doppler negative, heart is Doppler positive). **E,** Superior vena cava *(SVC)* maximum diameter measured during EBUS and during expiratory phase (patient on positive pressure ventilation during EBUS-TBNA). **F,** SVC minimum diameter during inspiration is measured and the SVC collapsibility index calculated. **G,** Diagram illustrates potential role of convex probe EBUS with white light bronchoscopy (WLB) for diagnosis of undifferentiated hypotension. *Pulmonary embolism (PE), pericardial effusions, and volume status may be assessed when computed tomography (CT) angiogram, transthoracic echocardiogram (TTE), or transesophageal echocardiogram (TEE) is nondiagnostic or not feasible.*
*PE may be missed in lobar and segmental airways.
**Central airway obstruction (CAO) can cause hypotension through ball-valve mechanism, leading to auto–peak end-expiratory pressure (PEEP) and increased intrathoracic pressure.
***The type of intervention depends on the nature of obstruction (e.g., dilation and stent for extrinsic compression, laser- or electrosurgery-assisted debulking for exophytic obstruction, foreign bodies, mucous plugs, or blood clots removal).

IMAGING CASE

A 69-year-old patient with smoking history, chronic obstructive pulmonary disease (COPD), orthopnea, and obesity is admitted to the ICU with impending respiratory failure warranting endotracheal intubation. A noncontrast CT chest radiograph revealed a large mass anterior to the lower trachea (see Figure 25-5A). Because tissue diagnosis was necessary, the patient was intubated with a No. 8.5 endotracheal tube (ETT) that would allow passage of an EBUS bronchoscope. With anesthesia at the bedside, an awake, flexible videobronchoscopy-guided intubation was performed through the mouth, with the patient in the semiupright position. The patient was then sedated and moved into the supine position. The anesthesiologist then noticed inability to ventilate. Chest auscultation revealed no air entry bilaterally. The patient did not improve after albuterol metered-dose inhaler (MDI) was administered through the ETT for presumptive acute bronchospasm. WLB showed near-complete closure of the lower trachea because of a combination of extrinsic compression from the mass and invagination of the posterior membrane (see Figure 25-5B), consistent with worsened airway obstruction during sedation and supine positioning. The patient was returned to the semiupright position, and sedatives were stopped to allow spontaneous-assisted ventilation. EBUS-TBNA was performed (see Figure 25-5C). Malignant cells were observed by rapid on-site cytology examination performed by a cytology technician. Small cell lung cancer was confirmed 2 days later. The patient was weaned from mechanical ventilation to continuous positive airway pressure (CPAP). Oncology, radiation oncology, interventional pulmonology, and palliative care services were consulted to discuss treatment options, and a family meeting was arranged.

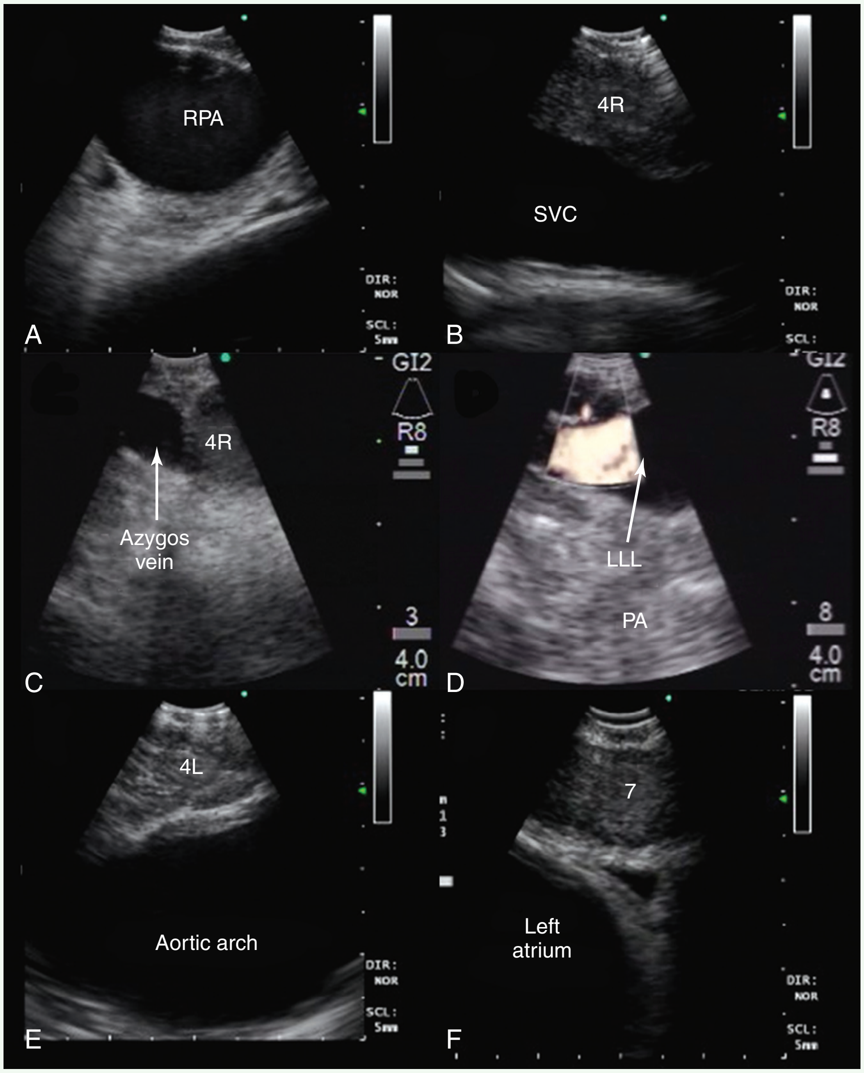

Figure 25-5 Convex probe endobronchial ultrasound (EBUS) visualization of mediastinal vascular structure. After introduction of the bronchoscope via the endotracheal tube (ETT), the right lower lobe bronchus is approached. The transducer is turned 90 degrees to the lateral wall to visualize the right lower lobe pulmonary artery *(PA).* Pulling back the bronchoscope, the take-off of the middle lobe PA is examined. With the transducer oriented anteriorly, the right pulmonary artery *(RPA)* is visualized crossing the right main bronchus **(A),** and the right upper lobe PA take-off is seen if the transducer is oriented anterolaterally near the main carina. After turning the bronchoscope medially, the pulmonary trunk is inspected. Above the RPA, with the transducer oriented anterolateral and pulled back, the superior vena cava *(SVC)* is examined **(B).** Continuing to turn the bronchoscope laterally, the azygos vein is visualized **(C).** The investigation of the left side also starts in the lower lobe bronchus after turning the bronchoscope to the lateral wall to visualize the left lower lobe *(LLL)* PA **(D)** and, after pulling back the bronchoscope and orienting it anteromedial, the left upper lobe PA. The left PA is visualized behind the lateral wall of the left main bronchus up to the left lower paratracheal region; continuing to pull back and orient the transducer laterally, the aortic arch is encountered **(E).** Subcarinal region with pulmonary veins and left atrium is visualized either from the left or right main bronchi when the transducer is oriented medially **(F).**

Pearls and Highlights

- Critically ill patients with intrathoracic lymphadenopathy may warrant EBUS-TBNA for unclear sources of fever, sepsis, initial diagnosis, and recurrence or progression of thoracic or extrathoracic malignancy.
- Combination WLB and EBUS-TBNA can differentiate and diagnose types of CAO.
- Radial probe EBUS reveals cartilage abnormalities in stenosis and malacia and may impact treatment decisions.
- Convex probe EBUS reveals SVC collapsibility and may be helpful for assessing intravascular volume status.
- Convex probe EBUS allows visualization of the pulmonary trunk, main and lobar branches, and sections of the pericardium, potentially helping diagnose pulmonary embolism and pericardial effusion.

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For a full list of references, please visit www.expertconsult.com.

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SECTION V

Echocardiography

26

Transthoracic Echocardiography: An Overview

DAVID STURGESS

Overview

The first reported use of ultrasound to assess cardiac function was almost 60 years ago.[1] Technologic advances have now placed echocardiography as the intensivist's only option for bedside visualization of cardiac anatomy and function in real time.

Although echocardiography began as the domain of the specialist cardiologist, a number of factors have contributed to increasing interest and training among critical care physicians. These include, a move away from invasive hemodynamic monitoring (such as the pulmonary artery catheter); increasing clinical and research echocardiography experience in the critically ill; availability of smaller, less expensive, better-quality ultrasound machines; as well as greater access to education and training in clinical ultrasound.[2]

The critical care environment presents many challenges to the performance of transthoracic echocardiography (TTE). The bedspace may be crowded and more accommodating to compact equipment; this compromise might generate lower image resolution. The images must be acquired and interpreted in a time-pressured fashion. Ultrasonographic windows must be improvised, to account for relative immobility, as well as 30-degree head-up positioning and positive end-expiratory pressure that may displace the diaphragm, pericardium, and heart caudally. Common pathologic processes may interfere with image acquisition (chest wall trauma, subcutaneous emphysema, lung hyperinflation/chronic obstructive pulmonary disease [COPD]), or interpretation (hemodynamic instability). Therapeutic intervention may further impede image quality (mechanical ventilation, surgical drains, dressings, mediastinal air after sternotomy) or image interpretation (intravascular volume manipulation, inotrope/vasopressor, positive pressure ventilation). On the other hand, immediate availability and a detailed appreciation of critical illness, as well as relevant pharmacology and physiology, place the critical care physician in a strong position to acquire and interpret echocardiographic data.

This chapter presents a brief overview of TTE. In particular, it aims to introduce the aspects of TTE that distinguish it from other modes of ultrasonography considered previously in this textbook. The chapter will begin with an introduction of echocardiographic imaging techniques, including an overview of the principles applying to each mode. An overview of two-dimensional (2D), M-mode, and Doppler echocardiography will be presented. Strain rate and three-dimensional (3D)/four-dimensional (4D) echocardiography, as well as intensive care unit (ICU) specifics will be discussed in subsequent chapters.

Technical Aspects

Equipment

Echocardiography typically uses phased-array transducers. The latter have a small footprint and consist of multiple miniature ultrasonic elements capable of being pulsed independently. Elements are activated with phase differences to generate a high-frequency (high-resolution) beam that can be focused and steered electronically. The tissue to be imaged is interrogated by sweeping the transducer around, something like using a searchlight. The resultant image is reconstructed from multiple beams and is represented by an expanding field of view that is also typical of a curvilinear transducer (see Chapter 1).

Radiologic and cardiologic laboratories tend to be well equipped with state-of-the-art echocardiography machines. These are well suited to comprehensive examination performed by experienced technicians in nonemergent circumstances.[3] The critical care environment, on the other hand, lends itself to the application of compact, robust equipment. Image quality is balanced against the desirability of a small physical profile when attempting to access critically ill patients during concurrent resuscitation. Compact devices capable of focused echocardiography complement other hemodynamic and physical examination findings.

TRANSDUCER MOVEMENTS

Small changes in movement of the transducer have the potential to significantly improve, or worsen, image quality. Pressure describes the force with which the probe is applied to the chest wall. Translation is the movement of the probe on the skin. Rotation is the movement of the transducer around its long axis. Angulation refers to tilting of the probe to change its angle to the skin and thus the angle at which the ultrasonographic plane transects the heart.

KNOBOLOGY

Modern echocardiography machines have a dazzling array of knobs and buttons. Familiarity with your machine's user interface is essential to manipulate and optimize image quality. The knowledge required to optimize images via the machine's user interface has become known as knobology (see Chapter 1).

Knobs are generally clustered according to function and are generally grouped into those controlling power, gain, time gain compensation (TGC), dynamic range, depth, zoom/magnification, freeze, calculations, alphanumeric, and save/print functions. Used appropriately, device presets usually minimize the amount of adjustment required by the user.

Image Optimization

When optimizing an image, it is generally advisable to adjust variables in the following order:

- Depth: Always start deeper than the area of interest to ensure that deeper structures and pathology may be appreciated.
- Focus: Adjust so that area of highest lateral resolution coincides with area of interest. Modern machines often have multiple focal zones. Beware: activation of more focal zones results in slower frame rates and loss of temporal resolution.
- TGC: Compensates for attenuation of ultrasound passing deeper into tissues. The resultant image should demonstrate a consistent level of ultrasonic intensity. Interchangeable terminology for TGC includes distance gain compensation (DGC) and spatial time compensation (STC).
- Zoom: May be used to magnify point of interest.
- Gain: Optimize to allow visualization of most points of interest. High gain can obscure detail.
- Dynamic range (contrast): High "dynamic range" translates to low "contrast."

Biological Signals

Echocardiographic images must be accompanied with an electrocardiographic (ECG) signal on the same time axis. This is mandatory to allow timing of images according to the cardiac cycle (systole/diastole).[4] Some echocardiography machines will also allow slaving of respiratory phase data from the ventilator or monitoring equipment. Respiratory phase may also be determined from thoracic electrical bioimpedence (from ECG leads). Incorporation of respiratory phase data allows appreciation and quantification of heart –lung interactions.

Echocardiographic Modalities

TWO-DIMENSIONAL ECHOCARDIOGRAPHY

Although both motion mode (M-mode) and Doppler modalities historically preceded 2D echocardiography, 2D will be detailed first because of the practicality that M-mode and Doppler modalities are now mostly used with 2D guidance. Cross-sectional ultrasonographic "slices" through the beating heart can be visualized in real time or recorded (as "clips") for subsequent review and analysis. Nomenclature and image orientation standards in TTE allow for description of images based upon transducer location and orientation to the heart (plane).[5]

Transducer Location

When placed in the suprasternal notch, this is referred to as the *suprasternal* location. When located near the midline of the body and beneath the lowest ribs, this is referred to as the *subcostal* location. When located over the apex impulse, this is the *apical* location. The area bound by the left clavicle (superiorly), sternum, and apical region (inferiorly) is referred to as the *parasternal* location. By default, apical and parasternal locations are assumed to be left sided. In unusual circumstances, when right-sided imaging is indicated, the *right apical* and *right parasternal* locations may be required (Figures 26-1 to 26-4).

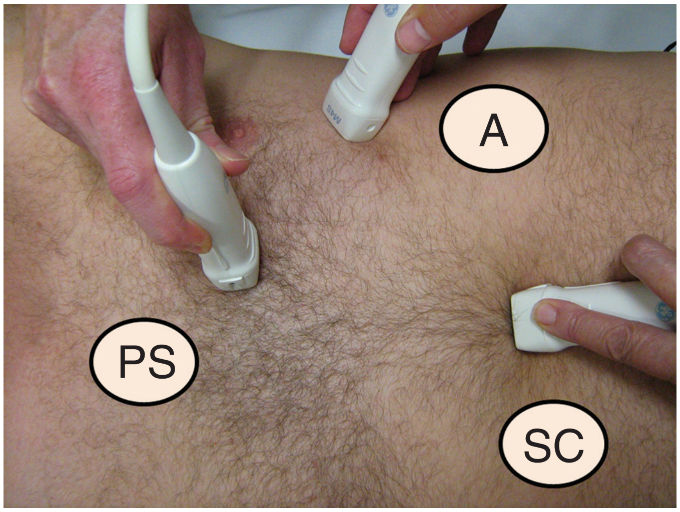

Figure 26-1 Approximate transducer placement for common windows. The patient is supine, which is typical in critical care. The patient's left side is toward the top of the image. *A*, Apical position; *PS*, parasternal position; *SC*, subcostal position.

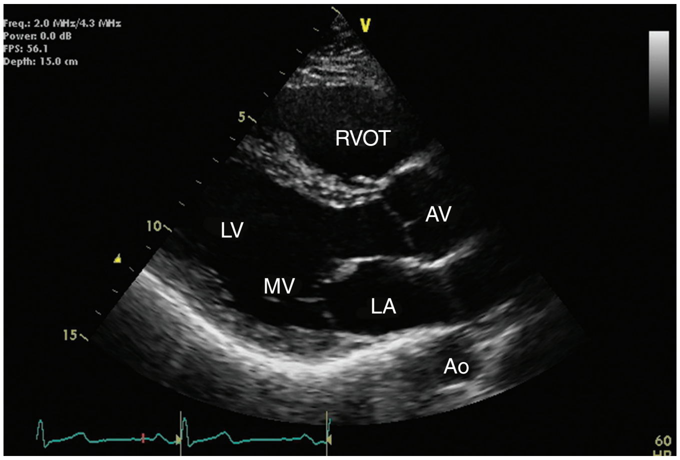

Figure 26-2 Parasternal long-axis view with relevant structures labeled. The left ventricle should appear almost horizontal, and the apex is not displayed. *Ao*, Descending aorta; *AV*, aortic valve; *LA*, left atrium; *LV*, left ventricle; *MV*, mitral valve; *RVOT*, right ventricular outflow tract.

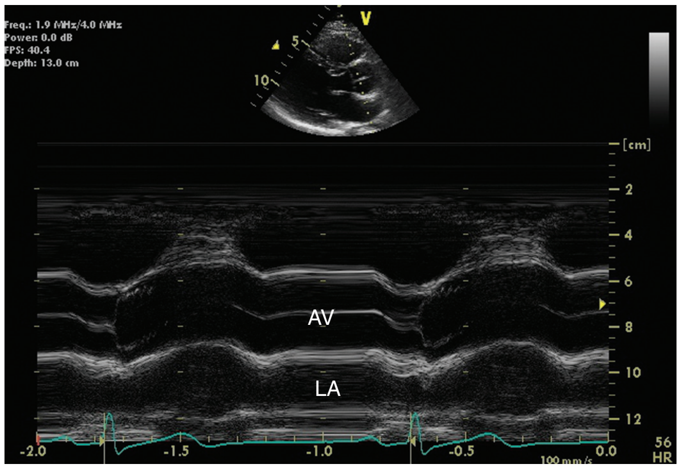

Figure 26-3 M-mode across the aortic valve in the parasternal long-axis view. The aortic valve (AV) is labeled during leaflet apposition in ventricular diastole. LA indicates the left atrium. It can be seen that it is potentially difficult to orientate the M-mode cursor squarely across the structure of interest, and as a result, measurements may not be representative.

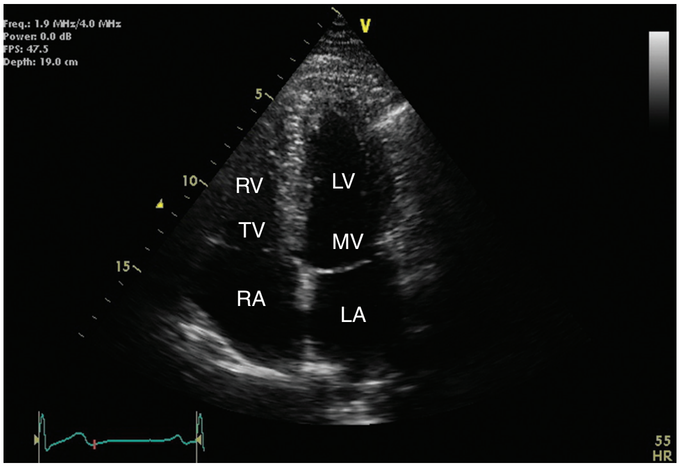

Figure 26-4 Apical four-chamber view. With appropriate transducer position, the septum should be vertical, and the left ventricle should not be rounded off (foreshortened). *LA,* Left atrium; *LV,* left ventricle, *MV,* mitral valve; *RA,* right atrium; *RV,* right ventricle; *TV,* tricuspid valve.

Imaging Planes

Rather than applying classic anatomic planes (sagittal, transverse, and coronal), 2D echocardiographic planes are based upon cardiac orientation. The *long-axis* plane transects the heart perpendicular to the ventral body surface and parallel to the long axis of the heart. The *short-axis* plane is perpendicular to the ventral body surface and long axis of the heart. The plane that transects the heart approximately parallel to the ventral body surface is referred to as the *four-chamber* plane (see Figures 26-1 to 26-4). With experience, the echocardiographer can imagine 3D cardiac anatomy based upon 2D scans.

M-MODE ECHOCARDIOGRAPHY

Rather than displaying a 2D representation of the heart, M-mode displays the depth and intensity of ultrasound reflection in a single dimension against time. Using modern equipment, M-mode is acquired by swinging the M-mode cursor across the structure(s) of interest visualized in a 2D image (see Figure 26-3). It offers excellent temporal resolution because of a high pulse rate and may complement 2D images. The major disadvantage arises from the challenge of aligning the M-mode cursor perpendicularly across the structure of interest to take accurate measurements.[6]

DOPPLER ECHOCARDIOGRAPHY

Doppler echocardiography[7] is predominantly used to determine the velocity (speed and direction) of blood flow within the heart and blood vessels. It is based upon the Doppler principle, which states that the frequency of ultrasound is altered by reflection from a moving object, such as red blood cells. The magnitude of frequency change (Doppler shift) is proportional to the speed that the object is moving relative to the probe. The polarity of the shift is dependent on the direction relative to the probe (toward = positive; away = negative). When solved for the velocity (V) of the moving object, the Doppler equation can be represented as:

$$V = (\Delta F \times c)/(2F_0 \times \cos\Phi)$$

Thus the velocity of the moving target (i.e., blood cells) is proportional to the Doppler shift (ΔF) and the velocity of sound in tissue (c = 1540 m/sec) but inversely proportional to the transducer frequency (F_0) and the cosine of the angle of incidence (Φ). In cardiac applications, the angle of incidence is assumed to be 0 or 180 degrees (cosine = 1.0). Accuracy is acceptable within 20 degrees of this.

Pulsed Wave Doppler

Pulsed wave Doppler (PWD) measures flow velocity at a targeted site (sample volume; Figure 26-5). It achieves this by transmitting ultrasound in pulses and then "listening" for reflected signals returning within the defined time period. A longer delay is expected when the sample volume is placed further from the probe. This technique cannot accurately measure velocities above a certain threshold (Nyquist limit) because of a phenomenon called aliasing. A number of interventions can be applied to prevent aliasing. These include

- Decreasing transducer frequency
- Moving the baseline
- Decreasing the depth of the volume sample
- Increasing the number of sample volumes
- Changing from pulse to continuous wave Doppler

Continuous Wave Doppler

Continuous wave Doppler (CWD) continuously sends and receives ultrasound. The resultant data are displayed as a spectral envelope of velocities along the line of the ultrasound beam. The highest velocity along this path defines the outer edge of the tracing and blurs out lower velocity signals. Very high velocities can be measured this way, but the site of origin cannot be localized along the path of the beam. Although corrections may be required for blood viscosity (e.g., anemia with hemoglobin (Hb) <8.0g/dL) or high proximal velocity (e.g., high-output state, serial stenosis), peak velocities may be converted to pressure gradients by application of the simplified Bernoulli equation[7]:

$$\text{Pressure gradient} = 4V^2$$

Color Flow Doppler

Color flow Doppler (Figure 26-6) superimposes flow velocity estimates from multiple gates or regions of interest upon

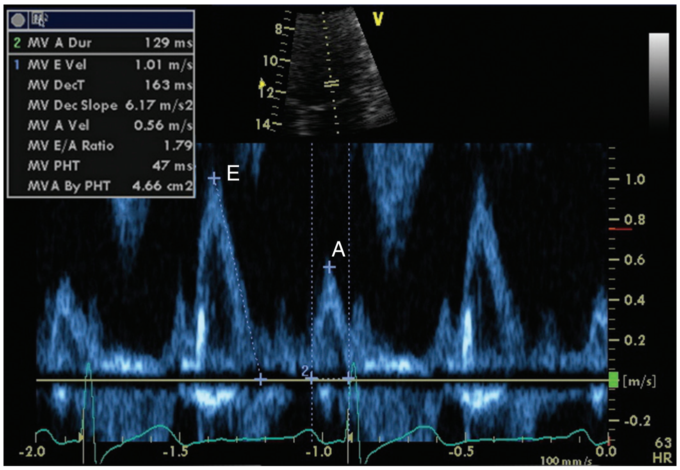

Figure 26-5 Normal mitral inflow Doppler. Peak early *(E)* and active *(A)* transmitral diastolic velocities are labeled.

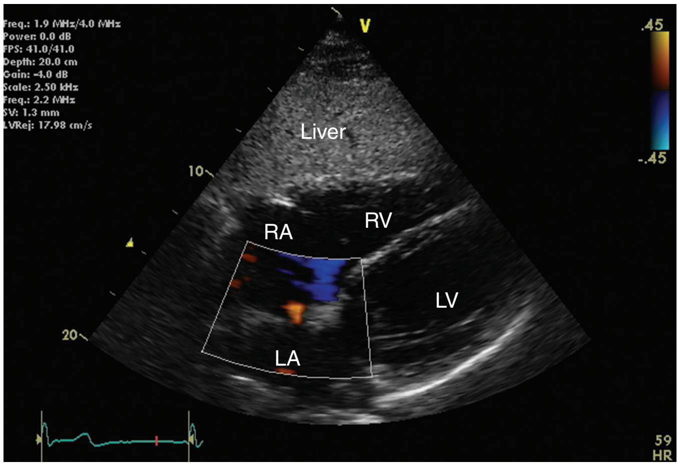

Figure 26-6 Subcostal four-chamber view with color flow Doppler demonstrating a patent foramen ovale. This is seen as a yellow jet from left to right atrium. *LA,* Left atrium; *LV,* left ventricle; *RA,* right atrium; *RV,* right ventricle.

2D images. It achieves this with PWD technology and is similarly prone to aliasing.

Tissue Doppler

Tissue Doppler (Figure 26-7) is available on many modern ultrasound machines. Cardiac tissue velocities can be determined by application of the Doppler principle. Removal of the ultrasonic filters required for measuring red blood cell velocities, allows analysis of the low-velocity, high-amplitude signal reflected from the myocardium. Analysis can be performed in either pulsed wave or color mode.

TRANSTHORACIC ECHOCARDIOGRAPHY EXAMINATION

Critical care echocardiography is often necessarily focused upon answering pertinent, time-sensitive clinical questions. It is frequently used as an adjunct to the physical examination. In this regard, the ICU and emergency department have similar requirements. Indications for focused TTE may include cardiac trauma, cardiac arrest, hypotension/shock, dyspnea/shortness of breath,

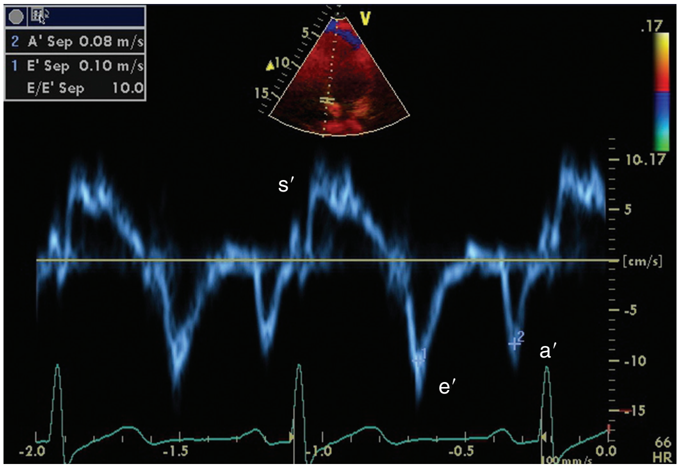

Figure 26-7 Normal tissue Doppler with the sample volume at the septal mitral annulus. Peak systolic (s′ = s prime), peak early (e′= e prime) diastolic, and peak active (a′ = a prime) diastolic velocities are labeled.

and chest pain.[8] A range of focused hemodynamic protocols exist and are advocated by respective societies and organizations.

Standard Transducer Positions

In critical care, both comprehensive and focused echocardiographic protocols tend to rely upon three main transducer positions or windows. These are the parasternal, apical, and subcostal positions (see Figure 26-1). The suprasternal view is used less commonly. Data must be interpreted as an integration of available views and clinical information. Reliance of information from a single view should be avoided because it may lead to erroneous conclusions.

The Parasternal Position. This is often the starting point for routine echocardiography. The probe is placed in the fourth or fifth intercostal space, about 2 inches to the left of the sternum (see Figure 26-1, parasternal [PS] position). The best windows are usually obtained with the patient on his or her left side. This is not always practical in critical care.

Parasternal Long-Axis View. Starting in the parasternal position, the transducer marker should point toward the right shoulder. The resultant view allows 2D (see Figure 26-2) and M-mode evaluation of structures, including the left ventricle, outflow tract, and aortic root. Color Doppler is usually also applied to the aortic and mitral valves. Zoomed views of the aortic and mitral valves may also allow more detailed structural and functional evaluation. The demonstration of fluid on the cardiac side of the descending aorta helps distinguish pericardial from pleural fluid.

By angling the transducer, it may also be possible to acquire right ventricular inflow and pulmonary artery long-axis views. From the parasternal long-axis view, the proximal ascending aorta is potentially visualized by moving the transducer up one interspace.

Parasternal Short-Axis Views. This group of views can be acquired from the parasternal position by rotating the probe clockwise, approximately perpendicular to the long-axis view (transducer marker pointing to patient's left shoulder). The transducer can be angled like a torch to sweep from basal to apical:

- Aortic valve: The normal tricuspid aortic valve looks like a "Mercedes Benz" symbol. This view also potentially visualizes the pulmonic and tricuspid valves. Right ventricular systolic pressure (RVSP) may be estimated by applying the simplified Bernoulli equation to any tricuspid regurgitation that might be present.
- Mitral valve: The valve usually looks like a fish's mouth. Planimetry and color flow Doppler aid evaluation of structure and function.
- Midpapillary view: Cross-sectional view at the mid–left ventricular level. Like comparable transesophageal views, this may help evaluation left ventricular filling and function as well as investigating coronary vascular territories.
- Apical view: Left ventricular apex. This view is essential to make a complete and comprehensive assessment of left ventricular segmental function (regional wall motion).
- It may be necessary to move the transducer up and/or down an interspace to optimize views throughout the length of the heart. All segments of the left ventricle should be visualized to allow evaluation for nonuniform pathology and regional wall motion abnormalities.

The Apical Position. Following from the parasternal position, the transducer is moved over the apex beat (point of maximal impulse). With minor adjustment, including rotation, this position allows acquisition of numerous views including the apical four-chamber, five-chamber, two-chamber, and long-axis (three-chamber) views.

Apical Four-Chamber View. Over the apex beat, the transducer marker is turned to the patient's left side (see Figure 26-1A). Transducer position should be adjusted to demonstrate the four major chambers of the heart (left atrium, left ventricle, right atrium, and right ventricle). The septum should appear vertical, near the center of the image (see Figure 26-4). The left ventricular apex should also be clearly demonstrated (not tangential or rounded).

- Left ventricular function: Left ventricular volumes, and therefore ejection fraction can be estimated by tracing the ventricular cavity (Simpson's method). Geometric assumptions are improved if the apical two-chamber view is also measured and results are averaged (biplane method).[6]
- Right ventricular function: Right ventricular geometry is complex (cresenteric) and difficult to quantify in 2D echocardiography. Qualitatively, the right ventricle should appear approximately two-thirds the size of the left ventricle. Tricuspid annular planar systolic excursion (TAPSE) gives an indication of normal right ventricular systolic function.
- Atrial anatomy: Left and right atrial size can be measured just before atrioventricular valve opening.
- Valvular function: Tricuspid and mitral valves.
- Diastolic function: Mitral valve inflow interrogation by spectral (see Figure 26-5) and color Doppler forms the cornerstone of evaluation of left ventricular diastolic function.[9] Evaluation can be supplemented by tissue Doppler imaging (see Figure 26-7) of the mitral valve annulus, which holds prognostic significance in a range of cardiac pathology, including septic shock.[10] Pulmonary venous flows may also be acquired from the apical position.

Apical Five-Chamber View. From the apical four-chamber view, the transducer is angled with the echocardiographer's hand moving closer to the patient. This usually brings more anterior structures, including the left ventricular outflow, aortic valve, and proximal aorta, into view. This allows Doppler interrogation of the aortic valve and both stenosis and regurgitation can usually be graded.[7] Dynamic outflow tract obstruction may also generate a characteristic pattern. When paired with left ventricular outflow tract diameter (best measured from zoomed parasternal long-axis view), stroke volume and cardiac output can be estimated.

Apical Two-Chamber. The apical two-chamber view is acquired by rotating the transducer approximately 90 degrees counterclockwise from the apical four-chamber view.

Apical Long Axis. By rotating the transducer almost 90 degrees farther counterclockwise, the apical long-axis, or three-chamber views, can be acquired. The three chambers are the left atrium, left ventricle, and right ventricular outflow. This replicates the parasternal long-axis view, except that the left ventricular apex is now in the near field, allowing better visualization of this area.

The Subcostal Position. The transducer is placed under the xiphoid process and angled up toward the heart (see Figure 26-1, subcostal [SC]). For best imaging, the patient is examined supine. Use of pillows to flex the head and neck or hips relieves anterior abdominal wall muscle tension. Increasing the depth of the image is usually also required.

The subcostal position gains particular significance in critical care. The subcostal position is less prone to interference from lung pathology or mechanical ventilation. It can be used to guide cardiopulmonary resuscitation with minimal interruption to chest compression. It is also useful for visualizing pericardial effusions and forms part of the focused abdominal sonography for trauma (FAST) examination after trauma.

Subcostal Long Axis. Starting with the transducer marker to the patient's left, the former is manipulated until an image resembling the apical four-chamber view is achieved. From this position, the ultrasound beam must traverse the liver before reaching the right then left ventricle. The alignment of the ultrasound beam roughly perpendicular to the interatrial septum also makes this view useful for applying color flow Doppler to assess for atrial septal defects or patent foramen ovale (see Figure 26-6).

Subcostal Short Axis. From the long-axis position, the transducer should be rotated counterclockwise until short-axis images of the left ventricle are acquired. These images are comparable to those from the parasternal short-axis position, except that the inferior aspect of the heart now lies closer to the transducer. These images may compensate for poor image quality from the parasternal position.

Subcostal Great Vessels. Continued counterclockwise, rotation of the transducer until its marker is pointed toward the patient's head can be used to visualize the great vessels. Tilt allows visualization of the aorta (pulsatile, thick walled) and inferior vena cava (tilted laterally to the patient's right).

Inferior vena cava diameter can be measured as an indicator of intravascular volume.[6] M-mode also allows evaluation of respiratory variation.[2]

Suprasternal Position. The suprasternal window is not routinely performed in critical care echocardiography. The probe is placed in the suprasternal notch and tilted down toward the heart (see Chapter 1). Access to this area of a mechanically ventilated patient can be challenging but is potentially made easier by removing the pillow, tilting the patient's chin up and to the left.

INDICATIONS

Evidence-based practice defends the application of TTE in a wide range of clinical scenarios. The strength of evidence supporting the use of TTE in a range of scenarios (indications) has recently been reviewed by the American College of Cardiology Foundation (ACCF), in partnership with the American Society of Echocardiography (ASE) and key specialty and subspecialty societies.[11] Indications were derived from common applications or anticipated uses; these were then arbitrarily classified into appropriate, unclear, or inappropriate indications based on the available literature. Indications that relate to acute care are presented in Box 26-1.

The Echocardiographic Report

The echocardiographic examination is not complete until reported. Recommendations are available for reporting comprehensive adult transthoracic echocardiography, but they are deliberately not prescriptive and allow for differences between laboratories.[12] Not all of this information may be available (or relevant) at the time of performing a critical care echocardiography. Box 26-2 offers a range of suggestions for components of the echocardiographic report.

BOX 26-1 INDICATIONS FOR TRANSTHORACIC ECHOCARDIOGRAPHY FOR CARDIOVASCULAR EVALUATION IN AN ACUTE SETTING

APPROPRIATE INDICATION

(For instance, the test is generally acceptable and is a reasonable approach for the indication.)

- Hypotension or hemodynamic instability
  - Hypotension or hemodynamic instability of uncertain or suspected cardiac etiology
- Myocardial ischemia/infarction (MI)
  - Acute chest pain with suspected MI and nondiagnostic electrocardiogram (ECG) when a resting echocardiogram can be performed during pain
  - Evaluation of a patient without chest pain but with other features of an ischemic equivalent or laboratory markers indicative of ongoing MI
  - Suspected complication of myocardial ischemia/infarction, including, but not limited to, acute mitral regurgitation, ventricular septal defect, free-wall rupture/tamponade, shock, right ventricular involvement, heart failure (HF), or thrombus
- Evaluation of ventricular function after acute coronary syndrome (ACS)
  - Initial evaluation of ventricular function after ACS
  - Reevaluation of ventricular function after ACS during recovery phase when results will guide therapy
- Respiratory failure
  - Respiratory failure or hypoxemia of uncertain etiology
- Pulmonary embolism
  - Known acute pulmonary embolism to guide therapy (e.g., thrombectomy and thrombolytics)
  - Reevaluation of known pulmonary embolism after thrombolysis or thrombectomy for assessment of change in right ventricular function and/or pulmonary artery pressure
- Cardiac trauma
  - Severe deceleration injury or chest trauma when valve injury, pericardial effusion, or cardiac injury are possible or suspected

UNCERTAIN INDICATION

(That is, the test may be generally acceptable and may be a reasonable approach for the indication.)

Uncertainty also implies that more research and/or patient information is needed to classify the indication definitively.

- Hypotension or hemodynamic instability
  - Assessment of volume status in a critically ill patient
- Respiratory failure
  - Respiratory failure or hypoxemia when a noncardiac etiology of respiratory failure has been established

INAPPROPRIATE INDICATION

(That is, the test is not generally acceptable and is not a reasonable approach for the indication.)

- Transthoracic echocardiography (TTE) for cardiovascular evaluation in an acute setting pulmonary embolism
  - Suspected pulmonary embolism in order to establish diagnosis
  - Routine surveillance of prior pulmonary embolism with normal right ventricular function and pulmonary artery systolic pressure
- TTE for cardiovascular evaluation in an acute setting cardiac trauma
  - Routine evaluation in the setting of mild chest trauma with no electrocardiographic changes or biomarker elevation

Information from American College of Cardiology Foundation Appropriate Use Criteria Task Force, American Society of Echocardiography, American Heart Association; Douglas PS, et al: ACCF/ASE/AHA/ASNC/HFSA/HRS/SCAI/SCCM/SCCT/SCMR 2011 Appropriate Use Criteria for Echocardiography. A Report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, American Society of Echocardiography, American Heart Association, American Society of Nuclear Cardiology, Heart Failure Society of America, Heart Rhythm Society, Society for Cardiovascular Angiography and Interventions, Society of Critical Care Medicine, Society of Cardiovascular Computed Tomography, and Society for Cardiovascular Magnetic Resonance Endorsed by the American College of Chest Physicians, J Am Coll Cardiol *57(9):1126-1166, 2011.*

BOX 26-2 SUGGESTED INFORMATION FOR RECORDING IN THE ECHOCARDIOGRAPHIC REPORT

DEMOGRAPHIC AND OTHER IDENTIFYING INFORMATION

- Patient's and hospital identification number
- Age or date of birth
- Gender
- Indications for echocardiography
- Height and weight (indicate whether estimated)
- Blood pressure
- Date on which study was performed
- Physician performing and interpreting investigation
- Referring physician if applicable

Other Identifying Information That May Be Helpful Includes:

- Study media storage/filing location
- Location where study was performed
- Person(s) performing the study
- Echocardiographic device used
- Imaging views obtained, or not obtained (especially if the study is suboptimal)

ECHOCARDIOGRAPHIC AND DOPPLER EVALUATION

Cardiac Structures

- Left ventricle and atrium
- Right ventricle and atrium
- Aortic valve
- Mitral valve
- Tricuspid valve
- Pulmonic valve
- Pericardium
- Aorta
- Pulmonary artery
- Inferior vena cava and pulmonary veins

Measurements

- Usually quantitative measurements are preferred. However, qualitative or semiquantitative assessments are frequently adequate.

Descriptive Statements

- Descriptive statements can be used to describe pertinent findings (e.g., normal, increased, decreased).

SUMMARY

- Address the indication for the study.
- Emphasize important findings.
- If appropriate and practical, compare the current study with previous echocardiographic studies.

Recommendations from Gardin JM, Adams DB, Douglas PS, et al: Recommendations for a standardized report for adult transthoracic echocardiography: a report from the American Society of Echocardiography's Nomenclature and Standards Committee and Task Force for a Standardized Echocardiography Report, J Am Soc Echocardiogr *15(3):275-290, 2002.*

Pearls and Highlights

- The move away from invasive hemodynamic monitoring, as well as increased availability of smaller, less expensive ultrasound machines has propelled echocardiography into mainstream critical care.
- Immediate bedside availability and a detailed appreciation of critical illness, including relevant pharmacology and physiology, place the critical care physician in a strong position to acquire and interpret echocardiographic data.
- The acquisition of timely, accurate echocardiographic data mandates an understanding of pertinent technical aspects, including basic ultrasound physics, transducer handling, and image optimization, as well as 3D cardiac anatomy.

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27

Echocardiography for Intensivists

PHILIPPE VIGNON

Overview

Since its early use in intensive care unit (ICU) settings by pioneers,[1] echocardiography has been increasingly performed in critically ill patients because it provides unparalleled information on central hemodynamics.[2] Initially, real-time morphologic and hemodynamic information, ease of use, portability, and safety constituted definite advantages of echocardiography over more invasive techniques, such as right heart catheterization. Subsequently, ultrasound systems have become smaller, higher quality, and less expensive. This facilitated the diffusion of echocardiography in the ICU environment.[3]

Rapidly, the use of echocardiography by intensivists appeared to be distinct from that of the cardiology community because of specific indications and requirements. Critical care echocardiography (CCE) refers to an examination performed and interpreted by an intensivist to establish diagnoses and guide therapeutic management of patients with cardiopulmonary compromise.[4] The required training of intensivists to reach competence in CCE has been diversely implemented among countries, in Europe and worldwide.[5] Scientific societies of critical care medicine have recently published international recommendations on the competence[4] and the training[6] required to perform CCE (see Chapter 61).

This chapter illustrates the current clinical use of echocardiography in the ICU settings and provides insights into future modalities of ultrasound-based clinical assessment of unstable patients with cardiopulmonary compromise.

Critical Care Echocardiography

SPECIFIC REQUIREMENTS OF CRITICAL CARE ECHOCARDIOGRAPHY

Hemodynamic assessment of ventilated patients with circulatory or respiratory failure is the main indication for performing CCE.[2,7,8] As opposed to conventional, state-of-the-art echocardiography performed in the cardiology laboratory, CCE has distinct requirements (Table 27-1). CCE must be available around-the-clock at the time of the clinical deterioration. Transesophageal echocardiography (TEE) is frequently required when the imaging quality of transthoracic echocardiography (TTE) is inadequate. Heart-lung interactions should be taken into account in the interpretation of CCE studies because critically ill patients are commonly mechanically ventilated. CCE may be focused on the hemodynamic assessment by using a qualitative rather than a quantitative approach.[9] CCE may be repeated to assess the efficacy and tolerance of induced therapeutic changes as a monitoring tool, or if the patient's condition changes over time.[10] Additional indications of echocardiography in the ICU settings are closely related to the specific recruitment of institutions (Box 27-1) and require extensive training to reach competence.[3]

TRANSTHORACIC VERSUS TRANSESOPHAGEAL ECHOCARDIOGRAPHY

TTE is the first-line approach because of its versatility, tolerance, and availability.[7,11] It typically allows an optimal Doppler

TABLE 27-1 Distinct Requirements of Critical Care and Conventional Echocardiography

Critical Care Echocardiography	Conventional Echocardiography
Main indications: cardiopulmonary compromise	Main indications: cardiopathies
Performed at the bedside by the ICU physician	Performed in the cardiology laboratory by the sonographer
Online interpretation by the ICU physician	Off-line interpretation by the cardiologist
Interpretation in light of the critical care medicine background of the physician	Interpretation in light of the cardiology background of the physician
Guides diagnostic workup and invasive procedures	Expertise allows identification and interpretation of complex findings
Around-the-clock availability	Daytime schedule
Ventilated patients (heart-lung interactions)	Spontaneously breathing (out)patients
TEE frequently required and easy to perform	TTE is most commonly performed
Frequently goal-oriented examination	State-of-the-art exhaustive examination
Qualitative or quantitative evaluation using simple yet robust parameters	Quantitative assessment using all existing imaging tools
Immediate diagnostic/therapeutic impact	Delayed diagnostic/therapeutic impact
Monitoring tool/short-term follow-up	Diagnostic tool/long-term follow-up

ICU, Intensive care unit; *TEE*, transesophageal echocardiography; *TTE*, transthoracic echocardiography.

BOX 27-1 COMMON INDICATIONS FOR PERFORMING ECHOCARDIOGRAPHY IN INTENSIVE CARE UNIT PATIENTS

Circulatory Failure (Hypotension, Shock)

Septic shock (first hours)
Complicated acute myocardial infarction (extended infarction or mechanical complication)
Acute aortic syndrome (suspected involvement of ascending aorta)
Massive pulmonary embolism (acute cor pulmonale, in-transit or entrapped embolus)
Cardiac tamponade (pericardial or extrapericardial burden)
Complicated course after cardiac surgery (complication related to the procedure or not)
Cardiac arrest (during or after successful resuscitation)

Acute Respiratory Failure

Cardiogenic pulmonary edema (elevated left ventricular filling pressures and cause)
Acute respiratory distress syndrome (exclusion of cardiogenic pulmonary edema, assessment of right ventricular size and function according to ventilator settings)
Weaning failure from the ventilator (patient with or without known cardiopathy)
Decompensated chronic respiratory failure (patient with or without known right heart failure)
Unexplained hypoxemia (spontaneously breathing or ventilated patient)
Severe blunt chest trauma (suspected cardiovascular injury)
Suspected endocarditis (diagnosis, complications)
Suspected cardiovascular source of systemic embolism
Assessment of circulatory assistance devices: intraaortic balloon counterpulsation, extracorporeal life support/extracorporeal membrane oxygenation (guide insertion, assess related complications)
Cardiac evaluation in brain-dead patients

Modified from Vignon P: Echocardiography in the critically ill: an overview. In De Backer D, Cholley B, Slama M, editors: Hemodynamic monitoring using echocardiography in the critically ill, *Berlin, 2011, Springer, pp 1-9.*

TABLE 27-2 Respective Advantages of Transthoracic and Transesophageal Echocardiography in the ICU Settings

Favors Transthoracic Echocardiography	Favors Transesophageal Echocardiography
Versatility, strictly noninvasive, availability, no contraindication (even in spontaneously breathing patients) Assessment of superficial anatomic structures (apical thrombus, pericardial space, inferior vena cava) Optimal alignment of Doppler beam with transvalvular blood flows (mitral, aortic, and tricuspid valves), and abnormal jets (valvulopathy, left ventricular outflow tract obstruction) Evaluation of pulmonary artery pressure (tricuspid and pulmonary regurgitant jets)	Consistent high imaging quality, reproducibility, and stability of imaging planes (especially in ventilated patients) Assessment of deep anatomic structures (great vessels, base of heart, mediastinum, prosthetic valves, atria, and appendages) Precise identification of the mechanism of certain native or prosthetic valve dysfunctions (eccentric mitral regurgitation, prosthetic valve dysfunction) Identification of intracardiac shunts Identification of great vessel diseases (proximal pulmonary embolism, spontaneous or traumatic acute aortic conditions)

ICU, Intensive care unit.

beam alignment with intracardiac flows and a broader field of examination of relatively superficial anatomic structures (Table 27-2).

TEE is usually used as an adjunct or subsequent test to TTE when surface examination is nondiagnostic. This may be related to poor imaging quality or to the inaccessibility of deep anatomic structures. Because of reduced interference with image acquisition, TEE has a greater diagnostic capability than TTE in ventilated ICU patients.[12] TEE is first performed when examination of deep anatomic structures is required, especially after cardiac surgery.[7,11] Finally, TEE provides more reproducible imaging planes than TTE when a hemodynamic monitoring is needed in unstable patients (see Table 27-2). Nevertheless, TEE is cumbersome to perform repeatedly and is contraindicated in the presence of any risk of esophageal injury (see Chapter 30). In ventilated ICU patients, TEE is safe, and unsuccessful probe insertion is rare when using laryngoscopic guidance under adequate sedation.[8] In spontaneously breathing patients, the major risk of TEE is related to the development of acute respiratory failure precipitated by the esophageal intubation.[13] Accordingly, TEE should be discouraged in unstable patients who are not on ventilatory support, especially when a tamponade or a massive pulmonary embolism is suspected.[10]

IMPACT OF CRITICAL CARE ECHOCARDIOGRAPHY ON PATIENT MANAGEMENT

CCE has a direct impact on management in a large proportion of ICU patients.[8,10] Although TEE has been shown to prompt reoperation without further workup in patients with complicated open-heart surgery and has a greater therapeutic impact than TTE,[12] surface echocardiography is also diagnostic in patients with shock.[14] CCE frequently corrects initial diagnoses derived from invasive hemodynamic monitoring.[10] When performed at the time of the acute insult, CCE best depicts the origin of the cardiopulmonary compromise before the effects of therapy, which may rapidly alter the hemodynamic profile. The anticipated therapeutic impact of CCE is maximal in the most unstable ICU patients at the time of examination.

Clinical Use of Critical Care Echocardiography

CIRCULATORY FAILURE

Septic Shock

Hemodynamic disturbances associated with septic shock are complex and may variously associate with hypovolemia, vasoplegia, and right ventricular (RV), or left ventricular (LV) dysfunction.[15] When performed during the initial phase of septic shock in fluid-resuscitated patients, who are usually under vasopressor support, CCE helps the intensivist in guiding acute therapy.[16]

CCE provides information on cardiac preload, reflected by end-diastolic ventricular volume or area (see Chapter 39), and allows prediction of fluid responsiveness in both mechanically ventilated and spontaneously breathing septic patients (see Chapter 40). CCE findings consistent with profound hypovolemia typically are associated with small cardiac cavities end-systolic obliteration of LV cavity in the presence of a hyperkinetic ventricle, small inferior vena cava size with full inspiratory collapse in spontaneously breathing patients, and large oscillations of interatrial septum that reflect low pressures of both atria (Figure 27-1). Nevertheless, most of these findings individually have a poor diagnostic capacity[17,18] because "static" indices of preload fail to accurately predict the cardiac response to fluid loading.[19] Of note, in fluid-resuscitated septic patients, overt hypovolemia is uncommon, and CCE is then useful in predicting fluid-responsiveness. Preload-dependent ventilated patients typically exhibit marked respiratory variations of aortic Doppler velocities and of the size of both the superior and inferior vena cavae.[20] In these patients, fluid loading significantly increases the stroke distance of LV outflow (i.e., stroke volume) (Figure 27-2). In patients with spontaneous breathing activity or nonsinus rhythms, the effect of passive leg raising on LV outflow stroke distance helps in predicting responders to a fluid challenge from nonresponders.[20]

In approximately one third of patients examined at the early phase of septic shock, CCE clearly depicts a LV systolic dysfunction (Video 27-1). The myocardial depression related to septic shock positively responds to inotropic agents (Video 27-2), and fully recovers in survivors, with the treatment of sepsis, regardless of its severity.[16,21,22] In contrast with congestive heart failure, LV filling pressures are typically not elevated.

RV failure is less frequently encountered in septic shock patients. When present, it is typically associated with an underlying acute respiratory distress syndrome (ARDS).[16] Finally, sustained vasoplegia is suspected in the absence of preload dependence, cardiac dysfunction, or any other echocardiographic abnormality that could account for the circulatory failure (e.g., acute valvular regurgitation secondary to an infective endocarditis, tamponade related to a purulent pericarditis).

In 42 ventilated patients with septic shock, we compared the therapeutic changes derived from the Surviving Sepsis Campaign guidelines[23] and TEE examination performed during the first hours of ICU admission.[24] In 30% of patients who would have been fluid loaded based on a central venous pressure less than 12 mm Hg, CCE ruled out a preload dependance, and patients actually did not receive any blood volume expansion. In 14 patients (33%), CCE led to initiate an inotropic support that would have been decided for only 4 patients according to current guidelines.[24]

Complicated Acute Myocardial Infarction

Circulatory failure secondary to acute myocardial infarction (AMI) may have various clinical presentations, including hypotension, low cardiac output, pulmonary edema, and cardiogenic shock, with frequent overlap. Cardiogenic shock is hemodynamically defined by a sustained systemic hypotension (systolic arterial pressure < 90 mm Hg) with adequate or elevated LV filling pressures (pulmonary artery wedge pressure $>$ 15-18 mm Hg) and a reduced cardiac output (cardiac index < 2.2 L/min/m^2).[25]

In patients with complicated AMI, cardiogenic shock typically results from an extensive infacted myocardial area or a mechanical complication (e.g., ruptured papillary muscle, ventricular septal, or free wall rupture). CCE clearly depicts the extension of AMI and allows the quantification of related LV systolic dysfunction.[26] TTE is valuable for the identification of ventricular septal rupture and of potentially compressing hemopericardium secondary to LV free wall rupture (Figure 27-3). TEE is best suited to depict an eccentric mitral regurgitation resulting from a papillary muscle dysfunction or rupture, which may be frequently missed when using TTE (Videos 27-3 and 27-4).

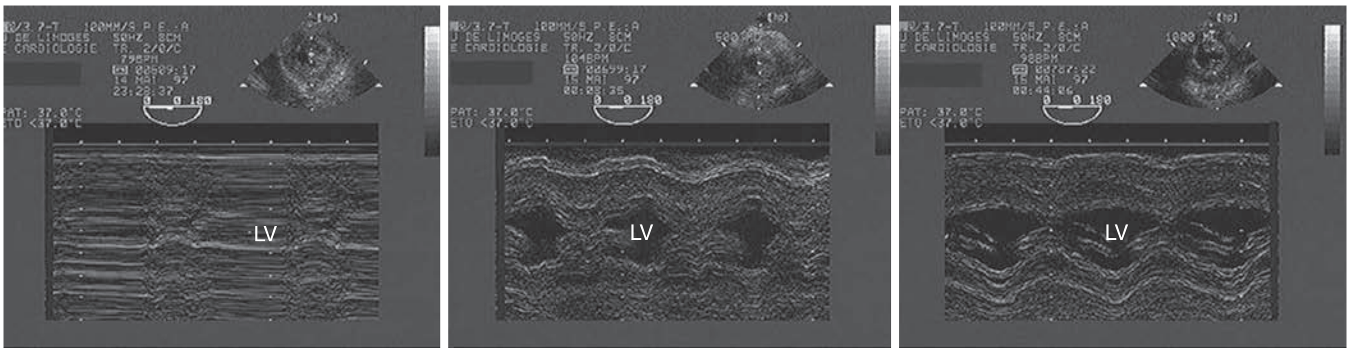

Figure 27-1 Profound hypovolemia detected by transesophageal echocardiography in a hypotensive ventilated patient after cardiac surgery. M-mode tracings obtained from the transgastric short-axis view of the left ventricle depict the presence of a virtual ventricular cavity with end-systolic obliteration *(left panel),* and the progressive increase of the ventricular size secondary to two consecutive fluid challenges which reflects increased preload (*middle* and *right panels*). Please note the improved thickening of left ventricular walls, which reflects the increase of stroke volume secondary to blood volume expansion in this fluid responder. *LV,* Left ventricle.

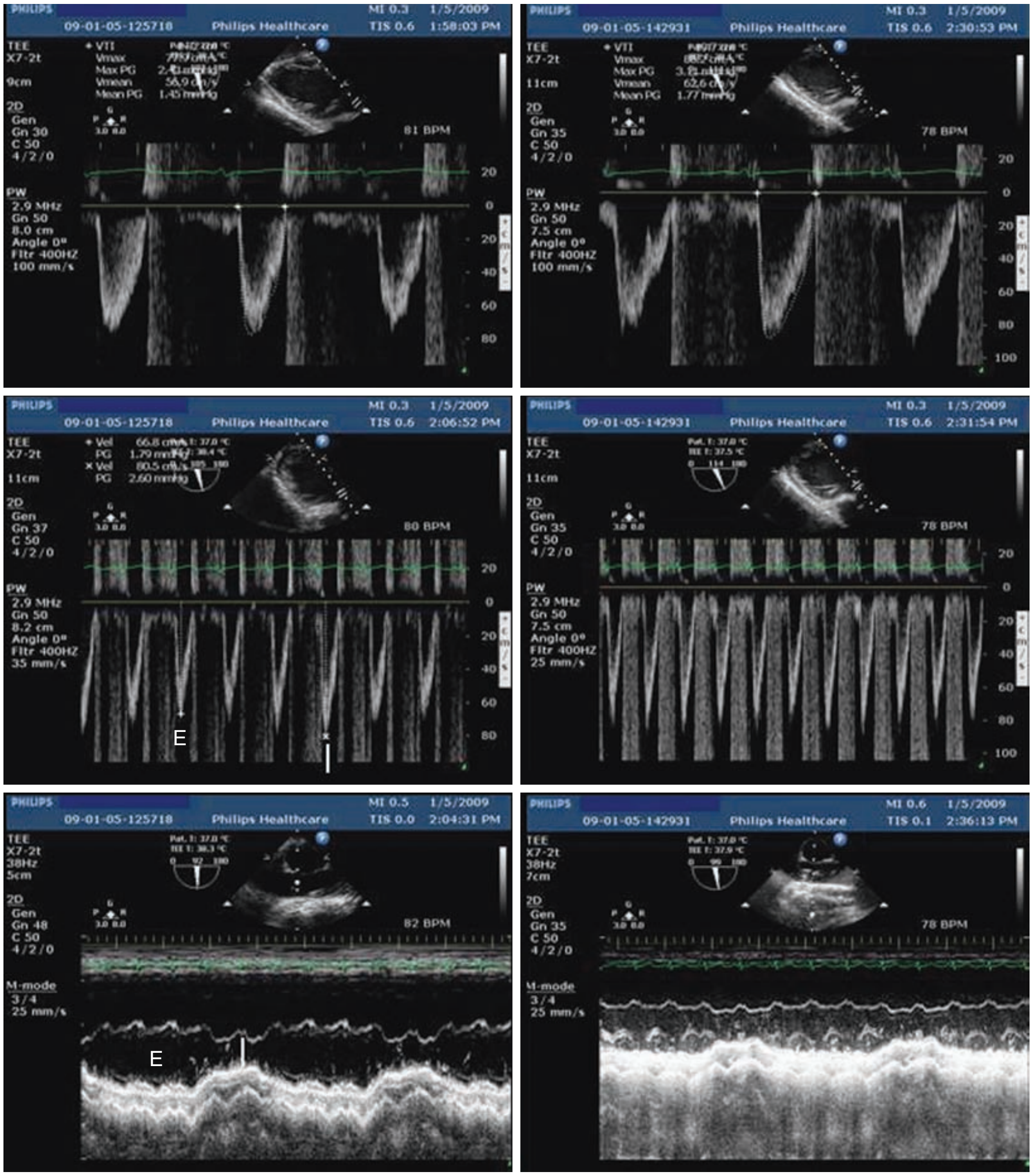

Figure 27-2 Assessment of fluid responsiveness by using transesophageal echocardiography in the early course of a ventilated patient with septic shock and sinus rhythm. At baseline, the stroke distance of left ventricular outflow was reduced (14.2 cm), reflecting decreased stroke volume *(upper left)*, and associated with marked respiratory variations of maximal Doppler velocities *(middle left)* and superior vena cava diameter *(lower left)*, which both suggested preload dependency. After 500-mL fluid loading, left ventricular outflow Doppler disclosed a 39% increase of stroke distance (19.7 cm), which confirmed fluid responsiveness *(upper right)*, and both the respiratory variations of maximal Doppler velocities *(middle right)* and superior vena cava diameter *(lower right)* were attenuated. *I,* Insufflation; *E,* expiration.

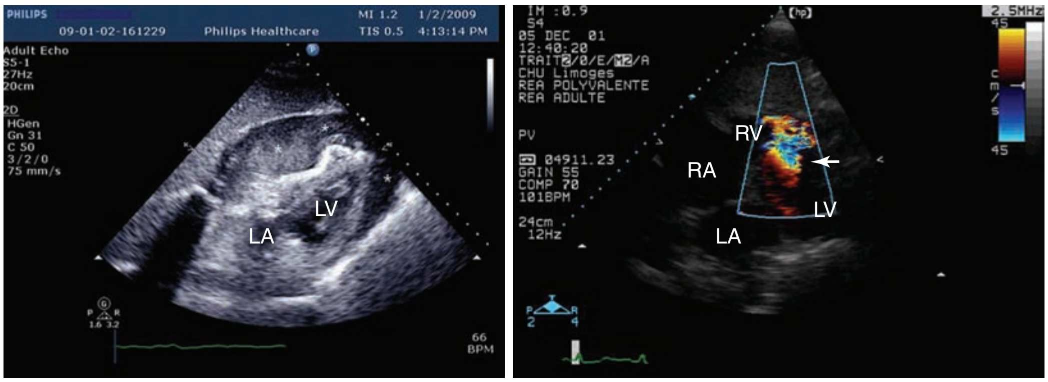

Figure 27-3 Mechanical complications of acute myocardial infarction diagnosed by using transthoracic echocardiography. In these two patients with severe shock, the subcostal view depicted a cardiac tamponade with compressed right cardiac cavities caused by a ruptured left ventricular free wall with hemopericardium *(left panel, asterisks)* and a ruptured ventricular septum with associated left-to-right shunt depicted by color Doppler mapping *(right panel, arrow)*. *LA,* Left atrium; *LV,* left ventricle; *RA,* right atrium; *RV,* right ventricle.

Acute Aortic Syndrome

Acute aortic syndrome (AAS) is characterized clinically by an "aortic pain" (i.e., severely intense, acute, searing or tearing, throbbing, and migratory chest pain) in a patient with a coexisting history of hypertension.[27] AAS may be secondary to various acute aortic conditions, including the classic aortic dissection, intramural aortic hematoma, and penetrating atherosclerotic aortic ulcer. Associated circulatory failure is usually present when the ascending aorta is involved.[28] In this setting, TTE should first be performed because it allows expeditous and accurate diagnosis of pericardial extravasation, which prompts surgical repair. TEE is then safely performed under general anesthesia during surgery, to precisely characterize the underlying aortic disease, its anatomic extension, and associated complications (Video 27-5). The ascending aorta is typically enlarged, and acute aortic regurgitation may be present. Associated findings depend on the causative aortic disease: intimal flap (aortic dissection), aortic wall thickening (intramural hematoma), or penetrating aortic ulcer.[29]

Massive Pulmonary Embolism

Massive pulmonary embolism and ARDS are the main causes of acute cor pulmonale (ACP) in critically ill patients (see Chapter 33). ACP refers to any sudden increase in RV outflow impedance. Afterloaded RV typically exhibits a combined diastolic overload (RV enlargement) and systolic overload (paradoxic ventricular septal motion).[30]

TTE best depicts RV cavity dilatation in a longitudinal view of the heart (apical four-chamber view) and the end-systolic bulging of the ventricular septum toward the LV cavity in a transverse view of the heart (parasternal or subcostal short-axis view) (Figure 27-4). Associated findings include right atrial dilatation, various levels of pulmonary hypertension, and systemic venous congestion reflected by a dilatated inferior vena cava with reduced respiratory variations.[30]

In ventilated patients, TEE may depict entrapped thrombus in the foramen ovale or in the proximal pulmonary artery (Video 27-6). In no instance should TEE be performed in spontaneously breathing patients with suspected massive pulmonary embolism because the esophageal intubation may precipitate cardiopulmonary compromise.

Cardiac Tamponade

In critically ill patients, cardiac tamponade may result from a diffuse or loculated pericardial effusion, or from atrial or ventricular compression by extrapericardial collections.[31] Classic clinical signs of cardiac tamponade are rarely encountered, especially in the presence of a localized tamponade resulting from the development of postoperative mediastinal hematomas in cardiac surgery patients. TTE rapidly depicts the presence of pericardial fluid around the heart, consistent with unloculated effusion (see Figure 27-3, left panel). Tamponade is present when any cardiac cavity is compressed (usually right cardiac cavities because of lower chamber pressures) and when interventricular dependence is increased, as reflected by augmented respiratory variations of Doppler ventricular inflow velocities in spontaneously breathing patients.[32] TEE should first be performed in ventilated cardiac surgery or blunt chest trauma patients who present with shock and suspected localized cardiac tamponade. It typically depicts the presence of an inverted free wall curvature of the cardiac chamber that is compressed throughout the cardiac cycle by the mediastinal hematoma.[31] Blood flow turbulences are frequently depicted by color Doppler mapping in the involved cardiac cavity (Video 27-7).

CARDIAC ARREST

CCE is valuable when performed during a cardiac arrest or after a successful resuscitation, to identify a potential cause (see Chapter 35). TTE can be performed during resuscitation using the subcostal approach. It may depict an ACP, a thrombus-in-transit consistent with massive pulmonary embolism, or a pericardial effusion with associated tamponade physiology.

ACUTE RESPIRATORY FAILURE

Cardiogenic Pulmonary Edema

Cardiogenic pulmonary edema (CPE) is related to the rise of hydrostatic pressure in the pulmonary vascular bed.[33] CCE allows the evaluation of LV filling pressures and the identification of a potential cardiopathy responsible for the CPE.[34]

In a patient presenting with suspected CPE, the first step is to confirm the presence of elevated filling pressures, which are

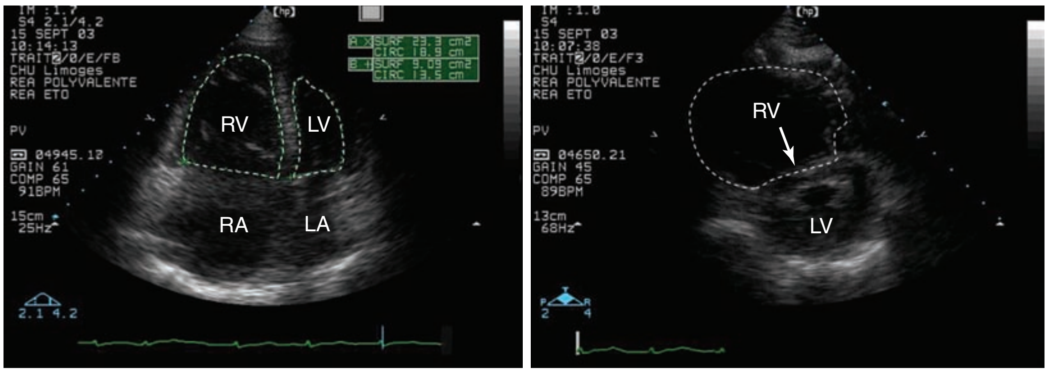

Figure 27-4 Transthoracic echocardiography performed in a patient presenting with hypotension and shortness of breath. Apical four-chamber view depicts a markedly enlarged right ventricle whose cavity size exceeds that of the left ventricle *(left panel, dotted lines).* Parasternal short-axis view confirms the right ventricular dilatation and depicts a flattened ventricular septum *(right panel, arrow).* These findings are consistent with an acute cor pulmonale, which is highly suggestive of a massive pulmonary embolism in the clinical context. *LA,* Left atrium; *LV,* left ventricle; *RA,* right atrium; *RV,* right ventricle.

frequently associated with (severe) LV diastolic dysfunction (see Chapter 32). Pulsed wave Doppler of the mitral inflow and pulmonary vein flow, combined with tissue Doppler imaging of the mitral annulus, can accurately identify elevated LV filling pressures. We have previously shown in mechanically ventilated patients that a ratio of maximal early diastolic velocities of Doppler mitral inflow and tissue Doppler of the mitral ring (E/E' ratio) equal or less than 8 predicted a pulmonary artery occlusion pressure less than or equal to 18 mm Hg, with a sensitivity and a specificity of 83% and 88%, respectively.[35] Other simple yet robust Doppler indices have been proposed to semiquantitatively assess LV filling pressures in ventilated critically ill patients.[34] The presence of a dilatated left atrium or the consistent bulging of the septum toward the right atrium reflect elevated left atrial pressure.

The second step of CCE is to identify the origin of pulmonary vein congestion by using a systematic diagnostic algorithm.[34] Congestive heart failure secondary to a cardiac ischemic disease or a dilatated cardiomyopathy is typically associated with a severe LV systolic dysfunction. Both the dilation of the LV cavity and thinning of LV walls are consistent with a chronic cardiomyopathy (Figure 27-5). Of interest, severe LV dysfunction with elevated filling pressures may be transient and secondary to noncardiac diseases, such as severe cerebral insults (Video 27-8). Although congestive heart failure is the most common cause of CPE, a normal or increased LV systolic function fails to rule out the diagnosis.[33] Elevated LV filling pressures with preserved ejection fraction should lead to search for severe valvulopathy, especially acute regurgitations.[34] Eccentric and transient severe mitral regurgitation may easily be missed by using TTE. Apparently isolated LV diastolic dysfunction may result in CPE if severe and is potentially associated with a precipitating factor (inadequate fluid loading, dysrhythmia, severe systemic hypertension). CCE is pivotal in establishing diagnostic criteria of diastolic heart failure in depicting elevated LV filling pressures, preserved ejection fraction, absence of relevant valvulopathy, and altered LV diastolic properties at the time or in proximity to the acute CPE (see Chapter 32).[36]

Acute Respiratory Distress Syndrome

ARDS is the second most common cause of ACP in critically ill patients.[30] CCE findings of ARDS-induced ACP are nonspecific. Nevertheless, CCE helps the front-line intensivist in setting the ventilator and adjusting therapeutic strategy (e.g., prone position, nitrous oxide [NO] inhalation) to treat or prevent RV afterloading (see Chapter 33). Because plateau pressure is significantly associated with the development of ACP,[37] and RV failure appears as a prognostic factor in ARDS patients,[38] CCE is valuable in monitoring RV function to guide therapy.[39]

Weaning Failure from the Ventilator

CCE allows the identification of patients at high risk of weaning failure and depicts in real time the effects of spontaneous breathing trials on central hemodynamics (see Chapter 34). We previously showed that patients who failed ventilator weaning had significantly lower LV ejection fraction and higher LV filling pressures when compared with patients who were successfully extubated. Spontaneous breathing trial significantly increased cardiac output and LV filling pressures (higher early to late maximal diastolic velocities of mitral Doppler inflow – E/A ratio – and shortened E wave deceleration time).[40] CCE may also depict transient or worsened mitral regurgitation secondary to abrupt changes in cardiac loading conditions induced by the interruption of positive pressure ventilation. The combination of TTE and chest ultrasound promises to efficiently guide the diagnostic workup at bedside in patients exhibiting weaning failure from the ventilator (see Chapter 34).

Decompensated Chronic Respiratory Failure

Severe long-standing respiratory failure may be associated with chronic cor pulmonale. Differential diagnosis with ACP mainly relies on the clinical context, the presence of RV free wall hypertrophy (close to 10 mm) and of marked pulmonary hypertension.[30] A systolic pulmonary artery pressure derived from the maximal velocity of tricuspid regurgitant jet greater than 60 mm Hg is consistent with a chronically afterloaded and usually hypertrophied RV (see Chapter 33) (Video 27-9).

Unexplained Hypoxemia

Anatomic shunts should be ruled out in patients with sustained hypoxemia but no relevant radiologic infiltrates or pulmonary ultrasound findings. Contrast study performed during a TEE examination is the reference method for the diagnosis of patent foramen ovale (PFO) with associated interatrial right-to-left shunt or for the identification of an anatomic shunt of the pulmonary vascular bed.[41] Microcavitations

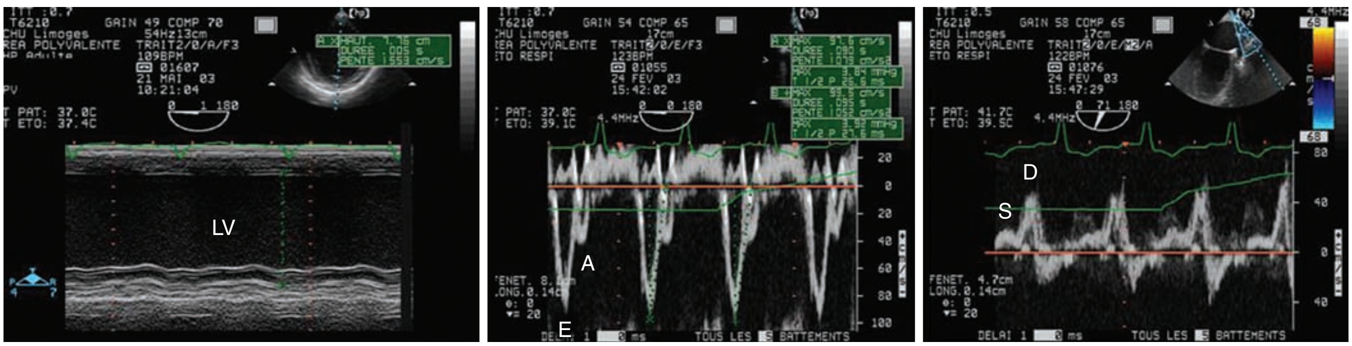

Figure 27-5 Transesophageal echocardiography performed in a ventilated patient with cardiogenic pulmonary edema. Two-dimensional imaging revealed a markedly dilatated and severely hypokinetic left ventricle with thin walls, as reflected by M-mode tracing *(left panel)*. Pulsed wave Doppler depicted a restrictive mitral pattern with E/A greater than 2 and shortened E wave deceleration time (<100 msec) *(middle panel)*. Pulmonary vein Doppler disclosed a blurred S wave in the absence of severe mitral regurgitation, which confirmed a marked increase of left atrial filling pressures *(right panel)*. E/E' was 13. *LV,* Left ventricle.

obtained by agitated saline are injected intravenously to obtain a full opacification of the right atrium. Early visualization of microcavitations in the left atrium suggests the presence of an underlying PFO, when this occurs within three cardiac cycles after right atrial opacification, and this is consistent with an anatomic shunt of the pulmonary vasculature when the left atrial opacification is delayed.[42] The volume of the anatomic shunt reflected by the amount of microcavitations observed in the left atrium and its consistency throughout the respiratory cycle determine its potential role in the sustained hypoxemia (Figure 27-6). In patients ventilated for ARDS, a PFO has recently been diagnosed by using TEE in 19% of the cases.[43] These patients exhibited an associated ACP more frequently and had a blurred response to positive end-expiratory pressure titration when compared with ARDS patients without PFO.[43]

SPECIFIC INDICATIONS

Cardiovascular Injuries

Penetrating chest trauma should prompt focused TTE to rule out blood extravasation. In this specific setting, the identification of a pericardial effusion strongly suggests the presence of a hemopericardium secondary to a cardiac wound, which requires rapid surgery. Patients sustaining blunt chest trauma are best assessed by using TEE, for which diagnostic accuracy for the identification of aortic and cardiac injuries is greater than that of TTE (see Chapter 31).[44] TEE findings associated with blunt aortic injuries are distinct from those encountered in patients with acute aortic dissections (Figure 27-7) and helps in guiding therapeutic management.[45]

Infective Endocarditis

Modified Duke criteria for the definite diagnosis of infective endocarditis include TEE findings.[46] In addition, TEE allows the clinician to accurately assess the severity of associated valvular regurgitation or prosthetic valve dysfunction and to evaluate the risk of systemic embolism of vegetations (Video 27-10). Because of a lower diagnostic accuracy, TTE should not be solely used to confidently exclude an infective endocarditis in a high-risk ICU patient.

Miscellaneous

Various additional clinical settings may lead to performance of CCE. A potential source of systemic embolism is best depicted by TEE (Video 27-11). Similarly, TEE allows guiding the initial positioning of intracardiac cannulae for extracorporeal life support (Figure 27-8). Subsequently, TEE allows monitoring the patient to identify potential cardiac complications and to determine the optimal time window to initiate weaning from circulatory assistance.[47]

Current Trends and Future Directions

The miniaturization of ultrasound systems led to the diffusion of pocket-size devices used as ultrasound stethoscopes for goal-directed assessment of ICU patients.[48] Because goal-directed ultrasound assessment appears superior to standard physical examination both for diagnostic purposes and for procedural guidance, the concept of point-of-care ultrasonography emerged.[3] It refers to an ultrasound examination performed and interpreted in real time by the provider at the patient's bedside; it may be focused on limited clinical questions and can be repeated if the patient's condition changes over time.[49]

Miniaturization of TEE probes promises to facilitate and safely prolonged esophageal insertion of the device for the purpose of hemodynamic monitoring. Recently, we showed that a miniaturized single-use monoplane TEE probe designed for a 72-hour esophageal insertion allowed serial qualitative assessment of central hemodynamics, which resulted in frequent therapeutic changes.[50]

Real-time three-dimensional TEE is feasible in ventilated ICU patients.[51] In the near future, automated gain settings will presumably facilitate data acquisition and off-line multiplane analysis by less experienced operators. Accelerated reconstructions will provide accurate RV volume measurements, which promise to provide access to valuable

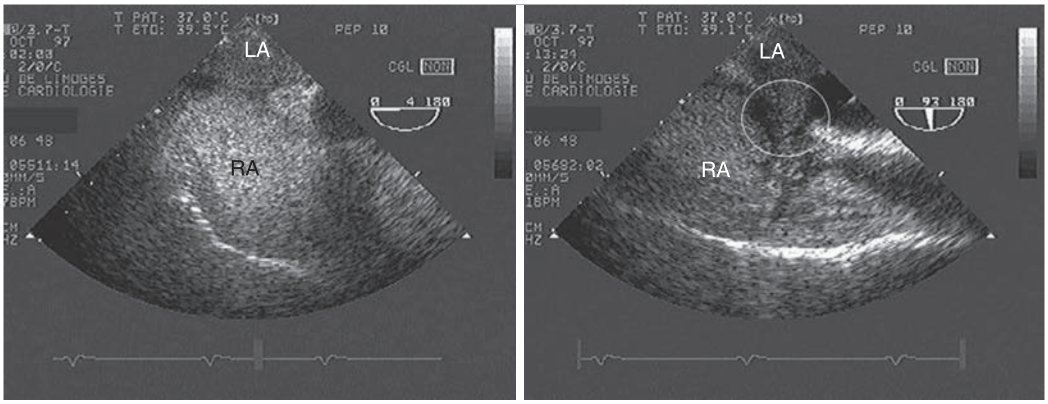

Figure 27-6 Positive contrast study performed during a transesophageal echocardiographic examination in a ventilated patient with unexplained hypoxemia. A large right-to-left interatrial shunt associated with a patent foramen ovale is seen both in the four-chamber view centered on the two atria *(left panel)* and in the 90-degree bicaval view *(right panel, circle).* The width of the anatomic shunt, the full opacification of left atrium, and sustained shunt throughout the respiratory cycle indicate a large shunted blood volume that could participate in severe and refractory hypoxemia. *LA,* Left atrium; *RA,* right atrium.

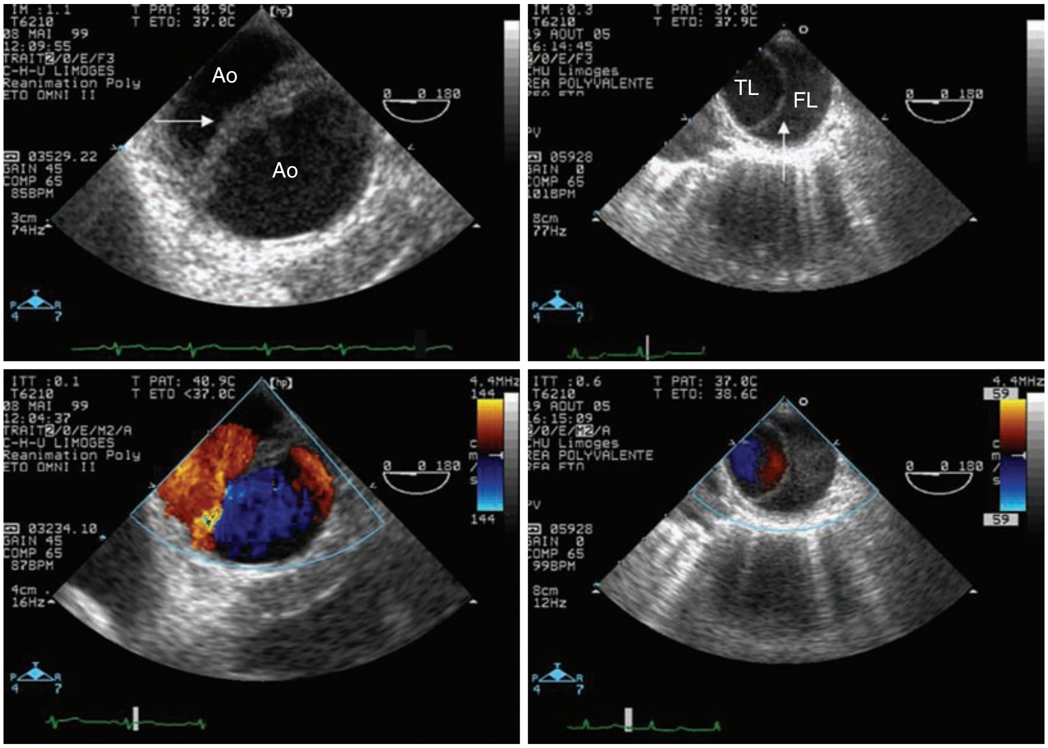

Figure 27-7 Differential diagnosis between aortic disruption and aortic dissection by using transesophageal echocardiography. In addition to the clinical context, echocardiographic findings allow distinguishing a spontaneous aortic dissection and a traumatic aortic disruption, which usually solely involves the aortic isthmus. In this transverse view of the descending aorta, the medial flap of the disrupted aorta appears thicker than the intimal flap associated with acute dissection *(upper panels, arrows)*. Color Doppler mapping typically depicts similar blood flow velocities on both sides of the disrupted aortic wall because the medial flap fails to delimit two distinct channels, whereas lower velocities are observed in the false lumen of the aortic dissection *(lower panels)*. Of importance, echocardiographic findings are usually confined within a few centimeters in the presence of an aortic disruption, whereas they are more extended according to the anatomic type of aortic dissection. *Ao,* Aortic isthmus; *FL,* false lumen; *TL,* true lumen.

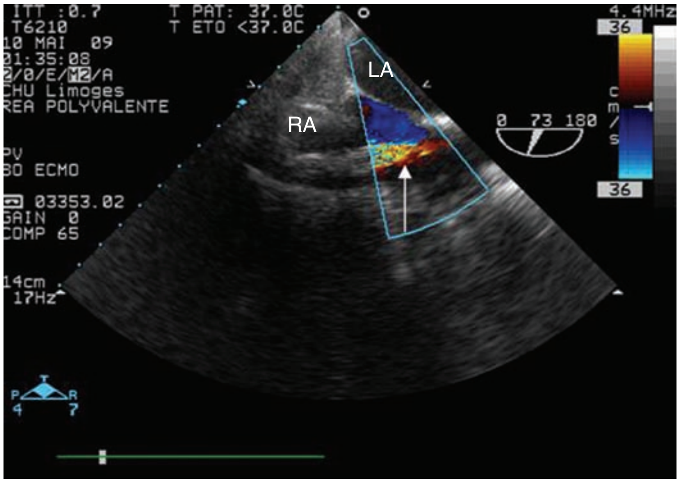

Figure 27-8 Transesophageal echocardiographic guidance of right atrial cannula insertion in a ventilated patient requiring extracorporeal life support for severe cardiogenic shock. The proper position of the cannula tip parallel to the atrial septum is confirmed and the adequate aspiration of venous blood is evidenced by color Doppler mapping *(arrow)*. *LA,* Left atrium; *RA,* right atrium.

information that are yet inaccessible to two-dimensional echocardiography.

Pearls and Highlights

- CCE is a bedside examination performed and interpreted by the intensivist in charge of the patient on a 24-hour basis. This distinguishes CCE from conventional echocardiography.
- The diagnostic and monitoring power of echocardiography has led to its extensive use in ICUs and to a marked expansion of its indications in critically ill patients.
- When properly used after an adequate training, CCE increases the accuracy of clinical assessment, guides the diagnostic workup, saves time, and promises to reduce cost while improving the outcome of ICU patients.

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28

Echocardiography: Beyond the Basics

BENEDICT WALDRON | GUIDO TAVAZZI | SUSANNA PRICE

(CONSULTANT-LEVEL EXAMINATION)

Overview

Echocardiography is one of the most powerful diagnostic and monitoring tools available to the modern intensivist. Although its potential was first recognized more than 20 years ago,[1] only recently has it become a mainstream imaging application in the intensive care unit (ICU). However, the widespread application of advanced echocardiographic techniques in the ICU remains disappointingly limited to isolated experts across the world, and the huge potential for collaborative research between cardiologists and intensivists in this field remains largely unrecognized. The reasons for this are largely historical; cardiology and intensive care have developed in parallel, with little overlap between the two specialties. With the paradigm shift in cardiologic interventions (percutaneous coronary, valve, and electrophysiologic procedures), there has been an understandable change in focus away from the more traditional specialties based upon cardiac physiology toward the newer interventional subspecialties. The development of complex and sophisticated imaging techniques (cardiac magnetic resonance and computed tomography) has presented further competition to echocardiography as a subspecialty within cardiology. Controversies regarding practice, training, accreditation, and "ownership" have until recently increased the potential conflict between cardiologists and intensivists regarding the use of echocardiography in the ICU (Table 28-1). Nonetheless, increasing availability of ultrasound machines, together with concerns regarding the safety of the pulmonary artery catheter, have resulted in intensivists adopting echocardiography as part of their repertoire of diagnostic and monitoring techniques. This chapter illustrates some neglected physiologic echocardiographic techniques as well as some of the potential areas where newer techniques might prove to be of use in the ICU.

Left Ventricular (LV) Function

The mechanism of LV function in systole and diastole is complex, with differing orientation of fibers at different muscle layers, and comprises minor and long-axis contraction, rotational contraction, as well as differential basal and apical rotational vectors. Of the older techniques, assessment of LV contractility generally either depends upon linear measures of changes in LV internal dimensions (fractional shortening) or differences between systolic and diastolic areas/volumes in the minor axis (ejection fraction), rather than thickening of the myocardium per se. Normal values of fractional shortening and ejection fraction are not known for the critically ill and remain highly variable depending upon ICU interventions in addition to the inherent contractility of the myocardium. The true value of other, less widely used techniques (long-axis function and total isovolumic time) has not yet been realized in the ICU setting, and that of emerging techniques (strain and strain rate) remains to be evaluated.

TABLE 28-1 Basic and Advanced Echocardiographic Techniques in the ICU

Technique	Routine ICU Use Recommended?	Comments
Focused basic echocardiography	Yes	Easy, binary decision-making to exclude/diagnose treatable causes of periarrest and arrest states
Ejection fraction	No	Normal values unknown in ICU Too many dynamic variables Does not measure contractility
Long-axis function	Yes	Easy to acquire (even with suboptimal views) Reproducible Sensitive to ischemia
Physiologic Doppler	Yes	Assessment of standard echodynamics Evaluation of t-IVT
Strain/strain rate	No	Research tool Not validated in critically ill adults Image resolution an issue
3D/4D	Yes: for specific indications	Delineation of paraprosthetic regurgitation Assessment of mechanism of MR (percutaneous repair) Right ventricular function/dyssynchrony (research)

3D/4D, Three-dimensional/real-time three-dimensional echocardiography; *ICU*, intensive care unit; *MR*, mitral regurgitation; *t-IVT*, total isovolumic time.

Long-Axis Function

The subendocardial fibers of the left ventricle run longitudinally, resulting in the characteristic movement of the mitral annulus toward the apex of the heart in systole, followed by retraction in diastole. *Regional myocardial ischemia* (induced by positive inotropic agents) may result in changes in regional wall motion scores associated with a fall in cardiac output at peak stress.[2] *Regional dyssynchrony* may also develop, demonstrated by the appearance/worsening of postejection shortening, prolongation of the total isovolumic time (t-IVT), and associated broadening of the QRS duration. This response is in contrast to the normal shortening of the QRS duration and t-IVT in response to inotropic agents. Thus there is potential to diagnose subclinical myocardial ischemia/type I/II myocardial infarction by using this simple technique (Figure 28-1). Further, because t-IVT is a major determinant of maximal cardiac output during pharmacologic stress, it may be possible to titrate, on an individual patient basis, the response to positive inotropic agents, to minimize electromechanical dyssynchrony and avoid limiting cardiac output (Figure 28-2).

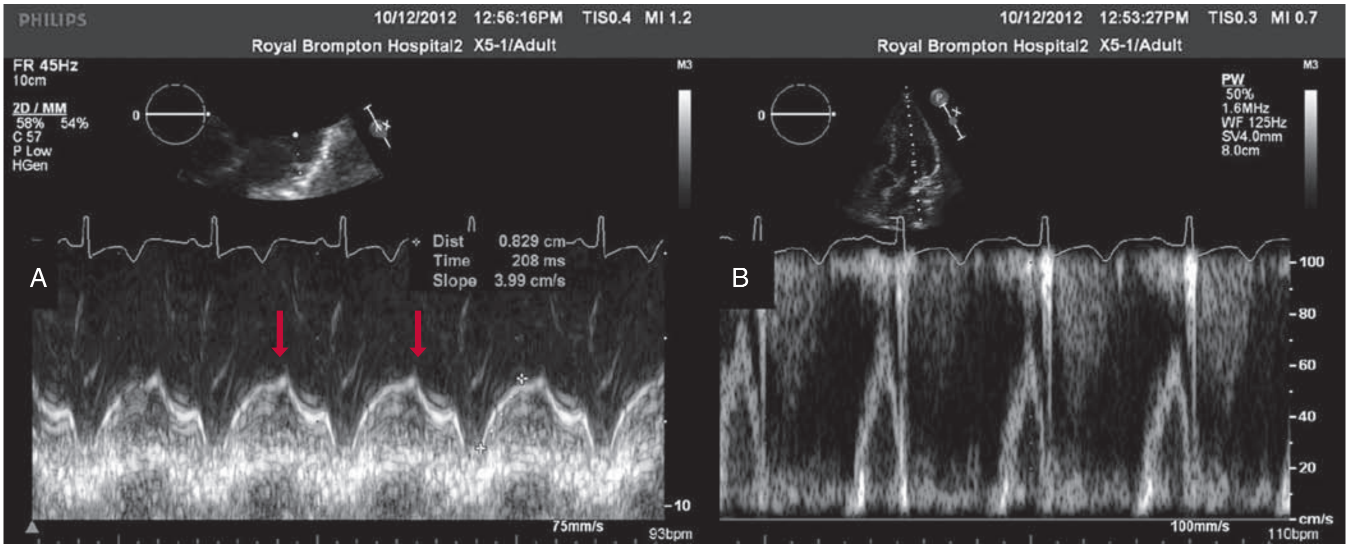

Figure 28-1 TTE in a young patient with type II myocardial infarction. **A,** MAPSE of the lateral wall, with postejection shortening *(red arrow).* **B,** PW Doppler of the mitral valve showing abnormal filling with summation (resulting from tachycardia) and a dominant A wave. *MAPSE,* Mitral annular plane systolic excursion; *PW,* pulsed wave; *TTE,* transthoracic echocardiogram.

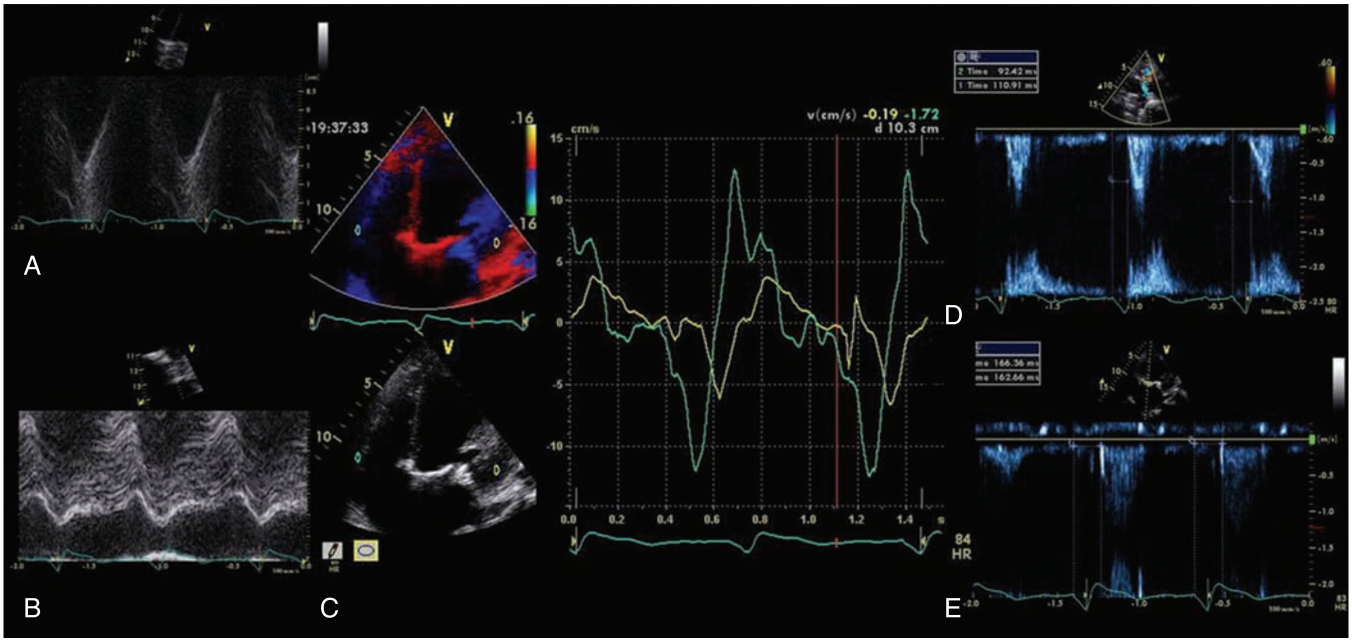

Figure 28-2 Interventricular dyssynchrony demonstrated by M-mode, TDI, and PW Doppler; **A** and **B,** M-mode traces of the right (TAPSE) and left (MAPSE) ventricle, depicting prolonged and late movement of the LV when compared with the RV free wall, as well as reduced excursion. **C,** PW TDI of the right *(green)* and left *(yellow)* ventricle taken from the illustrated regions (miniature images to the left; namely the LV and the RV free wall, respectively). LV TDI velocities are reduced and delayed. **D,** PW Doppler taken from the pulmonary valve showing a preejection period of 98 msec. **E,** PW Doppler from the aortic valve, showing a preejection period of 164 msec. Thus echo demonstrates a significant delay in LV contraction compared with the RV, resulting in a delay in ejection. *LV,* Left ventricle; *MAPSE,* mitral annular plane systolic excursion; *PW,* pulsed wave; *RV,* right ventricle; *TAPSE,* tricuspid annular plane systolic excursion; *TDI,* tissue Doppler imaging.

Total Isovolumic Time (t-IVT)

Factors increasing this measure of global LV electromechanical dyssynchrony include ischemia, conduction system disturbances, and loading conditions. Although there is not extensive literature regarding resynchronization therapy (atrioventricular [AV] and/or ventriculoventricular [VV]) in the ICU, the effects of dyssynchrony are well-recognized (including reduced LV contractility [dP/dT], pulse pressure, ejection fraction and cardiac output, diastolic filling time, and increased duration of mitral regurgitation and t-IVT). Even simple manipulations of heart rate and AV delay can result in significant improvement in cardiac filling (Figure 28-3). Global LV electromechanical dyssynchrony measured by t-IVT is common (22% patients in cardiothoracic ICUs) and is associated with increased mortality (7.5% vs. 25%, $P = .2$, Tavazzi et al, unpublished data). Emerging case series suggest that resynchronization therapy may be of use in selected critical care patients; however, case selection remains essential.[3]

Strain and Strain Rate Imaging

These techniques have been suggested to improve the ability to detect ischemia and ventricular dysfunction not demonstrable by other more "conventional" echocardiographic techniques. Strain/strain rate are measures of myocardial deformation and describe both the nature and function of cardiac tissue. These techniques differ significantly from traditional methods of LV function assessment, which measure changes in internal LV dimension. Strain/strain rate (Figure 28-4) can be

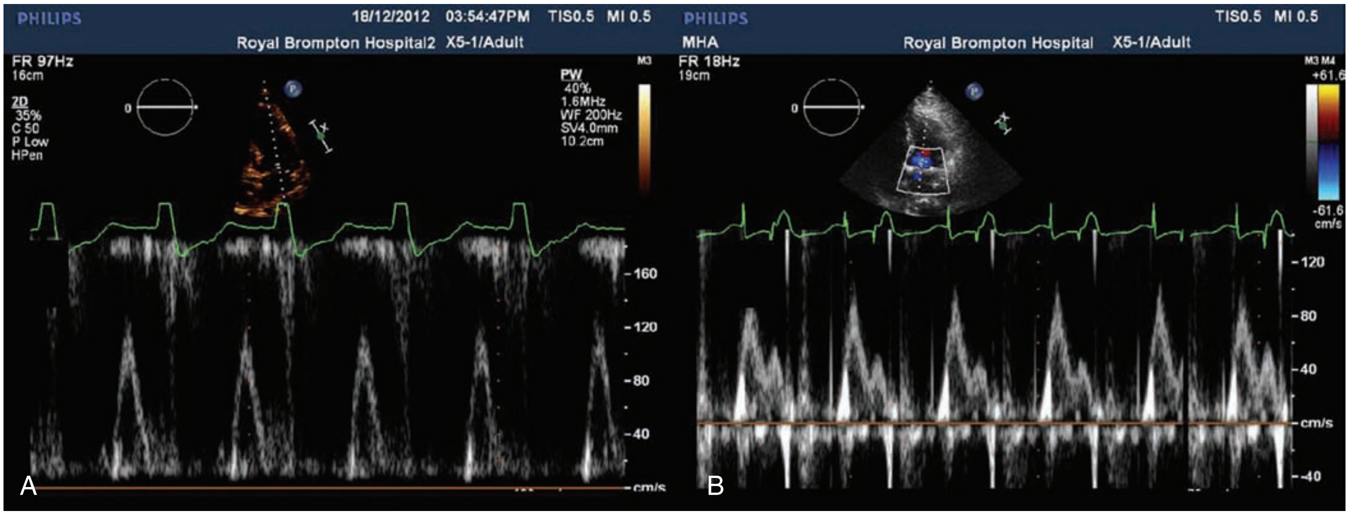

Figure 28-3 Transmitral PW Doppler in a patient showing the effect of pacing optimisation. **A,** Native conduction (note the broad QRS duration on the ECG) and single E wave filling. **B,** DDD pacing with short AV delay, with presence of E and A waves on transmitral Doppler. *AV,* Atrioventriculr delay; *DDD,* dual chamber; *ECG,* electrocardiogram; *PW,* pulsed-wave.

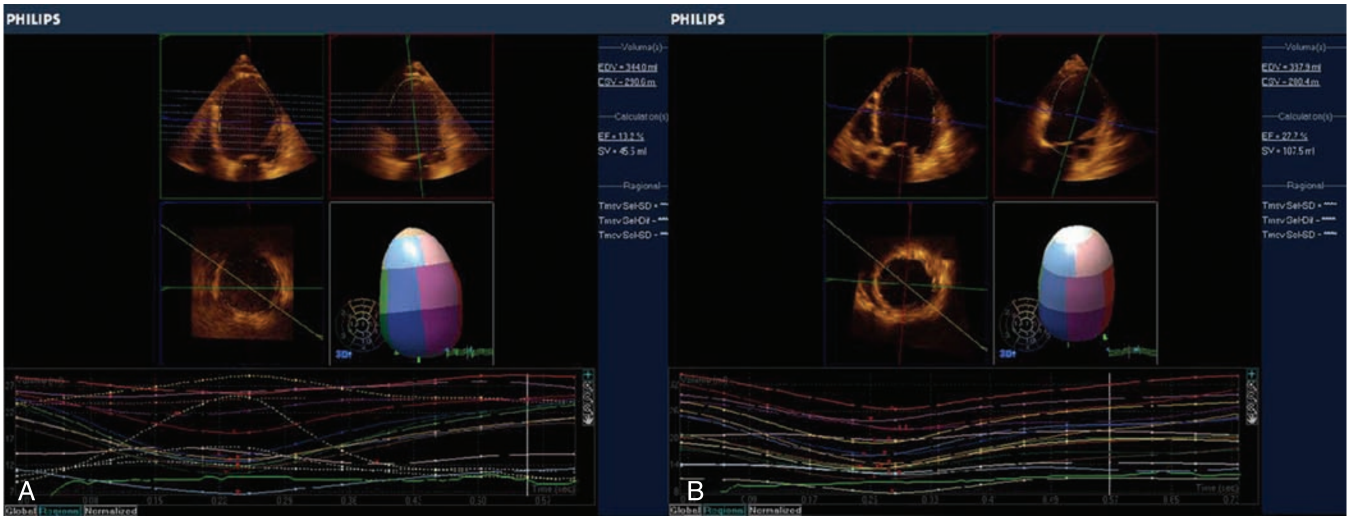

Figure 28-4 3D regional strain in patient with ischemic cardiomyopathy. **A,** Regional tracking shows severe intraventricular dyssynchrony (SV 41.3, EF 13.2%). **B,** After resynchronization therapy the same patient has more synchronous contraction. Note, also that the ejection fraction has concomitantly significantly increased (SV 127.5, EF 27.7%). *3D,* Three-dimensional; *EF,* ejection fraction; *SV,* stroke volume.

measured using Doppler or two-dimensional (speckle tracking) echocardiography.[4]

Strain rate is measured by obtaining a series of velocity curves (from tissue Doppler imaging [TDI] comprising isovolumic contraction, systolic, diastolic, and atrial components) to demonstrate a velocity gradient along a length of ventricular wall. A regression calculation between adjacent tissue velocity data points along this length is used to generate strain rate, which is integrated to calculate strain. Thus strain rate (SR) reflects dP/dT of adjacent areas of the myocardium *(SR =* $(V_1 - V_2)/L$*; where V = velocity and L = length),* and is thought to be less load-dependent than strain. Strain (ϵ) is a unitless measure of lengthening and shortening only (defined as the change in distance between two points divided by the initial distance between those two points, $\epsilon = [L_1 - L_0)/L_0]$), assumes noncompressibility of tissues and can be calculated for three axes of myocardial motion, resulting in longitudinal, circumferential, and radial strain.[4] The techniques have been well-validated with cardiac magnetic resonance scanning and animal models by using sonomicrometry. Because data are derived from TDI, certain caveats regarding their use exist; in particular sensitivity to signal noise and alignment. Speckle tracking uses two-dimensional echocardiography to identify areas of correlation within signature blocks of backscattered echocardiographic tissue, and tracks tissue motion accordingly, allowing simultaneous longitudinal, radial, circumferential, and also torsion analysis. It avoids the angle dependency of Doppler and allows interrogation of multiple movement vectors simultaneously (see Figure 28-4).

Currently, strain rate imaging is regarded as a tool for understanding myocardial mechanics. It is highly sensitive in detecting changes in wall motion, and current clinical applications include potential identification of myocardial viability and detection of subclinical ventricular dysfunction.[5] In the ICU, emerging studies (in pediatric patients) have suggested the potential use of speckle tracking to detect ventricular dysfunction in septic shock, which is not appreciated by conventional echocardiography. In these studies, despite no demonstrable difference in fractional shortening and ejection fraction between controls and children with sepsis, significant abnormalities in circumferential and longitudinal strain, strain rate, radial displacement and rotational velocity and displacement have been demonstrated.[6] Barriers to the widespread uptake of these tools exist, including requirement for in-depth understanding of the complex methodology underpinning their validity, technical challenges (image acquisition and analysis), and a continued lack of consensus regarding the superiority of any one of the array of potential measurements. These techniques should currently be regarded only as potential research tools in assessment of ventricular function in the critically ill, and, as with any highly derived imaging technique, attention must be paid to the actual versus potential temporal resolution of the technique. Moreover, the primary image quality remains a challenge in ICU patients. If what is emerging in the pediatric population is transferable to the adult ICU population, the potential for these techniques in elucidation myocardial dysfunction in critical care is promising.

Right Ventricular (RV) Function

The right ventricle is exquisitely sensitive to increases in afterload and reduction in coronary perfusion, and failure may ensue because of either of these factors (or a combination of the two). Both factors can be readily detected using echocardiography (see Chapter 33). In the ICU, RV dysfunction is most commonly secondary to increased afterload resulting from pulmonary disease and/or to left ventricular dysfunction, where again echocardiography is pivotal for diagnosis (see Chapters 28 and 33). A range of conventional echocardiographic techniques are routinely used to assess RV systolic function, including tricuspid annular plane systolic excursion (TAPSE), TDI (see Chapter 33), and the RV myocardial performance index (see Figure 28-2); however, measurements of RV geometry and volumes are complex.[7] Three-dimensional (3D) echocardiography has great potential to change the way that RV volume is assessed in the ICU. On the other hand, when using echocardiography much can be learned from a more physiologic approach to the right ventricle by using simple techniques (e.g., right ventricular fractional area change). These may guide therapeutic interventions to improve RV performance in the ICU.

Duration of Tricuspid Regurgitation

All echocardiographers routinely interrogate the tricuspid regurgitation signal to estimate the severity of pulmonary hypertension, which is calculated by the simplified Bernoulli equation (see Chapter 33). What is less common is to focus on the duration of tricuspid regurgitation. When the regurgitation is prolonged (either because of prolonged systole related to pulmonary hypertension or to conduction system disorder) it may temporally affect cardiac filling (on both the right and occasionally the left side of the heart), thereby limiting cardiac output (Figure 28-5). As with mitral regurgitation of prolonged duration, the cause should be sought, and, if possible, corrected.[8] In addition, echocardiographic heart rate optimization should be performed to maximize the time available for diastole, although this must be balanced against the often concomitant requirement

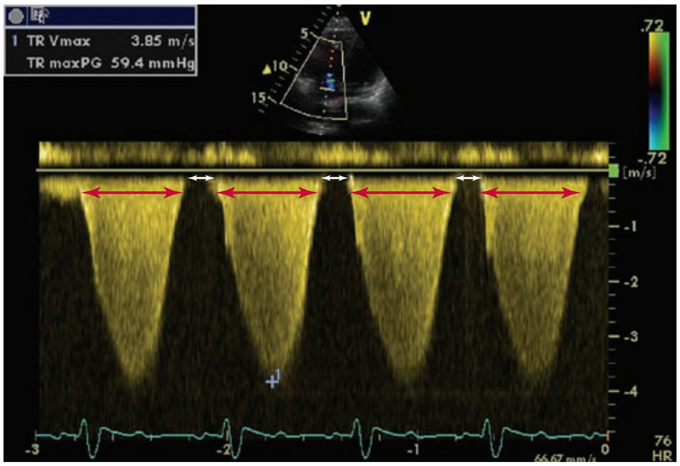

Figure 28-5 CW Doppler in a patient with severe pulmonary hypertension (RAP = 15, PASP = 75 mm Hg). The duration of TR is 596 msec (delineated by *red arrows*), with a RR interval of 789 msec. This allows only 193 msec for ventricular filling (delineated by *white arrows*). *CW,* Continuous wave; *PASP,* pulmonary artery systolic pressure; *RAP,* right atrial pressure; *TR,* tricuspid regurgitation; *TRVmax,* tricuspid regurgitation maximal velocity; *TRmaxPG,* tricuspid regurgitation maximum pressure gradient.

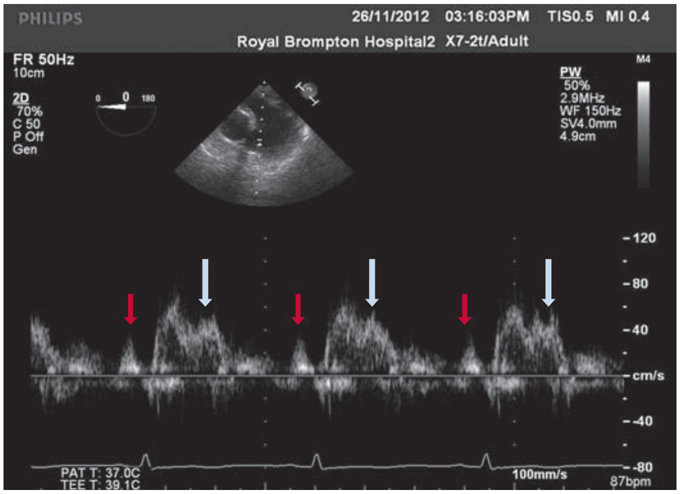

Figure 28-6 TEE image of PW Doppler across the pulmonary valve. Presystolic a wave *(red arrow)* indicating a restrictive RV filling pattern. The first systolic peak occurs shortly after valve opening (in this case, 65 msec) and this, together with second peak of systolic wave *(white arrow)*, is suggestive of pulmonary hypertension and/or a high pulmonary vascular resistance. *PW,* Pulsed-wave; *RV,* right ventricle; *TEE,* transesophageal echocardiography.

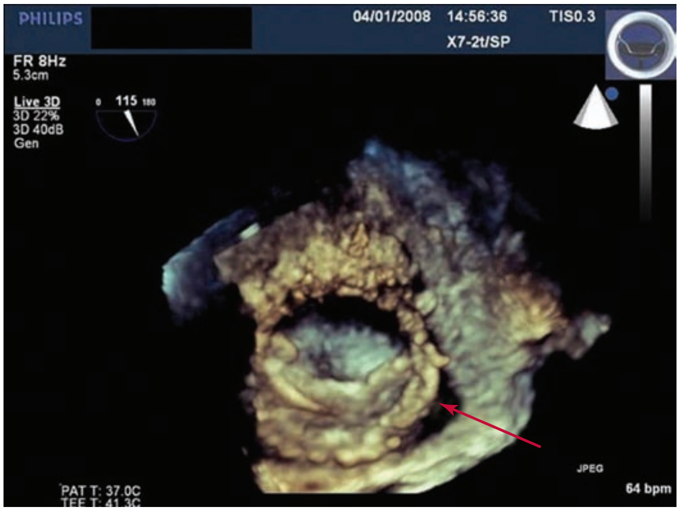

Figure 28-7 Live 3D (4D) TEE view taken from the roof of the left atrium depicting single tilting disc mitral valve prosthesis with paraprosthetic dehiscence *(arrow)*. A miniature of the valve is shown at the top right of the figure. *3D,* Three-dimensional; *4D,* four-dimensional; *TEE,* transesophageal echocardiography.

for an adequate heart rate in the presence of a fixed stroke volume.

RV Restriction

Although the concept of LV restriction is well-recognized that of RV restriction is less so, except within the pediatric cardiology arena. The diagnosis is made using pulsed wave Doppler of the pulmonary valve, demonstrating forward flow in late diastole and the pulmonary valve opening during atrial systole. This occurs when the RV end diastolic pressure exceeds that of the pulmonary arterial diastolic pressure, with the proposed mechanism being that the stiff right ventricle is unfillable (Figure 28-6).[9] Positive-pressure ventilation results in an increase in tricuspid E/A ratio and may abolish the pulmonary arterial diastolic wave, making the diagnosis more challenging. Adult ICU literature is scarce; however, the above-mentioned echocardiographic features may be seen in 43% to 50% of patients (Tavazzi, unpublished data).[10] Confounding factors include the presence of LV restriction, elevation of pulmonary arterial diastolic pressures, tachycardia, and requirement for high ventilator pressures. However, the importance of the diagnosis is evident when considering the impact of inspiration on this forward flow. The relative contribution of the restrictive antegrade A wave to pulmonary flow (and hence right-sided output) changes as a result of positive-pressure ventilation (inspiration 7 $\pm$ 8% vs. expiration 22 $\pm$ 10%), suggests that, when diagnosed, mechanical ventilation should be modified to minimize this adverse effect when possible.[11]

Three-Dimensional (3D) and Four-Dimensional (4D) Imaging

Despite the major advances in cardiac imaging (e.g., magnetic resonance), recent technologic advances in echocardiography have transformed image quality, allowing the development of 3D and four-dimensional (4D) (real-time 3D) imaging via transthoracic and, more recently, transesophageal echocardiography. In the ICU, 3D echocardiography may permit simultaneous assessment of all segments of the left or right ventricle for regional wall motion abnormality and/or dyssynchrony, detailed assessment of the mechanism and severity of mitral regurgitation, and delineation of paraprosthetic valvular regurgitation (Figure 28-7), although advanced mitral valve assessment is more relevant to the cardiothoracic rather than general ICU setting.

3D echocardiography has been proposed to be superior to two-dimensional (2D) imaging for estimating ejection fraction and diagnosing regional wall motion abnormalities. Its ability to assess intraventricular dyssynchrony of the left ventricle is based upon the regional time-to-minimum systolic volume, which is measured from the onset of the QRS complex, and is inferred from either the maximal difference between two regions or standard deviation of up to 17 regional volumes.[12] Assessment of the right ventricle by 3D imaging has been reported to be superior to 2D echocardiography in assessing volumes and contractility. Although 3D echocardiography may underestimate RV volumes (compared with the gold standard of cardiac magnetic resonance imaging), the advantages of a sophisticated bedside imaging technique are clear.[13] The potential for 3D/4D echocardiography in assessment of ventricular function in the ICU has not yet been fully explored, but its potential is evident.

Conclusion

The applications of advanced critical care echocardiography are vast, especially when considering cardiac electromechanics.[14] With cardiologists returning to the cardiac ICU and intensivists embracing the technique of echocardiography, the potential for future collaborative research in this exciting and dynamic field is clear. The application of older echocardiographic techniques in the ICU should not be neglected, because these techniques still have much to offer.

Pearls and Highlights

- Complex critical care echocardiography is not just about complex techniques.
- Use all the echocardiographic tools you have to answer the clinical question, but beware of their applicability in the critical care setting.
- Make echocardiography work for you as a physiologic tool to inspect the heart.
- Remember that normal values in the outpatient setting probably do not apply to your patients.
- Always interpret the echocardiogram within the clinical and pathophysiologic context of the patient.

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For a full list of references, please visit www.expertconsult.com.

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29

Transesophageal Echocardiography

DAVID DUTHIE | SUSANNA PRICE

Overview

After development of an esophageal stethoscope, the first transesophageal echocardiographic (TEE) equipment provided simple M-mode images to measure left ventricular (LV) dimensions. First used for intraoperative monitoring of LV function and intracardiac air more than 30 years ago,[1] TEE is now widely considered the standard of care for a number of cardiac surgical procedures.[2,3] In parallel with transthoracic echocardiography (TTE), development of phased-array transducers; spectral and color Doppler; biplane, multiplane, and three-dimensional (3D) imaging; and progressive miniaturization of equipment has increased the quality and range of information available from the technique. For 20 years it has been recognized that TEE can provide additional information to other hemodynamic monitors (including the pulmonary artery catheter), which changes patient management and may improve outcomes.[4] Currently, in the United States, the majority of anesthesiologists trained in TEE believe the technique to be superior to other hemodynamic monitors.[5] Guidelines for performance of and training in TEE have been published by a number of national and international bodies (see Chapter 27). Although in general, TTE should be the first imaging mode used, its usefulness in the intensive care unit (ICU) may be limited by the patient (immobility, body habitus, pulmonary pathology), the pathology (i.e., prosthetic valve endocarditis), or ICU interventions (intermittent positive-pressure ventilation [IPPV], dressings/drains). In these instances, TEE may be required. Despite not being considered essential for basic critical care echocardiography, TEE is increasingly regarded as an essential skill for those who wish to perform more advanced ICU echocardiography,[6,7] with experienced practitioners using the two techniques in a complementary and potentially interchangeable manner.

The TEE Probe

This comprises a miniaturized ultrasound transducer incorporated into a custom-made transesophageal probe. The device uses an array of piezoelectric crystals and phased-array technology to steer the ultrasound beam through 180 degrees. The frequency range used varies (generally) between 5 to 10 MHz, and all modalities available in TTE are potentially available for TEE, including the ability to acquire real-time high-quality 3D images (Figure 29-1). Progressive technologic development has allowed availability of pediatric and neonatal TEE probes, and a disposable miniaturized probe has been devised for use as a continuous hemodynamic monitor in the ICU.

Preparation for TEE in the Critically Ill

Before undertaking any study, the practitioner must consider the indications and relative/absolute contraindications to TEE, with a structured approach to assessment of both the process and the patient before, during, and after the procedure. This applies equally to focused and comprehensive diagnostic studies.

PROCESS REVIEW

This should include infection control (knowledge of local and national guidelines, probe sterilization, cleaning, and tracking), and care of the probe (including procedures for checking integrity before each use). Nasogastric tubes are often in situ, and to ensure interruption of feed is minimized, gastric contents should be aspirated before the study, and postprobe removal protocols should be in place to ensure no displacement has occurred, and feeding is recommenced only and as soon as judged safe.[3,7] The process of consent varies between countries, and although invasive procedures are usually undertaken only after consent is obtained, exceptions are generally allowed in the case of life-threatening emergencies and/or when the patient is unable to give informed consent. In some countries, informing the patient's documented next of kin before a nonemergency invasive procedure is normal practice. Where research is undertaken, ethical approval must be obtained and consent obtained according to the agreed research protocol and local guidelines. The study should be recorded and reported according to local, national, and international guidelines and recommendations.

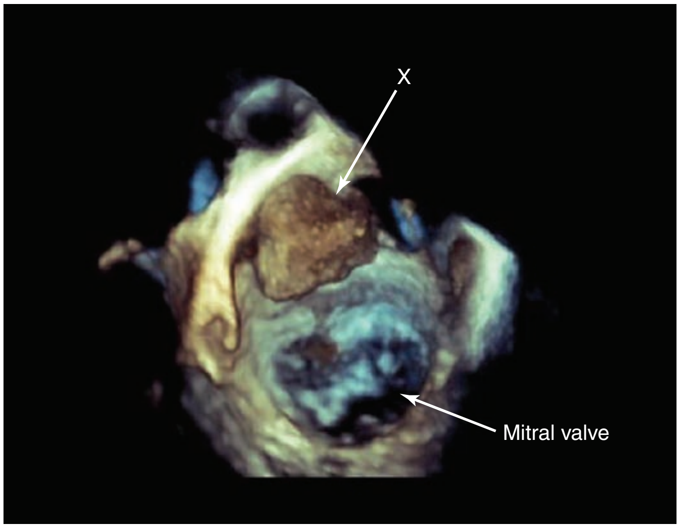

Figure 29-1 Three-dimensional (3D) transesophageal echocardiography (TEE). 3D-TEE in a patient presenting with acute cerebrovascular accident in multiple carotid artery territories. The image is a full-volume rendition, manipulated to be looking down on the mitral valve from the roof of the left atrium. There is a mass *(X)* attached to the atrial wall. At surgery, this was shown to be a left atrial myxoma.

PATIENT REVIEW

This should include the indication for TEE and the patient history in terms of the relative and absolute contraindications to TEE (Table 29-1) and to its risk-benefit to the patient. The most significant serious complication from TEE in the outpatient population is esophageal perforation, with the usually quoted rate of 1:10,000 in studies; however, this is variable and may increase with an increasingly aged patient population.[8] TEE in the intensive care is generally regarded as safe; however, because the critically ill patient is frequently coagulopathic, knowledge of the coagulation status of the patient is vital and, where indicated, possible correction undertaken. When the patient is fully anticoagulated or coagulopathic, probe insertion with laryngoscopic guidance is recommended. This is important if the patient is receiving extracorporeal support; in this circumstance, oropharyngeal bleeding can be life threatening. Critically ill patients undergoing TEE will be intubated and ventilated, and consistent with guidelines in many ICUs, there should be an independent ICU practitioner managing the airway, ventilation, and hemodynamic status of the patient during the study.

The practitioner planning and performing the study must consider the specific question being asked and the effects of vasoactive agents, sedation, and ventilation on patient hemodynamics that might have an impact on findings. For complex studies, the practitioner must also plan any strategy required to mimic/provoke/resolve the echocardiographic findings (i.e., changing ventilator settings, volume challenge, ventricular assist device (VAD) weaning, increased afterload, pacing optimization) and ensure the appropriate skills are present to be able to apply TEE appropriately within this setting.

IMAGE ACQUISITION: THE STANDARD VIEWS

Guidelines for performance of a comprehensive TEE study have been published, with recommendations for a minimum dataset in a number of circumstances.[3,7] The practitioner will then focus on the specific question that requires answering. In existing guidelines and recommendations, these predominantly relate to the perioperative cardiac surgical setting; however, it is not the mode of echo (TTE vs. TEE) but, rather, the information required that drives the study. Indeed, in undertaking repeated focused studies and/or using TEE as a hemodynamic monitor, only limited views may be required.

The standard order of image acquisition depends upon a number of factors, including the urgency of the study and time frame for acquisition, the type (comprehensive vs. focused), and individual practitioner preference. Ideally, in the critically ill patient, the amount of probe manipulation should be minimized, in particular in the elderly and/or coagulopathic patient. Movement of the probe is described in terms of its position with respect to the patient: withdraw/advance, rotate left/right, anteflex/retroflex, and flex right/left. Additional movement of the ultrasound beam relates to electronic rotation (from 0-180 degrees). As with TTE, as there is anatomic variation between patients, although numbers are given regarding the degree of electronic rotation, these are for guidance only. The standard views are described in Table 29-1, together with the main structures seen (Table 29-2).

Of note, the deep transgastric view is not achievable in all patients. Again, care should be taken to avoid excessive probe manipulation. Imaging of the pulmonary veins can be achieved by standard views (as described in Table 29-1) and additionally at 0 degrees, interrogating the right and left sides of the left atrium (both superiorly and inferiorly) in turn.

TABLE 29-1 Contraindications to Transesophageal Echocardiography[3,7,8]

Relative	Absolute
History of esophageal surgery	Esophageal obstruction
Esophageal varices or diverticulum	Esophageal stricture
Gastric/esophageal bleeding	Poor airway control
Oropharyngeal pathology (i.e., pharyngeal pouch)	
Severe coagulopathy	
Cervical spine injury	

INDICATIONS FOR TRANSESOPHAGEAL ECHOCARDIOGRAPHY IN THE CRITICALLY ILL

The indications for echocardiography in the ICU have been discussed in Chapters 26 and 27, including the choice of TTE versus TEE. Images of diagnostic quality are unobtainable in up to 30% of the general ICU patient population, rising to 85% in those with severe, acute respiratory failure referred for extracorporeal respiratory support (Figure 29-2).[9] Thus, when image quality precludes obtaining adequate information from the transthoracic route, TEE may be indicated. In addition, there are specific indications for TEE as opposed to TTE (Table 29-3). Guidelines for the appropriateness of undertaking TEE have been published; however, these will inevitably change with the ongoing development of critical care technologies, for example, extracorporeal support.[10,11]

EVALUATION FOR INTRACARDIAC THROMBUS

Intracardiac thrombus is most commonly found in the left atrial appendage (LAA) in patients with atrial arrhythmias. Guidelines have been published regarding the use of TEE for the evaluation of the LAA in atrial fibrillation before cardioversion.[12] Critical care patients may be relatively prothrombotic, and therefore the indication for TEE in the critically ill, to exclude the presence of thrombus, may lie outside the guidelines (Figure 29-3). More research is required in this area, and when the patient is hemodynamically stable and no contraindications to TEE exist, there should be a low threshold for performing a study.

Patients with myocardial infarction and extensive areas of akinesia are at risk of developing ventricular thrombus. Care must be taken when using TEE to evaluate the apex of the LV because foreshortening may occur in the midesophageal views. A modified long-axis transgastric long-axis view can be useful in these circumstances.[13] Where an associated apical ventricular septal defect (VSD) is suspected, rotation of the probe between the LV and right ventricle (RV) in this modified view can be used to demonstrate the apical portion of the interventricular septum.

In patients receiving extracorporeal respiratory and/or cardiac support, there is a significant risk of developing intracardiac thrombus despite full anticoagulation. This may be either associated with a cannula, and/or with a nonopening valve, or

TABLE 29-2 Images for Transesophageal Echocardiography

Window	Nomenclature	Angle Range	Modes Used	Structures Imaged	Notes
Transgastric	Basal SAX	0°-20°	2D, M-mode, color	LV + MV, RV + TV	Color provides location of MR
	Two chamber	80°-100°	2D, M-mode	LV, MV, subvalvar apparatus, CS, LA	
	Mid-SAX	0°-20°	2D, M-mode	LV, RV, papillary muscles	Simultaneous view of all three CA territories
	LAX (left heart)	120°-140°	2D, PW, CW, color	LVOT, AV, MV	Measurement of aortic VTI and gradient
	LAX (right heart)	90°-120°	2D, PW, CW, color	RV, TV, RA, subvalvar apparatus	Measurement of pulmonary VTI
Midesophageal	Four chamber	0°-10°	2D, PW, CW, color	LA, RA, LV, RV, IAS, IVS, MV, TV	
	Mitral commissural	60°-70°	2D, color	MV, LV, LA	
	Two chamber	80°-100°	2D, color	LA, LV, MV, LAA, CS	
	Long axis	120°-160°	2D, PW, CW, color	LA, MV, LV, LVOT, AV, Asc aorta, right PA	Good for imaging type A dissection
	SAX AV	30°-60°	2D, color	AV, IAS, prox CAs, LVOT, PV	Useful for imaging (color) proximal CAs
	RV inflow-outflow	60°-80°	2D, color	RA, RV, TV, RVOT, PV, PA	
	Bicaval	80°-115°	2D, color	LA, RA, IAS, SVC, IVC, RAA, RUPV	Care to interrogate whole of IAS
	IVC-RA junction	40°-50°	2D, PW, CW, color	IVC-RA junction, first hepatic vein	
Upper esophageal	LAX aortic arch	0°	2D, color	Aortic arch, brachiocephalic	
	SAX aortic arch	90°	2D, color	Aortic arch, PA, PV, brachiocephalic	Useful for IABP positioning
Deep transgastric	Deep transgastric	0°-20°	2D, color, PW, CW Doppler	LV, LVOT, Asc aorta, arch	Used for CO measurement
High/mid/low transgastric	Aortic	0° and 90°	2D, color, PW	Descending aorta, pleural spaces	

2D, Two-dimensional; *Asc,* ascending; *AV,* aortic valve; *CA,* coronary artery; *CO,* cardiac output; *color,* color Doppler; *CS,* coronary sinus; *CW,* continuous wave Doppler; *IABP,* intraaortic balloon pump; *IAS,* interatrial septum; *IVC,* inferior vena cava; *IVS,* interventricular septum; *LA,* left atrium; *LAA,* left atrial appendage; *LAX,* long axis; *LV,* left ventricle; *LVOT,* left ventricular outflow tract; *MR,* mitral regurgitation; *MV,* mitral valve; *PA,* pulmonary artery; *prox,* proximal; *PV,* pulmonary vein; *PW,* pulsed wave Doppler; *RA,* right atrium; *RAA,* right atrial appendage; *RV,* right ventricle; *RUPV,* right upper pulmonary vein; *RVOT,* right ventricular outflow tract; *SAX,* short axis; *TV,* tricuspid valve; *VTI,* velocity time integral.

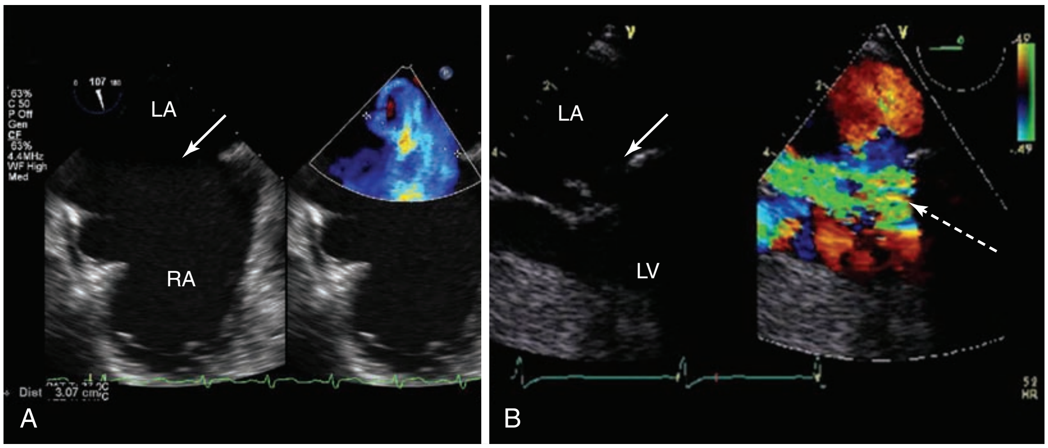

Figure 29-2 The role of transesophageal echocardiography (TEE) in patients referred with severe acute respiratory failure. TEE studies in two patients with the diagnosis of severe acute respiratory failure referred with refractory hypoxemia for ECMO. In both cases, there were no transthoracic echocardiographic windows. **A,** Bicaval view showing a large secundum ASD) *(arrow).* Color flow Doppler showed biphasic flow (current frame demonstrating left-right flow in blue). **B,** Midesophageal view focusing on the mitral valve in systole, showing a flail posterior mitral valve leaflet *(arrow)* with ruptured chordae and a corresponding jet of severe mitral regurgitation *(broken arrow).* Information from these two studies guided management. In patient **A,** ECMO was not instituted; the patient was managed in the standard manner, and after recovery from respiratory disease, the patient underwent subsequent formal hemodynamic evaluation with successful closure of the ASD. In patient **B,** the diagnosis was revised to pulmonary edema secondary to severe structural mitral valve disease. An intraaortic balloon pump was inserted, and the patient underwent successful mitral valve repair. *ASD,* Atrial septal defect; *ECMO,* extracorporeal membrane oxygenation; *LA,* left atrium; *LV,* left ventricle; *RA,* right atrium.

TABLE 29-3 **Specific Indications for Transesophageal Echocardiography**

Indication	Notes
Intracardiac thrombus/mass	Most commonly, LAA thrombus in patient with AF May see LV thrombus related to akinetic segment (NB apex difficult to visualize with TEE) Potential for paradoxic embolization with PFO/ASD
Endocarditis	Prosthetic valve endocarditis frequently paraprosthetic leak only Infection may be associated with indwelling lines/wires All patients, expert echocardiographic review required
Extracorporeal support	Useful for insertion and positioning of IABP ECMO and VAD: Highly specialized echocardiography
Aortic disease	Not all the aorta can be imaged, alternative imaging may be required Aortic dissection: Origin of coronary arteries (true vs. false lumen)
Valvular disease	**Mitral** MR may be dynamic, stress +/− volume loading may be required Assess mechanism of MR Critical MS: Suitability for valvuloplasty Indicated to assess potential prosthesis malfunction **Aortic** Critical AS: Suitability for valvuloplasty Indicated to assess potential prosthesis malfunction
Cardiac monitoring	Multiple potential uses; however, operator dependent and intermittent measure of cardiac function
Unexplained hypoxia	Intracardiac shunting not uncommon in ventilated patients Potential to visualize intracardiac/pulmonary artery thrombus
Tamponade	Low sensitivity of TTE postcardiac surgery: May be required to exclude small and/or localized collection

AF, Atrial fibrillation; *AS,* aortic stenosis; *ASD,* atrial septal defect; *ECMO,* extracorporeal membrane oxygenation; *IABP,* intraaortic balloon pump; *LAA,* left atrial appendage; *LV,* left ventricle; *MR,* mitral regurgitation; *MS,* mitral stenosis; *PFO,* patent foramen ovale; *TEE,* transesophageal echocardiography; *TTE;* transthoracic echocardiography; *VAD,* ventricular assist device.

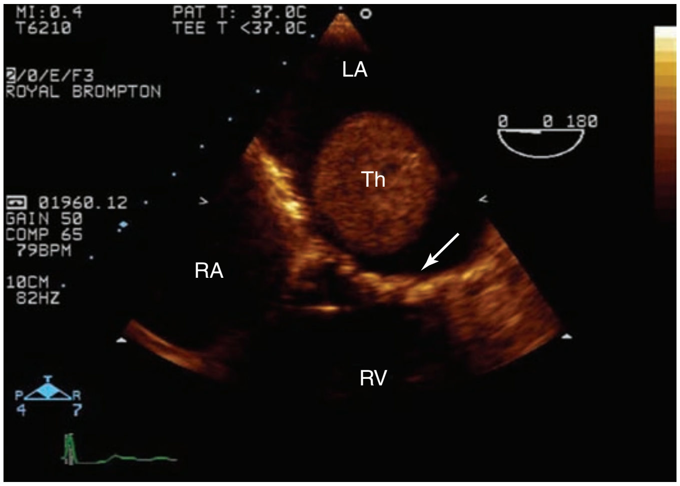

Figure 29-3 Transoesophageal echocardiography of left atrial thrombus. Midesophageal four-chamber view in a patient in atrial fibrillation with mitral stenosis (mitral valve, *arrow*). There is a large thrombus *(Th)* visible in mid-LA despite full, therapeutic anticoagulation. *LA,* Left atrium; *RA,* right atrium; *RV,* right ventricle.

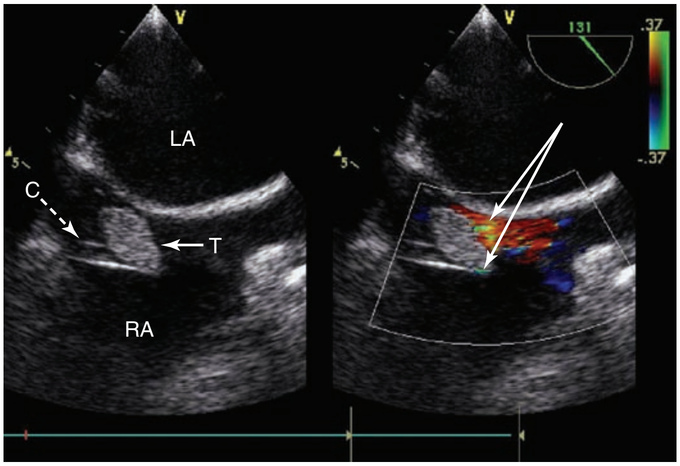

Figure 29-4 Intracardiac thrombus in a patient receiving extracorporeal support. Midesophageal bicaval view showing a cannula in the RA (inlet cannula for VA ECMO) and a large associated thrombus *(solid arrow)* at the mouth of the cannula. *C,* Cannula; *LA,* left atrium; *RA,* right atrium; *T,* thrombus; *VA ECMO,* venoarterial extracorporeal membrane oxygenation.

an akinetic area of the LV.[14] Here TEE is pivotal to making the diagnosis and planning a treatment strategy (Figure 29-4).

INFECTIVE ENDOCARDITIS

Guidelines for the use of TEE in the diagnosis of endocarditis have been published,[15] including prosthetic valve endocarditis.[15] When endocarditis is suspected, there should be a low threshold for undertaking TEE, and it is indicated in all critical care patients with suspected prosthetic valve endocarditis (Figure 29-5). Examination should not be limited to the valves and associated structures but should include lines, cannulas, pacing wires, and any intracardiac patch or device. In prosthetic valve endocarditis, large vegetations are rarely seen, the more usual echocardiographic findings being paraprosthetic regurgitation and/or abscess or fistula formation (Figure 29-6). In intensive care, the diagnosis of severe acute respiratory failure with associated bilateral pulmonary infiltrates in a patient with previous left-sided valve repair/replacement should prompt close interrogation of the relevant valve, including

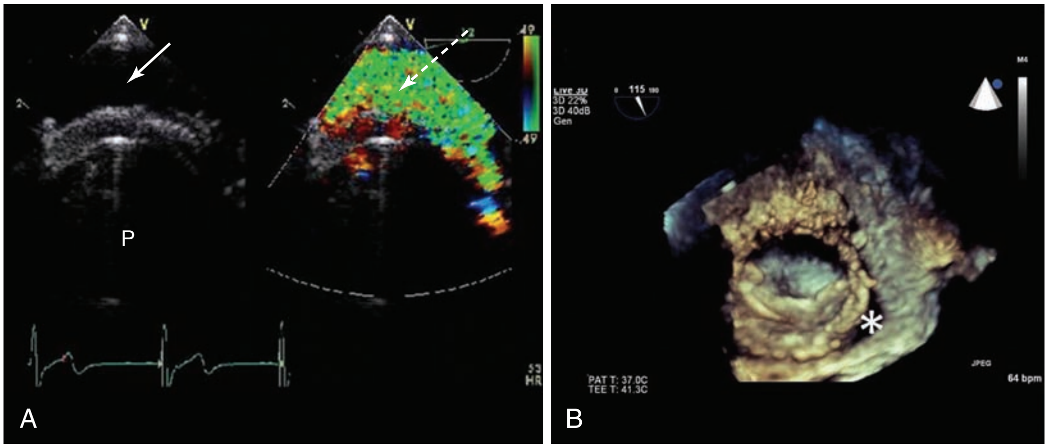

Figure 29-5 Two-dimensional (2D) and three-dimensional (3D) TOE in assessment of valve prosthesis malfunction. A, Conventional 2D imaging shows patient with a bileaflet mechanical valve *(P),* an echo-free space between the inferoposterior annulus, and the valve sewing ring *(arrow).* Corresponding color Doppler shows a broad jet of paraprosthetic regurgitation *(broken arrow).* The patient had the clinical features of cardiogenic shock and pulmonary edema in the context of a history suggestive of endocarditis. Note the valve anatomy is difficult to discern, and there are no obvious vegetations. **B,** 3D transesophageal echocardiogram (TEE) of a single tilting disc mitral valve seen from the atrial aspect. An echo-free space is seen *(*)* that corresponds to a jet of mitral regurgitation. The clinical features were of severe anemia resulting from hemolysis. The patient subsequently underwent TEE-guided catheter-based intervention to close the paraprosthetic leak.

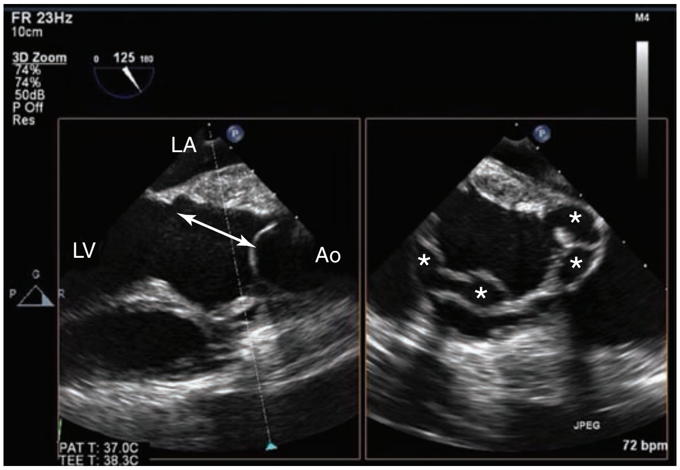

Figure 29-6 Complicated infective endocarditis. Biplane imaging in a patient with previous homograft aortic root replacement, representing clinical features of infective endocarditis. On the left, a conventional left ventricular outflow tract (LVOT) view is shown, with discontinuity between the base of the accessory mitral valve leaflet (AMVL) and the aortic leaflets *(double arrow).* On the right, the orthogonal view of the LVOT is seen, with multiple abscess cavities *(*). Ao,* Ascending aorta; *LA,* left atrium; *LV,* left ventricle.

TEE because significant paraprosthetic regurgitation must be actively excluded (see Figure 29-2B).

EXTRACORPOREAL SUPPORT

The use of echocardiography in extracorporeal support is described in detail in Chapter 28. Regular echocardiography in this patient population is highly recommended; however, repeated TEE studies should be avoided (because of the risk of hemorrhage), and TTE should generally be the first modality used.[14] TEE does have specific roles in confirming the underlying diagnosis and/or estimation of left atrial pressure (patients referred for venovenous–extracorporeal membrane oxygenation [VV-ECMO]), assisting in cannula placement (either real time or postprocedurally), and detecting associated complications, including cannula displacement, worsening valvular regurgitation, tamponade, thrombus formation (cannulas and/or valves, see Figure 29-4), and inadvertent overload or excessive offloading of one or both ventricles.

AORTIC DISEASE

In the diagnosis of aortic dissection, TEE is comparable to computed tomography (CT) and aortography and superior to TTE (Video 29-1). It has the additional advantages of providing a shorter time to diagnosis and intervention, demonstration of the entry site (and coronary ostia), and characterization of the mechanism and severity of any aortic regurgitation (AR), in which holodiastolic reverse flow greater than 15 cm/sec indicates severe regurgitation (Figure 29-7). It is, however, inferior in its ability to image the descending aorta and aortic arch because of interference from the left main bronchus. In aortic trauma, TEE has been shown to have a high specificity (91%-100%) but variable sensitivity (57%-100%) compared with aortography in demonstration of aortic interruption and hematoma.[16]

TRANSESOPHAGEAL ECHOCARDIOGRAPHY AS A CARDIAC MONITOR

There are a number of publications that support TEE as a hemodynamic monitor[17] (Video 29-2). Cardiac output (CO) measured using TEE has been shown to provide quantitative assessment of CO that correlates well with continuous thermodilution methods.[18] However, when compared directly, it tends to underestimate CO in both ventilated and nonventilated patients, thereby precluding their use interchangeably. The use of echocardiography to measure CO can be useful, however, in patients where placement of a pulmonary artery (PA) catheter is relatively or absolutely contraindicated, or where there are multiple cardiac factors that potentially limit CO and advanced interrogation of the heart is required.

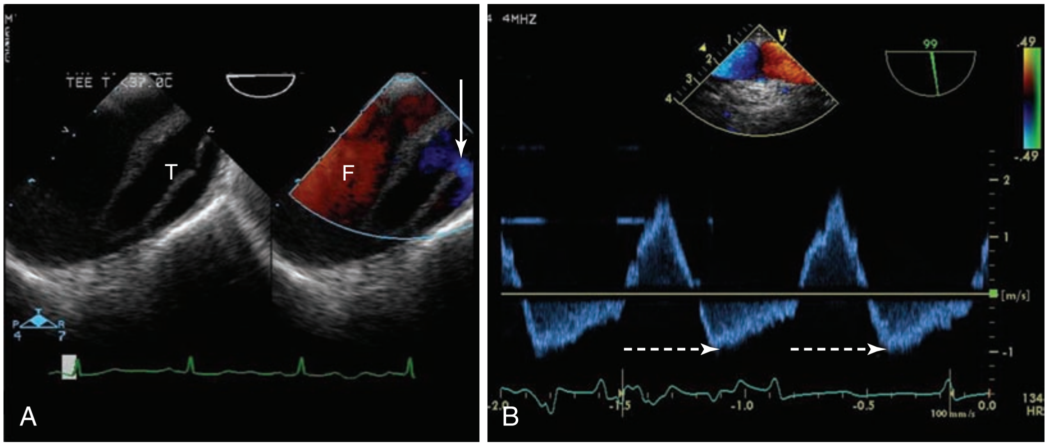

Figure 29-7 Transesophageal echocardiogram (TEE) of the aortic arch in a patient with aortic dissection. A, On the two-dimensional image to the left, the true lumen *(T)* is smaller than the false lumen *(F)*, and a connection between the two (with flow from true to false lumen) is shown with an *arrow.* **B,** In the image to the right, pulsed wave Doppler of aortic flow is shown, with holodiastolic flow reversal *(broken arrow).*

Left atrial pressure may be estimated using a combination of TEE-based techniques (combining E/E´, color Doppler propagation and pulmonary venous flow, in conjunction with ejection fraction[19]). Although gray zones still remain, and, as with TTE, it is not possible to measure the pressure within any cardiac chamber, extreme values may prove helpful. When a high left atrial pressure is suspected but not found on TEE in a patient who fails to wean from mechanical ventilation because of respiratory distress, stress echocardiography should be considered. The nature of stressor used will depend upon the suspected etiology of the underlying pathology (dobutamine in suspected ischemia, volume and pressor loading in shock). TEE has been proposed as a potential monitor of volume responsiveness, by analysis of the changes in stroke volume with respiration and/or inferior vena cava (IVC) diameter in response to respiration in positive-pressure ventilated patients. However, a number of technical and patient-related limitations exist.[20] Indeed, TEE has inherent limitations when compared with the features of an ideal monitor, requiring repeated studies and skill for performance and interpretation and providing only intermittent information. Further, many of the published studies had significant relevant exclusions to the critical care patient population. To minimize patient risk and avoid the requirement for repeated intermittent studies, a miniaturized TEE device has been devised for continuous monitoring.[15] However, the greatest strength of echocardiography over all other monitors is that it provides additional insight into the underlying diagnosis and can thus be used to determine potential interventions to optimize cardiac output (Figure 29-8).

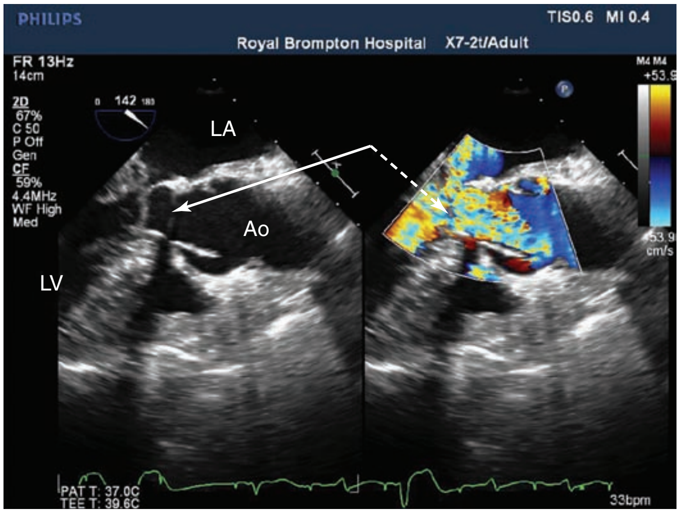

Figure 29-8 Severe SAM with outflow tract limitation in a patient with falling cardiac output in response to increasing inotropic support. Midesophageal LVOT view in systole showing the anterior mitral valve leaflet is in the LVOT *(solid arrow)* and is associated with a high-velocity aliasing jet *(broken arrow).* Conventional CO monitoring had revealed a falling cardiac index in response to increasing inotropic support. The TEE findings resulted in cessation of inotropic therapy, volume, and pressor loading, with resolution of the LVOTO, and a rise in cardiac index. *Ao,* Aorta; *CO,* cardiac output; *LA,* left atrium; *LV,* left ventricle; *LVOT,* left ventricular outflow tract; *LVOTO,* left ventricular outflow tract obstruction; *SAM;* systolic anterior motion of the mitral valve; *TEE,* transesophageal echocardiogram.

VALVULAR DISEASE

There are numerous publications regarding the use of echocardiography in the evaluation of valvular heart disease.[21] Valvular heart disease relating to or causing ICU admission is likely to be severe and affect the left-sided valves. When significant valve disease is suspected but TTE is nondiagnostic, TEE has a role in confirming or refuting the diagnosis, in evaluating possible endocarditis (and local complications), and in assessing of prosthesis malfunction (i.e., thrombosis or paraprosthetic regurgitation or valve degeneration). When critical aortic stenosis (AS) or mitral valve stenosis (MS) is present, TEE is additionally indicated to define suitability for valvuloplasty and exclusion of intracardiac thrombus.[21] When there is severe regurgitation, TEE will aid the surgeon in planning the intraoperative strategy. Mitral regurgitation may be dynamic and reduce significantly with positive-pressure ventilation and sedation or anesthesia (Figure 29-9). Here stress echocardiography should be considered with TEE when TTE images are inadequate.[21]

UNEXPLAINED HYPOXIA

TTE is recommended to assist in the diagnosis of pulmonary embolism when the patient is too hemodynamically unstable

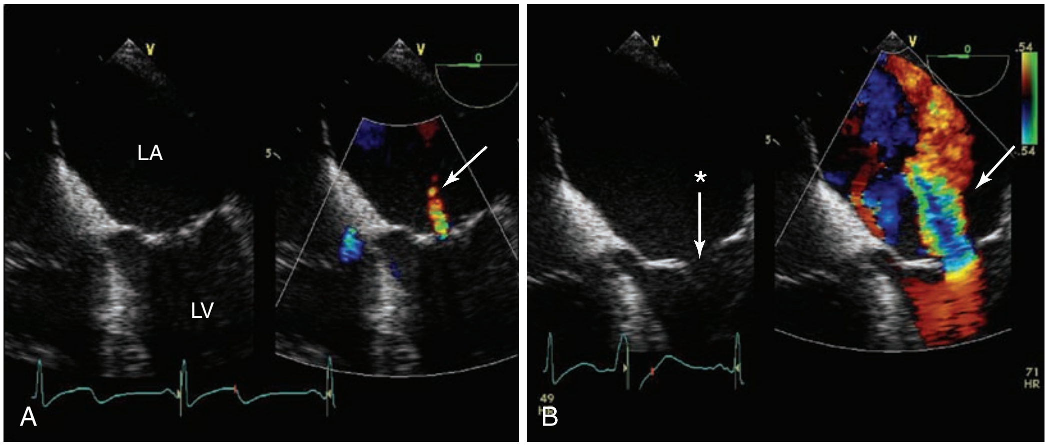

Figure 29-9 The effects of sedation and ventilation on mitral regurgitation. Midesophageal four-chamber view focused on the mitral valve in a patient with dynamic secondary mitral regurgitation undergoing stress echocardiography. In **A,** the patient is sedated and ventilated, and only a small jet of mitral regurgitation can be seen *(arrow)* and the anterior and posterior leaflets are coapting (albeit with minimal coaptation length). Because dynamic mitral regurgitation (MR) was suspected, the patient underwent volume and pressor loading **(B),** the mitral valve leaflets no longer coapt *(*)*, and a broad jet of severe mitral regurgitation is seen *(arrow).*

to transfer to the CT scanner.[22] When TEE is undertaken in critically ill patients with disproportionate/unexplained hypoxemia, on occasion, thrombus may be seen transiting the right heart, in the main pulmonary artery, or in the proximal right or left pulmonary arteries (Video 29-3); however, TEE is not the investigation of choice in patients with suspected pulmonary embolism.

TEE can be used to demonstrate presence and mechanism of intracardiac shunting. The anatomy of the interatrial septum and effects of ventilation on size and magnitude also may suggest intrapulmonary shunting, in which the timing of arrival of bubbles (and the site of their arrival, that is, from pulmonary veins) may suggest the diagnosis. In all patients with SARF, the clinician must consider the presence of an interatrial shunt because this may significantly impact management (see Figure 29-2A).

PERICARDIAL DISEASE

Usually evaluated in the outpatient setting with physiologic parameters of venous return, the most common pericardial disease encountered in the ICU is tamponade. When a patient has a pericardial fluid collection sufficient to cause hemodynamic instability, it is generally large, readily detected using TTE, and TEE is not indicated. An important exception is postcardiac surgery. Here the nature of the patient's underlying cardiac disease and size and location of collections make detection difficult, with up to 50% of hemodynamically important collections missed using TTE. Although primarily a clinical diagnosis, where uncertainty exists that a patient has tamponade ,TEE can be undertaken (Video 29-4). Here collections causing may be small, and/or localized (Figure 29-10), and with no respiratory variation in cardiac filling/emptying.[23]

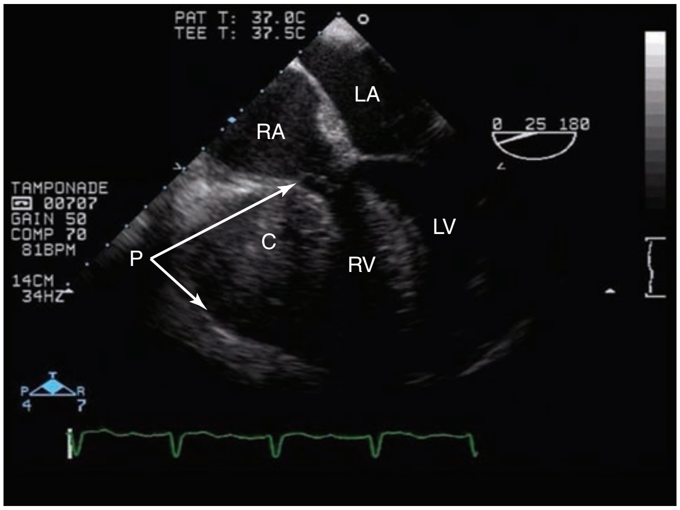

Figure 29-10 Tamponade after cardiac surgery. TEE view (mid-esophagus, four-chamber view) in a patient with a localized pericardial collection resulting in profound hemodynamic compromise. Here, although measured filling pressures were normal, there was a significant hematoma within the pericardial space, compressing the RV and atrioventricular groove, resulting in tamponade. *C,* Collection; *LA,* left atrium; *LV,* left ventricle; *P,* pericardium; *RA,* right atrium; *RV,* right ventricle, *TEE,* transesophageal echocardiogram.

CORONARY ARTERY DISEASE

TEE can be used to visualize the first 1 to 2 cm of the coronary arteries (Figure 29-11) and has been specifically evaluated in patients after mitral valve surgery. Its use in demonstrating significant coronary artery disruption has been validated in the cardiac perioperative setting but not in the general ICU population. However, in a ventilated patient with borderline CO or an abnormal echocardiogram, abnormal coronary Doppler flow patterns and velocities seen in association with a corresponding regional wall motion abnormality suggest significant coronary artery disease (Video 29-5).

Conclusion

TEE has been increasingly adopted by intensivists to supplement information available from cardiac output monitoring and provide imaging where TTE is suboptimal. Although used interchangeably by experienced practitioners, there are certain

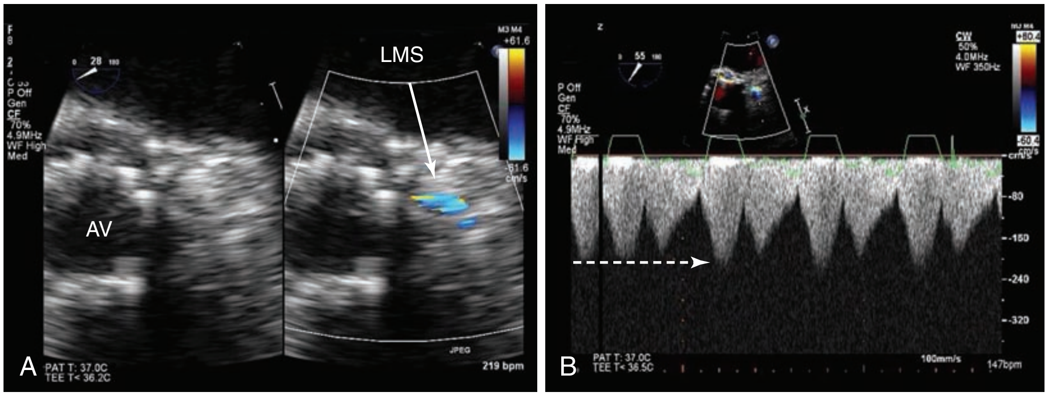

Figure 29-11 Imaging of proximal coronary arteries. Two-dimensional TEE (midesophageal view) focusing on the LMS coronary artery. **A,** On the left is a short-axis view of a transcatheter aortic valve implant *(AV)*, with corresponding color Doppler of the LMS *(arrow)*. There is high-velocity aliasing at the ostium, which appears narrowed. **B,** CW Doppler of the LMS shows high velocity *(broken arrow)* that never returns to zero (continuous flow). Coronary angiography confirmed LMS compression because of displacement of calcium during the transcatheter procedure. *AV,* Aortic valve; *CW,* continuous wave; *LMS,* left mainstem coronary artery; *TEE,* transesophageal echocardiogram.

situations in the ICU in which TEE is specifically indicated. Clear guidelines exist with respect to the procedural aspects of the technique; however, as intensive care technologies continue to expand and become increasingly complex, the indications for TOE on the ICU are likely to evolve.

Pearls and Highlights

- The indications for TEE in the ICU include suboptimal TTE image quality and specific indications for TEE.
- The experienced practitioner will be trained in both TEE and TTE and able to apply each appropriately to the clinical question being asked.
- In the critically ill patient, TEE must never be performed with an unprotected airway.
- An independent and appropriately experienced practitioner should manage the airway and hemodynamic status of the patient during the study.
- In every patient, the risk:benefit ratio of undertaking TEE must be considered before performing a study.
- Evolving techniques in the ICU are likely to result in an expansion of indications for TEE in this patient population.

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Echocardiography in Cardiac Trauma

ALEXANDER BECKER | GUY LIN

Overview

Cardiac injury as a result of blunt or penetrating chest trauma is common and associated with significant morbidity and mortality. Approximately 25% of traumatic deaths are caused by cardiac-related injuries, with the majority involving either cardiac or great-vessel damage.[1] Most penetrating cardiac wounds are immediately fatal. For those arriving at the hospital alive, focused assessment with sonography for trauma (FAST) and transthoracic echocardiography (TTE) are the primary screening modalities. These injuries remain a challenge to trauma surgeons and are associated with high mortality. The incidence of blunt cardiac injury is unknown because of the lack of an accepted “gold standard” test for diagnosis. Blunt cardiac trauma can cause a wide spectrum of injuries (e.g., conduction abnormalities, valvular injuries, septum or free wall rupture, and coronary artery thrombosis).[2]

Patients with cardiac injury may have profound hypotension necessitating urgent surgery; however, a significant number of patients arrive at the emergency department without overt symptoms of heart injury.[3] Regardless of the cause or the clinical picture, diagnosis should be made rapidly. If these patients are exposed to delays in diagnosis or treatment, deaths may occur that would otherwise have been classified as preventable**.**

The initial evaluation of patients who sustain cardiac trauma includes physical examination and chest radiography. The sensitivity and specificity of both modalities for diagnosing cardiac injury are low, however.[4-6] Other diagnostic tools include subxiphoid exploration (SXE), two-dimensional TTE, transesophageal echocardiography (TEE), and FAST.

Diagnostic Methods

SUBXIPHOID EXPLORATION

SXE is a time-tested technique that has proved to be accurate in diagnosing cardiac injuries. Disadvantages of its use relate to its lack of specificity for significant injury. Moreover, it is an operative procedure that subjects patients to the risks associated with surgery and general anesthesia. The rate of negative explorations approaches 75% to 80% in most series.[7]

FOCUSED ASSESSMENT WITH SONOGRAPHY FOR TRAUMA

FAST has become an integral part of primary cardiac injury evaluation because it is valuable in the diagnosis of pericardial effusion (sensitivity, 92% to 100%; specificity, 99% to 100%).[6,8] However, absence of pericardial fluid rules out tamponade, but it does not rule out cardiac injury. FAST cannot assess cardiac function or detect valvular injuries.

TRANSESOPHAGEAL ECHOCARDIOGRAPHY

TEE identifies the presence of ventricular dysfunction in suspected cases of myocardial contusion[9] and is sensitive in detecting thoracic aortic injury and evaluating valvular structure and function.[10] However, TEE is a semiinvasive method that may require sedation, and it might sometimes prove difficult to perform the examination (e.g., cervical spine, facial, airway, or esophageal injuries). TEE is an operator-dependent imaging modality. It is difficult to find experienced operators to perform the examination in emergency environments; however, this does not apply to the intensive care unit (ICU).

TRANSTHORACIC ECHOCARDIOGRAPHY

TTE was introduced in the field of trauma surgery more than 30 years ago. This noninvasive diagnostic modality is readily available and portable and lacks ionizing radiation. TTE gained widespread acceptance in detecting cardiac injuries mainly because of its high sensitivity in identifying pericardial effusion. Jimenez et al[11] prospectively compared TTE with SXE. They performed TTE in 73 stable patients with penetrating chest wounds. The reliability of TEE was comparable to that of SXE, with a sensitivity of 90%, specificity of 97%, and accuracy of 96%. Freshman et al[5] performed TTE in 36 hemodynamically stable patients with penetrating chest injuries. Of the four patients with abnormal findings, three had small pericardial effusions. All three patients recovered without sequelae after a period of observation. The fourth patient had a large pericardial effusion, and sternotomy revealed significant left ventricular injury. The authors concluded that TTE is an adequate alternative to other conventional diagnostic tests. Beggs et al[12] evaluated 40 patients with blunt chest trauma. Nine patients had abnormal echocardiograms, with findings of pericardial effusion in four, chamber enlargement in three, and echodense right ventricular areas in two. The authors concluded that TTE can be used as a noninvasive modality to complement other clinical tools in the detection of blunt cardiac injury.

TTE can be used to assess valvular function, wall motion, and left ventricular ejection fraction and help detect the presence of small pericardial effusions and cardiac tamponade.

Disorders

CARDIAC TAMPONADE

Echocardiography is the method of choice for diagnosing pericardial effusion and cardiac tamponade. Echocardiographic findings in patients with cardiac tamponade include cardiac chamber compression, inferior vena cava (IVC) plethora, Doppler flow velocity paradoxus, compression of the pulmonary trunk, compression of the thoracic IVC, paradoxic motion of the interventricular septum, and swinging motion of the heart in the pericardial sac.[13] The thinner, more compliant right-sided chambers are usually the first to be compressed in the setting of cardiac tamponade. Right ventricular and atrial collapse is a commonly used clue for tamponade; however, neither is 100% sensitive or specific for tamponade.[7]

TRAUMATIC VALVULAR INJURY AND DYSFUNCTION

Traumatic valvular dysfunction is relatively uncommon but should be considered if pulmonary edema develops after chest trauma. The aortic valve is the most commonly injured, followed by the mitral and tricuspid valves.[14] Zakynthinos et al[15] reported two patients with severe acute mitral valve and tricuspid valve insufficiency caused by valve rupture as a result of blunt chest trauma. TTE disclosed atrioventricular regurgitation in both patients.

IMAGING CASE: TRAUMATIC VENTRICULAR SEPTAL DEFECT

The following case illustrates the role of TTE in detecting a traumatic ventricular septal defect (VSD). A healthy 43-year-old man was taken to the emergency department because of blunt thoracic injury after being caught in a machine. During transport the patient was hemodynamically stable. Findings on physical examination were normal except for tenderness over the left thorax and a new systolic murmur. Chest films were normal. Electrocardiography demonstrated an intraventricular conduction defect. TTE revealed an acute traumatic VSD. The patient underwent closure of the VSD with a xenopericardial patch, and his recovery was uneventful.

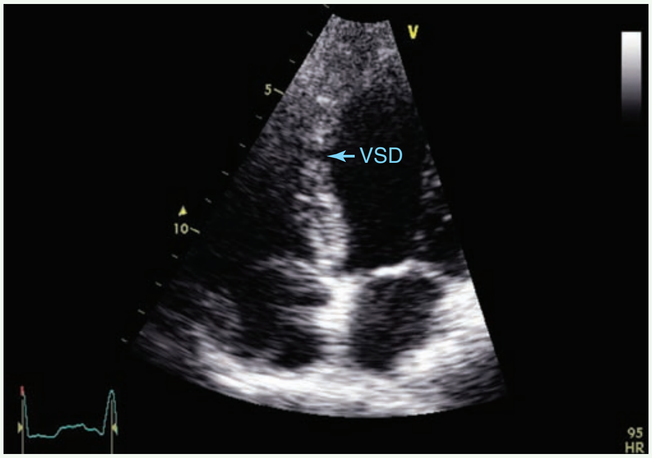

Figure 30-1 Transthoracic echocardiography depicting an acute traumatic ventricular septal defect (*arrow*) as a result of blunt chest trauma and cardiac injury.

Complications of Cardiac Injuries

Echocardiography is useful not only in evaluating acute cardiac trauma but also in detecting potential complications. Patients who survive the cardiac injuries may suffer from short- and long-term complications, such as ischemia and posttraumatic acute myocardial infarction, defects in the ventricular septum or valves, arteriovenous fistula, foreign body, and thrombus. Demetriades et al[16] assessed 44 survivors of penetrating cardiac injuries for late cardiac complications. TTE revealed abnormalities in 17 patients (39%). Ten patients (23%) had valvular or septal defects. Other abnormalities included pericardial effusion, ventricular and septal dysfunction, and ventricular dilatation. The authors concluded that the incidence of late sequelae after cardiac injury is high and recommended that follow-up be performed routinely in these patients. Mattox et al[17] investigated delayed sequelae and complications of penetrating and blunt cardiac trauma in 204 patients. They reported complications in 4% to 56% of survivors. One hundred twenty-eight of these patients survived. Of the 90 who underwent cardiorrhaphy in the operating room, 78 survived. TTE was performed in 40 patients for suspected significant residual injury. Eight of the 40 required secondary cardiac operations. TTE demonstrated pericardial effusion, abnormal chamber enlargement, abnormal cardiac wall motion, an intracardiac missile, and intracardiac and pleural thrombosis. Pulsed Doppler findings included a VSD, tricuspid insufficiency, and right ventricular turbulence secondary to arteriovenous fistulas.

Pitfalls and Limitations

Several authors have highlighted the pitfalls of TTE and FAST in the evaluation of cardiac injuries. Rozycki et al[18] presented a series of 313 consecutive patients with penetrating precordial or transthoracic injuries. Two patients (0.6%) were found to have false-positive findings on pericardial FAST examination. Both patients had large left hemothoraces and blood in the mediastinum without associated heart injuries. The authors suggested that a massive hemothorax surrounding the pericardium may result in false-positive findings and therefore recommended repeating the examination after evacuation of the blood by tube thoracostomy. Massive hemothorax may also lead to false-negative results. In a cohort of 228 patients with penetrating wounds involving the precordial area, false-negative FAST and TTE results were found in 5 patients (2.2%). All five patients also had concurrent left hemothoraces.[19] Meyer et al evaluated 145 hemodynamically stable patients for occult cardiac injury.[20] All patients underwent TTE and SXE. TTE missed four significant injuries. When comparing SXE with TTE in patients without hemothorax, however, the sensitivity (100% vs. 100%), specificity (89% vs. 91%), and accuracy (90% vs. 91%) were comparable, thus suggesting that TTE is an acceptable diagnostic option for detecting cardiac injury but may have significant limitations in identifying cardiac injury in patients with concurrent hemothorax.

Moreover, TTE may be difficult to perform in patients with subcutaneous emphysema, pneumothorax, and major lacerations over the acoustic window and in those with multiple lines, tubes, and dressings, especially during initial assessment in the trauma bay. Patients with cardiac injury often have associated injuries such as cranial trauma, limb fractures, or abdominal trauma, which tend to “obscure” the cardiac damage.

TTE is of limited diagnostic value in patients with aortic injury.[21] Contrast-enhanced computed tomography (CECT) scans and TEE are considered the methods of choice for evaluating aortic injuries (see Section 8). Finally, the performance of TEE and TTE operators is based on their experience and technical skill.[22,23] Blaivas et al[24] asked residents and faculty members from an emergency medicine training program at a level 1 trauma center to view digitized video clips of ultrasound subxiphoid cardiac examinations in patients with chest trauma.

The participants had difficulty distinguishing between epicardial fat pads and true pericardial effusions, which resulted in an overall sensitivity of 73% and specificity of 44%.

Chest trauma results in a broad spectrum of cardiac injuries bearing significant morbidity and mortality. Currently, multidetector CECT is the imaging modality used for the initial evaluation of patients with chest trauma, because the entire thorax can be imaged quickly and accurately and life-threatening injuries can be diagnosed and treated rapidly. TEE is equally important in visualizing the proximal part of the ascending aorta, which cannot be evaluated adequately with CECT.

Despite their limitations, FAST and TTE examinations are noninvasive and can rapidly detect clinically relevant cardiac injuries. Undeniably, echocardiography should be in the armamentarium of cardiac trauma imaging in acute settings and in the ICU.

Pearls and highlights

- TTE is a readily available bedside examination that does not require transfer of patients to another facility.
- TTE in the acute trauma setting may allow detection of myocardial wall motion and valvular abnormalities, as well as pericardial effusions; however, it may be difficult to perform if the chest acoustic windows are obscured, and it is also subject to various other technical limitations.
- FAST examination is easily applicable and has become an integral part of the primary survey for cardiac trauma since it is valuable in diagnosing pericardial effusions.
- Multidetector CECT and TEE are both pivotal imaging modalities for the evaluation of patients with cardiac and aortic injuries. TEE has a limited role in acute trauma settings but is useful in the ICU to monitor for possible complications.
- Oftentimes, diagnostic modalities are of limited importance in the acute phase of cardiac injury because patients may need to be transferred urgently to the operating room.

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31 Echocardiography in Cardiac Arrest

MARY WHITE | SUSANNA PRICE

Overview

The incidence of out-of-hospital cardiac arrest is estimated to be 50 to 55 per 100,000 in the United States.[1] When a primary electrical cause of cardiac arrest is found, definitive treatment is directed toward reversing the rhythm disturbance (cardioversion, defibrillation, pacing). When a nonelectrical cause of cardiac arrest is diagnosed (pulseless electrical activity [PEA]/asystole), practitioners are urged to exclude and treat potentially reversible causes because otherwise the outlook is poor (Figure 31-1).[2] Of the reversible causes, only hypoxia, hypokalemia, hyperkalemia, and hypothermia may be diagnosed definitively with existing standard point-of-care testing. Hypovolemia, tamponade, pulmonary embolism (PE), coronary thrombosis, and tension pneumothorax are diagnosed primarily clinically and toxins by laboratory investigations.

Appropriately applied and interpreted transthoracic echocardiography (TTE) may be used to diagnose or exclude many potentially reversible causes of cardiac arrest while guiding potentially lifesaving therapeutic interventions.[3] Echocardiography has been used in several studies to determine the presence or absence of cardiac activity; indeed, in some cases it has been shown to predict outcome. Moreover, echocardiography facilitates the diagnosis of true electromechanical dissociation (EMD)—the absence of effective cardiac activity despite electrical activity, which in and of itself may also determine the probable outcome of resuscitation.[4] Although the American Heart Association continues to recommend that the history and clinical examination be used to direct management of PEA/asystole (low sensitivity and specificity),[5] the 2010 International Liaison Committee on Resuscitation (ILCOR) guidelines suggest that ultrasound imaging may help identify reversible causes of cardiac arrest and, when appropriately trained personnel are available, should be used to assist in the assessment and treatment of potentially reversible causes of cardiac arrest.[6]

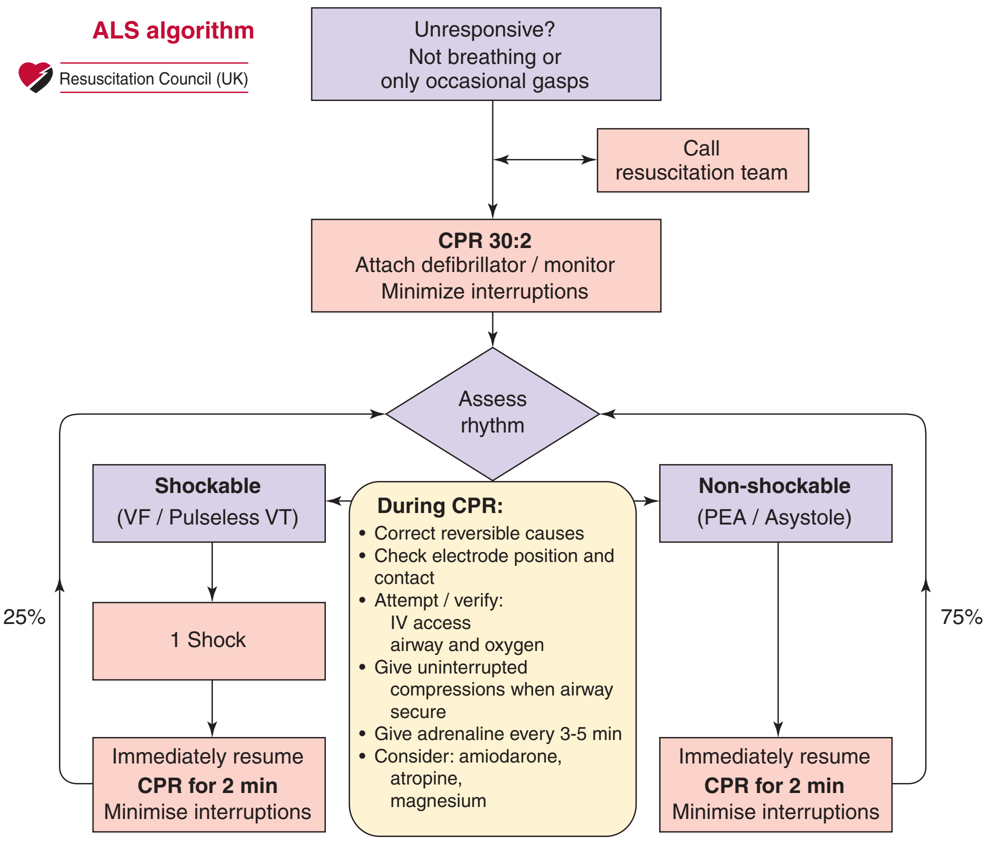

Figure 31-1 Advanced life support (ALS) algorithm. On the right side of the algorithm, in the nonshockable rhythm, the team is urged to seek and correct reversible causes of cardiac arrest. Such causes include the four H's and four T's: hypovolemia, hypocapnia/hypercapnia, hypoxemia, hypothermia, tamponade, thrombosis (coronary/pulmonary), toxins, and tension pneumothorax.

Echocardiography for the Diagnosis of Cardiac Arrest

Traditionally, detection of cardiac output is achieved by palpation of central pulses or by noninvasive blood pressure measurement, although both these methods have been shown to be imprecise,[7,8] with up to 45% of health care professionals being unable to accurately assess central pulses during cardiac arrest, which can potentially result in prolonged periods with no chest compressions and premature cessation of resuscitation.[9] Periresuscitation echocardiography has not only been shown to identify the presence or absence of cardiac motion during resuscitation but can also be performed without detracting from the advanced life support (ALS) protocol.[10]

Echocardiography and the Underlying Cause of Cardiac Arrest

The potential causes of cardiac arrest that can be diagnosed with TTE include tamponade, coronary artery disease, PE, and hypovolemia. Extension of ultrasound imaging beyond the heart can be used to diagnose or exclude pneumothorax with lung views.[10,11]

HYPOVOLEMIA

Left ventricular (LV) end-diastolic volume has been shown to correlate well with blood loss and can reportedly be used to detect small changes in intravascular volume.[12] In the critically ill, a number of parameters have been found to indicate severe hypovolemia, including the presence of a small hyperkinetic left ventricle (Figure 31-2) (and a normal right ventricle) with obliteration of the cavity at end-systole,[12] an LV end-diastolic area of less than 5.5 cm^2/m^2 body surface area (BSA), a small inferior vena cava (IVC) with inspiratory collapse in spontaneously breathing patients,[13] or a small IVC at end-expiration[14] with variable respiratory changes in mechanically ventilated patients.[15] Hypovolemia leading to cardiac arrest is likely to be severe, and although there is debate in the literature regarding the sensitivity and specificity of echocardiographic features of hypovolemia in the arrested state, the finding of a small, underfilled left ventricle with collapsed caval veins suggests the need for aggressive volume resuscitation and a search for the cause of the hypovolemia.[16]

TAMPONADE AND PERICARDIOCENTESIS

The physiologic features of tamponade result from an increase in intrapericardial pressure causing impaired filling and an adverse effect on cardiac function. Echocardiographic features that indicate hemodynamic significance of a collection include the presence of a swinging heart, right ventricular (RV) diastolic collapse, right atrial diastolic collapse, pseudo-SAM (systolic anterior wall motion abnormality), an enlarged nonpulsatile vena cava (all parts of the respiratory cycle), reciprocal changes in the size of cardiac chambers, and transvalvular flow that varies with respiration.[17] Demonstration of these echocardiographic features of tamponade has erroneously become synonymous with the diagnosis of tamponade, which is a clinical diagnosis. In cardiac arrest, demonstration of a pericardial collection (Figure 31-3) should lead to consideration of immediate drainage since the echocardiographic features of tamponade may not be present in certain circumstances (particularly following cardiac surgery).

It is recommended that pericardiocentesis be performed under echocardiographic guidance (class I), with success rates higher than 90% being achieved, depending on the volume and location of the collection and operator experience.[18] Major complications include cardiac perforation, pneumothorax, coronary perforation, trauma to abdominal organs, and death, but the incidence of complications is significantly reduced with echocardiographic guidance.[18] Indeed, TTE has been used routinely in some units for more than 30 years to guide pericardiocentesis with the aim of reducing complications.[19]

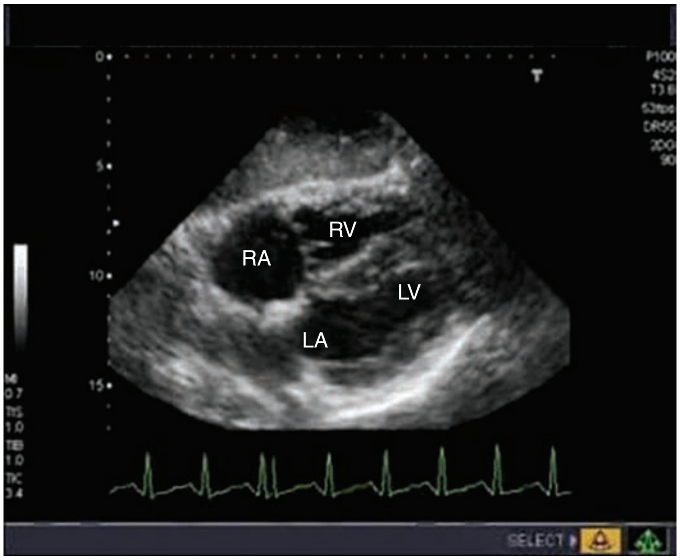

Figure 31-2 Subcostal view of a patient with severe hypovolemia. *LA*, Left atrium; *LV*, left ventricle; *RA*, right atrium; *RV*, right ventricle.

Figure 31-3 Subcostal view of a patient with tamponade. The image taken is shown in late diastole, where indentation and collapse of the right ventricular free wall are seen (*arrows*). *coll*, Collection.

CORONARY ARTERY THROMBOSIS

TTE is used routinely for the diagnosis of myocardial infarction (MI)/ischemia, evaluation of its complications, monitoring of therapeutic interventions, and risk stratification. In cardiac arrest with ongoing cardiac activity, echocardiography may reveal regional wall motion abnormalities (RWMAs) related to either previous MI or new ischemia. Although RWMA is not 100% sensitive or specific for coronary artery disease, in the context of cardiac arrest these findings may alter both the cardiovascular support and therapeutic interventions undertaken (e.g., avoidance of drugs that increase myocardial oxygen demand, insertion of an intraaortic balloon pump, and rapid/immediate revascularization). Free wall rupture is documented in 0.8% to 6.2% of patients after acute MI[20] and frequently results rapidly in sudden death secondary to tamponade. When the findings are subacute, early diagnosis with TTE may be lifesaving. Other complications of coronary artery disease (ventricular septal defect, mitral regurgitation, intracardiac thrombus, RV infarction) resulting in cardiogenic shock are readily detectable with echocardiography, and when suspected, urgent TTE is indicated.[18]

PULMONARY EMBOLISM

Cardiac arrest secondary to PE is likely to be massive and result from occlusion of more than two thirds of the pulmonary vascular bed. Echocardiography is recommended in the current guidelines for investigation of suspected PE only in patients too unstable to be transferred for computed tomography,[21] the extreme of which is during cardiac arrest. TTE findings of RV dilatation (Figure 31-4) in the absence of significant left-sided valve or ventricular disease or known pulmonary disease are indicative of a high probability of PE, with the diagnosis confirmed by demonstration of thrombus in the right side of the heart, pulmonary arteries, or both.[21]

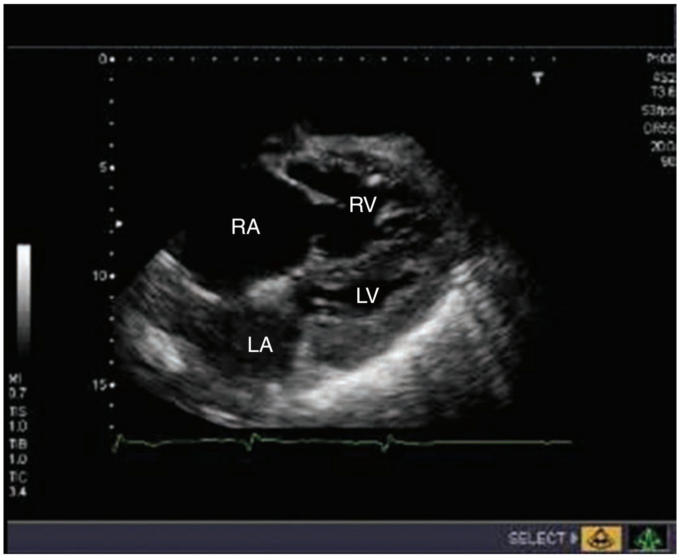

Figure 31-4 Subcostal view of a patient with massive pulmonary embolism. Note the hugely dilated right side of the heart and the small, squashed left ventricle. *LA*, Left atrium; *LV*, left ventricle; *RA*, right atrium; *RV*, right ventricle.

The sensitivity and specificity of TTE for the diagnosis of PE are still being debated. In some studies the presence of RV hypokinesis has been found to identify patients with 30% or greater nonperfused lung, who may benefit from thrombolysis; others have not found any correlation between the extent of the perfusion abnormality and the degree of RV dilatation or dysfunction.[22] The degree of RV dysfunction noted on TTE does correlate with mortality, however.[23]

Echocardiography in the Post–Cardiac Arrest Setting

TTE is routinely used in critical care to diagnose underlying cardiac pathology and to monitor the effects of therapeutic interventions. In the post–cardiac arrest setting, echocardiography may be used to determine the optimal volume status, identify further complications related to the initial cause of the cardiac arrest, and monitor cardiac output. In addition, echocardiography can be used to guide the clinician in maximizing cardiac output while minimizing any increase in myocardial oxygen demand—by optimizing filling status, heart rate, and atrioventricular delay.[24]

Performance of Advanced Life Support–Compliant Periresuscitation Echocardiography

In the peri-arrest setting, a fully comprehensive TTE study is neither necessary nor relevant. In this situation, performance of rapid, accurate, ALS-compliant focused echocardiography as an extension of the clinical examination with the aim of ruling in or ruling out potential causes of the cardiac arrest is required. Current American Society of Echocardiography guidelines recommend that limited, focused transesophageal echocardiography be performed when intraoperative cardiac arrest occurs,[9] and the ILCOR guidelines support this recommendation for nontraumatic cardiac arrest when appropriately trained personnel are present. The 10-second pulse check provides an opportunity when TTE may be performed, and a practitioner experienced in echocardiography and trained in ALS compliance should be able to perform this study (Figure 31-5).[25]

Because experienced echocardiographers are not a standard part of the cardiac arrest team, the question then arises whether it is possible to train members of the arrest team in performing focused echocardiography. There is increasing evidence that performance of focused echocardiography by nonexpert echocardiographic practitioners in the context of significant hemodynamic instability and cardiac arrest is feasible.[25] Focused ultrasound is now considered a routine part of advanced trauma life support in patients with traumatic cardiac arrest, and in some hospitals in the intensive care setting, novice echocardiographers perform and interpret studies on the critically ill as part of their routine care.[26] There is evidence that a focused, time-limited study is adequate and that noncardiologists/nonexperts can be successfully trained to perform such studies. However, although some studies suggest that focused echocardiography can be performed in an ALS-compliant manner and that clinicians can potentially predict the outcome depending on the echocardiographic findings,[25,26] none have yet shown that the use of focused echocardiography improves outcomes per se.

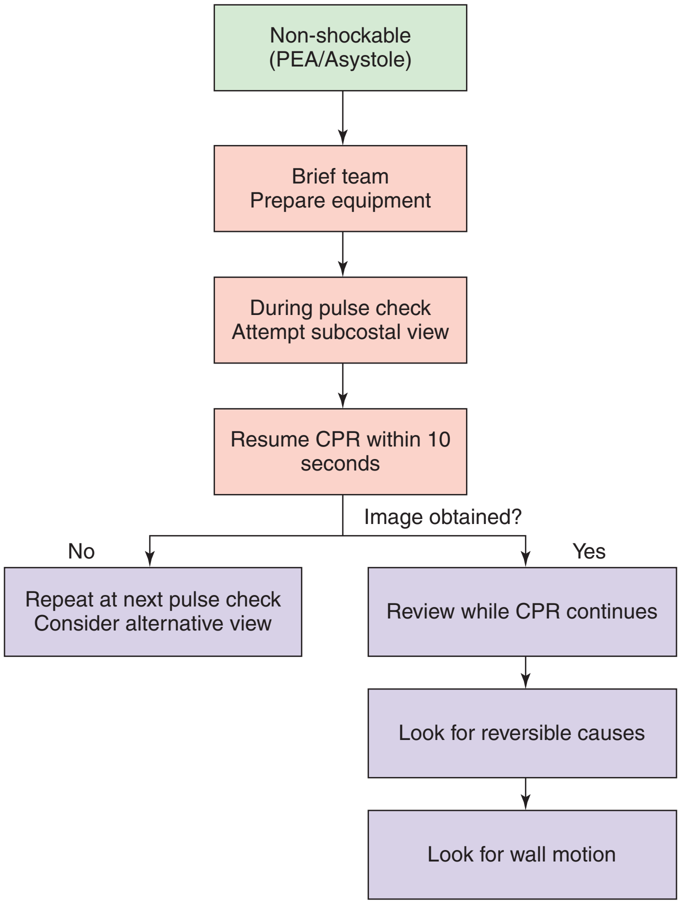

Figure 31-5 When to implement echocardiography in cardiac arrest. Here, in the nonshockable part of the algorithm, the subcostal view is attempted during the 10-second pulse check, and cardiopulmonary resuscitation is resumed at 10 seconds. The image obtained is then reviewed to look for reversible causes. If no image is obtained, at the next 10-second pulse check a further attempt is made with either the subcostal or another view. *CPR*, Cardiopulmonary resuscitation; *PEA*, pulseless electrical activity.

To date, electrocardiography has been regarded as the "gold standard" for the diagnosis of asystole or ventricular fibrillation, but echocardiography may prove to be more accurate.[27] The diagnosis of EMD is no longer used in ALS algorithms, but echocardiography is able to demonstrate its existence, as opposed to simply profound hypotension with an impalpable pulse. The outcomes of patients with true EMD (vs. profound hypotension) are significantly worse, and it may be that their management can be more tailored to the findings on echocardiography.[27] Finally, routine use of TTE as a coordinated part of the ALS algorithm should be investigated for both in-hospital and out-of-hospital arrest and with physician and nonphysician (e.g., paramedic) operators, perhaps by using telemetry of images for expert review, to determine whether it improves outcomes. The introduction of lightweight, handheld echocardiographic machines has provided important opportunities to extend research beyond the hospital setting, such as for assessment of the prevalence of important echocardiographic findings in a critically ill patient some distance from the hospital and for evaluation of the role of interventions that could correct these findings before the patient reaches the hospital (or trigger transfer direct to a specialist center).

Conclusion

Periresuscitation echocardiography is the only real-time bedside diagnostic tool that can be used to diagnose some of the potentially reversible causes of cardiac arrest, and it should be regarded as analogous to performance of pulse oximetry or electrocardiographic monitoring. Even though performance of periresuscitation echocardiography has been accepted by some authorities, the method of training and the number of scans required to demonstrate competency have not yet been agreed upon. It is likely, however, that with the progressive development of handheld devices, improvement in image quality, and increased use of ultrasound as an extension to clinical examination in undergraduate medicine, echocardiography will become a standard part of our evaluation of peri-arrest patients.

Pearls and highlights

- Paramount is not interrupting chest compressions/ALS algorithm. TTE images must be obtained during the 10-second pulse check.
- Potentially reversible causes are readily recognizable—even by novice echocardiographers, provided that they have received appropriate training.
- Reporting should be in a binary fashion.
- TTE images must be stored for review.

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32

Evaluation of Left Ventricular Diastolic Function in the Intensive Care Unit

JULIEN MAIZEL | SHARI EL-DASH | MICHEL SLAMA

(CONSULTANT-LEVEL EXAMINATION)

Overview

Left ventricular (LV) diastolic dysfunction is a clinical entity that remains poorly understood and identified in the intensive care unit (ICU) setting. It is essential to clarify the difference between diastolic heart failure, LV diastolic dysfunction, and increased LV filling pressure. Diastolic heart failure is a clinical syndrome defined by the presence of symptoms of congestive heart failure in the setting of diastolic dysfunction (and preserved systolic function).[1] This syndrome is also called heart failure with a normal LV ejection fraction and, in cardiology, accounts for more than 50% of all cases of acute heart failure. The proportion may be even higher in the ICU setting, although no precise statistics are available.

Diastolic dysfunction is an alteration in LV properties marked by degradation in LV relaxation or an increase in LV stiffness (or both). Some evidence indicates that diastolic dysfunction increases the risk for death in patients with septic shock.[2] In addition, evaluation of diastolic function can provide the intensivist with important hemodynamic information concerning patients' fluid responsiveness. In patients with a steep LV pressure-volume relationship, infusion of small amounts of fluid may significantly increase LV diastolic pressure and precipitate acute pulmonary edema. Diastolic dysfunction may coexist with systolic dysfunction in patients with congestive heart failure. Furthermore, in the absence of congestive heart failure, LV filling pressure or LV end-diastolic pressure is not necessarily increased in patients with diastolic (or even systolic) dysfunction. Both diastolic function and LV filling pressure can be explored with echocardiography.

Diastole is classically split into three different physiologic events: LV relaxation, LV passive filling, and left atrial (LA) contraction. Impairment in each of these events may lead to congestive heart failure. Impairment of LV relaxation is mainly due to failure of calcium recapture in the sarcoplasmic reticulum, whereas myocardial infiltration or fibrosis increases LV stiffness.[3]

Recently, Nagueh et al described a practical approach for classifying diastolic function with transthoracic echocardiography (TTE) that involves taking several parameters into account: mitral inflow, early septal and lateral mitral annular systolic velocity with tissue Doppler, LA volume, pulmonary venous return flow, and even the response to a Valsalva maneuver.[4] In ICU patients, obtaining some of these parameters (e.g., the response to a Valsalva maneuver) can pose quite a challenge.[5] Detection of other parameters (e.g., pulmonary venous flow [PVF]) may require the application of transesophageal echocardiography (TEE).

Mitral Flow: Left Ventricular Filling

Mitral inflow can be recorded (with both TTE and TEE) by placing the pulsed wave Doppler sample volume at the tip of the mitral leaflets (Figure 32-1). Color flow imaging can help optimize alignment of the Doppler beam, particularly if the left ventricle is dilated. Two waves are described in mitral inflow: the E wave (early filling velocity), which corresponds to the early LV/LA pressure gradient and is affected mainly by LV relaxation and preload, and the A wave, which is due to atrial

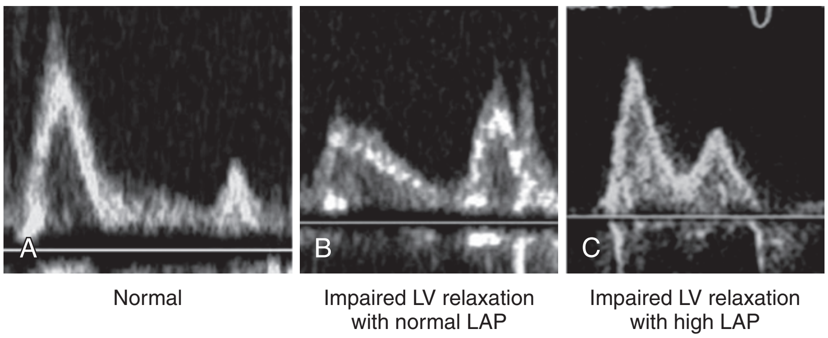

Figure 32-1 Mitral flow recorded with pulsed wave Doppler. **A,** Normal pattern; **B,** Impairment of left ventricular (LV) relaxation with normal left atrial pressure (LAP); **C,** Impairment of LV relaxation with high LAP.

contraction, reflects the LA/LV pressure gradient during late diastole, and is affected by LV compliance and LA contractile function (and thus disappears in atrial fibrillation) (see Figure 32-1).

Parameters of mitral inflow include measurements of E and A peak systolic velocity, the E/A ratio, and the deceleration time (DT) of E. The E/A ratio has three main patterns. In the normal pattern, E has a higher peak velocity than A does and therefore E/A is greater than 1 (Figure 32-1A). The second pattern has a small E wave with an E/A ratio of less than 1 and increased DT. This pattern usually corresponds to impairment of LV relaxation, yet with low atrial pressure (Figure 32-1B). The third pattern consists of very high E velocity with an E/A ratio higher than 2 and a short DT. It is associated with severe impairment of LV compliance and with high LV diastolic and pulmonary arterial occlusion pressure (Figure 32-1C).[6] Mitral flow is affected by many factors, such as heart rate, preload, afterload, and LA and LV contractility. Nonetheless, since many of these factors are frequently altered in critically ill patients, diastolic function should not be assessed by the mitral flow pattern alone but rather by a global interpretation of all the available information.

Pulmonary Venous Flow

To record PVF, the pulsed wave Doppler sample volume is placed in the pulmonary vein just distal to its entry point. Although good alignment can be achieved with TTE in some patients (Figure 32-2), measurement of PVF usually requires performance of TEE. The pulmonary venous waveform consists of a peak systolic (S) velocity, which is usually divided into two peaks, S1 and S2, and a peak diastolic (D) velocity. Following these antegrade waves is a retrograde reverse A wave (Ar) caused by atrial contraction (see Figure 32-2). Further information can be obtained by analyzing ensuing parameters such as the S/D ratio, systolic filling fraction (integral of S/[S + D]), peak Ar (reverse A) velocity in late diastole, duration of Ar velocity, and its difference from the mitral A-wave duration. The velocity of the S1 component is primarily defined by variation in LA pressure, as well as by both LA contractility and relaxation.[7] The S2 component is instead related to stroke volume and propagation of the pulse wave along the branches of the pulmonary artery. D-wave velocity, on the other hand, is a function of LV filling and compliance and thus accompanies the changes observed in mitral E velocity. Pulmonary venous Ar velocity and duration are influenced by late diastolic LV pressure, atrial preload, and LA contractility. Decreasing LA compliance with increasing LA pressure decreases S velocity and increases D velocity, respectively, thereby reducing the S/D ratio to less than 1.[8-10] This situation is also characterized by a drop of less than 40% in the systolic filling fraction[8] and shortening of the DT of D velocity, usually less than 150 msec.

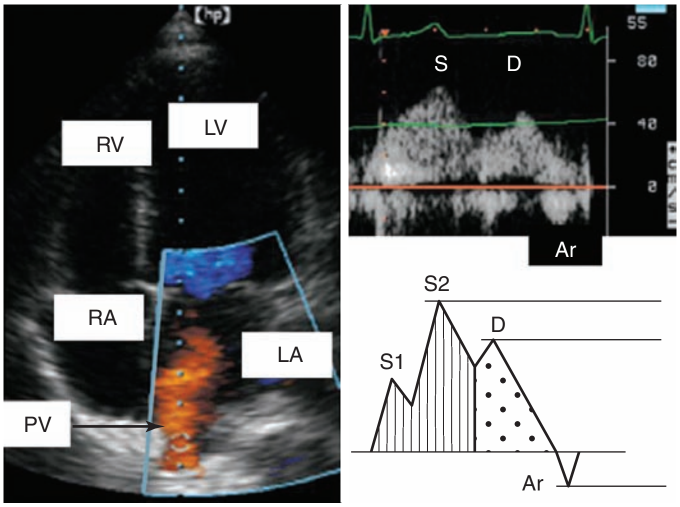

Figure 32-2 Pulmonary venous flow. *Left,* Color pulmonary venous flow (orange) on an apical view; *right,* pulmonary venous flow recorded with pulsed Doppler. *Ar,* Atrial reverse flow; *D,* diastolic flow; *LA,* left atrium; *LV,* left ventricle; *PV,* pulmonary vein; *RA,* right atrium; *RV,* right ventricle; *S,* systolic flow.

Color M-Mode Propagation Velocity

The propagation velocity (Vp) of mitral inflow is obtained from an apical four-chamber view by placing the color Doppler box on LV inflow and adding an M-mode across it. Vp is measured on M-mode image as the slope of the red-blue transition (Figure 32-3).[11] A steeper Vp of greater than 50 cm/sec is considered normal, and a flatter Vp lower than 45 cm/sec is predictive of diastolic dysfunction.[4] Vp is closely related to LV relaxation and has been suggested to be independent of loading conditions, but it has poor reproducibility.

Tissue Doppler Mitral Annulus Velocity

Mitral annular velocity is measured on an apical view with tissue Doppler imaging (TDI). The sample volume should be positioned on the septal or lateral insertion sites of the mitral annulus, at the level of the insertion of the mitral leaflets, and its size should be adjusted as necessary (usually 5 to 10 mm) to cover the full range of excursion of the mitral annulus in both systole and diastole. Because mitral annular velocities have high signal amplitude, Doppler spectral gain should be set low enough to ensure a thin, clear Doppler trace. TDI waveforms

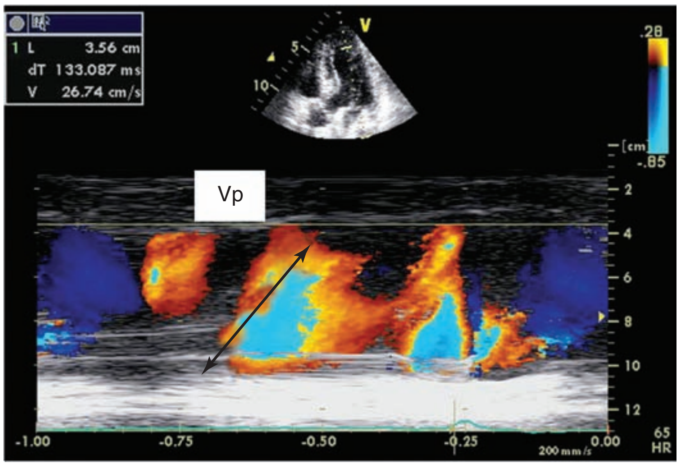

Figure 32-3 Vp (velocity of mitral flow propagation) measured on color M-mode.

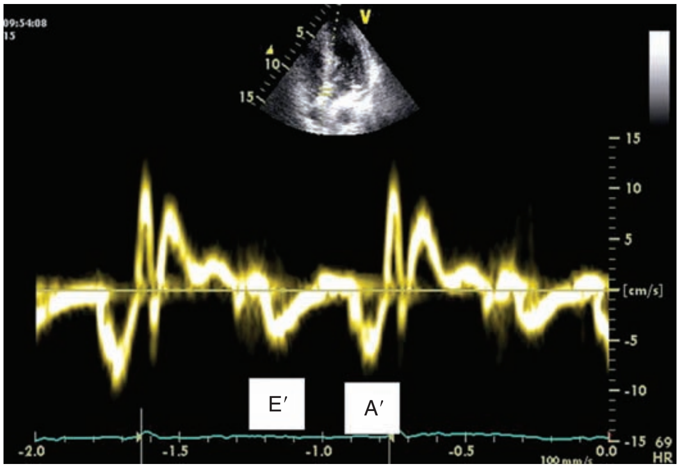

Figure 32-4 Tissue Doppler imaging of the mitral annulus at the level of the septum. Impaired relaxation is seen with an E′ of less than 8 cm/sec and an E′/A′ ratio of less than 1. *A′*, Late diastolic velocity; *E,′*, early diastolic velocity.

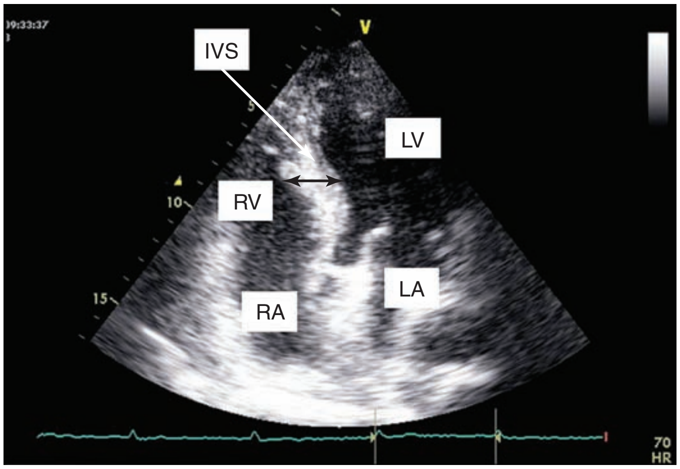

Figure 32-5 Apical view depicting left ventricular hypertrophy. *IVS*, Interventricular septum; *LA*, left atrium; *LV*, left ventricle; *RA*, right atrium; *RV*, right ventricle.

can be obtained in nearly all patients (>95%) regardless of the two-dimensional image quality (Figure 32-4). Primary measurements include the peak velocities of systolic (S) and early and late diastolic excursion. Early diastolic annular velocity can be referred to as Ea, Em, E′, or e′, whereas late diastolic velocity is referred to as Aa, Am, A′, or a′. Peak E′ velocity is related to LV relaxation[12] and is considered to be relatively independent of preload. An E′ value lower than 8 cm/sec at the level of the septum or lower than 10 cm/sec at the level of the lateral wall is considered indicative of impaired LV relaxation.[4] An E′/A′ ratio of less than 1 is also highly suggestive of impaired LV relaxation.

Left Atrial Volume

LA volume is measured with apical four-chamber and two-chamber views. It is clinically important because of the significant relationship between LA remodeling and other echocardiographic indices of diastolic function. LA volume often reflects the cumulative effects of filling pressure over time. A normal-sized left atrium effectively rules out any chronic diastolic dysfunction. An LA volume greater than 34 mL/m^2 is associated with diastolic dysfunction and chronic increases in LV and LA diastolic pressure; it is an independent predictor of death, heart failure, atrial fibrillation, and ischemic stroke.[4,13]

Left Ventricular Hypertrophy

LV hypertrophy is a main cause of diastolic dysfunction, although relaxation may also be impaired in patients with normal wall thickness. Systemic hypertension is the most common cause of LV hypertrophy, and diastolic dysfunction may be the first sign of the disease (preceding ventricular wall thickening or even a measurable rise in blood pressure).[14] LV hypertrophy is best assessed by measuring LV mass. In the ICU it is rather difficult to calculate the latter, and thus LV thickness may serve as a surrogate (Figure 32-5). Nevertheless, in patients with hypovolemia and severely decreased preload, the decrease in diastolic diameter may cause the thickness of the walls to appear increased despite a normal ventricular mass (*pseudohypertrophy*), which is usually associated with LV obstruction.

Assessment of Diastolic Dysfunction

Diastolic dysfunction is classified into three grades (according to Nagueh et al): mild (grade I), moderate (grade II), and severe (grade III). This classification is a strong prognosticator of all-cause mortality in the general population (Figure 32-6).[15]

Grade I corresponds to mild diastolic dysfunction with normal filling pressure, grade II corresponds to impaired relaxation with a moderate elevation in LV filling pressure, and grade III is a frankly restrictive LV filling pattern with high LV filling pressure. With adequate therapy, grade III impairment may potentially revert to grade II or even to grade I.

Several Doppler indices derived from mitral flow (E/A ratio), PVF (D-wave DT and systolic filling fraction), and TDI (E/E′ ratio) have been proposed to quantify LV filling pressure and have been validated against pulmonary artery occlusion pressure in different conditions. Most of the studies performed in the ICU have focused on mechanically ventilated patients, and thus we lack data for spontaneously breathing patients and must extrapolate from catheterization laboratory studies of cardiology patients.

It is essential to know the limits of each parameter. The E/A ratio appears to have better diagnostic value in patients who

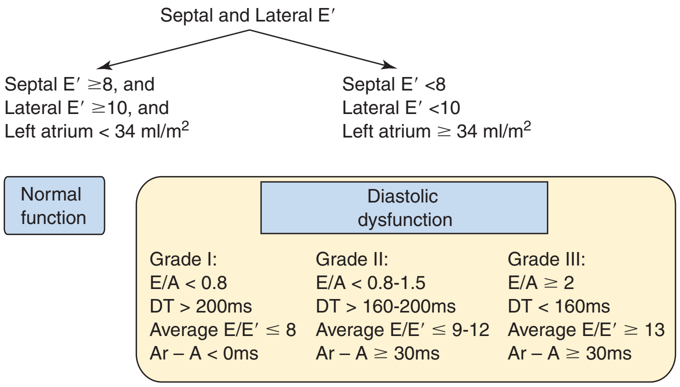

Figure 32-6 Diagnostic algorithm for left ventricular diastolic dysfunction.

also have depressed systolic function than in those with normal function. The E/E′ threshold differs when E′ is recorded in the lateral or medial junction of the mitral annulus (particularly in the case of myocardial ischemia), and thus both should be recorded and averaged.

E/Vp is difficult to measure and has the lowest reproducibility of all the other Doppler indices. PVF can provide various indices but invariably requires performance of TEE. Nonetheless, E/E′ is the most feasible and easily obtained parameter and has good reproducibility. From a practical point of view, estimation of LV filling pressure in ICU patients is best achieved by evaluating all available parameters rather than focusing on only one.[16]

This classification does, however, have a few limitations. In older patients (>60 years) it is common to find an age-related grade I pattern (E/A ratio <1 and DT >200 msec) regardless of the actual diastolic dysfunction. Therefore a history of cardiovascular disease or the presence of LV hypertrophy is helpful in establishing a clear diagnosis. In athletes, LA size may be enlarged (≥34 mL/m[2]), but this is not diagnostic of diastolic dysfunction if there is no decrease in E′. Despite these limitations, the Nagueh classification provides valuable information in routine ICU practice (see Figure 32-6).

Assessment of diastolic dysfunction with echocardiography is helpful in many clinical scenarios (e.g., sepsis, respiratory failure, shock). Early mitral annulus velocity is the simplest and the most easily applicable and reproducible Doppler parameter used (in conjunction with assessment of the mitral flow pattern and LA size) for the evaluation of LV diastolic function in ICU patients.

Pearls and Highlights

- LV diastolic dysfunction is commonly observed in ICU patients and should be assessed by means of echocardiography, especially in patients with sepsis, respiratory failure, or shock.
- LV diastolic dysfunction is classified into three grades (according to Nagueh et al): mild (grade I), moderate (grade II), and severe (grade III). This classification is a strong prognosticator of all-cause mortality in the general population.
- The hemodynamic status of ICU patients is constantly changing (e.g., preload, afterload), and thus LV diastolic function cannot be evaluated solely by the mitral flow or pulmonary venous flow pattern.
- Normal LA size effectively rules out chronic LV diastolic dysfunction.
- Early mitral annulus velocity is the simplest and most easily applicable and reproducible Doppler parameter used (in conjunction with assessment of the mitral flow pattern and LA size) for the evaluation of LV diastolic function in ICU patients.
- The E/E′ threshold differs when E′ is recorded in the lateral or medial junction of the mitral annulus (particularly in the case of myocardial ischemia), and thus both should be recorded and averaged.
- From a practical point of view, estimation of LV filling pressure in ICU patients is best achieved by evaluating all available parameters rather than focusing on only one.

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For a full list of references, please visit www.expertconsult.com.

IMAGING CASE

A 72-year-old man with a history of ischemic heart disease, systemic hypertension, and type 2 diabetes was evaluated in the emergency department for hypovolemic shock (he had been vomiting for the last 3 days). Ultrasound examination revealed signs of hypovolemia and inferior vena cava collapsibility suggesting fluid responsiveness with an E/A ratio of less than 1 and an E/E′ ratio of 8.5 (Figure 32-7A and B). After 1.5 L of crystalloid was administered, a second examination found an E/A ratio of 1 and an E/E′ ratio of 14 (Figure 32-7C). Next, another 500 mL of crystalloid was administered, and dyspnea suddenly developed (desaturation to 90% on pulse oximetry with 3-L/min oxygen therapy). At that time a third ultrasound examination showed an E/A ratio of 2 and an E/E′ ratio of 20 (Figure 32-7D). Lung ultrasound confirmed pulmonary edema. In patients with LV diastolic dysfunction, the "euvolemic range" can be indeed very narrow! Echocardiographic assessment of LV filling pressure helps avoid fluid overload (see black arrows on Figure 32-8).

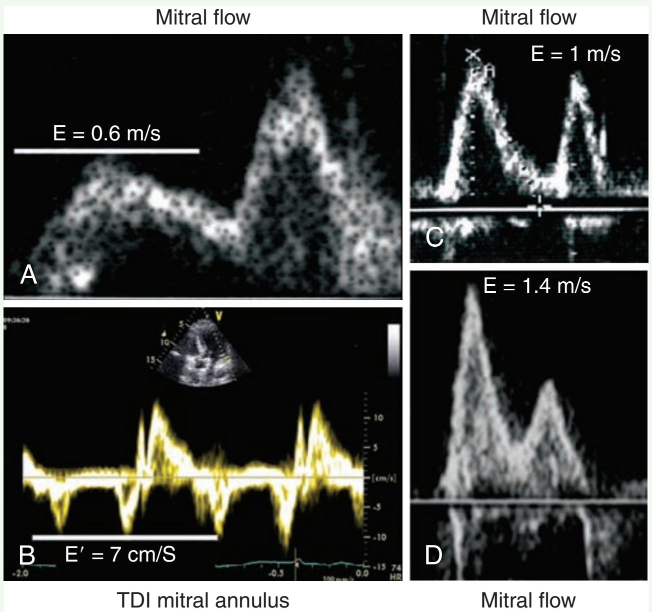

Figure 32-7

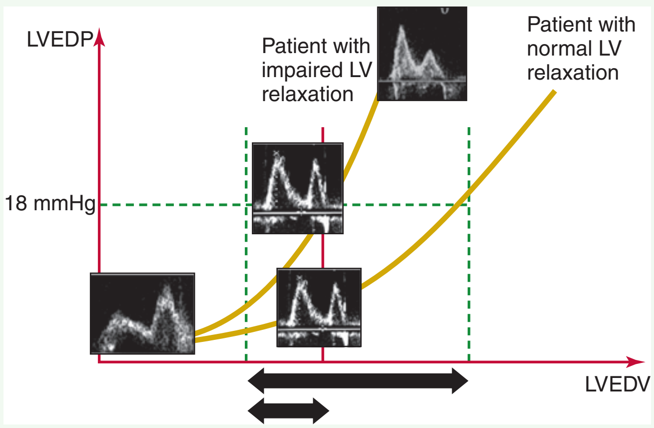

Figure 32-8

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Evaluation of Right Ventricular Function in the Intensive Care Unit by Echocardiography

MICHEL SLAMA | JULIEN MAIZEL | YAZINE MAHJOUB | SHARI EL-DASH

(CONSULTANT-LEVEL EXAMINATION)

Overview

Assessment of right ventricular (RV) function is a key element in the hemodynamic evaluation of patients in the intensive care unit (ICU) with shock or respiratory failure.[1,2] For several decades the former was considered to play a minor role in hemodynamic failure. However, RV dysfunction may be a crucial element in the hemodynamic compromise that intensivists encounter in various clinical scenarios such as pulmonary embolism (PE), sepsis and septic shock, myocardial infarction, and acute respiratory distress syndrome (ARDS).[3-5] The right ventricle is highly sensitive to changes in preload and afterload and, unlike the left ventricle (LV), may become acutely enlarged. A pulmonary artery catheter can be used to estimate right atrial pressure (RAP), pulmonary arterial pressure (PAP) and resistance, and cardiac output. In recent years, echocardiography has progressively replaced the former in the ICU. Echocardiography facilitates accurate, noninvasive, prompt, and serial evaluation of RV function in ICU patients.

Right Ventricular Physiology

The configuration of the right ventricle is rather complex in that it has two perpendicular chambers—a horizontal one corresponding to the filling chamber (the sinus) and a vertical one corresponding to the outflow tract (the cone or infundibulum). The right ventricle has a normal free wall thickness of 4 mm and is less muscular than the LV since it is adapted to the pulmonary vasculature. It is very sensitive to changes in afterload and becomes acutely dilated; its ejection fraction is radically decreased whenever abrupt increments in PAP occur. In the latter case, RV pressure may become transiently greater than pressure in the LV and thus cause end-systolic bowing of the interventricular septum into the LV.[6,7] Chronically increased PAP induces RV hypertrophy. Because the heart is enveloped by the pericardium and the right ventricle is wrapped around the LV, any modification in one ventricle will modify the size and the function of the other (left-right ventricular interdependency). The LV normally contributes 25% of RV contraction, which may be increased up to 35% in patients with pulmonary hypertension.[7,8] The right ventricle is very sensitive to coronary flow and is perfused, unlike the LV, during both systole and diastole.[9]

Evaluation of Right Ventricular Function by Echocardiography

RIGHT VENTRICULAR SIZE

RV size may be assessed by measurement of volume. Two-dimensional (2D) echocardiography is unable to provide an accurate estimate of RV volume because of its complex shape. Three-dimensional (3D) echocardiography is more accurate. However, it is time-consuming and not yet readily available, and a perfect view of the endocardial contour is required (which is hard to achieve in the critically ill). Vieillard Baron et al proposed measuring the right (RVEDA) and left (LVEDA) ventricular end-diastolic areas by tracing the endocardium on an apical four-chamber view.[10] When the endocardium is not well identified, the area should be traced to the epicardium. The RVEDA/LVEDA ratio was assessed in normal subjects and found to vary between 0.36 and 0.60. Thus a ratio lower than 0.6 (Table 33-1) is considered normal, whereas ratios between 0.6 and 1 and higher than 1 correspond to moderate and severe RV dilatation, respectively (Figures 33-1 and 33-2). This sonographic evaluation is performed by using either transthoracic (TTE) or transesophageal (TEE) echocardiography.[10] The American Society of Echocardiography and the European Association of Echocardiography have published guidelines for evaluation of RV function by echocardiography[11]; However-however, several of the recommendations are not easily applicable in the ICU.

Alterations in RV shape may be used to assess dilatation. As it dilates, the right ventricle loses its characteristic triangular shape and becomes more rounded. Quantitative measurement of RV size by means of the RVEDA/LVEDA ratio is simple and has good reproducibility. Charon et al proposed using subjective (qualitative) assessment of RV size by eyeballing the right ventricle on an apical four-chamber view since they found significant correlation with measurements of the RVEDA/LVEDA ratio.[12] The subcostal view, which is usually more accessible than other views (e.g., apical) in mechanically ventilated patients, may be used to perform RV measurements in the ICU.

INTERVENTRICULAR SEPTAL SHAPE AND MOVEMENT

The interventricular septum should be analyzed in patients with RV dysfunction. It is best analyzed on a parasternal short-axis

TABLE 33-1 Evaluation of Right Ventricular Function by Echocardiography: Abnormal Values of Various Doppler and Two-Dimensional Echocardiographic Indices

	Abnormal Value
Maximal RV diameter (parasternal view) (see Figure 33-3)	>42 mm
RVEDA/LVEDA (apical 4-chamber view) (see Figures 33-1 and 33-2)	>0.6
RV two-dimensional fractional area contraction (apical four-chambers view)	<35%
RV ejection fraction	<44%
RV free wall thickness	>4 mm
SPAP (on tricuspid regurgitation or pulmonary regurgitation; see Figures 33-5 and 33-6C)	>35-40 mm Hg
TAPSE (see Figure 33-4A)	<16 mm
S on TDI (see Figure 33-4B)	<0 cm/sec

Data from Jardin F, Dubourg O, Bourdarias JP: Echocardiographic pattern of acute cor pulmonale, Chest 111:209-217, 1997; and Rudski LG, Lai WW, Afilalo J, et al: Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography, J Am Soc Echocardiogr 23:685-713, quiz 786-788, 2010.

LVEDA, Left ventricular end-diastolic area; *RV*, right ventricular; *RVEDA*, right ventricular end-diastolic area; *SPAP*, systolic pulmonary arterial pressure; *TAPSE*, tricuspid anterior plane systolic excursion, *TDI*, tissue Doppler imaging.

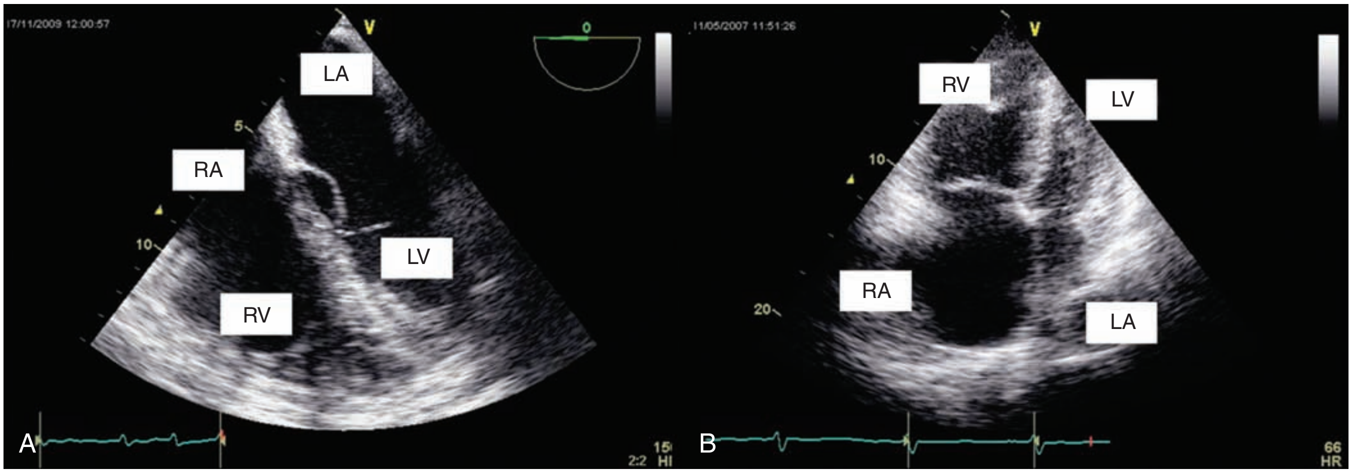

Figure 33-1 Transesophageal (**A**) and transthoracic (**B**) echocardiographic four-chamber views.

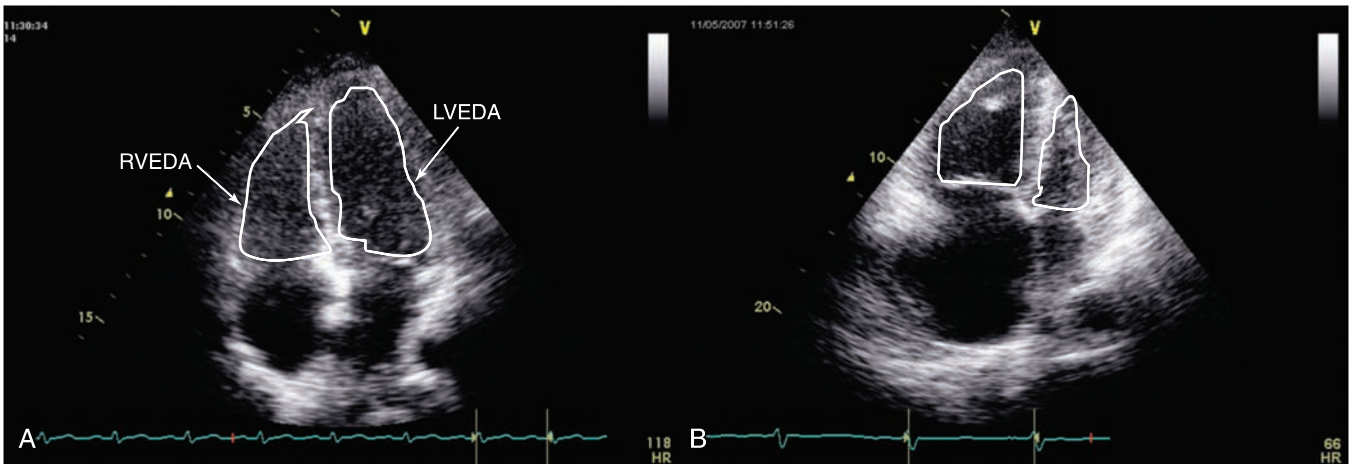

Figure 33-2 Transthoracic echocardiographic apical four-chamber view: assessment of the ratio of right ventricular to left ventricular end-diastolic area in a normal patient (**A**) and one with acute cor pulmonale (**B**).

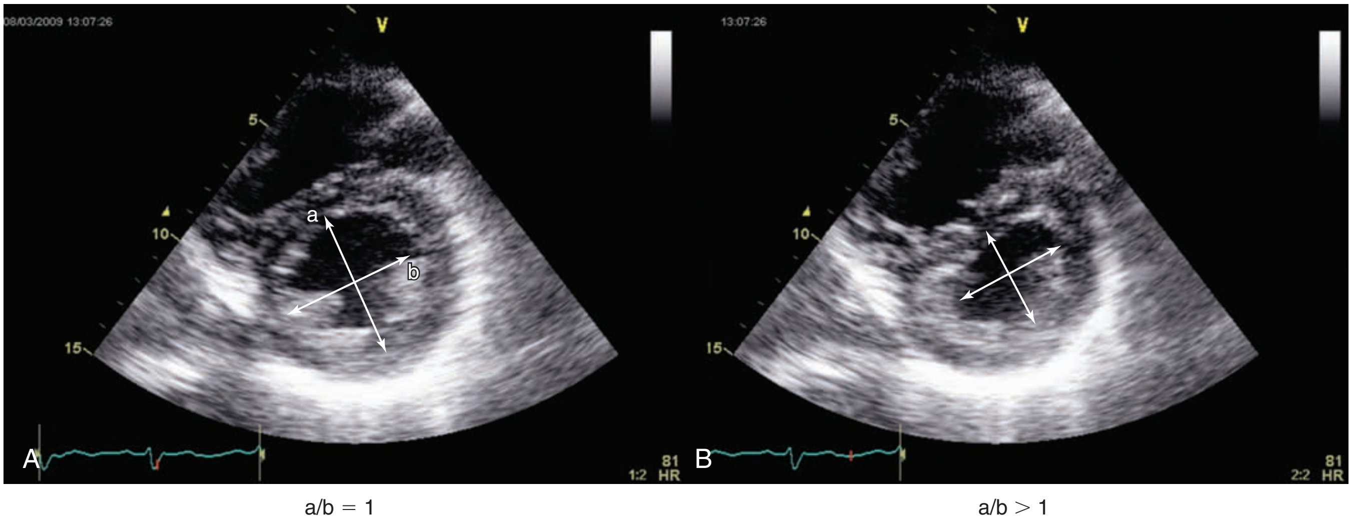

Figure 33-3 Short-axis view of the heart at the level of the left papillary muscles in diastole (**A**) and systole (**B**). Paradoxic septal movement and measurement of the end-systolic eccentricity index in patients with acute cor pulmonale (**B**) are shown.

view at the level of left ventricular papillary muscles. In normal subjects, left ventricular pressure is always higher than RV pressure. Consequently, on a parasternal short-axis view the septum bows into the right ventricle, thus giving the LV its circular shape (O shape). Whenever RV systolic overload occurs, RV end-systolic pressure exceeds that in the LV (because of a prolongation in RV contraction), and this causes the interventricular septum to move toward the LV (septal dyskinesia). This flattening of the septum produces a D-shaped LV and represents a qualitative assessment of this paradoxic septal movement. In addition, a quantitative evaluation can be achieved by direct measurement of the systolic eccentricity index.[10-12] The latter, which is measured on a parasternal short-axis view at the level of left ventricular papillary muscles, is the ratio of the diameter that bisects the papillary muscle to the perpendicular diameter at end-systole. In septal dyskinesia, the systolic eccentricity index is higher than 1 (Figure 33-3; also see Figure 33-2).

Assessment of Right Ventricular Systolic Function

RV contraction is complex and remains hard to assess. Echocardiographic evaluation is of limited use because of the complex RV geometry and prominent trabeculations, and obtaining good-quality images is difficult. The following paragraphs briefly present several echocardiographic indices that may be used to assess RV contraction in the ICU.

RIGHT VENTRICULAR FRACTIONAL AREA CHANGE

Percent RV fractional area change (RVFAC) has been shown to correlate with the RV ejection fraction (RVEF) obtained via cardiac magnetic resonance imaging.[13,14] RVFAC is calculated by tracing the RV endocardium in both systole and diastole from the annulus along the free wall to the apex and back to the annulus along the interventricular septum (apical four-chamber view). Normal RVFAC values are usually greater than 35% to 40% (see Table 33-1).[11] Several experts consider RVFAC a simple and reliable measure for assessing RV function and monitoring the effects of therapy (e.g., administration of vasoactive substances).

RIGHT VENTRICULAR EJECTION FRACTION

The RVEF is based on measurements of systolic and diastolic RV volume by 2D or 3D echocardiography (different techniques), but this method has high intraobserver and interobserver variability and is not recommended in critical care patients because of the habitually poor quality of RV images, foreshortening, and apical dropout.

TRICUSPID ANNULAR PLANE SYSTOLIC EXCURSION

Tricuspid annular plane systolic excursion (TAPSE) measures the distance of tricuspid annulus systolic excursion at the RV lateral wall level by placing an M-mode cursor through the tricuspid annulus (four-chamber apical view, Figure 33-4A). TAPSE-derived values lower than 16 mm indicate RV dysfunction. TAPSE is easy to record, simple, and reproducible, but it depends on preload and afterload conditions, as well as on left ventricular function.[11,15]

TISSUE DOPPLER IMAGING OF THE TRICUSPID ANNULUS

The longitudinal velocity of tricuspid annulus excursion is assessed by tissue Doppler imaging. On a four-chamber apical view the Doppler sample volume is placed at the level of the junction of the tricuspid annulus and the RV lateral wall (Figure 33-4B). The recorded systolic velocity is called "S." S is simple to record and reproducible. An S velocity lower than 10 cm/sec is usually associated with an RVEF lower than 50%.[11,16]

Estimation of Pulmonary Arterial Pressure

Systolic pressure, diastolic pressure, and mean PAP can be estimated from tricuspid (TR) and pulmonary (PR) regurgitant flow by using the simplified Bernoulli equation. Trivial pulmonary and tricuspid regurgitation occurs frequently in normal subjects and may be recorded on color and continuous wave Doppler.[17] Peak TR velocity corresponds to the maximal systolic gradient between the right ventricle and the right atrium. By adding RAP to this gradient it is possible to estimate RV systolic pressure,

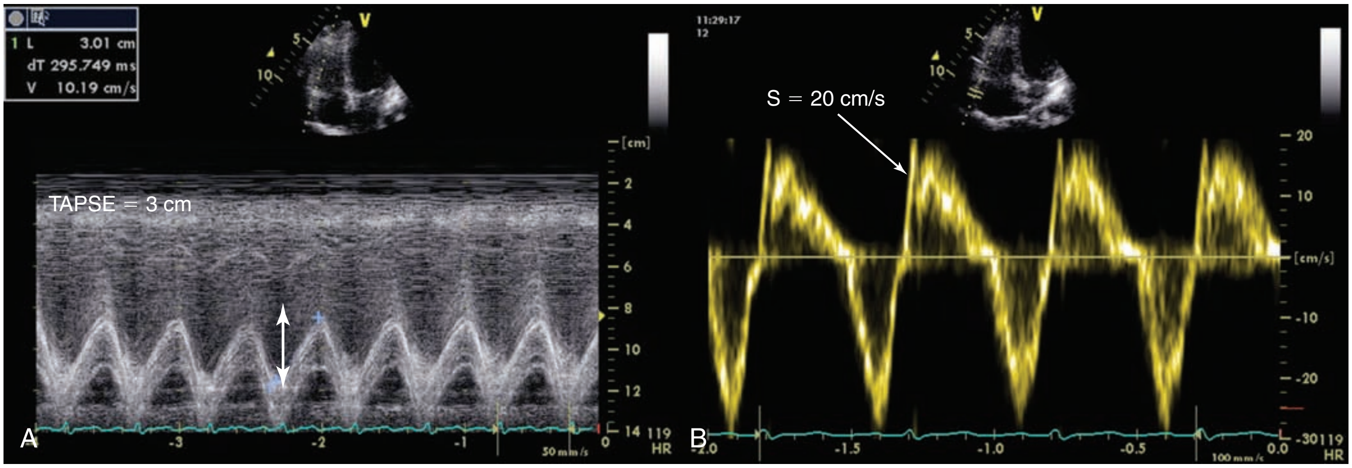

Figure 33-4 **A,** Measurement of tricuspid annular plane systolic excursion on an apical four-chamber view. **B,** Tissue Doppler imaging at the tricuspid annulus. The S wave corresponds to systolic velocity.

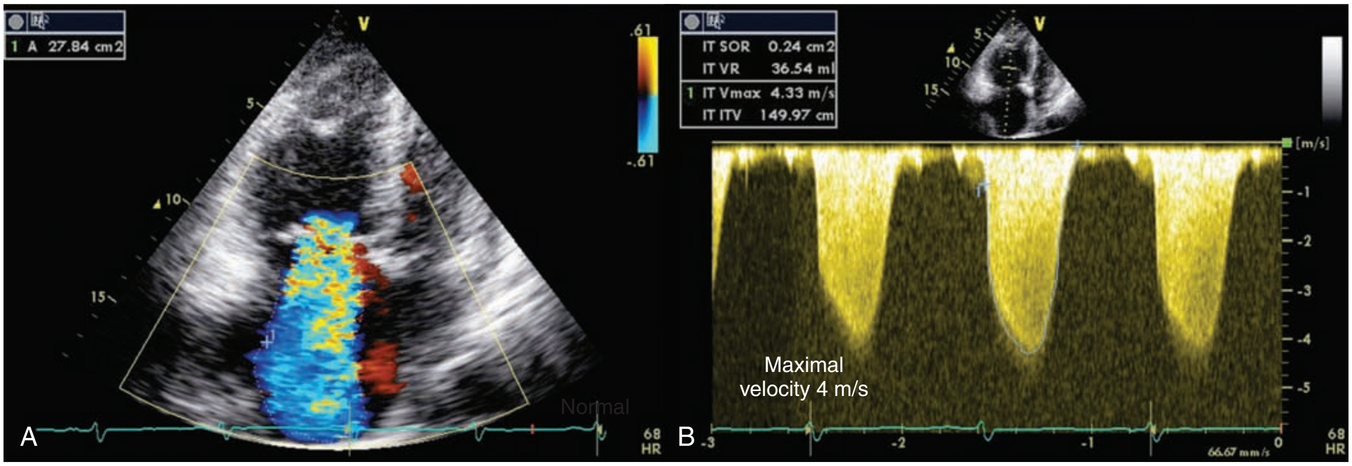

Figure 33-5 Apical four-chamber views. **A,** Two-dimensional severe tricuspid regurgitation on color Doppler. **B,** Tricuspid regurgitation with a maximal velocity of 4 m/sec (right ventriculoatrial gradient of 64 mm Hg) depicted by continuous wave Doppler.

which in the absence of pulmonary valve stenosis, is equal to systolic PAP (Figure 33-5 and see Imaging Case Figure 33-6C).[11] In the ICU, RAP can also be measured with a central venous catheter or be estimated from the size and collapsibility of the inferior vena cava (IVC).[11] Systolic PAP in excess of 35 to 40 mm Hg is considered high. Diastolic pressure and mean PAP can be estimated from the end-diastolic and peak velocity of PR flow, respectively. Pulsed wave Doppler of RV outflow was shown to be useful in assessing pulmonary hypertension. Acceleration time (time between the pulmonary valve opening and maximal velocity of pulmonary flow) correlates to PAP. A time to peak velocity of less than 100 msec is associated with pulmonary hypertension and a time shorter than 60 msec is associated with PAP higher than 60 mm Hg, whereas the presence of a midsystolic deceleration (notch) is indicative of pulmonary hypertension secondary to PE with proximal obstruction.[18-20]

Acute Cor Pulmonale

Acute cor pulmonale (ACP) occurs as a result of acute increments in PAP that may be attributed to various causes (e.g., ARDS, PE). ACP is characterized by systolic and diastolic RV overload. With RV dilatation, increments in the RVEDA/LVEDA ratio are usually observed; the former can equally be assessed by eyeballing, as mentioned in previous pargraphs.[10] The RVEDA/LVEDA ratio has good prognostic value, especially in patients with PE.[21,22] As the right ventricle dilates, various alterations in its configuration may be evident: it appears more rounded on apical four-chamber views and oval (rather than crescent shaped) on parasternal views. Alternatively, subcostal views can be used in patients with poor parasternal or apical windows.[21] Also, right atrial and IVC enlargement can occur as a result of increased RV preload, and left ventricular size is reduced because of RV enlargement.[22] Hence mitral flow recordings (pulsed wave Doppler, four-chamber view) show a pattern of impaired relaxation with a decreased E/A ratio of less than 1. The D-shaped configuration of the LV (parasternal short-axis view) and an eccentricity index higher than 1 can also be attributed to the aforementioned ventricular interdependency (see Figure 33-3), whereas pulmonary hypertension is featured by high-velocity TR flow (0.3 m/sec) (see Figure 33-5).

Chronic Cor Pulmonale

RV dilatation, abnormal septal motion, and pulmonary hypertension may be due to chronic disorders such as left ventricular failure, chronic pulmonary hypertension secondary to lung disease, primary pulmonary hypertension, or congenital cardiovascular disorders. The RV free wall thickens in chronic pulmonary hypertension, and LV hypertrophy is not rare.[23] In ACP, RV hypertrophy can develop rapidly (within 48 hours of PAP elevation), but it is usually moderate (around 4 to 6 mm), whereas in chronic cases the RV wall may thicken to as much as 10 to 11 mm (usually .7 mm). RV free wall thickness is measured from the subcostal view at end-diastole.[10,11] If ACP suddenly develops on the grounds of chronic pulmonary hypertension, ruling out left ventricular pathology such as severe valve disorders, prosthetic valve dysfunction, or acute myocardial failure is mandatory.

Cor Pulmonale in Various Clinical Scenarios

ARDS is associated with ACP in 20% to 40% of cases. It may be attributed to various factors, such as regional occlusion of the pulmonary vascular bed and increments in RV afterload secondary to compression of pulmonary capillaries by high plateau pressure, as well as acidosis and hypoxemia, which increase pulmonary vasoconstriction. Monitoring of RV function by serial echocardiographic examination aids in optimizing mechanical ventilation strategies: adjust tidal volume and plateau pressure, monitor the effect of positive end-expiratory pressure (PEEP), and decide whether to place patients prone.[24] Notably, PE is associated with RV dysfunction in 25% to 70% of cases.[25,26] The latter variation may be partially due to miscellaneous definitions used to describe RV dilatation or dysfunction. For example, RV dilatation has been featured as an RVEDA/LVEDA ratio higher than 1 or an RV end-diastolic diameter greater than 30 mm (from a precordial view), whereas RV dysfunction has been described as global hypokinesia, hypokinesia sparing the apex (McConnell sign),[27] paradoxic septal movements, and pulmonary hypertension without RV hypertrophy. However, RV dysfunction seems to have strong prognostic value in PE.[25] Recently, Platz et al[28] used speckle-tracking software to show that in acute PE, RV free wall longitudinal strain was altered and mid and basal septum strain rates were reduced (only in the RV free wall), even in absence of dilatation. Though not usually identified by TTE or TEE, in cases of PE, clots may appear as mobile and serpiginous structures in the right ventricle or atrium, as well as in the right or main pulmonary arteries.

IMAGING CASE

A 76-year-old woman was admitted to our unit with septic shock secondary to pneumococcal pneumonia. On day 5 acute lung injury developed, and thereafter she was intubated and mechanically ventilated (tidal volume, 8 mL/kg; F_{IO_2}, 100%; PEEP, 10 cm H_2O; respiratory rate, 25 breaths/min; plateau pressure, 35 cm H_2O). On day 6 hemodynamic failure developed (mean arterial pressure, 50 mm Hg; PPV, 22%). Echocardiography revealed ACP with severe RV dilatation (Figure 33-6A) and paradoxic septal movement (Figure 33-6B). We found moderate tricuspid regurgitation with a maximal velocity of 3.4 m/sec, which corresponds to a gradient of 36 mm Hg (4×3.4^2) between the right ventricle and right atrium. Central venous pressure was 14 mm Hg, and thus PAP was estimated to be 50 mm Hg (gradient 1 RAP = 36 + 14 = 50 mm Hg) (Figure 33-6C). Superior vena cava analysis confirmed that the patient was not fluid responsive despite a PPV of 22%, which was due to an inspiratory RV afterload effect (Figure 33-6D). After decreasing tidal volume and plateau pressure, mean arterial pressure increased as ACP subsided.

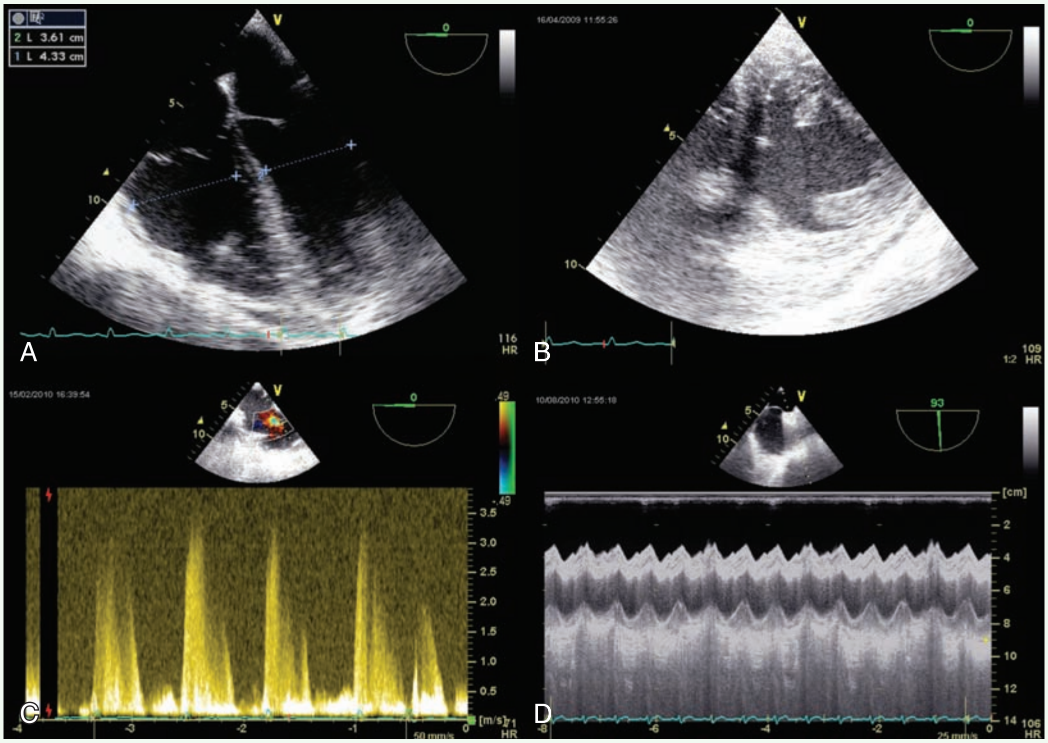

Figure 33-6

RV dysfunction can be responsible for pulse pressure variations (PPVs) in mechanically ventilated patients, which may be erroneously interpreted as a sign of fluid responsiveness and thus lead to fluid loading.[29] This may be due to the effect of positive-pressure ventilation on RV afterload (and not on preload). Therefore, when predicting fluid responsiveness in patients with RV dilatation or dysfunction, PPV measurements are considered false-positive ones.[30] In septic shock, RV dysfunction is usually accompanied by left ventricular systolic dysfunction.[31] This septic myocardial depression tends to occur early and recover completely within 7 to 10 days.

Finally, RV dysfunction occurs in myocardial infarction (usually of the inferior wall) as a result of occlusion of the right coronary artery. Decreased endomyocardial thickening with hypokinesia, akinesia, or dyskinesia of the RV free wall is typically depicted by echocardiography. RV dilatation may be seen, but unlike ACP, PAP is usually normal. Dilatation of the tricuspid annulus may cause tricuspid regurgitation with right atrial and IVC enlargement. Acute RV dysfunction is commonly observed in the ICU, especially in patients with ARDS and PE. The echocardiographic techniques that are used to evaluate RV function can optimize the management of mechanically ventilated patients with RV dysfunction in various clinical scenarios.

Pearls and Highlights

- The right ventricle is highly sensitive to changes in preload and afterload and, unlike the LV, may become acutely enlarged. Moreover, it is sensitive to coronary flow and is perfused during the entire cardiac cycle.
- Though a key element in the hemodynamic evaluation of ICU patients with shock (e.g., PE, sepsis) or respiratory failure (e.g., ARDS), RV dysfunction remained an underdiagnosed clinical entity in the ICU for several decades.
- The echocardiographic techniques that are used to evaluate RV function can optimize the management of mechanically ventilated patients with RV dysfunction in various clinical scenarios.
- Several experts consider RVFAC a simple and reliable measure for assessing RV function and monitoring the effects of therapy (e.g., administration of vasoactive substances).
- An RVEDA/LVEDA ratio lower than 0.6 is considered normal, whereas ratios between 0.6 and 1 and higher than 1 correspond to moderate and severe RV dilatation, respectively. This ratio has good prognostic value for ACP, especially in patients with PE.
- In ACP, RV hypertrophy can develop rapidly (within 48 hours of PAP elevation) but is usually moderate (around 4 to 6 mm), whereas in chronic cases the RV free wall may thicken to as much as 10 to 11 mm (usually 0.7 mm).

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34

Evaluation of Patients at High Risk for Weaning Failure with Doppler Echocardiography

PHILIPPE VIGNON

(CONSULTANT LEVEL EXAMINATION)

Overview

Weaning failure is a major complication of mechanical ventilation with associated morbidity and mortality. It is usually defined as an unsuccessful spontaneous breathing trial (SBT) or need for tracheal reintubation within 48 hours following extubation.[1] According to study populations and diagnostic criteria, the incidence of weaning failure ranges from 25% to 42% in large cohorts.[1] Although the mechanisms are varied and potentially complex, failure to wean a critically ill patient from the ventilator frequently has a cardiac origin. Indeed, the transition from positive-pressure ventilation to spontaneous breathing abruptly alters cardiac loading conditions and has been compared with an exercise test that increases cardiac and breathing workload and metabolic expenditure.[2] Accordingly, patients at high risk for weaning failure have long been identified as those with cardiovascular disease or chronic obstructive pulmonary disease (COPD).[3,4]

Echocardiography has progressively supplanted the use of blind, invasive hemodynamic techniques for bedside assessment of central hemodynamics in the intensive care unit (ICU). Because of the real-time, anatomic, and functional information provided on the heart and great vessels, echocardiography is ideally suited for screening the targeted population, assessing the hemodynamic changes induced by SBTs, diagnosing weaning-related pulmonary edema, and identifying its origin. This chapter discusses the clinical value of using echocardiography to assess patients in the ICU at high risk for weaning failure.

Echocardiographic Examination

Since transthoracic echocardiography (TTE) is usually informative in this specific clinical setting, transesophageal echocardiography (TEE) is rarely required and performed only as an adjunct to TTE in a patient reconnected to the ventilator. The apical four-chamber view is mainly used to obtain the requested information because it allows evaluation of global and regional ventricular systolic function, left ventricular (LV) diastolic properties and filling pressure, valvular function, intraventricular pressure gradient, and systolic pulmonary artery pressure (Figure 34-1).

Interestingly, TTE may be combined with chest ultrasound to best guide the diagnostic workup of patients with weaning failure at the bedside. After completion of TTE, chest ultrasonography can be performed to obtain valuable morphologic information on the lungs and pleurae, both of which are potentially involved in the weaning failure. For example, chest ultrasonography allows a quantitative diagnosis of pleural effusion and helps in deciding whether to perform thoracentesis in hypoxemic ICU patients.[5]

Hemodynamic Changes Induced by Spontaneous Breathing Trials

The transition from positive-pressure ventilation to spontaneous breathing abruptly increases ventricular preload and LV afterload, decreases effective LV compliance,[3] and may even induce cardiac ischemia.[6] All these factors tend to increase LV filling pressure, which may result in weaning-induced cardiogenic pulmonary edema, especially in patients with left-sided heart disease.[7] Nevertheless, in the absence of left heart failure (e.g., COPD patients), the rise in pulmonary artery occlusion pressure (PAOP) remains limited.[8]

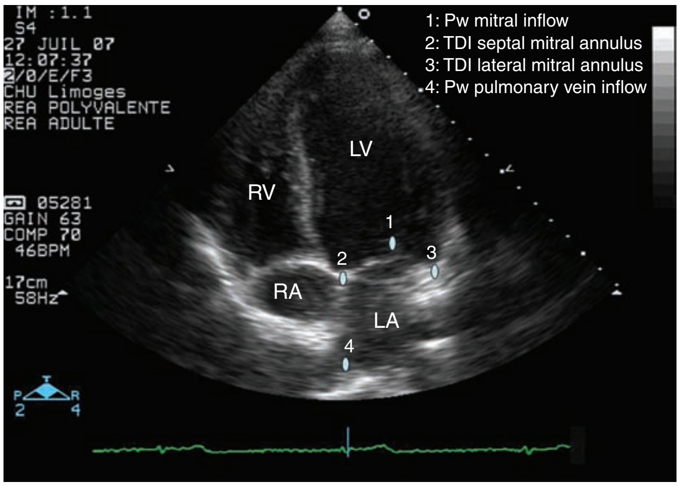

Figure 34-1 Apical four-chamber view disclosing the positioning of pulsed wave Doppler and tissue Doppler imaging samples for assessment of left ventricular filling pressure (blue dots). In addition, this transthoracic echocardiographic view allows evaluation of ventricular function and identification of mitral or tricuspid regurgitations via color Doppler mapping and continuous wave Doppler. *LA*, Left atrium; *LV*, left ventricle; *Pw*, pulsed wave Doppler; *RA*, right atrium; *RV*, right ventricle; *TDI*, tissue Doppler imaging.

In 117 ICU patients fulfilling the criteria for weaning, we performed TTE immediately before and at the end of a 30-minute SBT. The SBT significantly increased LV stroke volume (and hence cardiac output) and LV filling pressure over baseline values as reflected by a higher mitral Doppler E/A ratio and shortened E-wave deceleration time.[9] Similarly, Ait-Ouffela et al[10] showed that SBTs increase the mitral E/A ratio and shorten the E-wave deceleration time.

Identification of Patients at High Risk for Pulmonary Edema during Weaning

Echocardiography allows screening of ventilated ICU patients to identify those at high risk for pulmonary edema during weaning. A dilated or hypertrophic cardiomyopathy associated with LV diastolic dysfunction and a relevant left-sided valvulopathy are potential risk factors for weaning-induced pulmonary edema since baseline filling pressure is typically high in these patients and may further increase at the interruption of positive-pressure ventilation.

We previously showed that ICU patients who failed ventilator weaning had a significantly lower LV ejection fraction (median [25th to 75th percentiles]: 36% [27% to 55%] vs. 51% [43% to 55%], $P = .04$) and higher LV filling pressure (E/E′ ratio: 7.0 [5.0 to 9.2] vs. 5.6 [5.2 to 6.3]; $P = .04$) before the SBT than did patients who were successfully extubated.[9] Papanikolaou et al[11] reported that a lateral E/E′ ratio higher than 7.8 at baseline (pressure-support ventilation) predicted SBT failure in 50 ventilated ICU patients with a sensitivity and specificity of 79% and 100%, respectively.

Identification of Pulmonary Edema during Weaning

Cardiogenic pulmonary edema induced by weaning from the ventilator is suspected in high-risk patients when alternative causes of weaning failure have been confidently ruled out.[7] It is a leading cause of weaning failure. In a TTE study performed in 117 ventilated ICU patients, we showed that weaning failure was of cardiac origin in 20 of 23 patients (87%) with an unsuccessful SBT or extubation.[9] In patients in whom weaning-induced pulmonary edema develops, echocardiography depicts the presence of increased LV filling pressure and helps identify the potential underlying cause to guide therapy.

IDENTIFICATION OF ELEVATED LEFT VENTRICULAR FILLING PRESSURE

Using right-heart catheterization, Lemaire et al[3] have long reported that patients in whom weaning-induced pulmonary edema developed exhibited a marked increase in PAOP from a mean value of 8 mm Hg to 25 mm Hg after disconnection from the ventilator.

TTE diagnosis of pulmonary edema induced by weaning relies on depiction of elevated LV filling pressure during spontaneous breathing by means of mitral inflow and pulmonary vein Doppler velocity profiles (Figure 34-2). Combined assessment of early diastolic mitral annulus displacement with tissue Doppler imaging provides valuable information on LV relaxation and may be used to more precisely assess filling pressure (Chapter 32). In ventilated ICU patients, a mitral E/A ratio higher than 2, a systolic fraction of pulmonary vein flow lower than 40%, and an E/E′ ratio higher than 9.5 best predict a PAOP higher than 18 mm Hg.[12] In contrast, we showed in 88 ventilated ICU patients that a mitral E/A ratio of 1.4 or lower, a pulmonary vein S/D ratio higher than 0.65, a systolic fraction of pulmonary vein flow higher than 44%, and a lateral E/E′ ratio of 8 or greater best predicted a PAOP of 18 mm Hg or higher.[13]

Lamia et al[14] recently performed a TTE study in 39 ICU patients with a right-heart catheter after two consecutive SBT failures. PAOP greater than 18 mm Hg ($n = 17$) was consistently associated with weaning failure. A combined mitral E/A ratio higher than 0.95 and an E/E′ ratio higher than 8.5 at the end of the SBT predicted a PAOP of 18 mm Hg or greater with a sensitivity of 82% and a specificity of 91%.[14]

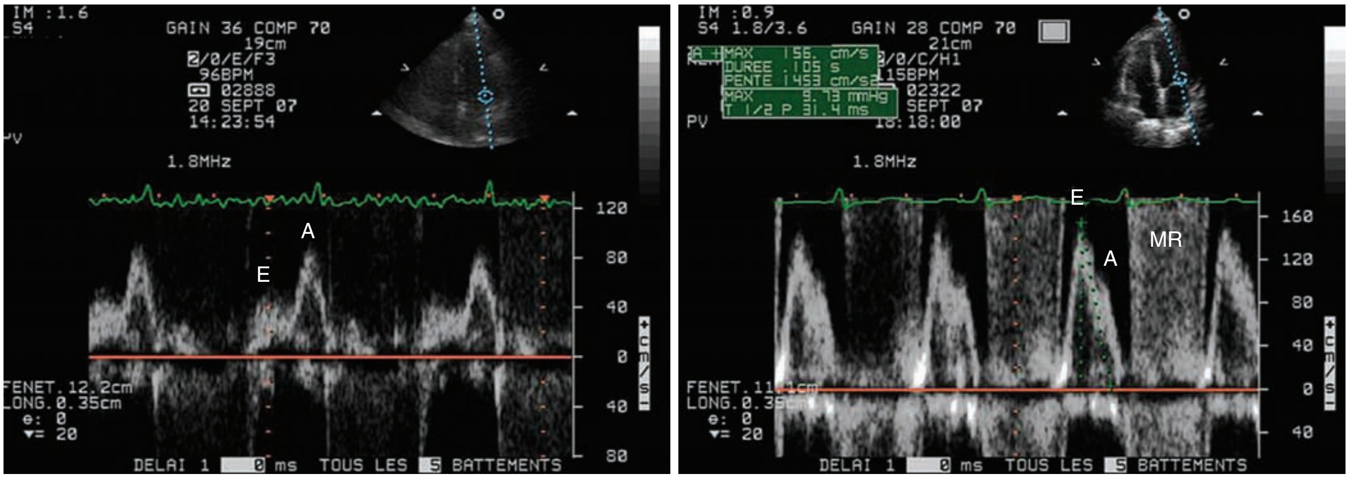

Figure 34-2 Mitral pulsed wave Doppler velocity profiles recorded from an apical four-chamber view in a patient who failed ventilator weaning. Under pressure-support ventilation, the patient exhibited abnormal relaxation with an inverted E/A ratio and a prolonged E-wave deceleration time at baseline (*left panel*). After extubation, the patient's clinical status deteriorated secondary to pulmonary edema induced by weaning. The mitral Doppler pattern markedly changed, with a predominant E wave and shortened E-wave deceleration time, which were consistent with elevated left ventricular filling pressure (*right panel*). Note the development of associated mitral regurgitation (MR) and global acceleration of anterograde mitral Doppler velocity. All these factors contributed to the development of weaning-induced pulmonary edema.

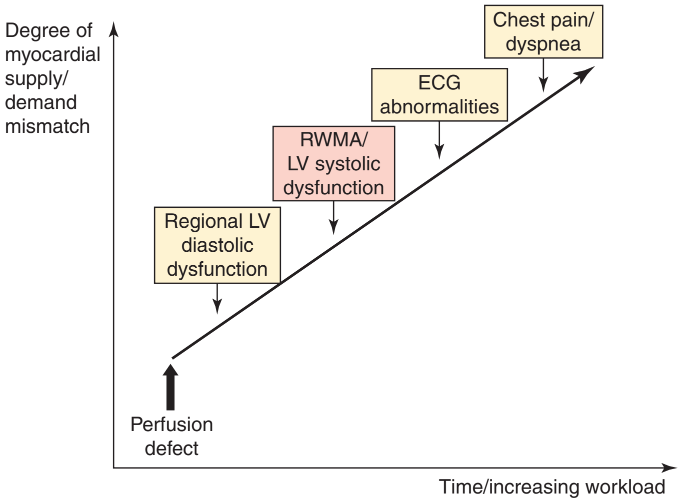

Figure 34-3 Schematic representation of the ischemic cascade of the heart. Regional wall motion abnormality (RWMA) as seen on echocardiography occurs before electrocardiographic (ECG) abnormalities and symptoms. Myocardial ischemia may result in chest pain, as well as in rest dyspnea, secondary to pulmonary venous congestion, especially with exercise.

IDENTIFICATION OF ETIOLOGY

Myocardial Ischemia

The increased cardiac workload and increased load of breathing, especially in patients with COPD,[7] induced by SBT may result in myocardial ischemia, which in turn may participate in weaning failure.[6] The development of regional wall motion abnormalities (RWMAs) secondary to myocardial ischemia occurs earlier than electrocardiographic changes in the ischemic cascade (Figure 34-3). Accordingly, a new-onset RWMA as evidenced by TTE in a patient who fails ventilator weaning is consistent with myocardial ischemia secondary to unmatched myocardial oxygen demand. Depending on its location and extension, myocardial ischemia may result in a significant increase in LV filling pressure, LV systolic failure, or acute mitral regurgitation (MR) of various mechanisms.[15]

Transient or Exacerbated Mitral Regurgitation

MR is a frequent occurring valvulopathy in which the regurgitant volume may be altered acutely by changes in LV loading conditions. Specifically, any abrupt increase in LV afterload may worsen MR, especially when central and "functional" (i.e., related to dilatation of the mitral annulus). It may be particularly pronounced in patients with associated LV diastolic dysfunction and chronically elevated filling pressure. Although transient MR is not present in spontaneously breathing patients who arrive at the emergency department with acute pulmonary edema,[16] it may be observed during an SBT. In the presence of marked systolic hypertension, arterial vasodilators may be used to offset the deleterious effects of SBT-induced sympathetic stimulation on LV afterload.

Ischemic MR has been observed in patients who were admitted with acute pulmonary edema but no evidence of acute ischemia or arrhythmia.[17] In these patients, semisupine bicycle exercise increased MR volume and pulmonary artery pressure as assessed by TTE and was associated with exercise-limiting dyspnea. Accordingly, an SBT may potentially induce transient, yet relevant MR (Figure 34-4) secondary to tethering of the mitral leaflets, which tents the leaflets toward the LV apex.[17] When eccentric, MR may result in asymmetric or unilateral pulmonary edema since the regurgitant flow increases pulmonary vein pressure unilaterally.[18] In this case, papillary muscle dysfunction associated with concomitant RWMA is frequently observed, and TEE has greater diagnostic accuracy than TTE does. Regardless of its mechanism, ischemic MR induced or worsened by an SBT may lead to performance of percutaneous coronary angioplasty to facilitate weaning from the ventilator. Ischemic MR induced or worsened by an SBT may lead to an evaluation of the performance of a coronary revascularization procedure in patients who cannot be weaned from the ventilator after the optimization of medical therapy and repeated SBT failures.

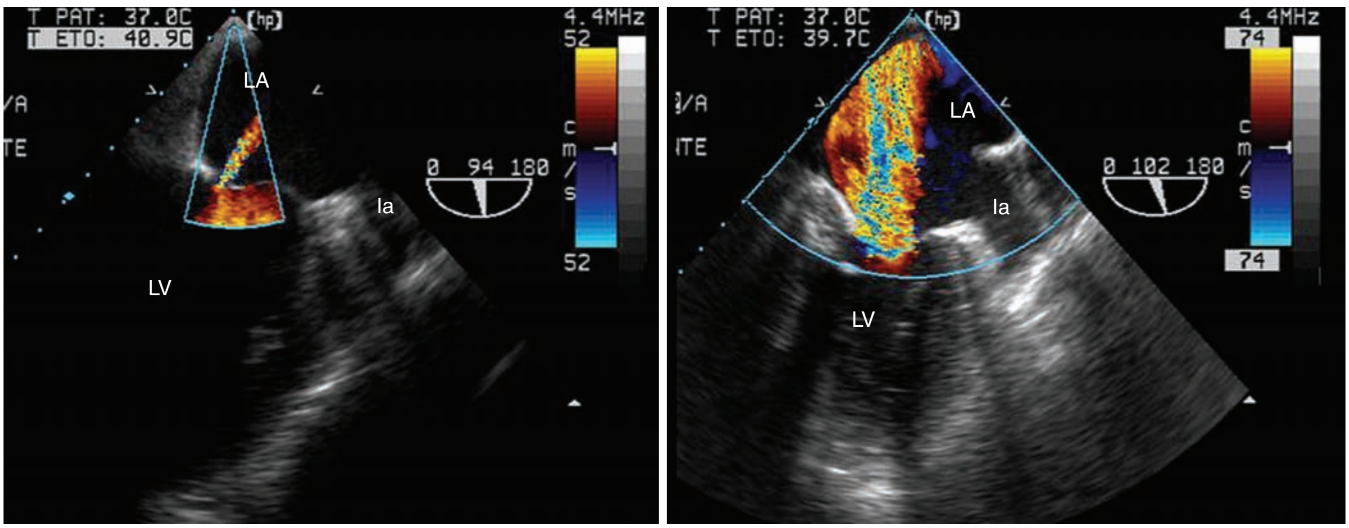

Figure 34-4 Transesophageal echocardiographic diagnosis of acute massive mitral regurgitation in a patient reconnected to the ventilator because of a failed spontaneous breathing trial. Under pressure-support ventilation, the transesophageal two-chamber view disclosed trivial central mitral regurgitation (*left panel*). Disconnection from the ventilator was rapidly interrupted because of the abrupt onset of weaning-induced pulmonary edema. In a similar echocardiographic view, a large regurgitant jet consistent with massive mitral insufficiency was found to be the origin of the acute respiratory failure (*right panel*). A concomitant new-onset regional wall motion abnormality strongly suggested myocardial ischemia. *la*, Left appendage; *LA*, left atrium; *LV*, left ventricle.

Figure 34-5 Dynamic left ventricular outflow tract obstruction in a hypertrophied left ventricle depicted by transesophageal echocardiography in the four-chamber view. In this patient, who underwent ventilation for severe cardiogenic pulmonary edema, systolic anterior motion of the mitral valve (*left panel*, *circle*) was associated with massive mitral regurgitation (*right panel*, *2*). Note that the outflow tract obstruction induces blood flow turbulence (*right panel*, *1*) and may significantly reduce cardiac output. *LA*, Left atrium; *LV*, left ventricle; *RV*, right ventricle.

Finally, transient SBT-induced MR may be attributed to systolic anterior motion (SAM) of the mitral valve.[19]

Dynamic Left Ventricular Outflow Tract Obstruction

Patients with a small LV cavity (e.g., LV hypertrophy) are at risk for the development of dynamic obstruction of the LV outflow tract associated with SAM secondary to SBT-driven adrenergic stimulation.[19] A dynamic LV outflow tract increases LV filling pressure and reduces LV stroke volume, whereas SAM induces acute and usually eccentric MR. Echocardiography is best suited to depict these intricate mechanisms that jointly lead to weaning-induced pulmonary edema (Figure 34-5). In these patients, right-heart catheterization may erroneously suggest severe LV systolic dysfunction in the presence of elevated PAOP and low cardiac output and lead to the deleterious administration of diuretics, inotropes, or both. Therapy may include interruption of any inotropic support and blood volume expansion, correction of any associated arrhythmia, use of antihypertensive drugs when necessary, and introduction of β-blockers, especially in those with hypertrophic cardiomyopathy and severe LV diastolic dysfunction.[20]

Monitoring of Acute Therapy with Echocardiography

TTE should be performed before an SBT in high-risk patients to identify any underlying cardiomyopathy and evaluate baseline LV filling pressure. This allows the weaning strategy to be guided and therapy to be adjusted for optimization of LV loading conditions before weaning from the ventilator. When an SBT fails, TTE is valuable in detecting the mechanism of the weaning failure and tailoring therapy (e.g., diuretics, vasodilators). After attaining more favorable LV loading conditions, TTE may confirm the decrease in LV filling pressure before resuming the weaning process and allows close monitoring of hemodynamic tolerance with further SBTs (Figure 34-6).

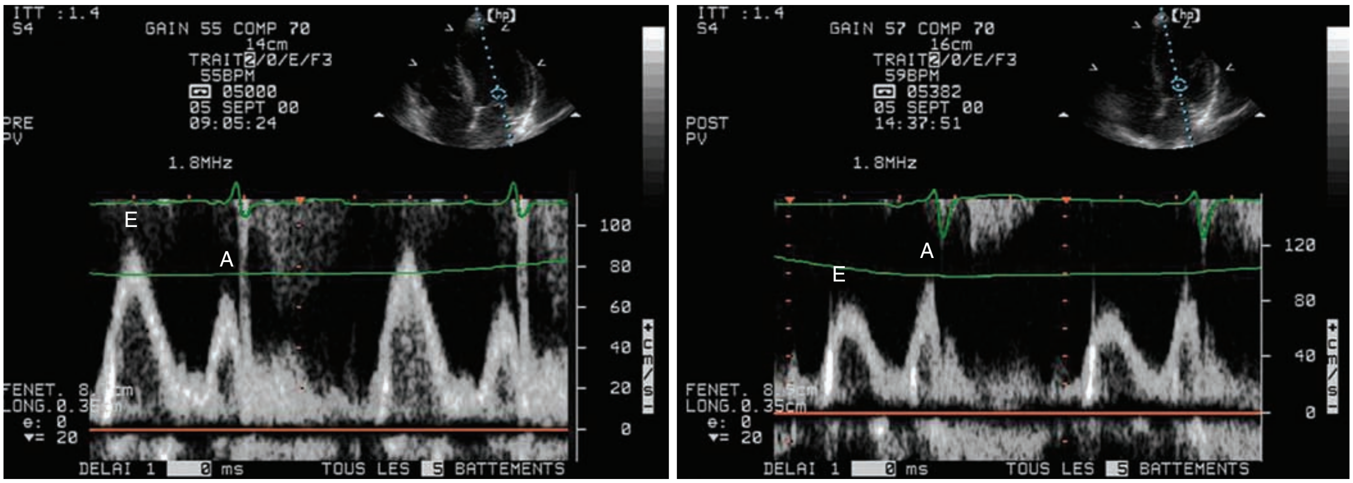

Figure 34-6 Acute effects of left ventricular loading conditions on the mitral Doppler velocity profile recorded from the apical four-chamber view. In this spontaneously breathing hemodialysis patient with shortness of breath at baseline, transthoracic echocardiography recorded a "normalized" mitral Doppler pattern consistent with elevated filling pressure (*left panel*). The patient's symptoms disappeared after large-volume ultrafiltration, which induced a drop in left ventricular filling pressure, as reflected by an inverse E/A ratio (*right panel*).

Pearls and Highlights

- Cardiogenic pulmonary edema is frequently responsible for failure to wean patients from the ventilator. Patients at high risk should be screened with TTE so that they can best be managed before the planned extubation.
- In case of weaning failure, TTE allows rapid confirmation of the diagnosis of weaning-induced pulmonary edema by depicting increased LV filling pressure and disclosing a potentially associated cardiopathy.
- Echocardiography helps the intensivist in tailoring therapy to facilitate the weaning process.

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35

Improving Cardiovascular Imaging Diagnostics by Using Patient-Specific Numerical Simulations and Biomechanical Analysis

MICHAEL XENOS | DIMITRIOS KARAKITSOS | DANNY BLUESTEIN

Overview

Ultrasound is the only imaging modality, apart from magnetic resonance imaging (MRI), that provides real-time functional and structural information on the beating heart. However, modeling moving cardiovascular structures is a complex process that requires three- dimensional (3D) reconstruction of two-dimensional (2D) data by fast imaging techniques (e.g., MRI) to thus yield dynamic four-dimensional (4D) views of cardiovascular pulsations. The unique 3D geometry of the cardiovascular system is partially responsible for the diversity of physiologic interactions between blood flow and cardiovascular structures. Recent advances in 3D echocardiography, cardiac computed tomography (CT), and MRI techniques have improved cardiovascular diagnostics considerably. In addition, with the advances achieved in graphics techniques for surface rendering, the potential for attaining useful information from graphics in medical imaging has emerged. Several techniques have been developed, such as the maximum intensity projection, shaded surface display, volumetric rendering, and others. The visualization tool kit (VTK) and the insight tool kit (ITK) are two examples of packages developed for performing image registration and segmentation based on ITK and VTK libraries. These open-source tool kits have an active development community that includes laboratories, institutions, and universities from around the world.[1,2]

Notably, with advanced 3D cardiovascular imaging techniques, complex intraventricular and intraaortic blood flow patterns can be partially evaluated. Even sophisticated 4D MRI cannot analyze all the fine details of the miscellaneous phenomena active in a 3D field of cardiovascular flow, which may be important in patients with subtle cardiac dysfunction, or evaluate the interactions between blood flow and vascular structures, which may be captured, for example, by models predicting the evolution of aortic disorders (e.g., predicting rupture of an abdominal aortic aneurysm [AAA]). These considerations have led to the development of numerical simulation models that provide functional imaging approaches to the investigation of blood flow patterns. These models are theoretic, which is a major limitation, and thus do not provide *in-vivo* data. However, the latter may be integrated into the boundaries used to run numerical simulations. This chapter outlines computational fluid dynamics (CFD) and fluid structure-interaction (FSI) models used in the study of cardiovascular flow phenomena in normal and aneurysmal aortas, respectively.

Computational Fluid Dynamics Model of Normal Aortic Flow

Although 3D imaging techniques are invaluable in the diagnosis of aortic pathology, they do not provide detailed information on intraluminal blood flow patterns and hemodynamically driven wall stress or explain the generation of instability in the 3D aortic flow field with accompanying recirculation zones. Analysis and mapping of intraluminal blood velocity can be performed with CFD models, which use the discretized form of the nonlinear and fully coupled equations of fluid motion (Navier-Stokes equations) on a refined computational grid. CFD works by dividing the area of interest (the aorta in this example) into a large number of cells (the grid). Numerical grid generation is a branch of applied mathematics that is used for running computer-based simulations of fluid flow problems via advanced software packages. The objectives of CFD consist of developing the simulation approach, modeling the geometry and grid generation, providing a numerical solution of flow field mathematic equations, and analyzing the solution.

CFD models were used to describe the fine diversities in normal 3D rotational aortic flow: the *aortic vortex*.[3-5] The aortic geometry (curved-shaped vessel) and preformed asymmetric flow originating from the left ventricle enable the formation of counterrotating helical vortices with associated secondary flow, which are characterized by the dimensionless Dean number. Also, the pulsatility of cardiovascular flow leads to rapid changes in inertia, limited boundary layer development, and the promotion of unstable flow.

Recently, our group used previous CFD models[3-5] and patient-derived hemodynamic and transesophageal echocardiography data, which were used as boundaries, to run aortic vortex numerical simulations.[6] An example of a simplified CFD model of normal aortic flow that integrates a swirling component of the inlet velocity at the root of the ascending aorta is illustrated in Figure 35-1. CFD flow patterns were calculated according to aortic topography (ascending aorta, aortic arch, descending aorta), whereas the vessel was modeled as a simple curved tube without any peripheral branches. Flow patterns at late systole (0.28 second) and early diastole (0.42 second) were recorded in a normal aorta. During systole, a predominant clockwise rotational flow component in the ascending aorta was documented. In the aortic arch, a pair of fused counterrotating vortices that were further amplified downstream was observed (see Figure 35-1, systole, planes D, E, and F). During diastole, the fused counterrotating vortices decomposed

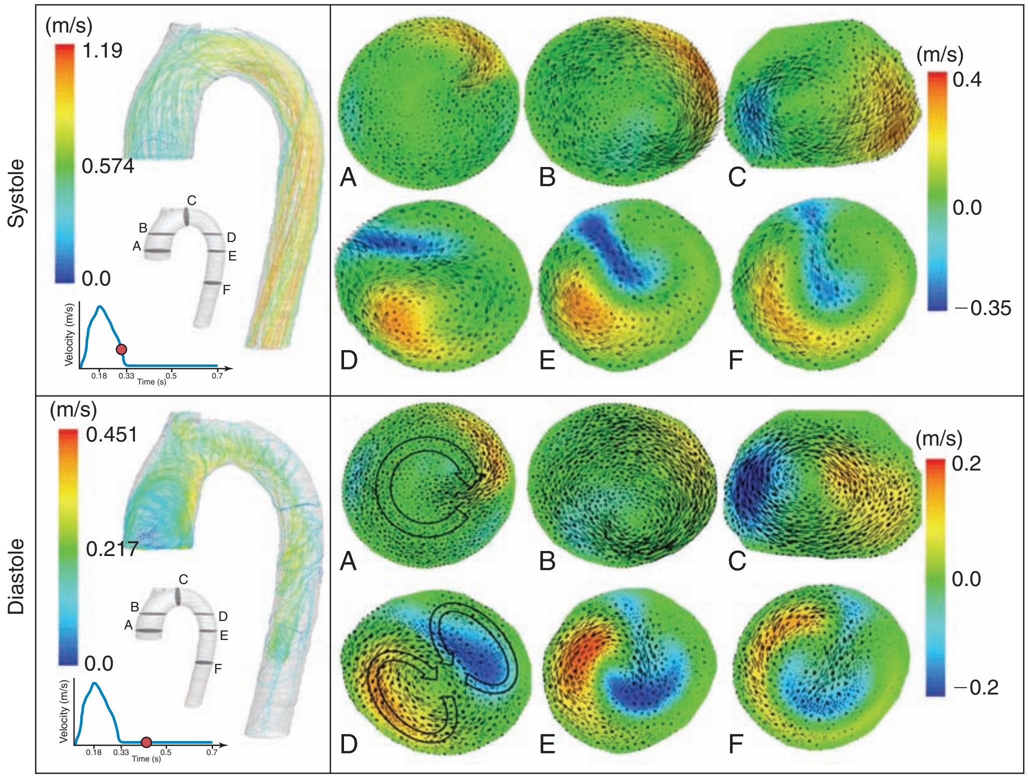

Figure 35-1 Normal aortic vortex phenomena at late systole and early diastole. Path lines reflect aortic blood flow, whereas cross sections of velocity vectors at the ascending aorta (*A* and *B*), aortic arch (*C* and *D*), and descending aorta (*E* and *F*) correspond to a clockwise rotational component (ascending aorta) and complex helical flow (aortic arch), which are gradually transformed to a pair of counterrotating vortices with retrograde flow (descending aorta).

to a pair of distinct vortices with secondary flow phenomena when moving toward the descending aorta (see Figure 35-1, diastole, planes D, E, and F). This example shows that 3D aortic flow tends to be even more polymorphic than previously hypothesized, which is in accordance with *in-vivo* MRI data.[4] Complex intraventricular flow phenomena may at least partially be responsible for the generation of this normal polymorphic 3D aortic vortex, which in turns "feeds" the peripheral arteries. Indeed, left ventricular muscle fibers have complex 3D configurations consisting of internal and external loops that go from without to within in a clockwise and from within to without in a counterclockwise spiral (*vortex cordis*). The vortex cordis and associated intraventricular flow phenomena, the pulsatility of cardiovascular flow, the distinct structural and functional features of the cardiac valves, and the curved-shaped aorta may all contribute to creation of the aortic vortex. The latter may in fact exist as a result of natural optimization of fluid transport processes in the cardiovascular system that are intended to achieve efficient end-organ perfusion.

Fluid-Structure Interaction Models of Abdominal Aortic Aneurysms

FSI simulations, in which the dynamic interaction between AAA hemodynamics and wall deformation is modeled, were previously conducted to simulate the biomechanical behavior of the aortic wall.[7,8] Past studies were based on the isotropic assumption that the directional ambiguities associated with the mechanical response of abdominal aortic tissue to stress, which may play a major role in the behavior of the tissue under elevated stress, cannot be resolved. Bluestein et al performed FSI numerical studies in which patient-specific 3D geometries were reconstructed from CT scans of AAAs with different configurations, both with and without intraluminal thrombus (ILT).[7,9] The complex flow trajectories within the AAA lumen suggested a putative mechanism for ILT formation and growth. The resulting magnitude and location of the peak wall stress were dependent on the shape of the AAA. Currently, our numerical data suggest that although a thrombus does not significantly change the location of maximal stress in the aneurysm, its presence may reduce some of the stress on the wall. Inclusion of ILT and calcifications in AAA stress analysis may increase the accuracy of predicting risk for rupture. A model for accurate prediction of the stress developing within the AAA wall requires detailed information, including (1) patient-specific AAA geometry, (2) blood flow parameters and flow patterns (including flow rates and pressure at the various phases of the cardiac cycle and wall thickness and its variability), and (3) appropriate material models that can describe the mechanical tissue response of AAAs. Rissland et al[9] fitted the experimental data of AAA wall specimens to an exponential strain energy orthotopic material model[10,11] and further applied the orthotropic material model of Holzapfel et al,[12] which models the tissue as a fiber-reinforced composite material with the fibers corresponding to the collagenous component of the material. This material formulation was previously applied successfully to various arterial walls, such as the aorta, coronary arteries, and carotid arteries.[12]

An example of FSI simulation performed in a patient with a ruptured AAA in which the highest stress was found along

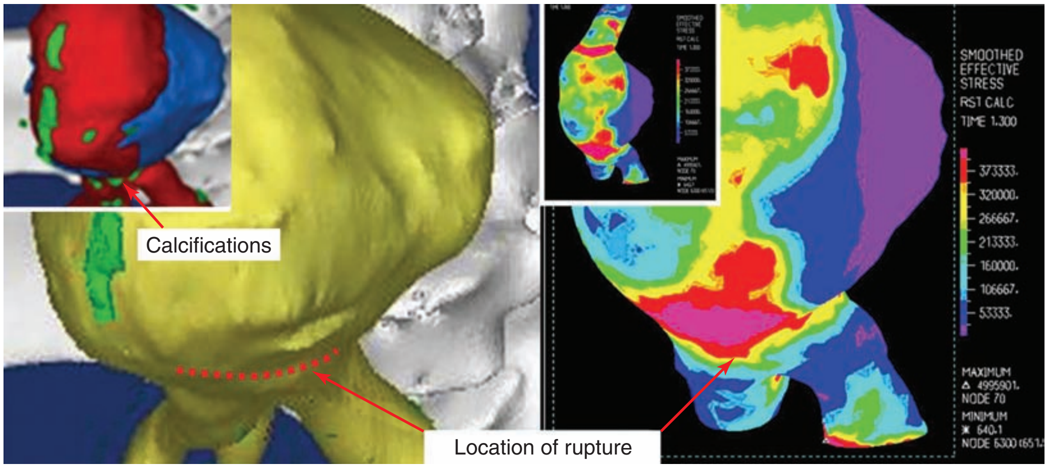

Figure 35-2 Fluid-structure interaction simulation of a ruptured abdominal aortic aneurysm. The location of maximal wall stress overlaps the actual rupture region. The *inner top panel* (*left*) shows the lumen with calcifications above the bifurcation and the iliac branch. The actual rupture is depicted on the wall surrounding it (*yellow*). The *right panel* shows the wall stress contours, with concentration of stress along the rupture line. *(Used with permission of the Annals of Biomedical Engineering from Xenos M, Rambhia SH, Alemu Y, et al: Patient-based abdominal aortic aneurysm rupture risk prediction with fluid structure interaction modeling,* Ann Biomed Eng *38:3323-3337, 2010; permission conveyed through the Copyright Clearance Center, Inc.).*

the actual rupture line with excellent agreement between the two is illustrated in Figure 35-2. In this configuration the highest stress occurred on the distal side of the spinal cord, whereas the ILT seemed to offer a significant protective effect by reducing the stress (colored purple) in the surrounding wall region (see Figure 35-2). Two major locations of stress concentrations were predicted: one at the location of the actual rupture and one close to the neck of the aneurysm. The calcifications (colored green) embedded along the rupture line created a stress concentration, unlike the larger calcifications that appear to be deposited (not embedded) on the wall. Though indicating that the neck area could have been a potential location for a secondary rupture, the peak stress values were prominent in the rupture area.[13] The combination of calcifications and a thinner wall, which was observed by CT in the rupture area of AAAs, presumably contributed to the weakening wall strength at the point where the rupture actually occurred. Biomechanical analysis and patient-specific numerical simulations are functional imaging techniques that may improve cardiovascular diagnostics.

Pearls and Highlights

- CFD models provide additional information over conventional imaging methods on complex intraventricular and intraaortic flow phenomena. Such analysis may be applied in diverse physiologic and cardiovascular disease states.
- FSI simulations are used to develop models for predicting the development of stress within the aortic aneurysmal wall and for analyzing hemodynamically driven vessel wall abnormalities in other disorders.

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SECTION VI

Hemodynamics

36

Hemodynamic Monitoring Considerations in the Intensive Care Unit

DAVID STURGESS | DOUGLAS R. HAMILTON |
ASHOT E. SARGSYAN | PHILIP LUMB | DIMITRIOS KARAKITSOS

. . . the blood somehow flowed back again from the arteries into the veins and returned to the right ventricle of the heart. In consequence, I began privately to consider that it had a movement, as it were, in a circle . . . by calculating the amount of blood transmitted [at each heartbeat] and by making a count of the beats, let us convince ourselves that the whole amount of the blood mass goes through the heart from the veins to the arteries and similarly makes the pulmonary transit. . . .

William Harvey: De motu cordis. In *The circulation of the blood and other writings* (1628), translated by Kenneth J. Franklin (1957), Chapter 8, pp 57-58.

Overview

In critical care, the goals of hemodynamic monitoring include mainly detection of cardiovascular insufficiency and diagnosis of the underlying pathophysiology. At the bedside, clinicians are faced with the challenge of translating concepts such as preload, contractility, and afterload into determinants of stroke volume and hence cardiac output. Ultrasound and echocardiography offer unique insight into ventricular filling and systolic function. In recent years there has been a general trend away from invasive hemodynamic monitoring. This was initially motivated by published data suggesting an association between the pulmonary artery catheter (PAC) and excess mortality in critically ill patients.[1] Despite specific risks, subsequent randomized controlled trials have not sustained the concerns about excess mortality.[2] The PAC should not be regarded as obsolete.

As already discussed in this text, ultrasound is proving useful in guiding safe and timely placement of many components of hemodynamic monitoring systems, including arterial, peripheral, and central venous access devices. Furthermore, because of its real-time nature, ultrasound, including echocardiography, offers the clinician a range of cardiovascular insights that are difficult or impossible to derive with other technologies. Ultrasound can be applied to a wide range of patients and is a safe, noninvasive, and reliable imaging method.

Hemodynamic Monitoring Devices

An overview of critical care hemodynamic monitoring would be incomplete without putting ultrasound in the context of the techniques available for estimating cardiac output, including nonultrasonic modalities. This broader topic is covered well in the literature[3] and is outlined only briefly here. Demonstrating an association between any monitoring modality and improved outcome is challenging. Monitoring must be coupled with an effective change in therapy for a positive association to be observed. Clinical practice is characterized by the subtleties of interpretation, ongoing review, and titration of therapy to response. This does not translate easily into large-scale, randomized, controlled trial designs.

Clinicians differ in their preferences for particular hemodynamic monitoring techniques. Accuracy and degree of invasiveness are not the only considerations. Familiarity, availability of local expertise, cost (equipment and consumables), and applicability to a particular patient and the patient's status must also be considered. Monitoring techniques tend to not be mutually exclusive and may be combined or changed to achieve the desired effect. For instance, initial hemodynamic evaluation with echocardiography may proceed to continuous monitoring, such as pulse waveform analysis.

Any form of hemodynamic monitoring (Table 36-1) should be viewed as an adjunct to the clinical examination and must be interpreted as an integration of all available data.[3-5] These may include the patient's mental state, urine output, and peripheral perfusion (temperature and capillary refill time). Heart rate, arterial blood pressure, jugular venous pressure (or central venous or right atrial pressure [RAP]), and electrocardiography should also be incorporated. Other adjuncts to the interpretation of hemodynamic data might include Svo_2, $Scvo_2$, lactate, blood gases, capnography, gastric tonometry, or other assessment of the microcirculation.

Ultrasound indicator dilution is a novel application of ultrasound technology. Unlike transpulmonary thermodilution, which bases estimates of cardiac output on changes in blood temperature, ultrasound indicator dilution measures changes in ultrasound velocity. Normothermic isotonic saline is injected into a low-volume arteriovenous loop between arterial and central venous catheters. The change measured in ultrasound velocity (blood, 1560 to 1585; saline, 1533 m/sec) allows the

TABLE 36-1 Examples of Cardiac Output Monitoring Techniques and Devices

Technique	Comment	Example of Device
Flow probe Doppler Electromagnetic	Sometimes used as a laboratory reference standard. Limited clinical application	
Fick method (O_2)	Requires a pulmonary artery catheter and metabolic cart. Often posed as the clinical reference standard but preconditions often not met in critical care	
Indirect Fick method (CO_2) Partial rebreathing technique	Partial rebreathing technique incorporating a number of mathematic assumptions, as well as changes in mechanically ventilated dead space, to remove the requirement for a pulmonary artery catheter	NiCO
Thermodilution	Pulmonary artery catheter (bolus or warm/semicontinuous)	
Transpulmonary indicator dilution Thermodilution Lithium Indocyanine green Dye dilution Pulsed dye densitometry		 PICCO VolumeView LiDCO
Ultrasound indicator dilution (saline)	The indicator dilution curve is formulated from changes measured in ultrasound velocity (blood, 1560-1585; saline, 1533 m/sec)	COstatus
Esophageal Doppler		CardioQ HemoSonic WAKIe TO
Transcutaneous Doppler	May be applied to suprasternal (aortic valve) and parasternal (pulmonic valve) windows	USCOM
Arterial pressure waveform analysis		PICCO LiDCO Vigileo MostCare
Thoracic electrical bioimpedance		Lifegard TEBCO Hotman BioZ
Thoracic electrical bioreactance		NICOM

Data from references 3 to 5.

formulation of an indicator dilution curve and calculation of cardiac output.[6]

Invasive Hemodynamic Monitoring

As mentioned previously, observational studies raised questions about increased morbidity and mortality with the use of PACs[1]; however, subsequent randomized trials indicated that PACs are generally safe and may yield important information.[2] The PAC has a trailblazing role in defining cardiovascular physiology and pathophysiology. The method provides "cardiodynamic insight" that other hemodynamic monitoring technologies still fail to elucidate. A PAC is not a therapy and cannot affect the prognosis, but it can be used to guide therapy. The usual clinical indications for placement of a PAC are shown in Box 36-1.

BOX 36-1 USUAL CLINICAL INDICATIONS FOR USE OF A PULMONARY ARTERY CATHETER

- Workup for transplantation
- Hemodynamic differential diagnosis of pulmonary hypertension and assesment of therapeutic response in patients with precapillary or mixed types of pulmonary hypertension
- Cardiogenic shock (supportive therapy)
- Discordant right and left ventricular failure
- Severe chronic heart failure requiring inotropic and vasoactive therapy
- Suspected "pseudosepsis" (high cardiac output, low systemic vascular resistance, elevated right atrial and pulmonary capillary wedge pressure)
- In selected cases of potentially reversible systolic heart failure (e.g., peripartum cardiomyopathy and fulminant myocarditis)

Echocardiographic Hemodynamic Monitoring

A comprehensive echocardiographic examination is time-consuming. In the management of potentially unstable, critically ill patients, physicians will often prefer to focus their examination on pertinent variables. Several focused hemodynamic echocardiographic protocols have been developed and applied. Among others, these protocols include FOCUS (focused cardiac ultrasound[7]), ELS (Echo in Life Support[8]) and HART scanning (hemodynamic echocardiographic assessment in real time[9]).

As well as being minimally invasive (transesophageal [TEE]) or noninvasive (transthoracic [TTE]), echocardiography also offers unique diagnostic insight into a patient's cardiovascular status. The presence of intracardiac shunts renders many hemodynamic monitoring devices invalid. Such shunts may be difficult to diagnose without echocardiographic techniques. Likewise, pericardial effusions, collections, and tamponade can also be difficult to diagnose without echocardiography.

In critical illness, cardiac function is not always globally affected. Echocardiography allows screening for and diagnosis of regional pathology, such as myocardial ischemia; furthermore, it allows evaluation of coronary arterial territories by regional wall motion abnormalities. Echocardiography may also disclose abnormalities such as dynamic left ventricular (LV) outflow obstruction and systolic anterior movement of the mitral valve. This may have particular therapeutic implications in critical care. Valvular dysfunction is also important to the critical care physician, and echocardiography is the clinical "gold standard" for detection and characterization (including grading). As an alternative to the PAC, echocardiography potentially offers important information about the right ventricle and pulmonic circulation.

Echocardiographically, cardiac output is calculated as the product of stroke volume and heart rate. Echocardiographic techniques for estimating stroke volume include linear techniques, volumetric techniques (two-dimensional [2D] and three-dimensional [3D] echocardiography), and Doppler. Guidelines have been developed for echocardiographic chamber quantification and should be applied for linear and volumetric assessments. Similarly, guidelines exist for Doppler measurements.

LINEAR TECHNIQUES

Linear measurements of LV internal dimensions can be made with M-mode echocardiography or directly from 2D images. Good reproducibility with low intraobserver and interobserver variability has been demonstrated; however, because of the number of potentially inaccurate geometric assumptions, this method is not generally recommended.

VOLUMETRIC TECHNIQUES

Two-Dimensional Echocardiography

Stroke volume is calculated as the difference between end-diastolic and end-systolic ventricular volumes. Right ventricular geometry is complex (crescenteric, wrapped around the left ventricle) and not well suited to quantification with 2D imaging. Evaluation of the right ventricle remains primarily qualitative.

The most important views for 2D TTE volumetric estimation of LV stroke volume are the apical four- and two-chamber views. Measurement of LV volume with TEE is challenging because of foreshortening of the LV cavity. However, carefully acquired TEE volumes show good agreement with TTE. The recommended views for measurement of LV volume are the midesophageal and transgastric two-chamber views.

Biplane Method of Disks. The biplane method of disks (modified Simpson rule) is the most commonly used method for 2D volume measurements. It is able to compensate for distortions in LV shape and makes minimal mathematic assumptions. However, the technique relies heavily on endocardial sonographic definition and is prone to underestimation as a result of apical foreshortening.

The underlying principle is that LV volume can be calculated as the sum of a stack of elliptic disks. When complementary views are not attainable, each disk is assumed to be circular. This method is less robust since assumptions of circular geometry may be inaccurate and wall motion abnormalities may be present.

Area Length Method. The area length method is an alternative to the method of disks that is sometimes used when endocardial sonographic definition is limited. The left ventricle is assumed to be ellipsoidal in shape. Cross-sectional area (CSA) is computed by planimetry on the parasternal short-axis view at the midpapillary level. The length of the ventricle is taken from the midpoint of the annulus to the apex on the four-chamber view.

Three-Dimensional Echocardiography[10]

3D echocardiography promises to revolutionize cardiovascular imaging. Technologic advances in computing and sonographic transducers now permit the acquisition and presentation of cardiac structures in a real-time 3D format with both TTE and TEE. 3D echocardiography can be used to evaluate cardiac chamber volumes without geometric assumptions. Real-time 3D echocardiographic measurements of ventricular volume may replace all other volumetric techniques and provide crucial hemodynamic monitoring solutions in the near future.

DOPPLER TECHNIQUES

In accordance with the Doppler effect, the frequency of sound waves is altered by reflection from a moving object. The flow velocity (V) of red cells can be determined from the Doppler shift in the frequency of reflected waves:

$$V = (2F_0 \times \cos\theta)^{-1} \times C\Delta F$$

where C is the speed of ultrasound in tissue (1540 m/sec), ΔF is the frequency shift, F_0 is the emitted ultrasound frequency, and θ is the angle of incidence. The most accurate results are obtained when the ultrasound beam is parallel to flow ($\theta = 0$ degrees, $\cos\theta = 1$; $\theta = 180$ degrees, $\cos\theta = -1$). However, angles up to 20 degrees still yield acceptable results ($\theta = 20$ degrees, $\cos\theta = 0.94$).

A primary application of Doppler is for the serial evaluation of stroke volume and cardiac output. In any given patient, the CSA of cardiac flow may be assumed to be relatively stable; however, Doppler flow velocity varies during LV ejection and thus flow velocity is summed as the velocity-time integral (VTI = area enclosed by baseline and Doppler spectrum velocity time). The VTI can be used to track changes in stroke volume. Velocity measurements demonstrate less variability (between days) with continuous wave Doppler (CWD) than with pulsed wave Doppler (PWD).

Doppler Flow Transducers and Monitoring Devices

Numerous compact devices based on Doppler principles (using either PWD or CWD) are available to critical care physicians (see Table 36-1). Differences exist in the site of application (transthoracic or transesophageal) and determination of the CSA of flow (estimated from 2D imaging or a normogram).

Echocardiography

Echocardiography can incorporate both PWD and CWD techniques. For patients in sinus rhythm, data from 3 to 5 cardiac cycles may be averaged; however, in patients with irregular rhythms such as atrial fibrillation, 5 to 10 cycles may be required to ensure that the results are accurate. It is essential that CSA (2D echocardiography) be measured reliably at the same site as the VTI (Doppler) while keeping in mind that accurate

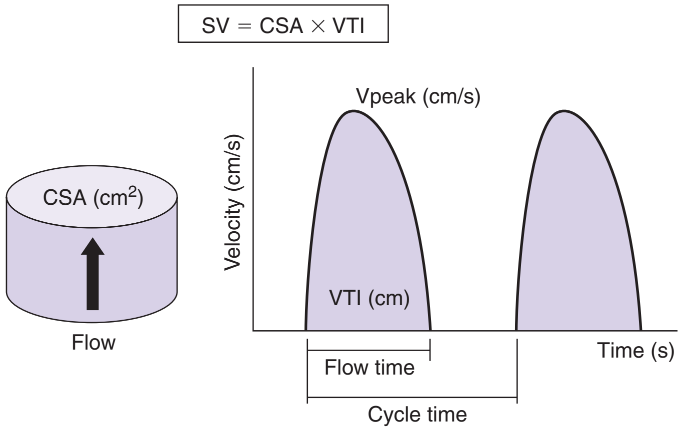

Figure 36-1 Calculation of stroke volume with Doppler. The cross-sectional area of flow (CSA) is calculated as a circle from echocardiographic measurements or from nomogram-based estimations. The velocity-time integral (VTI) is the integral of Doppler velocity with regard to time. Stroke volume (SV) is calculated as the product of CSA and VTI (mL/sec in this example). Cardiac output is calculated as the product of SV and heart rate. Peak velocity of flow (Vpeak) is also indicated. *(Used with permission from Sturgess DJ. Haemodynamic monitoring. In Bersten A, Soni N, editors:* Oh's intensive care manual, *ed 7, Sydney, Butterworth Heinemann, in press.)*

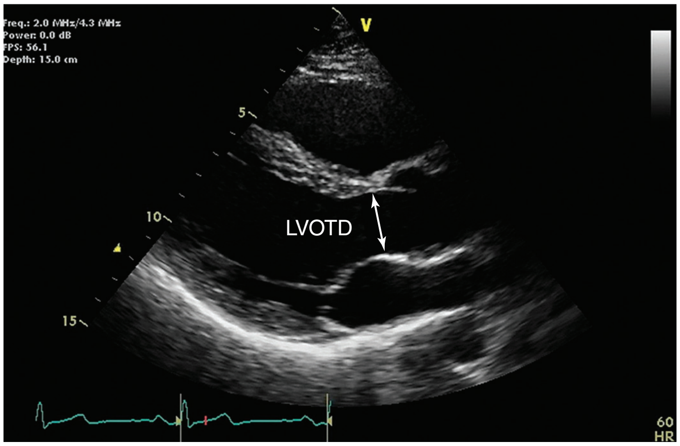

Figure 36-2 Parasternal long-axis view (transthoracic echocardiography) with the left ventricular outflow tract diameter (LVOTD) indicated by an *arrow*. The current view is not zoomed, to improve appreciation of the nearby anatomy.

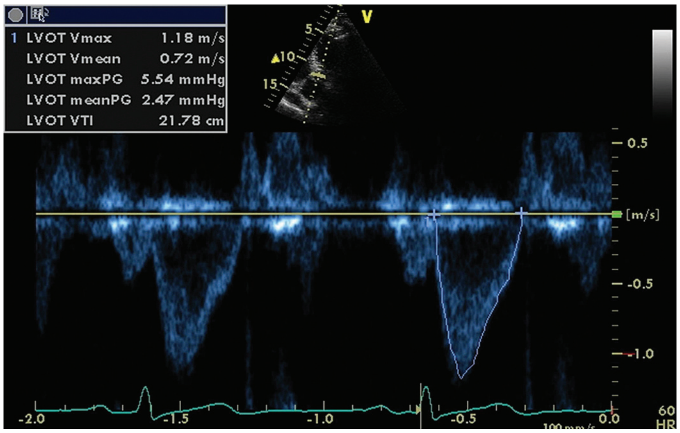

Figure 36-3 Tracing of a pulsed wave Doppler profile with the sample volume placed in the left ventricular outflow chamber in an apical five-chamber view (transthoracic echocardiography).

measurement of flow diameter (to calculate CSA) and flow velocity (VTI) potentially requires a perpendicular transducer alignment (Figure 36-1). The sites recommended for determining stroke volume are the LV outflow tract (LVOT) or aortic annulus, the mitral annulus, and the pulmonic annulus.

Pulsed Wave Doppler. PWD is used in combination with 2D echocardiography to measure flow at discrete sites. The LVOT is the most widely used site. The aortic annulus is circular and the diameter is measured on a zoomed parasternal long-axis view. Measurement is performed during early systole and bridges (inner edge to inner edge) from the junction of the aortic leaflets anteriorly with the septal endocardium and posteriorly with the mitral valve (Figure 36-2). The largest of three to five measurements should be used to avoid underestimation because of the tomographic plane.

LV outflow velocity is usually recorded from an apical five-chamber view, with the sample volume positioned just about proximal to the aortic valve. The closing click of the aortic valve (but not the opening click) is often seen when the sample volume is correctly positioned (Figure 36-3).

Flow across the mitral annulus is measured on an apical four-chamber view. The mitral annulus is not perfectly circular, but application of circular geometry generates similar or better results than do methods based on derivation of an elliptic CSA. The diameter of the mitral annulus should be measured from the base of the posterior and anterior leaflets during early diastole to middiastole (one frame after the leaflets begin to close). In contrast to transmitral diastology (leaflet tips), the PWD sample volume is positioned so that it is at the level of the annulus in diastole.

The pulmonic annulus is the least preferred of these three sites, mostly because poor visualization of the diameter of the annulus limits its accuracy and the right ventricular outflow tract is not constant through ejection (systolic contraction).

Continuous Wave Doppler. Unlike PWD, CWD records the velocities of all blood cells moving along the path of the ultrasound beam (see Chapter 1). The CWD recording therefore consists of a full spectral envelope with the outer border corresponding to the fastest moving blood cells. In CWD the velocities are always measured from the outer border (velocity envelope). In addition to the sites named for PWD, CWD is also used from the suprasternal notch to measure flow velocity in the ascending aorta.

The main limitation of CWD is that the velocity envelope reflects only the highest velocities, with all other velocity information being obscured. In turn, this represents flow only through the smallest CSA. This narrowest point may be difficult to localize or measure and may not be obvious on 2D images. For instance, CWD across the LVOT will usually reflect flow through the aortic valve rather than the annulus. The actual valve area (best approximated by an equilateral triangle) is challenging to visualize and measure with 2D TTE.

Noncardiac Ultrasound Hemodynamic Monitoring

Additional hemodynamic data can be derived from noncardiac ultrasound, including the integration of lung ultrasound and superior (SVC) and inferior (IVC) vena cava analysis (respiratory variations) in hemodynamic monitoring. Noncardiac ultrasound methods are analyzed extensively elsewhere (see Chapters 39 to 42).

In brief, characteristic artifacts on lung ultrasound (B-lines) reflect underlying interstitial pulmonary edema and presumably an associated hemodynamic disturbance. The sonographically detected interstitial syndrome ("wet lung") may appear at a preradiologic and preclinical stage (see Chapters 20 to 25). In contrast, the presence of solely A-lines (artifacts representing reflections of the pleural line) in hemodynamic terms reflects a "dry lung" or normal profile. The latter has been used to underpin cases of redistributive shock (e.g., septic shock) in the FALLS protocol (fluid administration limited by lung sonography).[11] However, one of the main diagnostic difficulties is that *septic* patients in the intensive care unit (ICU), who usually require fluid therapy, may well have a B-line profile because of various factors (e.g., pulmonary infection, acute respiratory distress syndrome, mixed type of pulmonary edema in which a cardiac component is integrated as well). Therefore, suggestions were made to incorporate Doppler and tissue Doppler echocardiographic indices (e.g., mitral flow E/E ratio) as measures of LV filling pressure in an effort to further clarify lung ultrasound-derived hemodynamic profiles.[11] Further analysis of this perspective is beyond the scope of this chapter.

Analysis of the sonographically detected respiratory variations in SVC and IVC size and diameter is a dynamic method that can be used for hemodynamic ICU monitoring. The aforementioned variations may at least partially reflect RAP and therefore right ventricular filling pressure. In a spontaneously breathing patient, estimation of RAP is improved by M-mode evaluation of IVC diameter and response to a brief sniff. A small IVC (1.2 cm) with spontaneous collapse suggests hypovolemia. Normally, the IVC is less than 1.7 cm, and normal inspiratory collapse ($\geq$50%) suggests normal RAP (0 to 5 mm Hg). A mildly dilated IVC ($>$1.7 cm) with normal inspiratory collapse suggests mildly elevated RAP (6 to 10 mm Hg). Inspiratory collapse of less than 50% suggests RAP of 10 to 15 mm Hg. A dilated IVC without inspiratory collapse suggests RAP higher than 15 mm Hg. Notably, more refined vena cava analysis algorithms have been implemented in mechanically ventilated patients (Chapters 39 and 40). In general, dynamic indices of cardiac preload (e.g., respiratory variations in Doppler-derived indices of aortic flow or vena cava analysis) and dynamic tests (e.g., the expiratory pause in mechanical ventilation or passive leg raising) are preferred over static indices for prediction of fluid responsiveness in the ICU.

The HOLA (Holistic Approach) Ultrasound Concept in Hemodynamic Monitoring

In terms of pathophysiology, two critical parameters may be used to optimize noninvasive hemodynamic monitoring in the ICU. The first refers to the ability to "pinpoint" the hemodynamic status of an individual patient as an exact spot on the *Frank-Starling curve* (and track the spot's path on the curve) during various therapeutic interventions (e.g., fluid loading, diuresis, changes in body posture). In this case the interventions represent a *dynamic* element that can be used to detect changes in various ultrasound-derived parameters (e.g., B-lines on lung ultrasound or respiratory variations in aortic flow VTI). The Starling curve relates stroke volume to end-diastolic ventricular volume (EDV). EDV is determined by transmural pressure, which is the difference between LV intracavitary end-diastolic pressure and pericardial constraint. When determining where a patient is on the Starling curve, these two confounding pressures must always be considered in a critically ill patient. Should the patient move along the Starling curve toward more cardiac output, was it because transmural pressure increased, and if so, did LV end-diastolic intracavitary pressure increase or did pericardial constraint decrease? The major issue when implementing dynamic elements in the equation is timing. For example, it takes time to identify the possible effects of fluid loading or diuresis on various ultrasound-derived parameters. Moreover, dynamic maneuvers that are considered to have a rather more "acute" effect (e.g., passive leg raising or expiratory pause in mechanical ventilation) are subject to various limitations. Our group is testing the recently introduced thigh cuff technology (Braslet-M) as a dynamic maneuver because of the fact that most of its effect on central hemodynamics is almost immediate (Figure 36-4).[12] Ultrasound should be helpful in determining the effect of acute hypovolemia induced by cuffs. In the case of volume overload and poor diastolic filling (reduced LV transmural pressure in the presence of increased RAP and pulmonary edema), reduced RAP and improved pulmonary edema are seen with increased EDV. This effect is identical to what occurs with the administration of nitroglycerin except for the absence of a confounding drop in afterload. Furthermore, release of the cuffs should generate an opposite effect. This same pericardial-ventricular interaction can be seen with high pulmonary vascular resistance such as pulmonary embolism. If thigh cuffs acutely improve the cardiac indices and LV EDV seen on echocardiography and reduce septal shift, volume loading of this patient to improve LV EDV might not be the preferred therapy.[13] Echocardiography provides real-time insight into the dynamic cardiac changes incurred by thigh cuff–induced fluid sequestration and subsequent release. Furthermore, other relatively load-independent parameters (e.g., Tei index) may be used to evaluate myocardial performance during the aforementioned dynamic bedside interventions.[14] The real-time combination of invasive monitoring, ultrasound, and bedside interventions should be investigated further.

The second parameter obviously reflects pertinent changes in cardiovascular morphology. In this case, four-dimensional monitoring of ventricular volume would represent an ideal solution; however, this technology is not yet readily available. Alternative indices that may be appraised are end-systolic obliteration of the LV cavity or a small cavity (not necessarily with end-systolic obliteration); oscillation of the interatrial septum, which if exaggerated could reflect low atrial pressure; or indices of preload dependence if hypovolemia is not overt, including the effect of a dynamic element on LVOT VTI.

The multimodal (integrating lung ultrasound, vena cava analysis, and echocardiography) HOLA ultrasound concept could well operate on binary logistics such as guiding fluid resuscitation with the intention of avoiding alveolar edema ("wet lung") and impaired gas exchange or optimizing diuretic

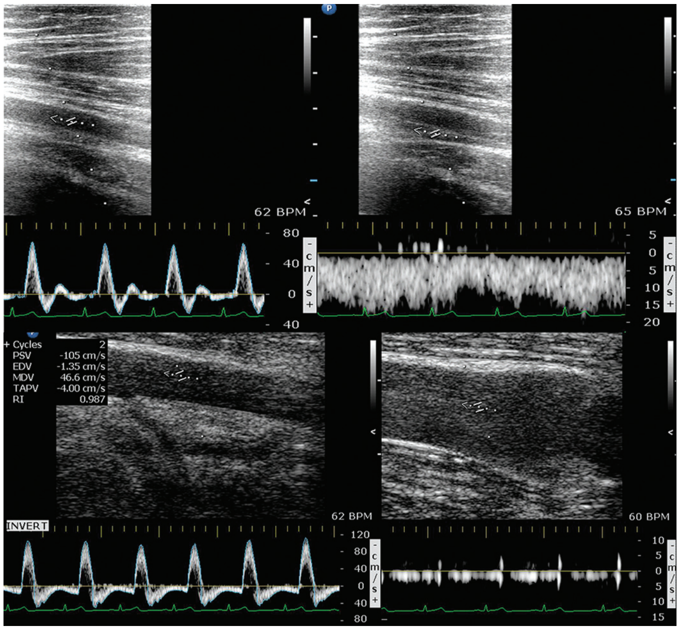

Figure 36-4 A healthy volunteer is lying supine at −30 degrees (head-down tilt) and wearing thigh cuffs (Braslet-M, Kentavr-Nauka, Moscow, Russia) tightened to an average skin-level pressure of approximately 35 mm Hg. However, the amount of pressure applied can be individualized until venous stasis is identified sonographically. The device remains tightened for only a few minutes and is immediately removed once an effect on central hemodynamics is registered (e.g., previous studies in healthy volunteers have depicted significant changes in parameters such as left ventricular stroke volume, E mitral velocity, lateral é on tissue Doppler imaging, right Tei index, and internal jugular vein area in just 10 minutes after the thighs were restrained).[12] *Top images,* Normal flow in the femoral artery and vein before inflation of the cuffs. *Bottom images*, A distended femoral vein with a distinctively hyperechoic lumen because of rouleaux formation in stasis conditions (slow steady flow is preserved in the real-time ultrasound used for monitoring). The Doppler waveform of the femoral artery shows diastolic flow reversal secondary to venous stasis (a dramatic increase in vascular resistance!). These images show sequestration of a large volume of blood in the lower extremity. Further tightening of the Braslet would create unsafe conditions that could possibly affect perfusion after interstitial edema eventually developed and therefore cannot be sustainable for long periods. In general, thigh cuffs should be used for only a very short time in patients and only for vital indications in those with coagulation disorders or a history of venous thrombosis for obvious reasons. *Further analysis is beyond the scope of this chapter. (Images courtesy Braslet Investigation Grant Experiment Team, National Space Biomedical Research Institute Grant No. SMST1602, 2011.)*

therapy in patients with cardiogenic (or mixed-type) pulmonary edema. These and some additional ultrasound-derived static and dynamic components are being considered thoroughly by our team for integration into a theoretic model and a resultant straightforward algorithm that will, we hope, be presented in the second edition of this textbook.

Pearls and Highlights

- Hemodynamic monitoring must be interpreted in the clinical context as an integration of all available data.
- Hemodynamic monitoring is not therapy, but it can guide therapy.
- Ultrasound and echocardiography complement other hemodynamic monitoring modalities by either aiding catheterization or providing additional information to aid in interpretation.
- Determining where a patient is on the Frank-Starling curve and monitoring alterations in cardiovascular morphology provide vital hemodynamic information.
- Ultrasound techniques for evaluating stroke volume and cardiac output include volumetric (linear, 2D, and 3D) techniques, as well as Doppler applications.
- Placement of a PAC is still indicated in certain patients because it may yield useful hemodynamic information.
- Lung ultrasound and vena cava analysis can be used in conjunction with echocardiography for noninvasive monitoring of volume status.
- All invasive and noninvasive hemodynamic monitoring methods have limitations.

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Measures of Volume Status in the Intensive Care Unit

DIETRICH HASPER | JÖRG C. SCHEFOLD | JAN M. KRUSE

Overview

Prescribing fluid therapy is a common therapeutic dilemma in the intensive care unit (ICU); however, different methods of evaluating volume status are available to guide this decision. This chapter discusses these methods briefly. Fluid therapy is of critical importance in the treatment of patients in shock since it may result in improved tissue perfusion and organ function. Administration of fluids is a key feature of "goal-directed" therapy protocols in patients with septic shock inasmuch as early fluid resuscitation was suggested to improve outcomes in such patients.[1] Nonetheless, overzealous resuscitation may result in tissue edema and thus impair pulmonary gas exchange, gastrointestinal motility, and wound repair. A negative impact of excessive fluid loading on outcome was demonstrated in patients with sepsis, acute respiratory distress syndrome, and renal failure.[2-4] The rationale for fluid administration is the anticipated increase in cardiac output (CO) in accordance with the Frank-Starling mechanism. Starling's law states that stroke volume (SV) increases in response to increased left ventricular end-diastolic volume or preload (Figure 37-1). Optimal preload corresponds to maximal overlap of actin-myosin fibrils. In healthy subjects, both ventricles are working on the ascending part of the Frank-Starling curve and therefore have a functional reserve in the event of acute stress.[5] In critical care patients, however, the ventricles often operate on the flat part of the curve. Hence increased preload does not result in increased SV but may lead to adverse effects such as pulmonary edema. A prudent policy is to identify patients in whom CO increases in response to increased preload (*fluid responsive*) well before prescribing fluid therapy.

Pressure-Related Techniques

Measuring volume status is rather sophisticated, whereas determining filling pressure appears to be simpler. Central venous pressure (CVP) or pulmonary artery occlusion pressure (PAOP) can be estimated by inserting a central venous and a pulmonary artery catheter, respectively. In healthy persons, CVP and PAOP should represent right and left ventricular filling pressure, respectively. Ventricular volume and pressure are linked by the volume-pressure curve. Increments in end-diastolic volume result in increased end-diastolic filling pressure. Unfortunately, there is no linear correlation between volume and pressure. Recently, it was demonstrated that both CVP and PAOP failed to predict changes in end-diastolic ventricular volume after the infusion of 3 L of saline into healthy volunteers.[6] If this principle does not apply to healthy subjects, it may indeed be of limited value in the ICU. Remarkable changes in ventricular compliance and intrathoracic pressure take place in the critically ill, mainly because most of them are mechanically ventilated and under the influence of vasoactive agents (e.g., inotropes). The impact of these changes on determination of CVP or PAOP is unpredictable. Surely, CVP is not associated with circulating blood volume and does not predict fluid responsiveness.[7] Accordingly, determination of PAOP is not recommended as a predictor of fluid responsiveness. Despite the aforementioned considerations, CVP and PAOP are routinely used as measures of volume status in the ICU. Surveys have confirmed that more than 90% of intensivists use CVP to guide fluid therapy.[8] The Surviving Sepsis Campaign recommended that septic patients be fluid-resuscitated to a CVP goal of 8 to 15 mm Hg.[9] This might be due to the fact that central venous catheters are standard tools in the hands of intensivists. Also, it is not always easy to alter clinical notions that have been shaped in a particular manner over a long period. If CVP is used to guide fluid therapy, single point estimations should not be interpreted in isolation but always in the context of pertinent clinical scenarios.

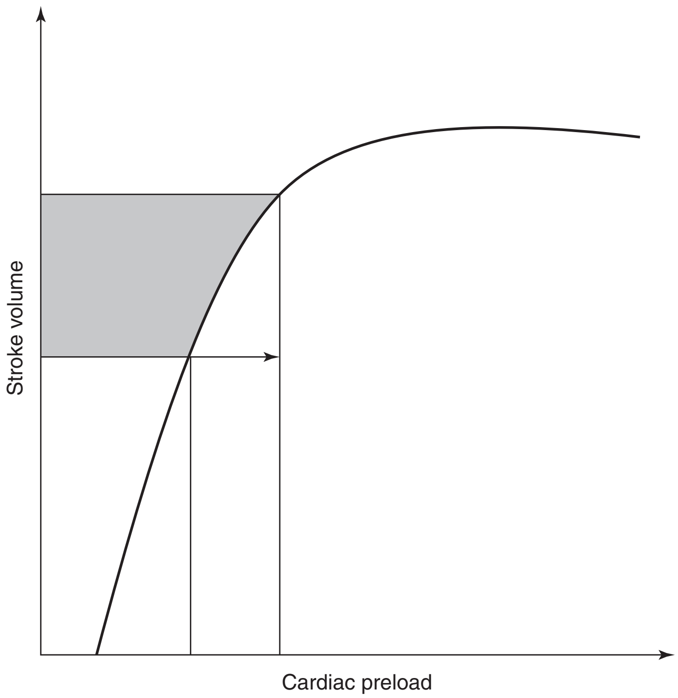

Figure 37-1 Cardiac preload plotted against stroke volume (Frank-Starling mechanism).

Static Volume-Based Parameters

Measuring end-diastolic filling volume is challenging, although estimates can be obtained with the transpulmonary thermodilution method. The latter is integrated into the PiCCO system (Pulsion Medical Systems AG, Munich, Germany). After injecting a cold saline bolus via a central line, the temperature is recorded with a large arterial thermistor. Mathematical analysis of the thermodilution curve provides the global end-diastolic volume (GEDV). This virtual volume reflects the volume of all four cardiac chambers in diastole. Several studies have demonstrated that GEDV is superior to filling pressure in estimating fluid responsiveness in various clinical scenarios.[10] The main issue is defining normal ranges of GEDV even after it is indexed for body surface area; moreover, GEDV seems to be influenced by age, gender, and left ventricular function.[11,12] Thus application of GEDV measurements in an individual patient may be difficult to interpret.

Dynamic Changes in Arterial Waveform

Currently, positive-pressure mechanical ventilation modes are used and are associated with cyclic changes in intrathoracic pressure. During inspiration, intrapleural pressure increases, which results in reduced venous return to the right ventricle (decreased preload). Additionally, a concomitant increase in right ventricular afterload takes place as a result of the increased transpulmonary pressure. Alterations in preload and afterload result in decreased right ventricular SV. The opposite is true for the left ventricle. However, with a short delay because of pulmonary circuit transit time, the reduced right ventricular SV leads to decreased left ventricular filling volume. If the ventricle is operating on the steep part of the Frank-Starling curve, decreased left ventricular SV with maximum depression in the expiration phase will be induced. Hence cyclic changes in SV and subsequently in systolic blood pressure occur in fluid-responsive patients during mechanical ventilation. Measures such as systolic pressure variation (SPV), pulse pressure variation (PPV), and SV variation (SVV) can be determined by sophisticated software analysis of the arterial waveform and pulse contour analysis. A variation threshold of 11% to 13% was reported to predict fluid responsiveness. PPV seems to be superior to SPV and SVV and has a sensitivity of 0.89 and a specificity of 0.88 in identifying fluid-responsive patients.[13] Although these measures exhibit higher diagnostic yield than do other hemodynamic markers (e.g., CVP), important limitations exist. Reliable analysis of the arterial waveform in mechanically ventilated patients can be achieved only in a volume control mode. Tidal volume is set to a value of between 8 and 10 mL/kg ideal body weight. Another important requirement is stable sinus rhythm. Arrhythmias, as well as spontaneous breathing, lead to errors in interpretation. Furthermore, the usefulness of arterial waveform analysis in patients under open chest conditions (e.g., heart surgery) remains debatable.

Passive Leg-Raising Test

Because of its easy application, the passive leg-raising (PLR) test has experienced a renaissance in recent years. PLR means lifting the limbs to an angle of about 45 degrees while the patient's trunk remains horizontal. This maneuver shifts blood volume into the thoracic compartment and therefore increases venous return. In the case of a preload-responsive ventricle, this procedure increases CO. In contrast to a traditional fluid challenge, the effects of PLR are quickly reversed by lowering the limbs. PLR is also applicable in spontaneous breathing patients and those with arrhythmias. Limitations are conditions associated with impaired venous return such as intraabdominal hypertension.

Evaluating SV and thus alterations in CO to optimize fluid therapy is a routine challenge. Alterations in arterial blood pressure are not a sensitive measure of changes in SV because the former represents one of the late pathophysiologic stages in the temporal order of hemodynamic events that start with alterations in SV and culminate in shifts in urine output.[14] Presumably, integration of continuous real-time CO monitoring into routine practice as provided by systems such as the PiCCO or the FloTrac-Vigileo (Edward Lifesciences, Irvine, CA) may provide solutions. Alternatively, ultrasound-based methods may be used.

Ultrasound

Ultrasound-based estimation of volume status may offer some advantages: surface ultrasound is noninvasive, has no relevant complications, and is readily available at the bedside. The basic concept involved in sonographic evaluation of fluid responsiveness is that venous return reflects cardiac preload. Venous return can be visualized by examination of the intrathoracic superior vena cava (SVC) and the mainly intraabdominal inferior vena cava (IVC) (*vena cava analysis*).

IVC diameter is measured with M-mode via subcostal views. These measurements should be made less than 2 cm from the right atrium (Figure 37-2). The absolute diameter of the IVC may provide a first impression of cardiac preload. Kosiak et al proposed an index (IVC/aortic diameter) for pediatric patients to evaluate volume status[15] because absolute diameters appear to be less sensitive. Physicians should be aware of the cyclic changes in intrathoracic pressure during ventilation. In spontaneously breathing patients, inspiration lowers intrathoracic pressure and thereby results in accelerated venous return. The sonographic feature is an inspiratory-related decrease and an expiratory-related increase in IVC diameter. In mechanically ventilated patients the opposite is true because of the application of positive end-expiratory pressure. Lack of variation in IVC diameter during ventilation reflects a poorly compliant vessel and excludes fluid responsiveness. In spontaneously breathing patients, changes in IVC diameter greater than 50% during the respiratory cycle were associated with low CVP.[16] In mechanically ventilated patients, IVC variation thresholds indicating fluid responsiveness seem to be lower. Feissel et al expressed the respiratory-related changes in IVC diameter as maximal inspiratory diameter minus minimal expiratory diameter divided by the average value of the two diameters. They found that a 12% increase in IVC diameter during inspiration could predict volume responsiveness with a positive predictive value of 93%.[17] Barbier et al used a different index ($\Delta IVC =$ (IVC_{max} “(” IVC_{min})/(IVC_{min}) (100, where IVC_{max} = maximal IVC diameter, IVC_{min} = minimal IVC diameter) to demonstrate fluid responsiveness with a sensitivity and specificity of 90% for ΔIVC greater than 18%.[18] Similar results have been presented by others.[19] In the case of elevated right atrial pressure (e.g., ventricular failure, cardiac tamponade), vena cava diameter does not reflect volume-dependent preload. Also, the method is not reliable in patients with intraabdominal hypertension. Finally, dynamic changes during the respiratory cycle should be

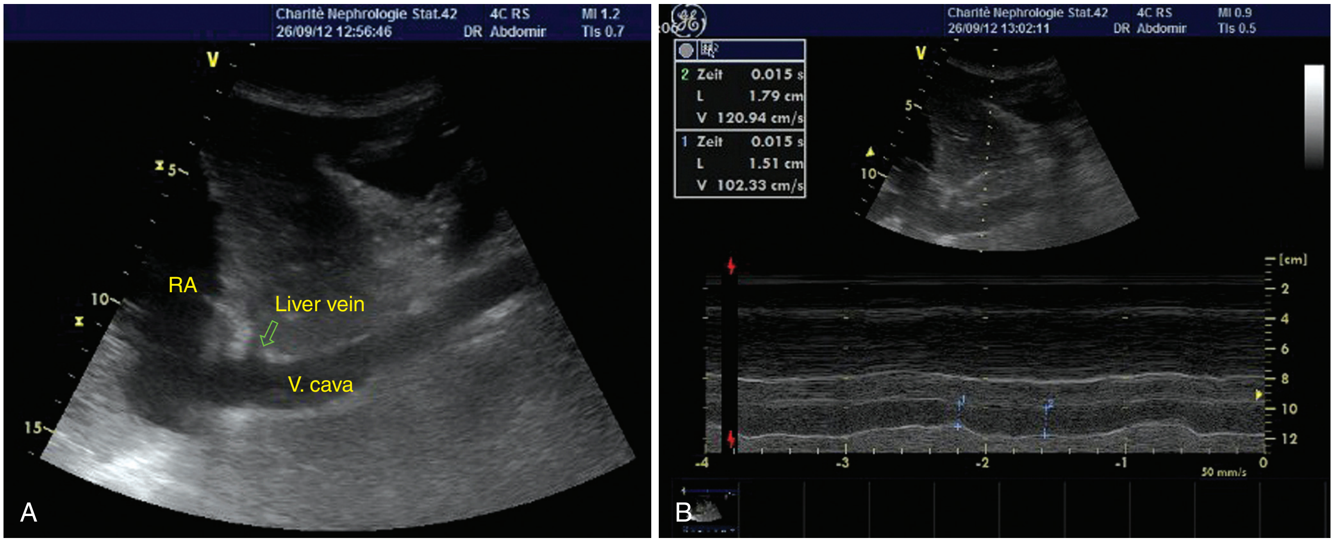

Figure 37-2 Visualization of the inferior vena cava (**A**) and determination of respiratory-related changes in diameter by M-mode (**B**).

IMAGING CASE

A 64-year-old male patient with ischemic heart failure (New York Heart Association class IV) was admitted to our hospital because of an exacerbation of his symptoms. His medications included high-dose diuretics (furosemide and spironolactone), a β-blocker, and an angiotensin-converting enzyme inhibitor. His serum creatinine level on admission was 2.8 mg/dL, as opposed to a 1.3-mg/dL baseline value. In the ward, an infusion of furosemide was initiated and led to exacerbation of the dyspnea and renal function (creatinine, 3.7 mg/dL); soon afterward he was admitted to the ICU. His acute kidney injury could have been attributed to volume depletion following diuretic therapy, or diuretic resistance with increased blood volume might have been the case. The dilemma was obvious: prescribe or remove fluids. Sonographic vena cava analysis revealed an IVC diameter greater than 25 mm without respiratory variation (Figure 37-3). Ultrafiltration resulted in radical clinical improvement in this patient with cardiorenal syndrome, and his creatinine values returned to baseline levels after a few days.

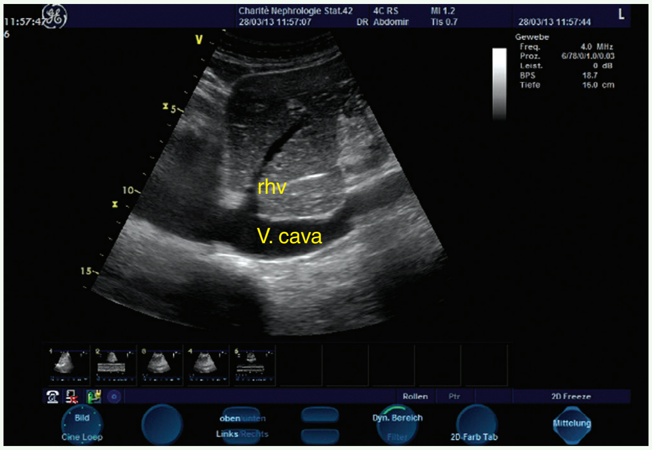

Figure 37-3 Vena cava analysis of a patient with cardiorenal syndrome.

evaluated with the patient on volume control ventilation and in sinus rhythm.

Although surface ultrasound using low-frequency 2- to 5-MHz microconvex transducers can depict the SVC, the latter is mainly visualized by transesophageal echocardiography (TEE). During mechanical ventilation, SVC diameter is minimal in inspiration and maximal in expiration. Vieillard-Baron et al demonstrated fluid responsiveness in mechanically ventilated patients with sepsis when the SVC collapsibility index was greater than 36%.[20] Although TEE is a semiinvasive method, it provides information about the structure and function of both ventricles, which is important in complex hemodynamic scenarios. TEE requires high educational standards and advanced skill levels for intensivists.

Pearls and Highlights

- Fluid responsiveness means patients' ability to increase CO after volume expansion.
- Static parameters such as CVP are poorly correlated with cardiac preload.
- Dynamic parameters such as SVV and PPV or PLR tests are more accurate measures of volume status than static ones are; however, their use has limitations.
- Sonographic vena cava analysis is a readily available, noninvasive approach for bedside evaluation of volume status, but it has limitations too.

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38

Evaluation of Fluid Responsiveness by Ultrasound

DANIEL DE BACKER | DAVID FAGNOUL

Overview

Fluid therapy is the cornerstone of hemodynamic resuscitation, and its aim is to increase tissue perfusion. Notably, a positive fluid balance is associated with a poor outcome. Thus it is important to optimize fluid administration and identify patients who may most benefit from it while trying to predict fluid responsiveness. Fluids increase tissue perfusion by means of an increase in cardiac output (CO), which is related to an increase in cardiac preload. However, the relationship between preload and CO or, more precisely, between left ventricular (LV) preload and stroke volume is curvilinear (Figure 38-1). In patients with altered contractility the curve is even flattened. Fluids should be administered only to those on the steep part of the curve.

Another important aspect is fluid tolerance. When preload increases, hydrostatic pressure also increases. The magnitude of the increase in hydrostatic pressure for a given increase in preload depends on patient's position on the Frank-Starling curve and on ventricular compliance (Chapter 36). In patients with altered diastolic function, the increase in hydrostatic pressure is more pronounced (Figure 38-2). Tolerance to fluids also depends on right ventricular (RV) function. In patients with RV dysfunction, fluid administration may induce RV dilatation. This chapter illustrates mainly the role of ultrasound in evaluating fluid responsiveness in the intensive care unit (ICU).

Prediction of Fluid Responsiveness

The literature reports that only half of patients respond to the administration of fluids. Several static and dynamic indices can be used to predict fluid responsiveness (Table 38-1). The technical details of these indices are discussed elsewhere in this book.

STATIC INDICES

Ventricular pressure and volume can be measured with echocardiography to assess preload. Because a multitude of Frank-Starling curves exist (depending on the patient's heart function), it is difficult to predict fluid responsiveness from a single estimate of preload. When preload is very low, only then is the likelihood of a patient being on the steep part of the Frank-Starling curve high. Conversely, when preload is very high, a patient's chance to be fluid responsive is low. However, patients are usually in a more indefinite situation (see Figure 38-1).

The diameter of the inferior vena cava (IVC) reflects central venous pressure (CVP) and can be used to predict fluid responsiveness. When IVC diameter is markedly increased (>20 mm), the likelihood of a patient to be fluid responsive is low, whereas when the diameter is decreased (<10 mm), the likelihood

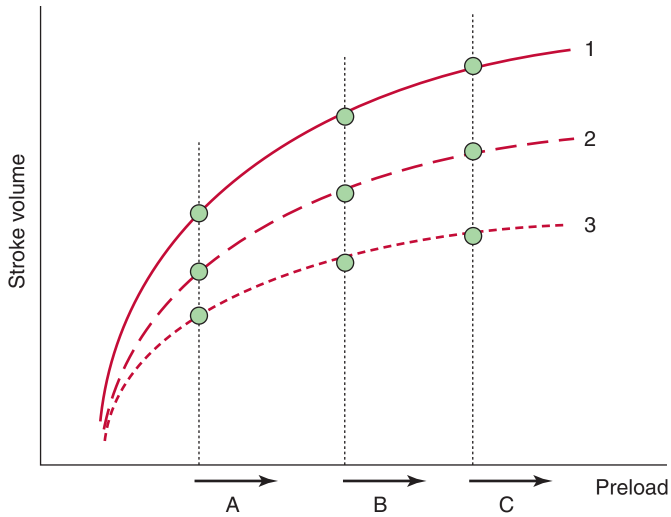

Figure 38-1 Prediction of fluid responsiveness with static indices. Fluid responsiveness depends on the patient's intrinsic contractility (1 = normal, 2 = moderately altered, 3 = severely altered) and position on the Frank-Starling curve (A, B, and C). A given value of preload (e.g., B) may be associated with a positive response to fluids (B1) or no response to fluids (B3). Only extreme values of preload such as A (very low) and C (very high) are predictive of fluid responsiveness. Of note, even patients with severely impaired cardiac function may respond to fluids (A3).

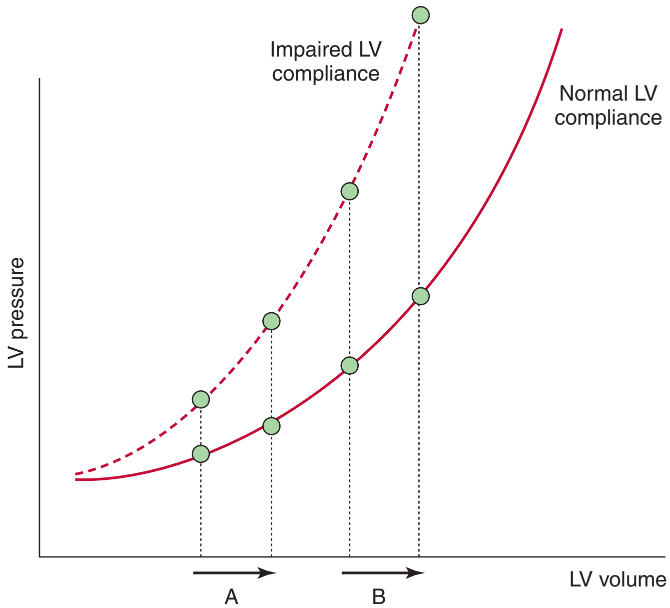

Figure 38-2 Relationship between left ventricular (LV) volume and pressure. In patients with impaired LV compliance, an increase in preload is associated with an increase in pressure, even when cardiac output (CO) also increases (**A**). The increase in hydrostatic pressure is more pronounced when patients are on the flat part of the Frank-Starling curve (**B**).

TABLE 38-1 Ultrasound Indices Used to Predict Fluid Responsiveness

Index	Principle	Comments
STATIC INDICES		
Inferior vena cava diameter	Diameter inversely proportional to CVP and thus RV preload	Poor predictive value
LV area	LV area inversely proportional to LV preload	Poor predictive value. Kissing ventricles highly suggestive of a positive response to fluids
Mitral inflow pattern	Small E wave suggests low PAOP and thus low LV preload	Poor to moderate predictive value
Mitral inflow–to–mitral annulus ratio	Low E/Ea suggest low PAOP and thus low LV preload	Poor to moderate predictive value
DYNAMIC INDICES		
Respiratory variations in aortic flow	Mechanical ventilation induces cyclic changes in preload that result in cyclic changes in stroke volume only in preload-responsive patients	Well-validated physiologic concept. Excellent predictive value. Many limitations. Cutoff value 12%
Respiratory variations in superior vena cava diameter	Mechanical ventilation induces cyclic changes in preload that result in cyclic changes in superior vena cava diameter only in preload-responsive patients	Excellent predictive value. Cutoff value 35%. Validated in only 1 trial
Respiratory variations in inferior vena cava diameter	Respiration induces cyclic changes in preload that result in cyclic changes in inferior vena cava diameter only in preload-responsive patients	Good predictive value. Cutoff value 15-18% (with different formulas). Proposed but questioned in spontaneously breathing patients
Expiratory pause	Expiratory pause induces an abrupt increase in LV preload that results in an increase in stroke volume only in preload-responsive patients	Excellent predictive value. Cutoff value 12%. Validated in only 1 trial
Passive leg-raising test	Passive leg raising induces an abrupt increase in LV preload that results in an increase in stroke volume only in preload-responsive patients	Excellent predictive value. Cutoff value 12%. Validated in several trials. Also valid in spontaneously breathing patients. Cumbersome

CVP, Central venous pressure; *LV,* left ventricular; *PAOP,* pulmonary artery occlusion pressure; *RV,* right ventricular.

appears to be higher. IVC diameter reflects RV preload, and even though it is measured from outside the thorax, it can be influenced by high intrathoracic and intraabdominal pressure. Hence return of blood to the heart may be impeded and fluid administration may not result in an increase in CO. A small IVC diameter usually indicates that RV preload is not elevated and venous return is not impeded; however, it cannot elucidate whether the left ventricle also works on the steep part of the Frank-Starling curve. The possibility of IVC collapse as a result of increased intraabdominal pressure or dilatation of the IVC when high positive end-expiratory pressure (PEEP) is used may further complicate the interpretation of changes in IVC diameter. Altogether, these factors explain why this method poorly predicts fluid responsiveness.

Color Doppler– and tissue Doppler imaging–derived mitral inflow patterns can be used to estimate pulmonary artery occlusion pressure (PAOP) and fluid responsiveness as mentioned elsewhere in this book.[1] A low mitral E wave or a low mitral inflow E wave–to–mitral annulus ratio (E/Ea) suggests low PAOP and may reflect a greater chance to respond to fluid therapy. Nevertheless, its predictive value for fluid responsiveness varies in different published series, and no definite cutoff values of these echocardiographic parameters can be used to distinguish fluid responders from nonresponders. LV and RV size may be used to estimate preload. Ventricular size can be assessed visually or with echocardiography (calculation of ventricular diameters, surfaces, or volumes). Only extreme values of ventricular size appear to have some value in predicting fluid responsiveness. In this context, a small LV cavity is associated with a positive response to fluids, provided that the right ventricle is not dilated.

DYNAMIC INDICES

Dynamic indices include either variations in stroke volume with respiration and its surrogates related to heart-lung interactions or several tests that can be applied to detect fluid responsiveness. Their basic principle is that when preload is transiently increased, the expected subsequent increase in CO would occur only in patients who are on the steep part of the Frank-Starling curve. These patients are likely to respond to fluid therapy. Echocardiography is an essential tool in evaluating transient alterations in CO during various dynamic tests.

Heart-Lung Interaction–Based Indices

Mechanical ventilation induces cyclic changes in intrathoracic pressure that result in cyclic changes in LV preload and stroke volume in preload-responsive patients (Figure 38-3). During inspiration, increments in intrathoracic pressure induce a decrease in the diameter and flow of the intrathoracic segment of the IVC, whereas its extrathoracic segment appears to be distended. RV afterload also increases. These changes lead to a decrease in RV and an increase in LV preload, respectively. Because of lung transmission time, the decreased RV stroke volume results in reduced LV preload after three to four beats, usually at midexpiration. During expiration, reverse changes in LV and RV preload occur. These hemodynamic changes can be assessed with echocardiography by noting specific alterations in aortic flow and IVC diameter, which occur only in preload-responsive patients.

Respiratory Variations in Aortic Flow

Variations in stroke volume with respiration can be assessed with color Doppler echocardiography. The latter depicts pertinent

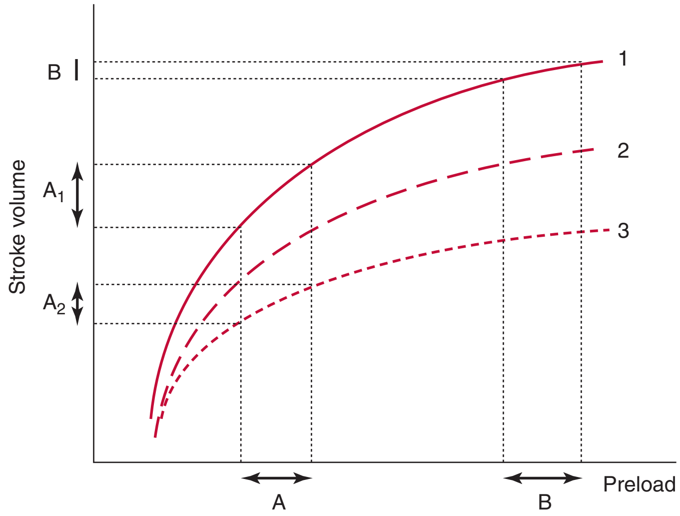

Figure 38-3 Prediction of fluid responsiveness with dynamic indices. In these tests, preload either spontaneously varies or is transiently manipulated (see text for details). These transient changes in preload are associated with transient changes in stroke volume in fluid responders (**A**); however, this is not the case in nonresponders (**B**).

respiratory variations in peak aortic velocity or the velocity-time integral (VTI) of aortic flow.[2,3] The former measurements are simpler than the latter, but their value in predicting fluid responsiveness is comparable.[3] These Doppler-derived indices were suggested to be reliable predictors of fluid responsiveness in a recent meta-analysis; however, their use carries several limitations.[4] When performing Doppler measurements of aortic flow, the heart rate should be regular and higher than the respiratory rate (heart-respiratory rate ratio >3.5). When patients are ventilated with tidal volumes of 8 mL/kg or lower, the predictive value of the Doppler indices is low.[5] Also, because no spontaneous respiratory movements should occur during the Doppler measurements, patients are usually deeply sedated; intraabdominal pressure should be within normal limits for reasons already explained in previous paragraphs.[6]

Vena Cava Analysis

Superior Vena Cava. The physiologic role of the right ventricle is to lower CVP and thus enable LV preload. During inspiration, the increased intrathoracic pressure induces a decrease in vena cava flow, but the right ventricle continues to eject blood at its maximal stroke volume. When the patient is preload dependent, vena cava flow transiently becomes lower than RV output, and the decreased CVP reflects the observed collapse of the superior vena cava (SVC). When the right ventricle is not preload responsive, intraluminal SVC pressure usually prevents its collapse. When a patient is afterload dependent (e.g., cor pulmonale), small fluctuations in SVC diameter may occur as a result of the decreased distensibility observed in an already enlarged SVC. Vieillard-Baron et al studied 66 patients with septic shock and reported that variation in the SVC collapsibility index (calculated as [maximum − minimum]/maximum SVC diameter) of at least 36% identifies fluid responders with a sensitivity of 90% and a specificity of 100%.[7] Ideally, SVC diameter is measured with transesophageal echocardiography at the level of the pulmonary artery (upper esophageal 90-degree view following identification of the SVC at 0 degrees). This location provides maximal sensitivity for determining intrathoracic pressure and minimizes artifacts. SVC analysis has several limitations and is not reliable when RV and LV preload dependency is dissociated (e.g., severe LV dysfunction). The method is of limited value in patients who are ventilated with low tidal volumes or undergo open chest surgery.

Inferior Vena Cava. Usually, only the extrathoracic segment of the IVC can be analyzed sonographically as described elsewhere in this book. IVC flow is maximal during expiration. During inspiration, flow stagnation occurs as a result of the increased intrathoracic pressure, and the IVC dilates. The latter occurs mostly in RV preload–dependent patients and in those with cor pulmonale (which can easily be identified with echocardiography). SVC and IVC analysis share the same limitations, whereas raised intraabdominal pressure influences the latter (by dampening the variations in IVC diameter with respiration) as described in previous paragraphs.[8] Two different formulas have been suggested for performing IVC analysis as described in other chapters in this section. These formulas produce results with slightly different cutoff values (15% for [maximum − minimum]/mean IVC diameter and 18% for [maximum − minimum]/minimum IVC diameter) but with similar values in predicting fluid responsiveness.[9,10]

IVC analysis can be also used during spontaneous breathing. During inspiration, right atrial pressure decreases and thereby leads to increased IVC flow. In patients with RV preload dependency this results in a marked decrease in IVC pressure and diameter. In spontaneously breathing patients, IVC diameter is minimal during inspiration (the opposite is true in those undergoing mechanical ventilation). Following IVC analysis, a cutoff value of 30% was proposed to distinguish fluid responders from nonresponders during spontaneous breathing, although this remains debatable.[1]

Other Dynamic Tests

Expiratory Pause. Mechanical ventilation generates a mean respiratory pressure that determines venous return and CO during one respiratory cycle. An expiratory pause abruptly decreases mean intrathoracic pressure to the level of PEEP and in turn induces an abrupt increase in LV preload. The latter results in increased stroke volume in preload-responsive patients. This dynamic test has been validated by aortic pulse contour analysis (although further echocardiographic validation is required) and can be used in patients who are mechanically ventilated with low tidal volumes or have arrhythmias.[11]

Passive Leg Raising. Passive leg raising (PLR) has previously been analyzed in this book. In brief, it consists of an abrupt change in body position (raising the legs together with a change in torso position from 30 to 45 degrees to 0 degrees), which results in acute blood mobilization (≈300 mL) from large capacitance veins (lower limbs and splanchnic regions).[12] Mobilization of blood may be limited in patients with severe vasoconstriction or in those with lower limb compression stockings. In preload-responsive patients, PLR induces an abrupt increase in LV preload that results in increased stroke volume. This effect is relatively transient (1 to 2 minutes) since compensatory mechanisms occur after a few minutes. The PLR test can be performed in both spontaneously breathing and mechanically ventilated patients.[13] In this test, Doppler-derived changes in the aortic VTI are usually measured (cutoff values >12% are suggested to identify fluid responders).

Final Thoughts

In the ICU, evaluation of fluid responsiveness has many limitations irrespective of the method used, and the concept itself has many "gray zones." However, assessing the effectiveness of fluid therapy in ICU patients is an essential parameter of hemodynamic and respiratory monitoring. In our practice, the aortic flow VTI is measured before and after administration of fluid boluses. A 10% increase in VTI values usually indicates fluid responsiveness. When the aortic VTI fails to increase, one important question is whether this is resulting from insufficient "fluid loading" or whether the patient is effectively failing to respond despite a significant increase in preload. A simple way to evaluate preload is to measure changes in echocardiographic indices such as the Doppler-derived mitral E/A ratio or the tissue Doppler–derived mitral E/Ea ratio (any significant change in PAOP usually corresponds to an increased mitral E wave). Another important clinical issue is whether fluids are well tolerated. Indeed, fluid therapy can unmask RV failure or precipitate pulmonary edema. Echocardiography can be used to evaluate RV dysfunction as analyzed elsewhere. Notably, in such cases the Doppler-derived aortic VTI often fails to increase and sometimes even decreases after a fluid challenge. Evaluation of impending pulmonary edema can be facilitated by monitoring changes in PAOP. This is usually performed by measuring the aforementioned Doppler and tissue Doppler echocardiographic indices, whereas the recent integration of lung ultrasound into the diagnostic arsenal has facilitated prompt identification of pulmonary edema in the ICU. Notably, the E/Ea ratio markedly increases in nonresponders after a fluid challenge, and this increase is more pronounced in patients with LV diastolic dysfunction.[14] No cutoff values have clearly been established, however, when the E/Ea ratio rises above 10; in general, further administration of fluids should be performed with caution.

Pearls and Highlights

- Echocardiography is an essential tool in predicting fluid responsiveness in the ICU.
- Dynamic indices of cardiac preload (e.g., variations in aortic flow or vena cava analysis with respiration) and dynamic tests (e.g., expiratory pause in mechanical ventilation or PLR) are preferred over static indices for prediction of fluid responsiveness.
- All static and dynamic indices of cardiac preload have limitations, and the concept of fluid responsiveness has many "gray zones."
- No cutoff values that predict fluid responsiveness or tolerance have clearly been established for the tissue Doppler–derived mitral flow E/Ea ratio in mechanically ventilated patients. In general, when the latter rises above 10, administration of fluids should be performed with caution.

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39

Ultrasonography in Circulatory Failure

JUSTIN WEINER | JOSE CARDENAS-GARCIA | RUBIN I. COHEN | SETH KOENIG

Overview

Shock is an emergency medical condition caused by inadequate tissue oxygenation. Treatment of shock depends on the underlying cause of the circulatory failure. Ultrasound facilitates rapid evaluation of hemodynamically unstable patients by providing valuable information about not only myocardial function but also the peripheral vasculature.[1] When performed in real time, intensivist-guided bedside ultrasonography can be used to differentiate between shock states, facilitate efficient early goal-directed therapy, and monitor the response to therapy.[2,3] Proficiency in basic critical care ultrasonography allows the intensivist to distinguish among shock secondary to obstruction (pulmonary embolism or cardiac tamponade), hypovolemia, and distributive causes (septic shock). Ultrasound is a bedside, reproducible, and noninvasive imaging modality. Furthermore, it obviates the need to transport unstable patients to the radiology department. This chapter discusses the role of ultrasound in the diagnosis and management of circulatory failure in the intensive care unit (ICU).

Ultrasound-Based Evaluation of Circulatory Failure in the Intensive Care Unit

We start by first noting that ultrasound should not in any way substitute for a thorough history and physical examination. The presence of heart murmurs, pericardial rubs, elevated neck veins, previous history of gastrointestinal bleeding, known malignancy, or unilateral absence of air entry on examination will suggest the cause of the shock. Ultrasound can be used to confirm clinical suspicion. Specific emergency department protocols exist for patients in shock with and without a history of trauma[4-7]; however, these protocols are not reviewed in this chapter. Moreover, ultrasound techniques have been described in detail elsewhere in this book and are not restated here. Implicit in the discussion of the use of ultrasound in shock patients is the dynamic nature of the symptoms and signs. The state of patients in circulatory failure is constantly changing secondary to both the initial insult and its subsequent treatment. Accordingly, ultrasound can be used to aid in both diagnosis of the cause of the shock and the response to interventions.[8]

Ultrasound examination of patients usually starts by assessing the heart with a low-frequency transducer. The following views are obtained[1]: parasternal long-axis (PSL), parasternal short-axis (PSS), apical four-chamber (4CV), subcostal (SC), and inferior vena cava (IVC) views (Table 39-1). The purpose is to evaluate myocardial function. The basic algorithm is shown in Figure 39-1. We assess left ventricular (LV) size and function, right ventricular (RV) size and function, gross valvular abnormalities, the pericardial space, and the size and variation of the IVC with respiration. Occasionally, the cause of the shock can be unambiguously diagnosed with ultrasonography.

TABLE 39-1 Basic Transthoracic Cardiac Views

Views	Technique	Optimal Image	Strength
Parasternal long axis (PSL)	The probe should be placed on the left parasternal line at the fourth intercostal space, with the marker pointing toward the right shoulder of the patient	Mitral and aortic valves on the same plane and horizontal mid left ventricle without the apex	Assessment of left ventricular size and function Gross assessment of mitral/aortic valves Assessment of pericardial effusion
Parasternal short axis (PSS)	After obtaining the PSL view, rotate the probe clockwise 90 degrees so that the marker points to the patient's left shoulder	Round left ventricle at the papillary muscle level	Global left ventricular function, regional wall motion abnormalities Right ventricular function and septal kinetics
Apical four chamber (4CV)	Place the probe where the PMI is palpated with the probe face pointing toward the right shoulder and the marker pointing toward the left shoulder	Bullet-shaped heart; the optimal image with the longest dimension of the left atrium will be sought	Assessment of left and right ventricular size and function Assessment for pericardial effusion
Subcostal (SC)	With the patient in the supine position, place the probe face on subxiphoid area pointing to the left shoulder with the marker pointing to the patient's left	Four-chamber view with mitral/tricuspid valves. The liver is anterior/lateral to the heart	Bailout view in ventilated patients Assessment of left and right ventricular size and function Assessment for pericardial effusion
Inferior vena cava (IVC)	After obtaining an SC view, rotate the probe 90 degrees counterclockwise to obtain a cross-sectional view of the heart	Measurements should be done at 3 cm below the right atrium or caudal to the inlet of the hepatic veins	Assessment of the IVC

PMI, Point of maximal impulse.

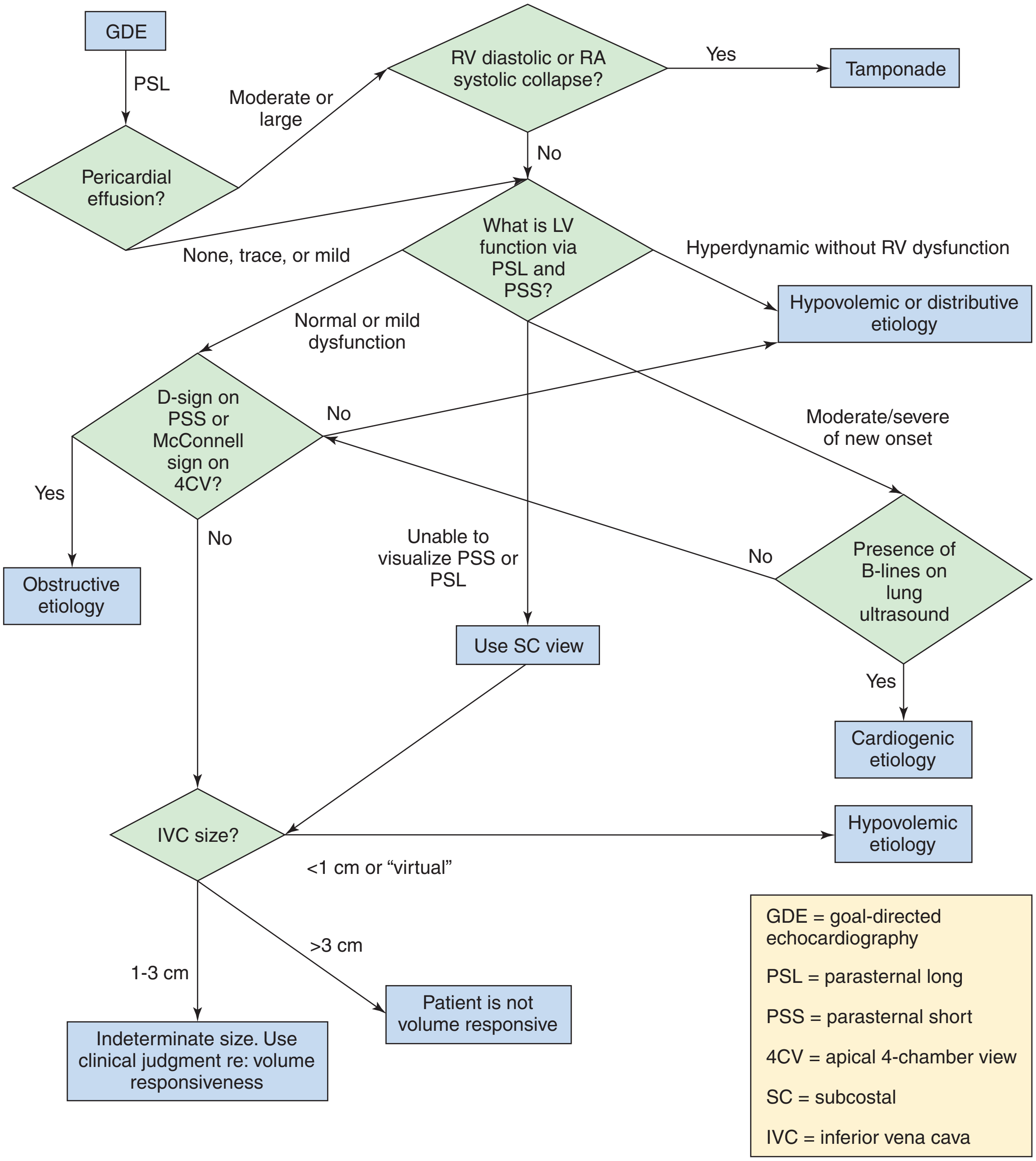

Figure 39-1 Flow chart for the use of ultrasound in managing circulatory failure.

For example, visualization of a thrombus in one of the main pulmonary arteries necessitates rapid intervention. *However, the cause of the shock is more likely to be found by ultrasound examination of several organs in a coordinated fashion, once again underlining the benefits of the holistic approach (HOLA) critical care ultrasound concept (see* Chapters 1 *and* 57*).* A normal finding on ultrasound examination is very useful because it rules out components of the differential diagnosis. For example, a hypotensive patient with a known underlying malignancy and a normally functioning right ventricle on ultrasound assessment virtually rules out the presence of a massive pulmonary embolus.

The suggested algorithm begins with evaluation of the pericardial space. Here it is important to clearly differentiate pleural from pericardial fluid. On the PSL view, it is easy to differentiate a *pericardial* from a *pleural effusion* by noting whether the fluid travels anteriorly in front of the aorta. A significant pericardial effusion should prompt the intensivist to assess for RV diastolic or right atrial systolic collapse. If either is present, tamponade physiology is probably present and drainage of the pericardial fluid is recommended. Ultrasound-guided pericardiocentesis can be then performed.[1,9]

Next, *LV function* is assessed with the PSS and PSL views. Moderate to severe LV dysfunction suggests cardiogenic shock, especially if it is a new finding. By using the PSS view at the level of the papillary muscles, regional wall motion abnormalities can be assessed. Although the PSS view is primarily used, the 4CV and PSL views can alternatively be used for the same purpose. A "normal" left ventricle (or hyperdynamic circulation) without RV dysfunction is suggestive of either a hypovolemic state or distributive shock. Reappraisal of LV function is crucial since contractility of the heart may change following changes in preload and afterload (after volume resuscitation or the use of diuretics or vasopressors).

Assessment of the *right ventricle* follows. RV dilatation (as seen on the PSS and 4CV views) with bowing of the interventricular septum into the left ventricle suggests obstructive shock (Figure 39-2). Furthermore, akinesia of the midportion of the RV free wall with sparing of the RV apex (McConnell sign) is also suggestive of pulmonary embolism causing obstructive shock.[10]

Next, the *IVC* is evaluated 3 cm below the right atrium or caudal to the inlet of the hepatic veins. One of the central questions in a hypotensive patient is whether a volume challenge will increase preload and therefore cardiac output. If the patient is passive and mechanically ventilated, dynamic changes in the IVC are assessed with M-mode in the SC or IVC view. The maximum and minimum diameters are recorded. A 12% or greater difference between minimum and maximum diameters suggests that the patient's blood pressure will increase following an infusion of fluids.[11] Of note, patients need to be fully sedated and on volume control mode with a tidal volume of 8 to 10 mL/kg, as has previously been reported.[11] Alternatively, if the patient is breathing spontaneously or triggering the ventilator, a small (<1 cm) IVC (along with end-systolic effacement of the papillary muscles on a PSS view and a hyperdynamic left ventricle) argues in favor of a volume challenge (Figure 39-3). A large (>3 cm) IVC argues against a fluid challenge (Figure 39-4).[12] Between these two extremes, the result is indeterminate and intensivists should use their clinical judgment. Another validated method for assessing fluid responsiveness in spontaneously breathing patients without arrhythmias is *passive leg raising* with evaluation of the variation in stroke volume (threshold of 12.5%).[13] This requires knowledge of advanced critical care echocardiography and is analyzed elsewhere in this section of the book.

Sometimes, the phenomenon of *dynamic LV outflow tract obstruction* secondary to hypovolemia may be present. In this case the patient is typically elderly with a history of hypertension. With older methods of assessing shock, a pulmonary artery catheter would have revealed elevated pulmonary capillary wedge pressure and a low cardiac index. This would lead the intensivist to believe that the hypotension is secondary to poor LV function and thus prompt inotropic support with preload reduction. However, the PSL view will show otherwise. Treatment of dynamic LV outflow tract obstruction is in fact the opposite of that for cardiogenic shock: volume administration along with a reduction in heart rate and the use of phenylephrine for blood pressure support.

Acute valvular dysfunction as a cause of circulatory failure is most commonly observed in the coronary care unit. However, a patient in the medical or surgical ICU will occasionally have an undiagnosed or previously unknown valvular pathology. Examples include a flail mitral valve leaflet or a severely stenotic aortic valve with decreasing excursion.[14] The PSL view is ideal for this evaluation. Color Doppler is crucial for a complete diagnosis of valvular disease but is beyond basic critical care echocardiography. The intensivist should be able to recognize

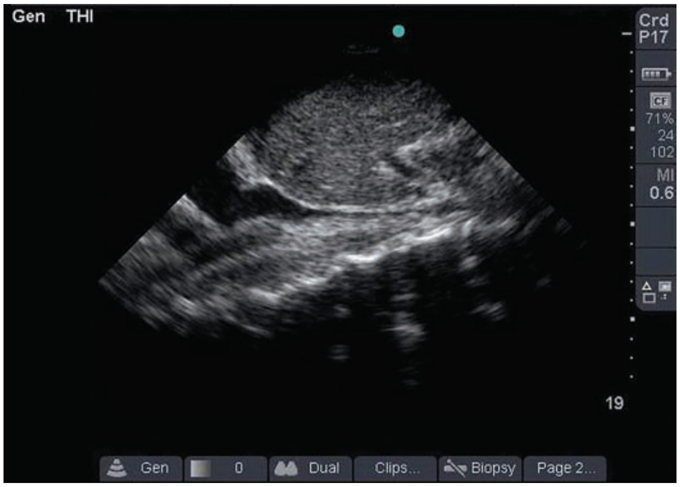

Figure 39-3 Collapsible inferior vena cava (IVC). In this longitudinal IVC view, the IVC is seen to be small and collapsible. This patient's blood pressure is likely to improve with fluid administration.

Figure 39-4 Distended inferior vena cava (IVC). The IVC is dilated and does not collapse with inspiration, thus indicating that the IVC is "filled." The patient's blood pressure is unlikely to improve following fluid administration.

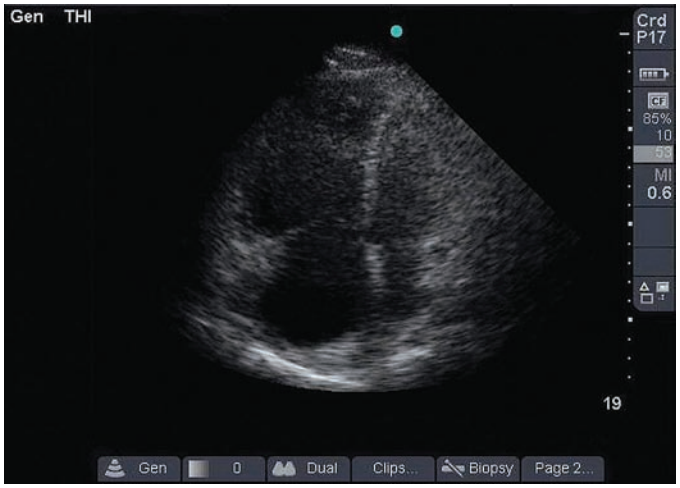

Figure 39-2 Dilated right ventricle. In this apical four-chamber view, the right atrium and right ventricle are much larger than the left side of the heart.

that a major valvular abnormality exists and then seek consultation from a cardiologist (Chapter 57).[1]

Lung ultrasound completes the evaluation. Even though lung ultrasound is covered in detail elsewhere, it is quite useful in the assessment of shock for evaluating pulmonary edema. Lung auscultation remains an important part of the physical examination; however, its sensitivity is poor, especially in a supine, mechanically ventilated, critically ill patient who is unable to cooperate. In contrast to chest auscultation and plain chest radiography, lung ultrasonography has greater than 90% sensitivity with regard to pulmonary edema and provides objective data.[15] Additionally, the presence of decreased or absent breath sounds on physical examination can point to the presence of massive pleural effusion, exacerbation of chronic obstructive pulmonary disease, or pneumonia. These conditions can easily be distinguished with bedside ultrasonography since they demonstrate different patterns (see the chapters on pleural and lung diseases), thereby reducing the need for portable radiography.

Ultrasound findings such as predominance of an A- or B-line pattern can further guide fluid resuscitation as described in the *FALLS* protocol (fluid administration limited by lung sonography).[3] For example, an initial A-line predominance (a surrogate for pulmonary artery occlusion pressure ≤18 mm Hg) that changes to a B-line pattern following aggressive fluid resuscitation argues against further fluid administration. However, the opposite does not hold true. The initial presence of diffuse B-lines on lung ultrasound cannot be assumed to be of cardiogenic etiology since they can found in multiple interstitial pathologies such as pulmonary edema (cardiogenic or noncardiogenic), chronic lung diseases, and certain infections such as *Pneumocystis pneumoniae*. We again stress two previously noted issues: (1) the importance of the history and physical examination and (2) the importance of continuous assessment by both clinical examination and ultrasound.

Lung ultrasound further aids in the diagnosis of obstructive shock. An A-line pattern in the setting of hypotension, a clear chest radiograph, and the presence of lung sliding bilaterally may represent obstructive shock in the correct clinical context. The next steps should include evaluation of the right ventricle and IVC in addition to a compression study of the lower extremities for deep vein thrombosis (DVT). A newly diagnosed dilated hypokinetic right ventricle with evidence of pressure overload makes the diagnosis of acute pulmonary embolism very likely. The thickness of the RV free wall may allow distinction between acute and chronic elevations in pulmonary pressure. Finally, the finding of DVT on ultrasound examination of the lower extremities further solidifies the diagnosis of massive pulmonary embolism. Another cause of obstructive shock is tension pneumothorax, usually accompanied by dyspnea and hypoxemia. It can be ruled out very quickly by the absence of lung sliding.

Ultrasound may also be used to determine the cause of the decreased urine output that often accompanies shock states. For example, bladder ultrasound, in the setting of decreased urine output, can be used to confirm that the Foley catheter is in the proper position (Figure 39-5). The presence of hydronephrosis on kidney ultrasound can also be ascertained.

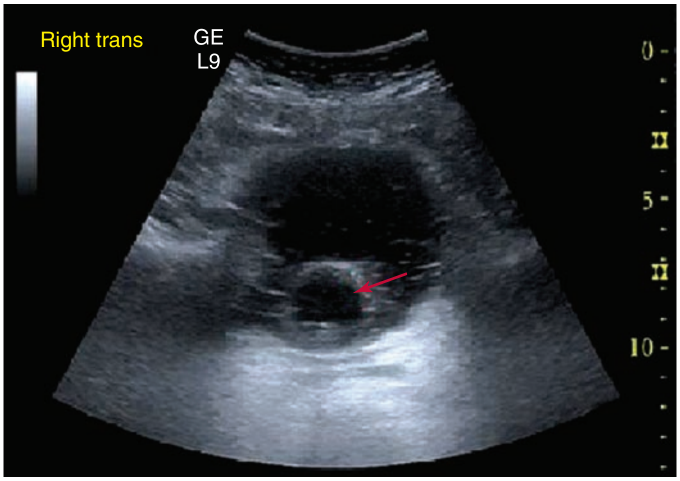

Figure 39-5 Foley catheter in the bladder. The clinician is reassured that misplacement of the catheter is not the cause of the decreased urine output.

Finally, ultrasound can assist in resuscitation. Rapid insertion of central venous lines is easier and safer with ultrasound. The complication rate associated with venous central line placement can be greater than 15%.[16,17] In a randomized study, 450 critical care patients who underwent real-time ultrasound-guided cannulation of the internal jugular vein were compared with 450 patients in whom the landmark technique was used. Access time (skin to vein) and number of attempts were significantly reduced in the ultrasound group. In the landmark group, puncture of the carotid artery occurred in 10.6% of patients, hematoma in 8.4%, hemothorax in 1.7%, pneumothorax in 2.4%, and central venous catheter–associated bloodstream infection in 16%. All these complications were significantly reduced in the ultrasound group. Indeed, the Agency for Healthcare Research and Quality presently recommends the use of ultrasound for central venous placement as one of their 11 practices to improve patient care.[18]

Pearls and Highlights

- Circulatory collapse is a common admitting diagnosis in the ICU; rapid determination of its cause and subsequent treatment are necessary for improved outcomes.
- Bedside critical care ultrasound aids the intensivist in assessing the cause of shock, change in the patient's status, and response to interventions.
- Real-time ultrasound is portable and reproducible, does not require transport of patients, and is performed by the treating intensivist.
- Critical care ultrasound has a steep learning curve, but its basic techniques can be mastered at the bedside in a relatively short time.

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Perioperative Sonographic Monitoring in Cardiovascular Surgery

DANIEL DE BACKER | DAVID FAGNOUL

Overview

Despite the well-known advances in cardiovascular surgery over the last 50 years, it remains a high-risk procedure associated with significant morbidity and mortality rates. Currently, patients undergoing cardiovascular operations tend to be older and have more comorbid conditions. This could be attributed to the progress in surgical procedures, as well as to improved preoperative, perioperative, and postoperative care, which includes hemodynamic optimization by implementation of goal-directed therapies and the use of β-blockade in selected patients. Recent guidelines have recommended the use of ultrasound for detection of perioperative complications and for hemodynamic management.[1,2] This chapter discusses the use of echocardiography for the evaluation of patients after cardiovascular surgery. Because image quality is usually poor with transthoracic echocardiography, transesophageal echocardiography (TEE) has been used routinely in the intensive care unit (ICU) for the detection of functional and structural cardiovascular abnormalities postoperatively.

Hypovolemia

Hypovolemia is the most frequent hemodynamic alteration after cardiovascular surgery. Even though bleeding is easily assessed by checking the various drains, it is sometimes overlooked because of clotting of drains or accumulation of blood in nonadequately drained cavities (e.g., pleural space). Notably, even when bleeding is detected, volume correction can be insufficient, and it is worth mentioning that cardiopulmonary bypass often provokes capillary leak syndrome secondary to a systemic inflammatory response. Postoperatively, patients may have hypotension or signs of tissue hypoperfusion necessitating close hemodynamic monitoring in the ICU. Whenever possible, fluid responsiveness should be assessed with dynamic indices (Chapter 38). Evaluation of variations in aortic flow with respiration is the most reliable method. Assessment of fluid responsiveness based on respiratory variations in the superior and inferior vena cava is less reliable because of direct compression of the vessel by blood and clots in the mediastinum (superior vena cava) or because of increased pericardial pressure (both vessels). Finally, systolic or diastolic left ventricular (LV) dysfunction (preexisting or related to cardiopulmonary bypass) may result in intolerance of fluid therapy and thus should be carefully evaluated.

Left Ventricular Dysfunction

LV dysfunction is the second most frequent hemodynamic alteration after cardiovascular surgery and can be attributed to preexisting LV dysfunction or to ischemic events or stunning as a result of cardiopulmonary bypass.[3] Preoperative evaluation of ventricular function is fundamental in these patients since it facilitates postoperative identification of a new segmental ventricular wall abnormality, which should prompt discussion of coronary angiography and reperfusion strategies. In addition, demonstration of impaired contractility does not inevitably constitute an indication for the use of inotropic agents, which are indicated only when impaired contractility is associated with an inadequate cardiac output contributing to the impaired tissue perfusion. Indeed, the patient is often hypothermic and metabolic needs are low during and just after surgery. Therefore low cardiac output in isolation should not be treated. Measurements of LV ejection fraction should be used in combination with cardiac output measurements (measured as the aortic flow velocity-time integral) and markers of tissue hypoperfusion (blood lactate levels, oliguria). Finally, right ventricular (RV) dysfunction may also occur, especially after selected procedures such as correction of mitral valve stenosis or pulmonary thromboembolectomy (Chapter 33).[4]

Pericardial Effusion and Localized Tamponade

Blood and clots may accumulate in the pericardial space even with the use of drains. Stagnation of blood in the pericardium facilitates the development of clots, which in turn may lead to drain occlusion and global tamponade by enabling continuous accumulation of blood. Localized tamponade may also occur as a result of the development of large clots compressing selected cardiac structures. In most cases these large clots compress the right cardiac cavities and especially the right atrium (Figure 40-1). In the latter clinical scenario, patients typically have severe hypovolemia that responds partially to fluid therapy, and ultrasound detects a very small right atrium and dilatation of the superior and inferior vena cava (increased central venous pressure). Rarely, clots may selectively compress the left atrium, which results in low cardiac output with some evidence of hypovolemia (usually a small left ventricle) and a very small left atrium with occasional pulmonary edema (often predominant on the left side) because of compression of the pulmonary veins (as confirmed by detection of very high color and pulsed wave Doppler velocity [>100 cm/sec] in the ipsilateral pulmonary veins).

Dynamic Obstruction of the Left Ventricular Outflow Tract

Dynamic LV outflow tract (LVOT) obstruction could be attributed to a Venturi effect in the context of excessive adrenergic

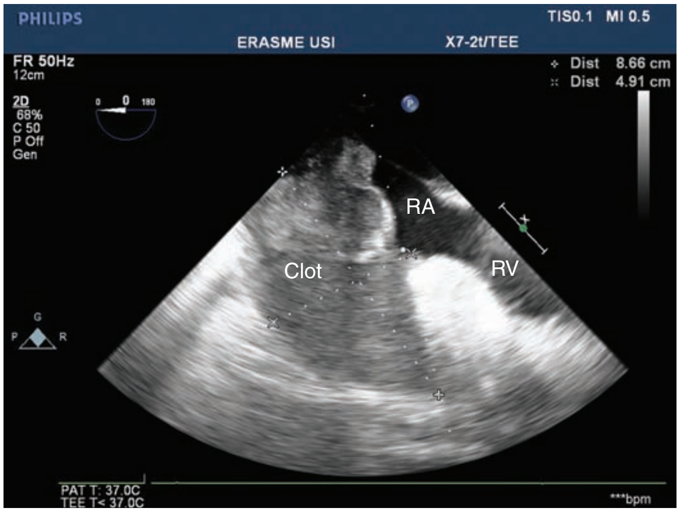

Figure 40-1 Localized tamponade. A large clot (8.7 × 4.9 cm) is compressing the right atrium (RA) and right ventricle (RV).

(endogenous or exogenous) stimulation of a usually well-contractile hypovolemic left ventricle.[5] LVOT obstruction is commonly associated with LV concentric or localized septal hypertrophy, a mitral-aortic angle smaller than 120 degrees, and excess tissue in the mitral valve.[5,6] Sometimes it may also occur in the context of mitral valvuloplasty with a flail or redundant subvalvular appendix. As a result of the Venturi effect, the anterior leaflet of the mitral valve is aspirated into the LVOT during systole (systolic anterior motion of the mitral valve leaflet), which causes partial obstruction (Figure 40-2A) and generates a high pressure gradient between the left ventricle and the aorta; this in turn results in a marked decrease in stroke volume. Mitral valve regurgitation may occur as a result of absent mitral valve leaflet coaptation during systole, with an eccentric regurgitant jet being observed in the direction of the left pulmonary veins (Figure 40-2B).

Identification of dynamic LVOT obstruction should be performed in several steps with TEE. Using different views, color Doppler techniques allow identification of the turbulent flow associated with LVOT obstruction. The midesophageal longitudinal and transverse views are used to evaluate motion of the anterior mitral valve leaflet, which moves anteriorly and partially obstructs the LVOT during systole (a good electrocardiographic signal is mandatory) (Figure 40-2A). This view is also useful for detecting premature closure of the aortic valve, but admittedly this sign is not specific because it is only a marker of low stroke volume. Via a deep transgastric view, pulsed wave Doppler should be applied from the midseptal area of the left ventricle to the LVOT (up to the aortic valve) in an effort to identify the location of the obstruction. Pulsed wave Doppler usually shows a brisk increase in velocity at the LVOT entrance. Continuous wave Doppler should also be used, in the absence of significant aortic valve disease, to better identify the typical dagger-shaped pattern (Figure 40-2C). Mitral valve regurgitation occurs frequently, and this pattern should not be confounded with mitral valve disease.

Once LVOT obstruction is identified, use of adrenergic (especially inotropic) agents should be discontinued. Fluids should be administered cautiously since these patients often have LV diastolic dysfunction. The fluid challenge technique should be

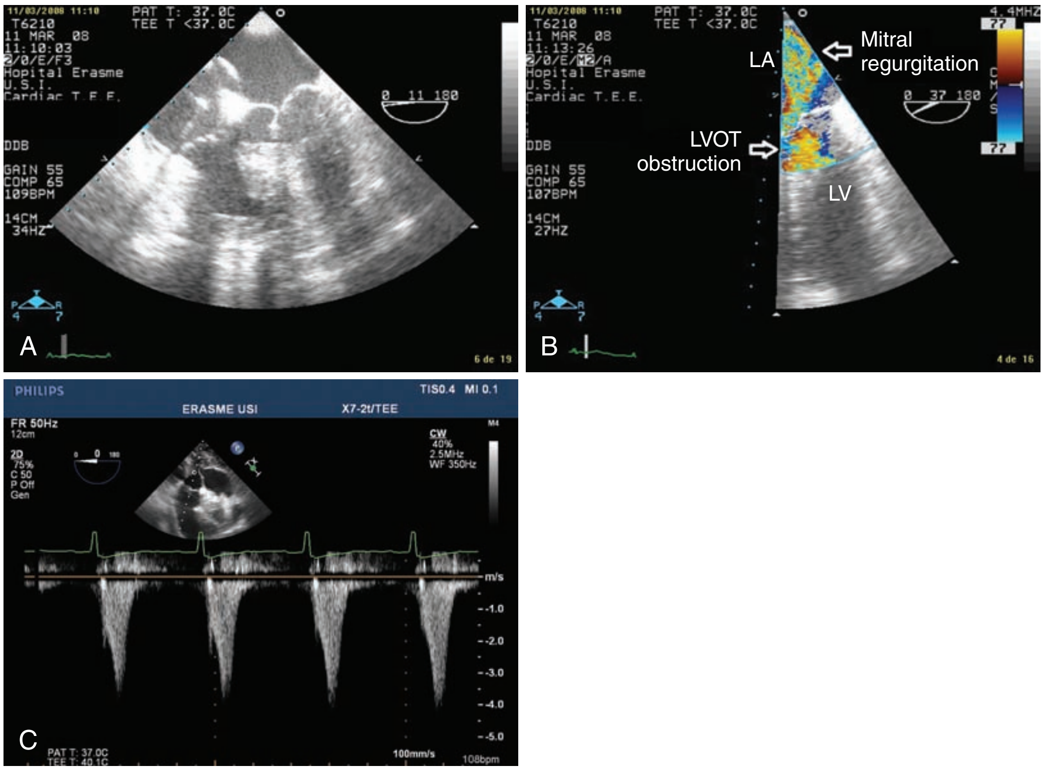

Figure 40-2 Dynamic left ventricular outflow tract (LVOT) obstruction. **A,** Two-dimensional image showing aspiration of the mitral valve leaflet into the LVOT during systole. **B,** Color Doppler view showing high velocity in the LVOT and a mitral valve regurgitation jet (*LA*, left atrium; *LV*, left ventricle). **C,** Pulsed wave Doppler showing the typical dagger-shaped pattern.

applied in small aliquots (100 to 200 mL), and fluid administration should be stopped when stroke volume fails to increase or when fluids are not tolerated because of increments in filling pressure or an exacerbation of mitral valve regurgitation. β-Blockers, often proposed in the cardiology suite, are difficult to use in shocked patients. The cause of the LVOT obstruction should be identified promptly to guide therapy. For example, if the LVOT obstruction is attributed to excess mitral valve tissue, surgical reintervention should be considered when medical therapy fails. *Valvular dysfunction* (mostly regurgitation) may occur after valve repair or replacement. It is beyond the scope of this chapter to analyze this subject in detail; however, it is recommended that an expert echocardiographer evaluate valvular structure and function before the end of the surgical procedure.[1,2,7] Occasionally, valvular dysfunction may develop as a late complication.

Aortic Dissection

Aortic cannulation and irruption of the cardiopulmonary bypass directly into the ascending aorta occasionally leads to iatrogenic aortic type A dissection (Chapter 8). After abdominal aortic surgery, thoracic aortic dissection may also occur as a result of the acute increase in blood pressure from aortic cross-clamping. These complications are rare and occur in less than 0.01% of all cardiac surgeries. Nevertheless, the perioperative echocardiographic examination should always include visualization of the aorta.[8]

Evaluation of Intraaortic Balloon Pump Position and the Pleural Space

Echocardiography is useful to ensure that the position of the intraaortic balloon is correct after insertion of an intraaortic balloon pump (IABP). The tip of the catheter should be positioned in the descending aorta, 2 to 3 cm after the origin of the left subclavian artery. This position yields the best hemodynamic performance of the IABP while minimizing its complications. In our center we guide IABP insertion by echocardiography whenever possible.

Despite the fact that the pleural space is usually opened during cardiac surgery and drained via mediastinal drains, accumulation of fluid and pneumothorax may occur postoperatively. Evaluation of a patient with hemodynamic instability or respiratory failure after cardiac surgery should include assessment of the pleura by means of ultrasound (Chapter 20).

Evaluation of Patients with Cardiac Transplants

Following cardiac transplantation, the most frequent hemodynamic alterations include hypovolemia, RV and LV dysfunction, and accumulation of fluid in the mediastinal space. Evaluation of hypovolemia should be conducted as described previously. RV dysfunction is more common in cardiac transplant recipients than in other cardiac surgery patients, possibly because the right ventricle is more sensitive to ischemia during the harvesting process and pulmonary artery pressure is greater following transplantation than in the pretransplant state. Fluids and blood accumulate in the entire pericardial mediastinal space in these patients because the pericardium is open. However, tamponade is less commonly observed, although significant compression of cardiac cavities may still occur as in other patients after cardiac surgery. It is worth mentioning that the left and right atria are markedly enlarged as a result of suturing of the middle and anterior parts of the donor atria on the posterior parts of the recipient atria. A suture band is always visible in the atria of a transplanted heart on echocardiography. Therefore evaluation of cardiac filling pressure and function should not be based on atrial size.

Pearls and Highlights

- TEE is the preferred imaging modality for hemodynamic monitoring, as well as for structural and functional cardiac examination, after cardiovascular surgery.
- Preoperative structural and functional evaluation of the heart is fundamental in patients undergoing cardiovascular surgery.
- Hypovolemia, LV and RV dysfunction, and cardiac tamponade are the most common findings in the early postoperative period.
- Localized cardiac tamponade may occur after cardiac surgery, with selective compression of the right atrium being the most frequent finding.
- Dynamic LVOT obstruction typically occurs in hypovolemic patients with a hypertrophic left ventricle when treated with adrenergic agents. Typical echocardiographic features include turbulent flow in the LVOT, anterior septal movement of the mitral valve in systole, and a dagger-shaped pattern on pulsed or continuous wave Doppler.
- The perioperative echocardiographic examination should include evaluation of the aorta and pleural space.
- When an IABP is used, correct position of the balloon should be assessed by echocardiography.
- Evaluation of cardiac filling pressure and function should not be based on atrial size (markedly enlarged) following cardiac transplantation.

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SECTION VII

Abdominal and Emergency Ultrasound

41

Various Targets in the Abdomen (Hepatobiliary System, Spleen, Pancreas, Gastrointestinal Tract, and Peritoneum)

GLYKERIA PETROCHEILOU | JOHN POULARAS | EMMANUEL DOUZINAS | ARIEL L. SHILOH | HEIDI LEE FRANKEL | MICHAEL BLAIVAS | DIMITRIOS KARAKITSOS

(CONSULTANT-LEVEL EXAMINATION)

Overview

Abdominal ultrasound can be used to obtain images of the hepatobiliary, urogenital, and pelvic structures. The approach to the urogenital system, point-of-care pelvic ultrasound, focused assessment with sonography for trauma, and other subjects are discussed in Chapters 42 to 46. In this chapter, examination of various abdominal targets such as the hepatobiliary system, spleen, pancreas, gastrointestinal (GI) tract, and peritoneum is featured as part of the holistic approach (HOLA) ultrasound protocol that was introduced in Chapter 1.

In the intensive care unit (ICU), patients' body habitus, the region of interest (ROI) in question, the presence of bowel gas, and acoustic windows influence the scanning approaches and types of transducer used. Moreover, physiologic stability affects the decision to pursue more robust imaging technologies such as computed tomography (CT) versus ultrasonography.

Technical Details of Abdominal Ultrasound Examination

Standard ultrasound examination is performed with curvilinear transducers (3.5 to 5 MHz), but phased-array or microconvex transducers can be of assistance. High-frequency transducers may be used to visualize the GI tract. It is helpful to apply HOLA scanning (Chapter 1) techniques (Figure 41-1). A detailed description of the technique suggested for abdominal scanning is illustrated in Figures 41 E-1 to 41 E-6. In brief, by sweeping the transducer from the epigastrium to the right posterior axillary line along a mainly sagittal approach, various structures are examined consecutively: the pancreas and left liver lobe anterior to the inferior vena cava (IVC), the right liver lobe (right hypochondrium), and the main portal triad (main portal vein [PV], common bile duct [CBD], and hepatic artery [HA]; the PV is posterior). The gallbladder (GB), liver, right kidney, and Morison pouch are also visualized. Oblique subcostal views allow visualization of both hepatic lobes and the hepatic veins (right, middle, left) converging toward the IVC. Intercostal, subcostal, and flank views complete the survey of the hepatobiliary system, pancreas, and spleen. The spleen is best visualized via a left posterolateral intercostal approach. Midabdominal and alternative (flank) views are used to visualize major vascular structures. The small intestine can be examined systematically in parallel overlapping lanes, although a cross-sectional examination of the colon is usually performed to identify its major segments. Bowel loops are best visualized if intraperitoneal fluid is present (see Figures 41 E-1 to 41 E-6).

The use of ultrasound to assess *liver size* is not particularly accurate; however, the maximal diameter of the right lobe (midaxillary line) should be less than 16 cm. Liver parenchyma should be homogeneous and isoechoic or slightly hyperechoic in comparison to the renal cortex. The *GB* is pear shaped with its longitudinal and transverse diameters normally measuring less than 10 and greater than 5 cm, respectively. It displays cystic features, including a smooth margin wall, anechoic interior, and distal acoustic enhancement. The anterior wall of the GB, best evaluated between its lumen and the liver parenchyma, should be less than 3 mm. The maximal normal diameter of the CBD is approximately 7 mm (up to 10 mm in the elderly or 12 mm after cholecystectomy). Intrahepatic bile ducts are identified occasionally, especially in the elderly, as anechoic thin cylindric tubes running anterior and parallel to branches of the PV. A guide for imaging the pancreas is to detect the splenic vein posterior to the pancreas. A fluid-filled stomach can be used as an acoustic window. The pancreas normally has a homogeneous appearance and is isoechoic or slightly hyperechoic relative to the liver. The spleen is a wedged-shaped organ with a craniocaudal diameter smaller than 12 cm and a thickness of less than 5 cm (midaxillary line) and is usually oriented parallel to the left 10th rib.

For imaging of the GI tract, graded compression is applied to displace interfering bowel loops with gas and feces, decrease the distance from the ROI, and assess the rigidity of the underlying structures. The *stomach* is scanned in longitudinal and transverse sections (subxiphoid approach), whereas a lateral transsplenic view best depicts the fundus. The *distal part of the esophagus* is visualized in the epigastrium by tilting the transducer cranially and using the left liver lobe as an acoustic window. Visualization of the gastric tube is a useful guide. The *duodenum* surrounds the head of the pancreas, and its third

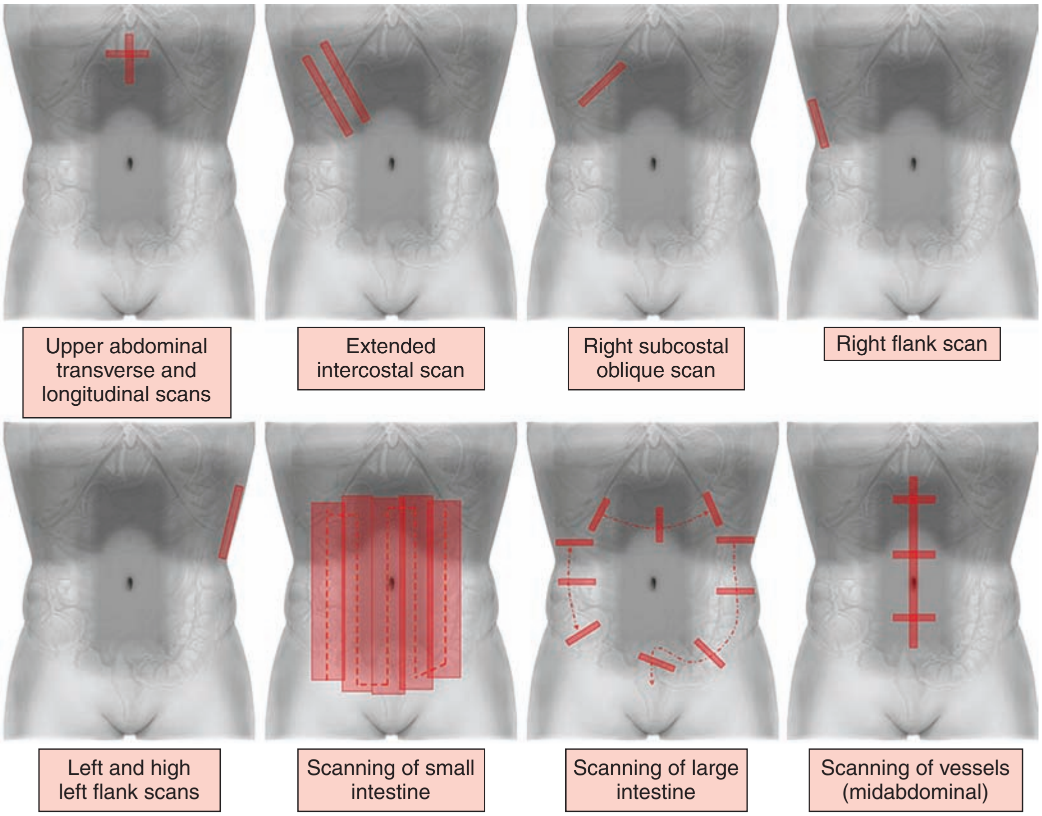

Figure 41-1 Standard and supplemental abdominal scanning planes (refer also to Figures 41 E-1 to 41 E-6).

part may be visible between the superior mesenteric artery and aorta. The *small intestine* cannot be evaluated over its entire length but is scanned in a general sweep by making vertical, parallel, and overlapping lanes. After identification of the *cecum*, the *colon* is usually scanned in transverse sections by carefully following along the ascending, transverse, and descending segments to the distal sigmoid into the pelvis. Finally, the *rectum* can be visualized through a distended urinary bladder. Normal bowel wall consists of five concentric layers (distal to the esophagus), and its thickness is practically unchanged from the stomach to the colon (2 to 4 mm). Distinguishing features of the small intestine include intense *peristalsis* and *valvulae conniventes* (mucosal folds are best visible with a fluid-filled lumen). Key features of the large intestine include a *fixed position* and *haustra*, which give the colon, especially the ascending and transverse parts, a segmented-like appearance. The "3, 6, 9 rule" refers to the maximal normal intestinal diameter (small intestine ≤3 cm, colon ≤6 cm, cecum ≤9 cm) and aids in identifying intestinal dilatation and distinguishing the small from the large intestine. Doppler provides information on the main mesenteric vessels and GI tract vascularity in general.

Disorders

HEPATOBILIARY SYSTEM, PANCREAS, SPLEEN

The presence of *hepatic portal venous gas* (HPVG) as a manifestation of pyelophlebitis (suppurative thrombophlebitis of the PV) may indicate a surgical emergency in ICU patients who are in shock (Figure 41-2). Gastrointestinal mucosal damage (e.g., ischemic bowel, arterial and venous mesenteric occlusion, perforated peptic ulcer), intraabdominal sepsis (e.g., cholecystitis, abscesses, diverticulitis), and ileus are possible causes. B-mode allows early diagnosis of HPVG by identifying hyperechoic foci moving with blood flow in the PV, whereas Doppler depicts sharp bidirectional spikes (an artifact appreciated audibly as a crackle). In smaller intraparenchymal portal branches, punctiform hyperechoic foci disseminated within the liver parenchyma may be depicted. If sufficient, these foci may display a linear branching pattern in either lobe. In supine ICU patients, gas bubbles accumulate in the rather anteriorly positioned left PV. HPVG should be distinguished from gas in the biliary tree and from other causes of hyperechoic foci, which are usually located randomly in the liver parenchyma (see Figure 41-2).[1]

Aerobilia, or *pneumobilia*, is commonly iatrogenic (e.g., after endoscopic retrograde cholangiopancreatography) or physiologic (incompetent sphincter of Oddi secondary to advanced age or drugs, bilioenteric bypass), but it could reflect pathologies such as a spontaneous biliary-enteric fistula secondary to gallstone ileus, perforating duodenal ulcer, neoplasia, trauma, or infections such as cholangitis or emphysematous cholecystitis. In contrast to HPVG, which usually extends peripherally, aerobilia is often located centrally in larger bile ducts (see Figure 41-2).

In the case of *hepatomegaly*, additional sonographic findings suggestive of the cause may be present. Hepatomegaly with dilated hepatic veins, IVC, and right heart chambers might indicate right-sided heart failure. A "starry-sky" liver appearance (hypoechoic parenchyma accentuating the portal venule walls) has been identified in patients with *acute hepatitis*, *toxic shock syndrome*, and *fasting liver* (Figure 41 E-7).[2] *Cirrhosis* initially causes hepatomegaly, but over time the liver becomes shrunken with an irregular surface and echogenic

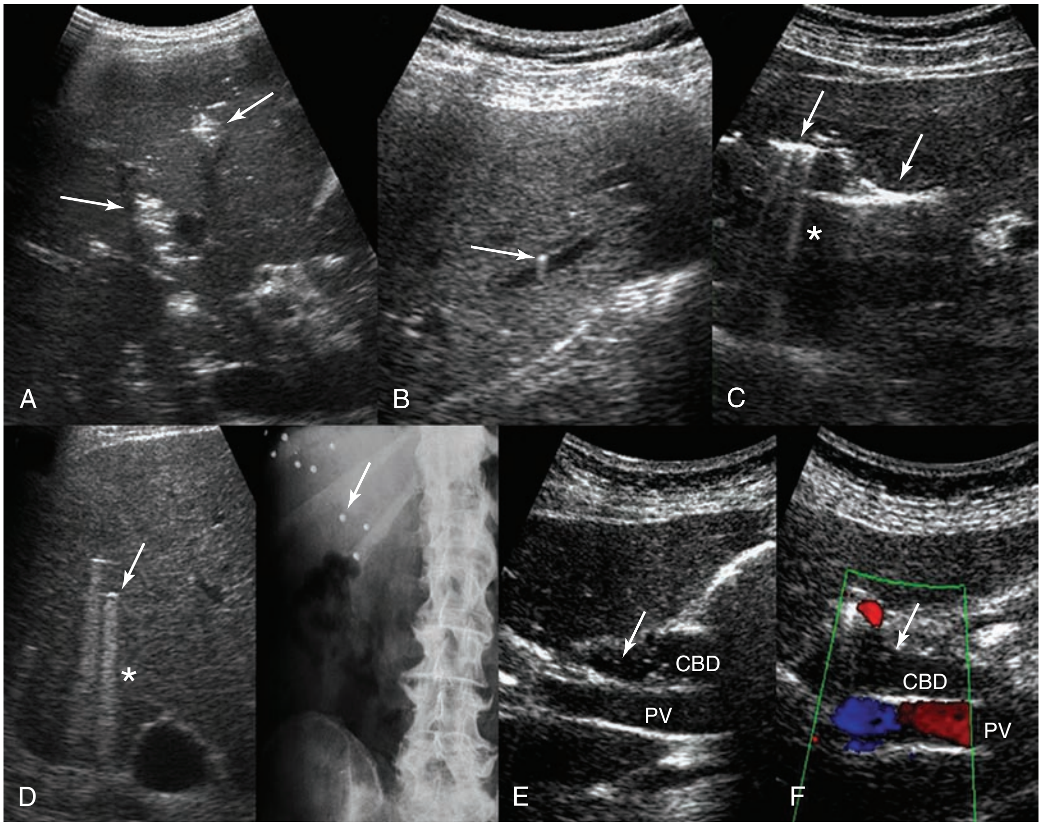

Figure 41-2 **A,** Transverse intercostal liver view: hepatic venous portal gas is demonstrated as patchy, highly reflective areas in the right liver lobe (*arrows*). **B,** Longitudinal left liver lobe view: aerobilia depicted as hyperechoic foci (*arrow*) adjacent to a branch of the portal vein. **C,** transverse left liver lobe view: aerobilia depicted as branching echogenic lines (*arrows*) in the liver parenchyma with associated reverberation artifacts (*). **D,** Sonographic visualization of randomly located hyperechoic foci (*arrow*) with comet-tail (*) artifacts produced by bullets embedded in the liver parenchyma (*arrow*, radiography). **E** and **F,** Aerobilia: visualization of moving hyperechoic foci (*arrows*) within the common bile duct. *CBD*, Common bile duct; *PV*, portal vein.

coarse or nodular parenchymal appearance (Figure 41-3). Evidence of *portal hypertension* (PH) includes a PV diameter greater than 13 mm, splenic and superior mesenteric vein diameter greater than 10 mm, and variation in PV diameter of less than 20% with respiration. PV blood flow gradually becomes monophasic (without respiratory variation), biphasic (to and fro), and ultimately hepatofugal (away from the liver). The HAs become enlarged and tortuous with increased flow. Portosystemic venous collaterals are highly diagnostic of PH (e.g., hepatofugal flow in a paraumbilical vein dilated >2 mm is 100% specific). Secondary signs of PH are splenomegaly and ascites (see Figure 41-3). A *transjugular intrahepatic portosystemic shunt* is used to treat complications of PH. Its function is monitored with Doppler ultrasound since stent stenosis or relapse of PV flow toward the liver indicate shunt malfunction.

Focal hepatic lesions (occasionally associated with hepatomegaly) are easily detected, and *hepatic abscesses* should be kept in mind in the ICU (Figure 41-4). An ill-defined, heterogeneous lesion, typically showing no central perfusion on Doppler, is usually encountered. Echogenic gas bubbles may be present. Travel history, serologic tests, and physical examination help in diagnosing an amebic abscess or other specific infections. Metastatic and intrinsic *hepatic tumors* may be incidental findings; however, since variable echo patterns are encountered depending on lesion histology, patients should be referred to imaging specialists (see Figure 41-4). *Hepatic vein thrombosis* (Budd-Chiari syndrome) is manifested as an acute onset of abdominal pain, ascites, and hepatomegaly. In the acute phase the liver is enlarged and tender with a heterogeneous mottled echo pattern. The hepatic veins may appear isoechoic to adjacent parenchyma as a result of an intraluminal echogenic thrombus, and Doppler demonstrates abnormal (absent) flow. *Acute PV thrombosis* is associated with sepsis, trauma, hypercoagulable states, neoplasms, and acute dehydration. The PV appears dilated, but an acute thrombus may be relatively anechoic and therefore be overlooked unless Doppler is used. Finally, *liver transplant* scanning can detect abnormalities in the HA or PV (e.g., thrombosis, stenosis) and CBD complications (e.g., leaks, strictures, necrosis, stones).[3]

In the ICU, *cholestasis* is attributed mainly to sepsis, impairment of venous return, trauma, ischemic hepatitis (shock liver), or drugs. Ultrasound is used to screen for both size and continuity of the intrahepatic and extrahepatic bile ducts to exclude obstruction (e.g., choledocholithiasis, blocked biliary stent). A dilated CBD appears as an enlarged, anechoic tubular structure in the main portal triad, anterior to and following the course of the main PV. A CBD larger than 1.1 cm in diameter is suggestive of obstruction. Dilated intrahepatic bile ducts with associated PV branches are shown as anechoic “tramlines” coursing through the hepatic parenchyma (Figure 41 E-8). *Acute cholangitis*, a complication of choledocholithiasis, is a possible cause of fever in the ICU. However, given the low sensitivity of ultrasound for

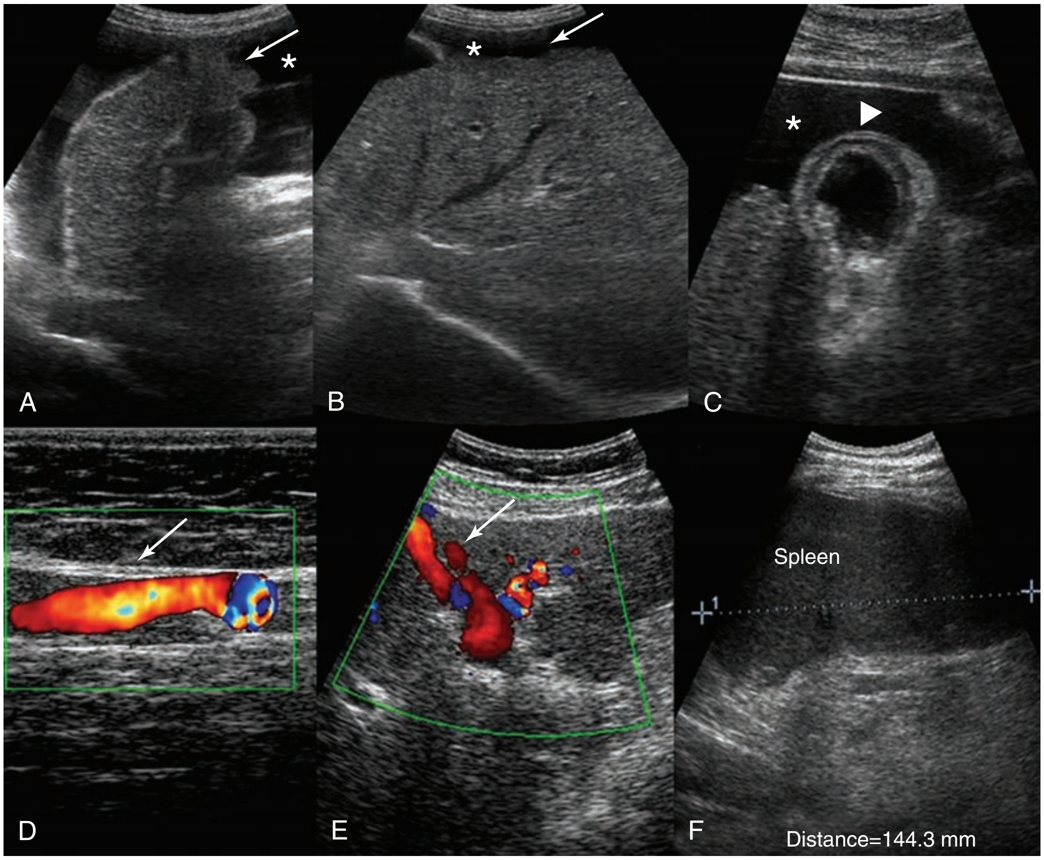

Figure 41-3 Liver cirrhosis. **A,** Anechoic ascites (*) outlining the irregular surface of the left liver lobe (*arrow*). **B,** Contracted right liver lobe with an irregular (coarsening) echotexture. **C,** Ascites (*) facilitates visualization of a nodular liver contour and a thickened gallbladder wall (*arrowhead*). A paraumbilical vein (*arrow*) larger than 2 cm is depicted traversing the anterior abdominal wall (**D**) and the falciform ligament (**E**). **F,** Splenomegaly (length, 14.4 cm).

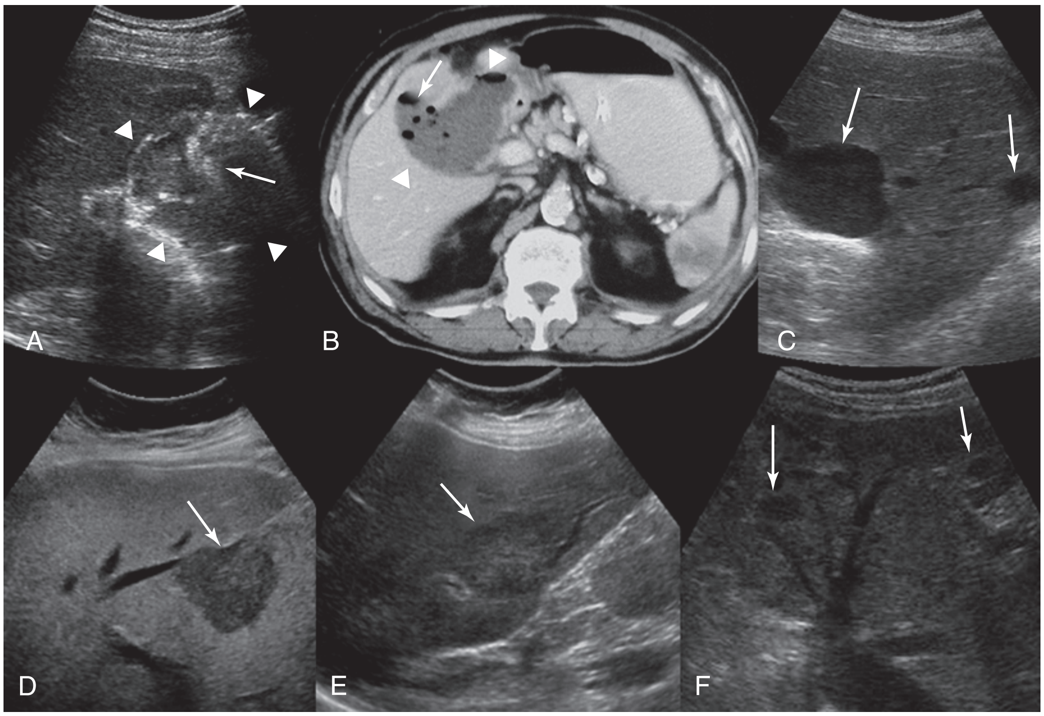

Figure 41-4 Subhepatic abscess (*arrowheads*). Sonographic visualization of hyperechoic foci (*arrow*) reflecting gas bubbles (**A**) and computed tomography (**B**) confirm the presence of air (*arrow*) within the abscess. **C,** Sharply defined margins, no internal echoes, and increased "through transmission" are demonstrated in these simple cysts in the right liver lobe (*arrows*). **D,** Hepatocellular carcinoma depicted as a hypoechoic mass (*arrow*). Colon cancer (**E**) and retroperitoneal sarcoma (**F**) metastases (*arrows*) are depicted as hypoechoic masses in the liver parenchyma. (**D,** *Courtesy Dr. K. Shanbhogue.)*

depicting stones in bile ducts (approximately 50%), normal findings on examination should not exclude it from the differential diagnosis.

Acute acalculous cholecystitis (AAC) is not rare in the ICU (Figure 41-5). Prolonged fasting, total parenteral nutrition, mechanical ventilation, trauma, burns, sepsis, drugs (opiates, sedatives, vasopressors), multiple transfusions, and shock are probable contributing factors leading to bile stasis, GB ischemia, and ultimately acute inflammation in the absence of gallstones. Left untreated, AAC may progress rapidly to GB gangrene, perforation, and empyema (incidence of approximately 40%), which are associated with high mortality. Prompt diagnosis and intervention are crucial. Although high clinical suspicion remains important in diagnosing AAC, the comorbid conditions and status of patients do not facilitate evaluation based solely on clinical criteria. Imaging tests used are ultrasound, CT, and hepatobiliary iminodiacetic acid cholescintigraphy. Ultrasound findings include the *sonographic Murphy sign* (maximal tenderness elicited by transducer pressure over the GB), thickened GB wall (>3.5 mm), distended GB or sometimes *hydrops* (which refers to distention with clear fluid), sludge (slightly hyperechoic material, echogenic dots—microlithiasis), intramural striations, and pericholecystic fluid (halo) or subserosal edema. However, GB wall thickening becomes illusory when contiguous to isoechoic hepatic parenchyma with superimposed edema, whereas "*GB hepatization*" (the GB looks isoechoic to liver because of massive sludge) makes recognition of the GB difficult (see Figure 41-5). Furthermore, the Murphy sign, which is crucial for sonographic diagnosis, may be absent in patients in the ICU as a result of analgesia and sedation. A thickened GB wall may be also encountered in patients with hypoproteinemia, hepatitis, heart failure, and ascites, whereas sludge and hydrops may simply indicate a prolonged lack of bile turnover. Repeated ultrasound monitoring may be of value, whereas *guided percutaneous cholecystostomy* establishes the diagnosis and results in stabilization of septic patients (thus cholecystectomy can be performed electively).[4-11]

GB stones are identified sonographically as mobile hyperechoic structures with posterior acoustic shadowing (see Figure 41-5). Stones may cause *acute cholecystitis*, which has an appearance similar to that of ACC. Complications of acute cholecystitis, such as GB empyema, result in increased morbidity and mortality and thus necessitate prompt intervention. However, GB empyema cannot be reliably differentiated from uncomplicated AAC because echogenic material consistent with pus within the distended GB is indistinguishable from sludge. Sonographic findings suggestive of *gangrenous* cholecystitis include floating intraluminal membranes (representing sloughed mucosa) and echogenic foci within the GB wall or lumen secondary to gas. Acute GB *perforation* with free intraperitoneal bile leading to peritonitis is rare. Usually, *subacute perforation* occurs and results in pericholecystic abscess formation within the GB fossa, liver, or peritoneal cavity that appears as a complex fluid collection with inflammatory changes in adjacent fat (Figure 41 E-9). *Emphysematous* cholecystitis is a rare complication associated mainly with gas-forming bacteria in elderly patients with diabetes. The diagnosis is suggested by bright air reflections in the GB wall with ring-down artifacts and moving gas echoes within the GB lumen.[11]

Pancreatic pathology is usually evaluated with CT. In the case of *acute pancreatitis*, contrast-enhanced CT (CECT) is indicated for diagnosis, initial staging, and follow-up. Ultrasound is an alternative monitoring tool for identifying complications

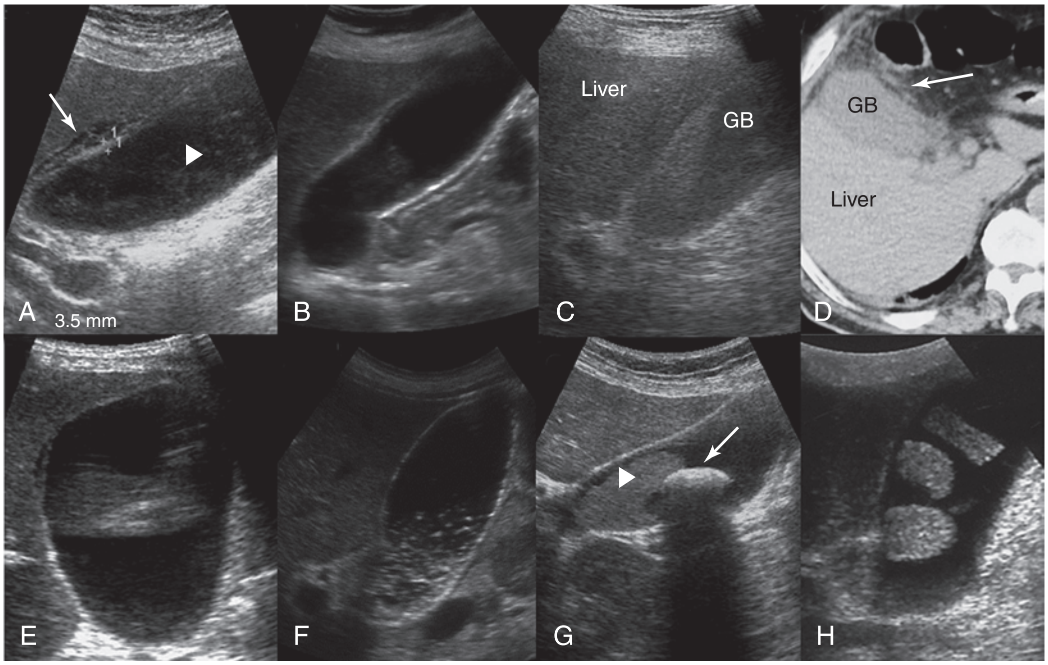

Figure 41-5 **A,** Longitudinal image of the gallbladder (GB) demonstrating marginal anterior wall thickening with associated edema separating the layers of the wall (*arrow*) and intraluminal sludge (*arrowhead*) in a patient with acute calculous cholecystitis. **B,** Anterior GB wall thickening and intraluminal sludge in a patient with acute acalculous cholecystitis (AAC) (a diagnosis of AAC requires a high level of clinical suspicion and presumably additional testing). **C,** Massive sludge within the GB that appears isoechoic relative to the liver parenchyma (GB hepatization). **D,** Computed tomography scan demonstrating GB hepatization (*arrow* = pericholecystic inflammatory changes). **E,** Dilated GB (11 × 6 cm) filled with clear fluid (hydrops). **F,** Biliary sludge demonstrated as a dependent layer of nonshadowing midlevel echoes (pseudolithiasis). **G,** Large solitary GB stone (*arrow*) with prominent acoustic shadowing and dense sludge (*arrowhead*). **H,** GB stones attached to its wall in a bizarre manner (incidental finding).

(e.g., fluid collection, abscess, pseudocyst, pseudoaneurysm, portal or splenic venous thrombosis, development of abdominal compartment syndrome) or for guiding interventional procedures (Figure 41 E-10, Video 41-1). A *pseudocyst* appears as a well-defined, smooth-walled anechoic mass often with multiple loculations and internal septations. Internal debris and fluid-fluid levels indicate hemorrhage or infection. Dilated biliary and pancreatic ducts suddenly terminating in a hypoechoic mass at the head of the pancreas are characteristic of a tumor (Figure 41 E-11). The diaphragmatic splenic surface is commonly detected sonographically in the ICU before a left thoracentesis is performed. In the case of *splenomegaly*, interrogation of the parenchymal echotexture does not usually indicate an underlying cause. A *splenic abscess* displays variable ultrasound appearances depending on the stage of infection (similar to all abdominal abscesses). Ultrasound may guide percutaneous aspiration for diagnosis and catheter placement. In an ICU patient with shock, "delayed" *splenic rupture* following blunt abdominal trauma (Figure 41 E-12), spontaneous splenic rupture (e.g., metastasis, hematologic disorders, infarction, infections), and rupture of a splenic artery pseudoaneurysm are possible causes of *hemoperitoneum*. The spleen may regenerate after splenectomy (Figure 41 E-13).

Solid organ injury is best visualized with CECT. Ultrasound may be used for diagnosis and follow-up examinations, especially in unstable patients who cannot be transferred. Acute liver or spleen lacerations appear as fragmented hyperechoic or hypoechoic areas. A diffuse hyperechoic pattern with hypoechoic areas may be observed in patients with liver contusion (Figure 41 E-14). Contained intraparenchymal hemorrhage, initially isoechoic or slightly hyperechoic with indistinct margins, may form a well-defined, hypoechoic hematoma or dissolve over time. Subcapsular hematoma appears as a crescent-shaped, hypoechoic (occasionally isoechoic) stripe surrounding the organ. Recently, contrast-enhanced sonography was found to enhance visualization of liver and spleen injuries.

GASTROINTESTINAL TRACT AND PERITONEUM

In the ICU, a key feature in interpreting GI tract pathophysiology is *gut failure*, which represents a syndrome of temporary or permanent intestinal malabsorption. It may be due to various causes such as iatrogenic disorders (short bowel syndrome), blunt or penetrating trauma, ischemia (arterial, venous embolism/thrombosis, shock), obstruction (adhesions, hernias), infiltrative disorders (neoplasia, carcinoid, amyloidosis), and functional disorders (pseudoobstruction, paralysis, bacterial overgrowth, inflammatory bowel disorders).

Ultrasound can be used to assess correct positioning of a feeding tube by visualizing a tubular structure with strong acoustic shadow. Acute *gastric dilatation* (e.g., acute abdomen) or *gastric stasis* (e.g., peptic ulcer) appears as a large fluid collection with multiple echoic particles and sometimes air or fluid levels (Figure 41-6). Ultrasound facilitates dynamic evaluation of the intestinal wall and surrounding environment by demonstrating peristalsis, which when suggestive of an acute abdomen is a strong argument against emergency surgery, and wall thickening, which often involves a large portion of the intestine even with focal disorders.

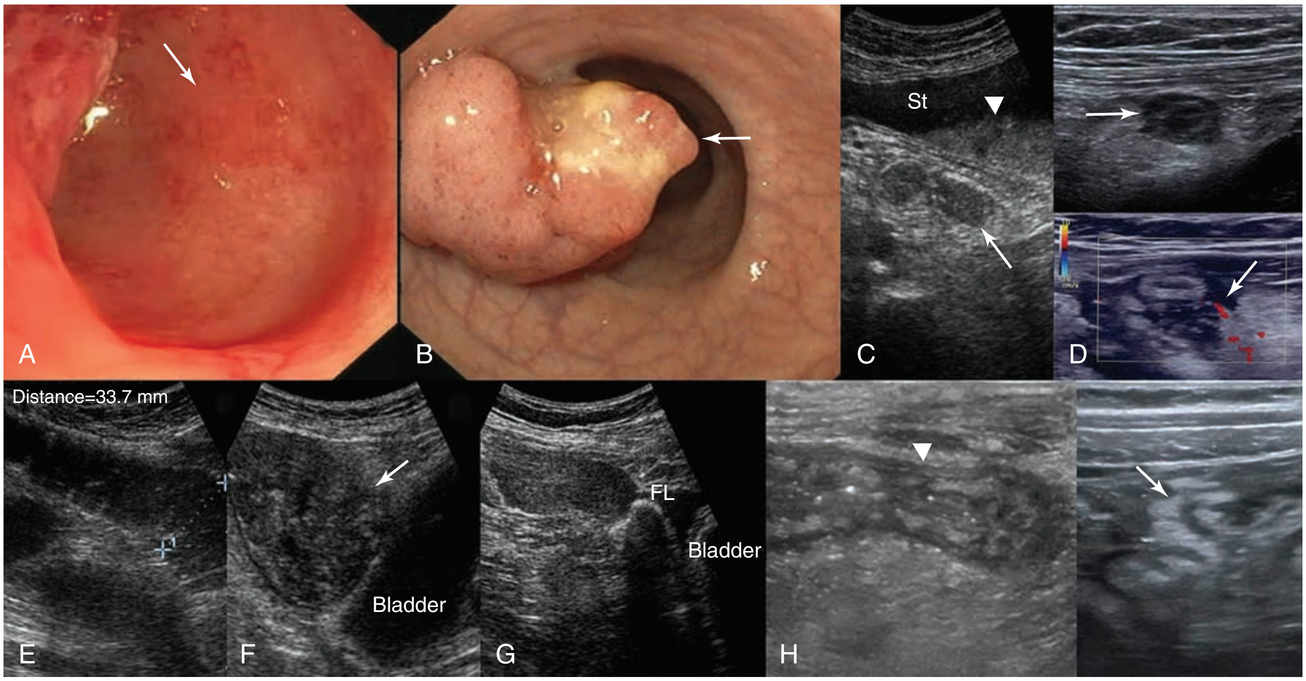

Figure 41-6 Endoscopic views of the colon. **A,** Areas of patchy erythema (*arrow*) reflecting early mucosal changes associated with ischemic colitis. **B,** Depiction of a polypoid adenocarcinoma. **C,** Sonographic view of an acutely dilated stomach (St) with a fluid-fluid level (*arrowhead*); the third part of the duodenum (*arrow*) appears normal. **D,** Appendicitis. On a transverse B-mode image the inflamed appendix appears as a noncompressible sausage-like structure that is surrounded by hyperechoic fat as a result of inflammation (*top*); on a transverse color mode scan the inflamed appendix appears as a compressible thickened structure with increased vascularity of the surrounding tissues, and a periappendiceal fluid collection is evident (*arrow*). The findings are consistent with rupture (*bottom*). **E,** Obstructive ileus. **F,** Dilated (>3 cm) small intestinal loops secondary to a large intestinal tumor (*arrow*). **G,** Peritoneal metastases secondary to ovarian cancer: depiction of a solid tumor (*arrow*) causing lumpy thickening of the peritoneal surface (*Fl*, ascites). **H,** Thickened bowel wall (*arrowhead*) and hyperechoic adjacent mesenteric fat with ill-defined borders in a patient with Crohn disease.

Acute mesenteric ischemia is caused by arterial or venous occlusion (or both) or low-outflow states. Mesenteric embolism or thrombosis is best appreciated with CECT. Doppler and contrast-enhanced ultrasound contribute greatly by detecting stenosis or occlusion of the celiac trunk and superior and inferior mesenteric arteries (e.g., significant stenosis of the celiac trunk is present with a peak Doppler systolic velocity >1.5 m/sec) and microperfusion intestinal wall defects. The role of endoscopy in identifying early signs of ischemic colitis cannot be overstated (see Figure 41-6). Ultrasound findings of *bowel ischemia* (right side involvement more common with several causes) include massively distended bowel loops, abolition of peristalsis, wall thickening (thickened hypoechoic wall of 5 to 7 mm as a result of venous causes but a thin wall of 1 to 2 mm as a result of arterial causes), no bowel wall perfusion, disappearance of wall stratification, and in late stages, intramural gas (hyperechoic foci within the bowel wall), portal venous gas, and peritoneal effusion.[12,13]

In the case of *intestinal dilatation*, ultrasound contributes to distinguishing obstructive from *paralytic ileus*. Findings suggestive of intestinal obstruction include dilated fluid-filled loops ("3, 6, 9 rule"), increased peristalsis of distended segments (ineffective contractions may cause to-and-fro fluid movements), and collapsed loops distal to the obstruction (see Figure 41-6). A small amount of intraperitoneal fluid is frequently present. Analysis of the dilated loops may help in determining the level of obstruction, and sometimes the cause is also identified (e.g., neoplasm, hernia, Crohn disease, intussusception, bezoar, or gallstone; see Figure 41-6). Prolonged obstruction causes *intestinal paralysis*, although loops distal to the obstruction appear contracted. In contrast, in paralytic ileus the entire intestine is congested, no empty bowel segments are visualized, fluid-filled levels may be present within dilated loops, and decreased or absent peristalsis is evident during real-time scanning.[14] In *pseudomembranous colitis*, a potentially life-threatening complication of antibiotic therapy, marked thickening of the colonic wall (frequently manifested as pancolitis), lumen collapse, pericolic fat changes, and hemorrhagic ascites may be observed. *Neutropenic enterocolitis* in immunosuppressed patients is characterized by ileal and to a variable extent right-sided colonic involvement. Bowel wall thickening, alteration of adjacent mesenteric fat, and ascites may be present.

Primary GI tract lesions (e.g., colon or gastric cancer, acute colonic diverticulitis) and surgical emergencies (e.g., appendicitis) can be identified with ultrasound. Further analysis is beyond the scope of this chapter; however, it should be emphasized that the role of endoscopy in diagnosing GI tract lesions is invaluable (see Figure 41-6). In shock states, sonographic detection of *fluid sequestration* within the bowel, which can reach several liters, may indicate hypovolemic mechanisms secondary to digestive disorders. The presence, amount, and rate of accumulation (through serial examinations) of *intraperitoneal fluid* can be detected sonographically. *Free* fluid flows, under the effect of gravity, to the most dependent peritoneal recesses (e.g., in supine patients to the hepatorenal recess and pelvic cul-de-sac) and outlines them as anechoic stripes with sharp edges. *Loculated* fluid collections resemble space-occupying lesions that displace bowel and adjacent organs. *Transudative ascites, urine, and bile are anechoic, whereas hemorrhage, pus, malignant ascites, and spilled GI contents may include echogenic particles, layering debris, or septations*. Ultrasound-guided paracentesis may facilitate the diagnosis (especially by ruling out bacterial peritonitis and distinguishing a pus collection from postoperative sterile blood) or provide symptomatic relief of tense ascites. *Perforation of the GI tract* may occur suddenly and be severe enough to produce shock; moreover, physical examination in sedated ICU patients is often unrevealing. Ultrasound may detect *pneumoperitoneum* (free intraperitoneal air) during scanning of the right intercostal area as hyperechoic foci or echogenic lines on the ventral surface of the liver with posterior reverberations that should be discriminated from gas echoes in the lumen of the GI tract (e.g., hepatodiaphragmatic interposition of the colon) or lung. Because intraperitoneal *abscesses* are usually formed in dependent recesses, pelvic scanning is crucial. Abscesses containing gas may be mistaken for gas-filled bowel and be overlooked.[14]

Metastatic implants (originating from the ovaries, pancreas, or GI tract) are the most common peritoneal tumors and appear as hypoechoic solid masses of varying size on the peritoneal surfaces (see Figure 41-6). Ascites is usually present, often with echogenic debris and septations. *Retroperitoneal adenopathy* is associated with lymphoma or metastatic cancer (testicular, renal, pelvic, GI tract, melanoma) or infection (e.g., human immunodeficiency virus–positive patients). *Retroperitoneal fluid collections* include hemorrhage (e.g., rupture of an abdominal aneurysm), infection, urinoma, and pancreatic fluid. Retroperitoneal masses or adenopathy and hypercoagulable states may cause abdominal venous (iliac veins, IVC) thrombosis (Videos 41-2 and 41-3). However, IVC thrombosis usually appears as a sequela of deep venous thrombosis of the lower limbs. Under certain circumstances, IVC thrombi, especially in patients in whom anticoagulation is contraindicated, may be treated by placing IVC filters.

IMAGING CASE: IMAGE "PUZZLE"

A resident was scanning the hepatobiliary system of a 50-year-old male trauma patient with severe systemic inflammatory response syndrome. Scanning of the GB revealed a polyp and a rather peculiar structure with acoustic shadowing that seemed to originate from the wall of the GB (*arrow*). However, follow-up examinations showed the cause of this image "puzzle" to be a normal bowel loop.

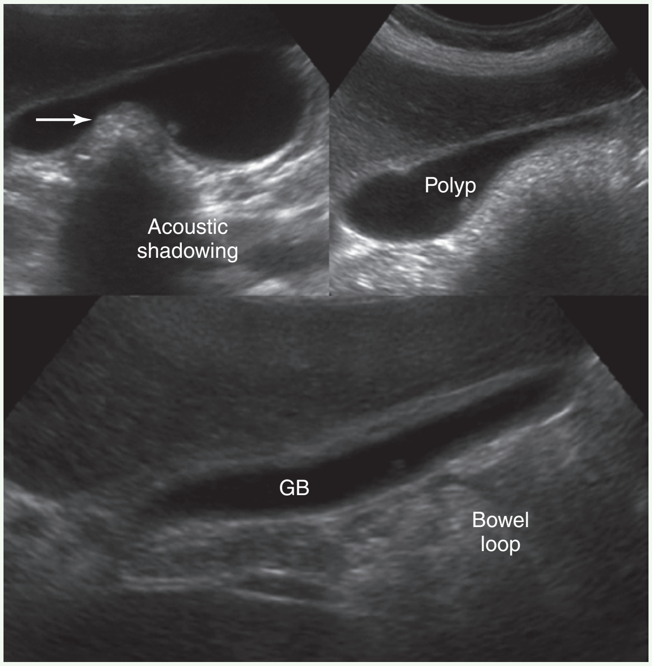

Figure 41-7

IMAGING CASE: DIAGNOSTIC PREDICAMENT

In a 75-year-old male patient with blunt abdominal trauma, oliguria and shock developed and the lower part of his abdomen appeared to be distended (at that time bowel perforation seemed to be a possible scenario). Abdominal ultrasound revealed normal bowel loops floating in a hypoechoic fluid collection (intraperitoneal because it was delineating the bowel loops) alongside the balloon of an indwelling bladder catheter (*arrow*). The bladder could not be recognized. Serial examinations confirmed the presence of uroperitoneum on the grounds of spontaneous bladder rupture.

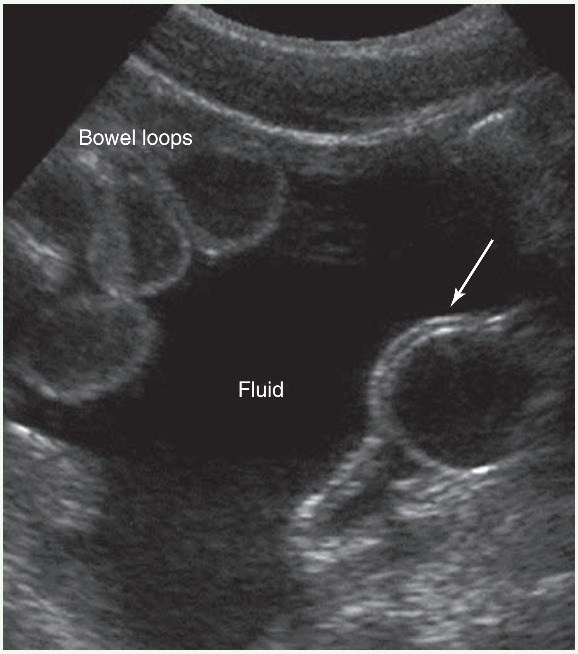

Figure 41-8

IMAGING CASE: GALLBLADDER PERFORATION AND ABSCESS FORMATION

A septic 72-year-old female patient with pneumonia was admitted to the ICU because of respiratory failure. She was intubated and mechanically ventilated. Antibiotic therapy and supportive measures resulted in gradual clinical improvement. Nevertheless, after approximately 1 week she experienced another septic episode. General chest ultrasound was inconclusive. However, a lesion adjacent to the GB suggestive of perforation (arrow) and another one suggestive of abscess formation were detected by abdominal ultrasound scanning (confirmed by CT). The patient was treated surgically.

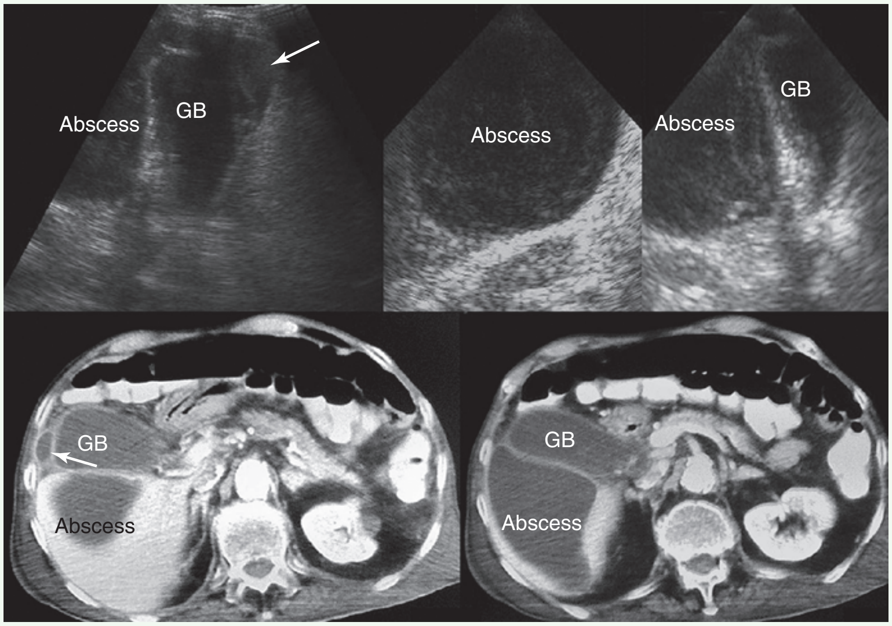

Figure 41-9

Pearls and Highlights

- Depiction of blurred images because of various factors may disappoint new users of abdominal ultrasound in the ICU; however, image quality could be improved by making scanning adjustments. Because a single examination may be inconclusive, performance of serial examinations (monitoring) is usually warranted.
- The presence of HPVG or aerobilia should not be interpreted lightly because they may correspond to serious underlying pathology.
- Ultrasound is valuable in detecting GB abnormalities; however, diagnosis of GB disorders such as AAC requires a high level of clinical suspicion and presumably additional testing.
- Solid organ injury is best visualized with CECT, although ultrasound is still useful for diagnosis and monitoring purposes in the ICU.
- Ultrasound depicts gastric dilatation, bowel obstruction (paralytic vs. obstructive ileus) and ischemia, intraperitoneal fluid, or pneumoperitoneum, thereby aiding in the interpretation of gut failure syndrome.

REFERENCES

For a full list of references, please visit www.expertconsult.com.

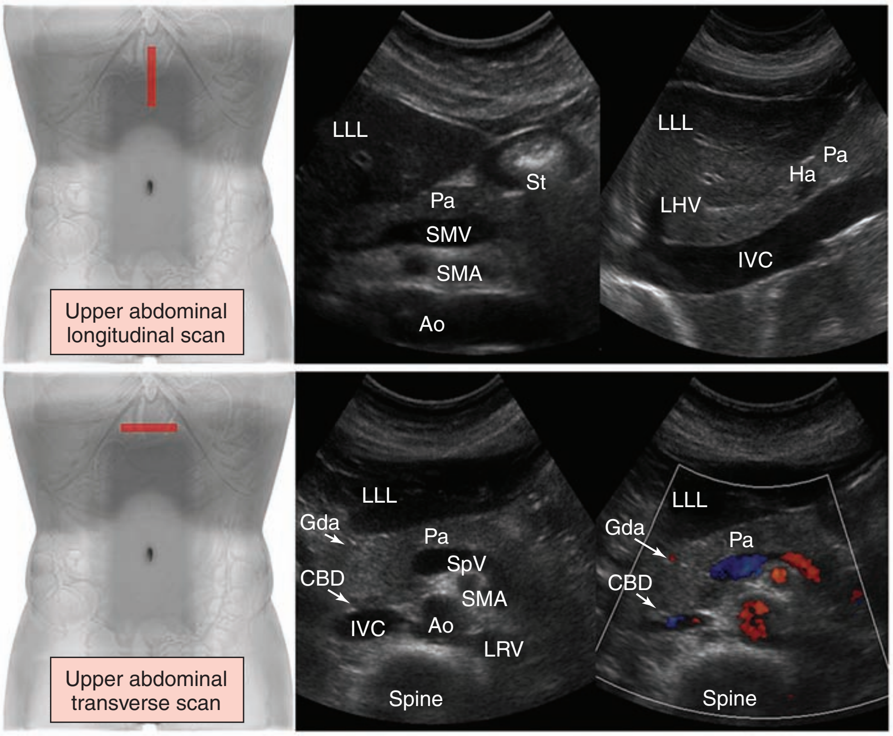

Figure 41 E-1 (*Top*) Upper abdominal scan. Longitudinal views of the structures that are visualized from anterior to posterior are presented: left liver lobe, pancreas, and midabdominal vessels. The aorta and superior mesenteric artery (arising from the aortic anterior wall) are visualized toward the midline (*left*). By sweeping the transducer slightly to the right, the inferior vena cava is visualized (*right*). (*Bottom*) Transverse views. The transducer is angled inferiorly by using the left liver lobe as an acoustic window to image the pancreas and midabdominal vessels. The aorta and splenic vein crossing over the superior mesenteric artery are used as landmarks to identify the pancreas. The gastroduodenal artery and common bile duct assist in outlining the lateral margin of the head of the pancreas. *Ao*, Aorta; *CBD*, common bile duct; *Gda*, gastroduodenal artery; *Ha*, hepatic artery; *IVC*, inferior vena cava; *LHV*, left hepatic vein; *LLL*, left liver lobe; *LRV*, left renal vein; *Pa*, pancreas; *SMA*, superior mesenteric artery; *SMV*, superior mesenteric vein; *SpV*, splenic vein; *St*, stomach (gastric antrum).

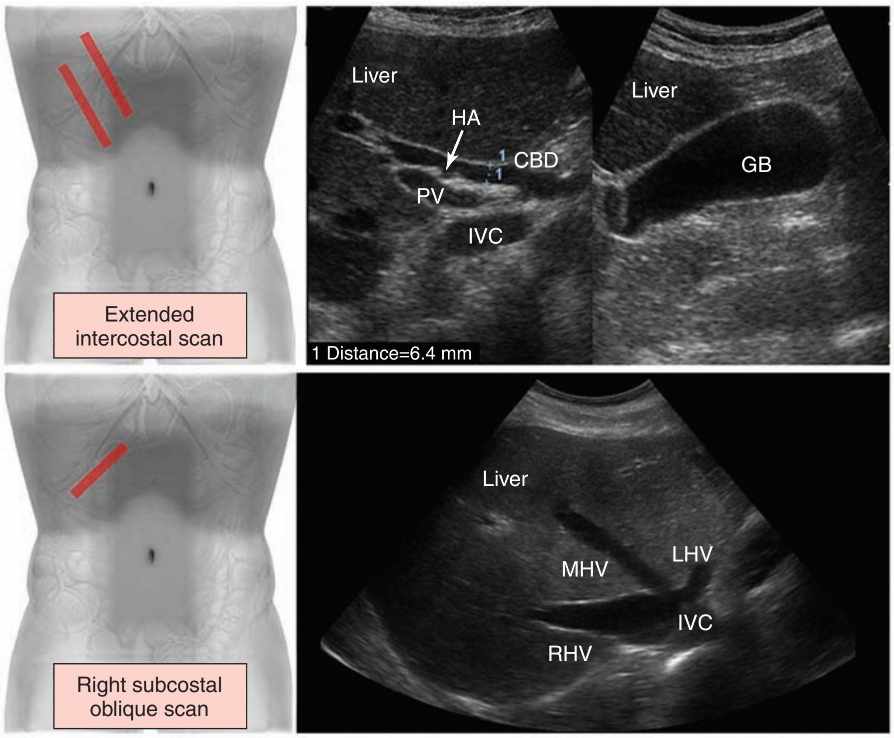

Figure 41 E-2 (*Top*) Extended intercostal scan. The transducer is oriented longitudinally and lateral to the midline in an intercostal space or below the costal arch. In the porta hepatis, the common bile duct (CBD) is depicted between the portal vein (PV) and the hepatic artery (HA). Including the inferior vena cava (IVC), the three tubular structures (CBD, PV, HA) are described as the "parallel channel sign" (*left*). Scanning can be advanced in the same direction along the costal arch to define the gallbladder (GB) in longitudinal section (*right*). (*Bottom*) Right subcostal oblique scan. The transducer is placed below the right costal arch in a slightly cephalad angulation. The hepatic veins (*LHV*, Left hepatic vein, *MHV*, middle hepatic vein, *RHV*, right hepatic vein) are depicted as they empty into the IVC just beneath the right side of the diaphragm.

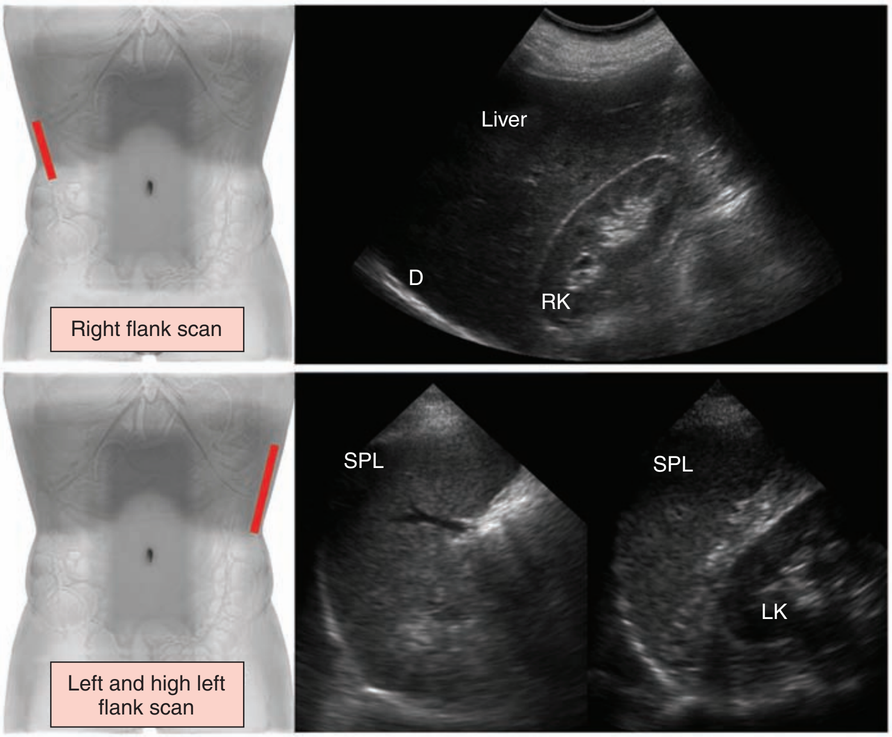

Figure 41 E-3 (*Top*) Right flank scan. The transducer is placed lateral to the midaxillary line to evaluate the pleural angle distal to the diaphragm (D), the right kidney (RK), the right liver lobe, and the hepatorenal space (Morison pouch). (*Bottom*) For left and high left flank (intercostal) scans, the transducer is placed in an intercostal space cranial to the left flank and angled cephalad to demonstrate the spleen (SPL) in longitudinal section. The length and thickness of the spleen are measured at the level of the splenic hilum (*left*). By sweeping the transducer caudally from the high flank scan, the left kidney (LK) appears in longitudinal section posterior to the spleen, and the splenorenal space can be evaluated (*right*).

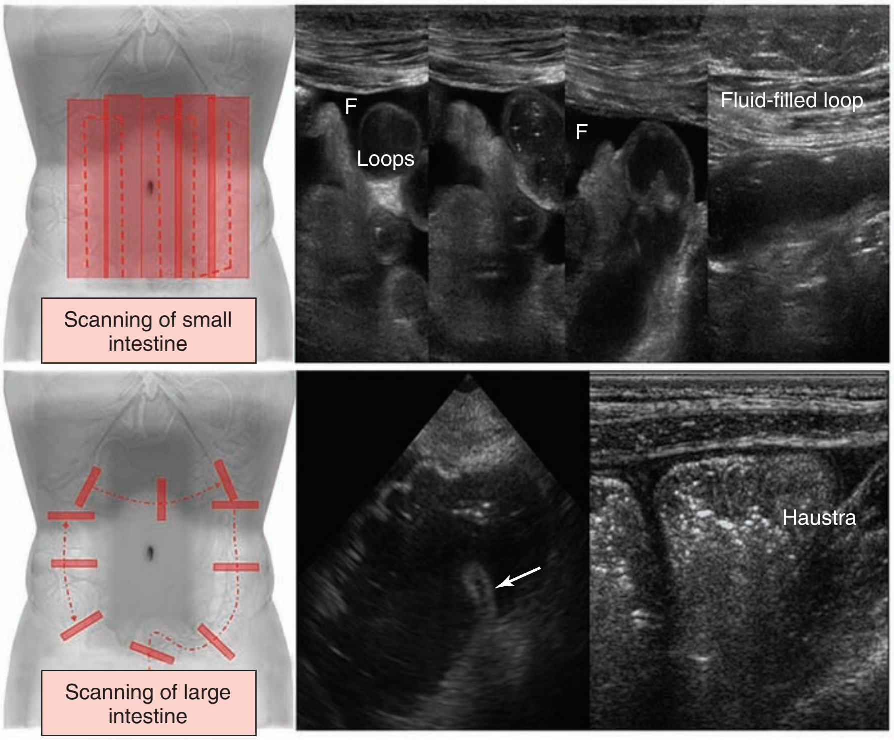

Figure 41 E-4 (*Top*) The small intestine can be examined systematically by using parallel overlapping lanes. Small intestinal loops are best visualized if intraperitoneal fluid (F) is present. (*Bottom*) Cross-sectional examination of the colon is usually performed to identify major colonic segments (*left*), such as the cecum and ileocecal valve (*arrow*), whereas scanning of the ascending colon in a longitudinal plane is used to visualize its typical haustration (*right*).

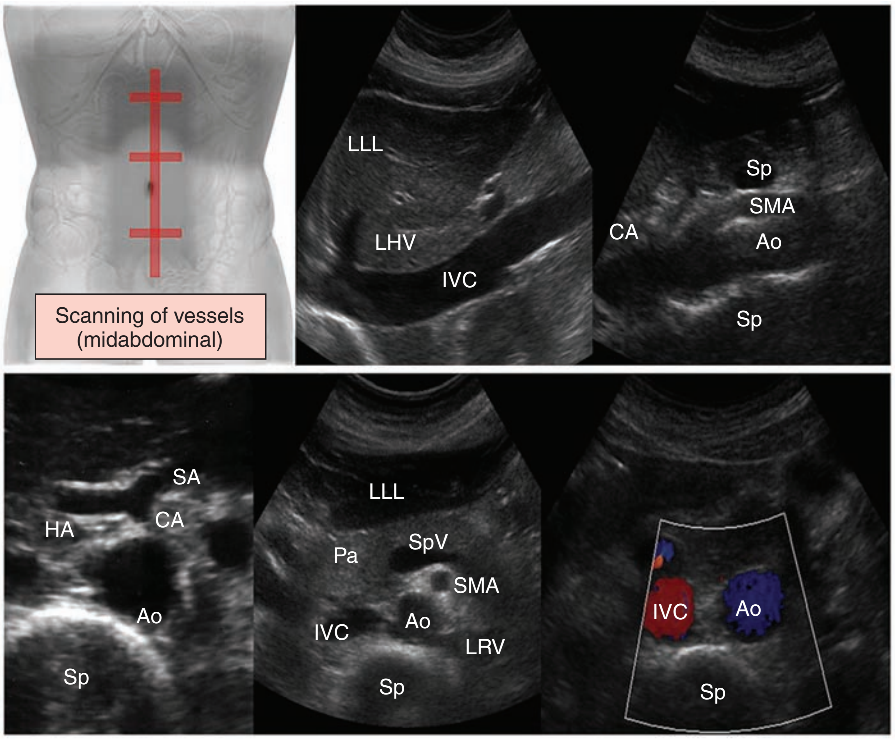

Figure 41 E-5 Standard scanning of abdominal vessels (midabdominal plane). On transverse (*top*) and longitudinal views (*bottom*) along the midline of the abdomen, the aorta, inferior vena cava, celiac axis, and superior mesenteric vessels are visualized anterior to the spine. *Ao*, Aorta; *CA*, celiac artery; *HA*, hepatic artery; *IVC*, inferior vena cava; *LHV*, left hepatic vein; *LLL*, left liver lobe; *LRV*, left renal vein; *Pa*, pancreas; *SMA*, superior mesenteric artery; *SA*, splenic artery; *Sp*, spine; *SpV*, splenic vein.

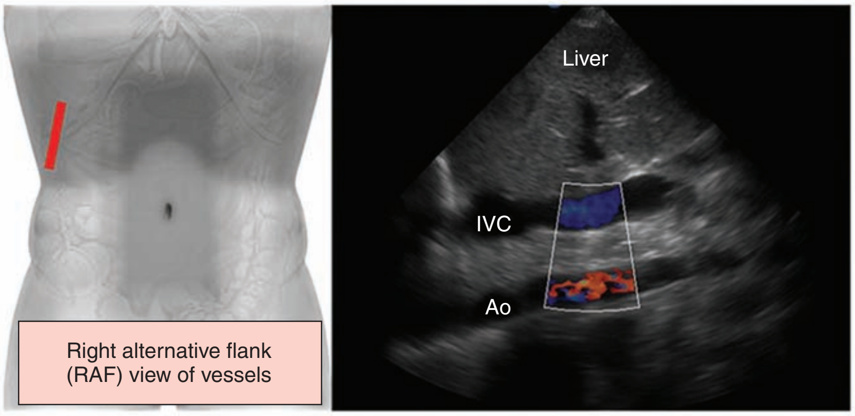

Figure 41 E-6 Alternative (flank) scanning of abdominal vessels. If midabdominal scanning is not feasible (e.g., trauma, aerocolia, surgery), major abdominal vessels can be depicted by alternative right flank views in supine patients in the intensive care unit. This view requires various adjustments of the transducer (rotating and tilting) and the scanning plane, which depends on positioning of the patient, to visualize major abdominal vessels such as the inferior vena cava (IVC) and the aorta (Ao) (*the right alternative flank [RAF] view* is suggested by Dr. Karakitsos; however, further analysis is beyond the scope of this chapter).

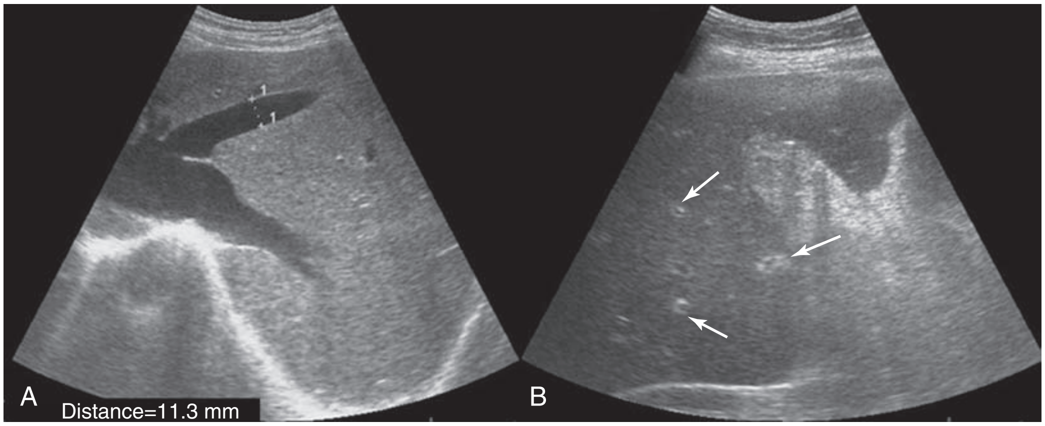

Figure 41 E-7 **A,** Right subcostal oblique views depicting hepatomegaly and dilated hepatic veins in a patient with right-sided heart failure. **B,** "Starry-sky" pattern of the liver parenchyma, which is characterized by diminished parenchymal echogenicity accentuating the portal venule walls (*arrows*) in a patient with acute hepatitis.

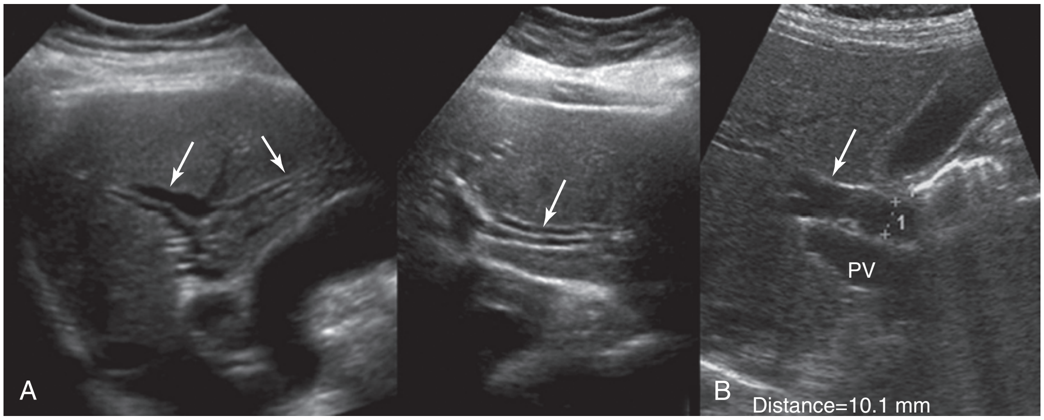

Figure 41 E-8 **A,** Dilated intrahepatic ducts (*arrows*) appearing as irregular anechoic tubules coursing through the liver parenchyma. If depicted parallel to the adjacent portal branches, a "double-barrel gun" or "tramline" appearance is evident. **B,** Marginally dilated (10.1 mm) common bile duct (*arrow*). *PV*, Portal vein.

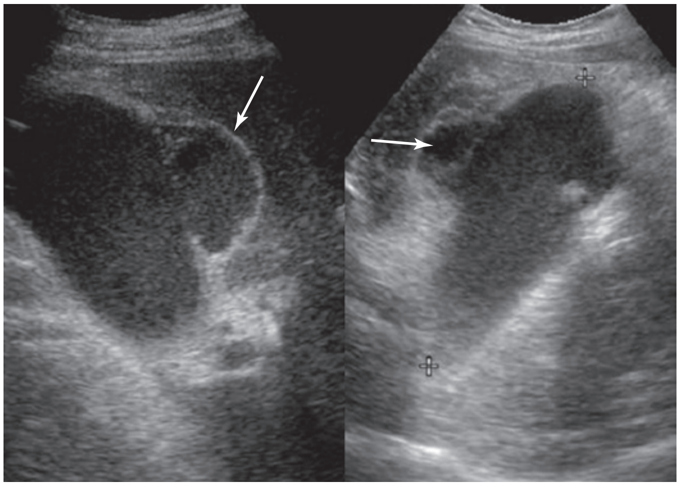

Figure 41 E-9 Subacute gallbladder perforation (*arrows*), a well-known complication of cholecystitis. *(Courtesy Dr. K. Shanbhogue.)*

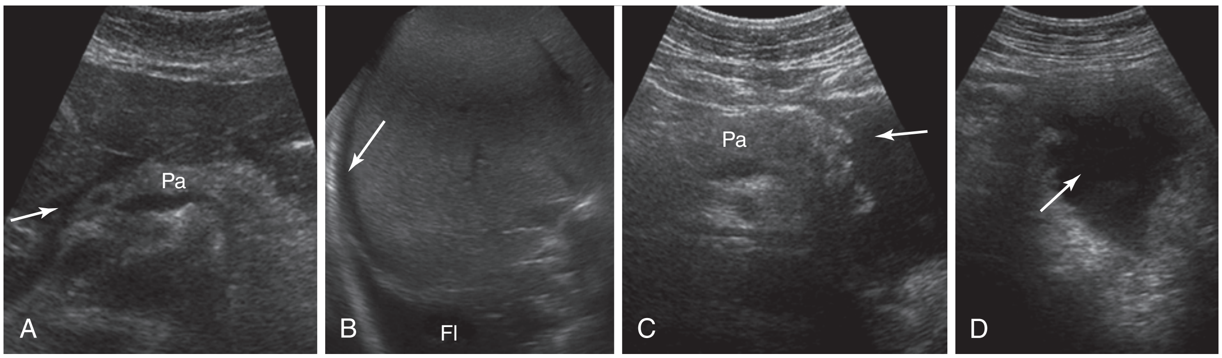

Figure 41 E-10 Pancreatitis. Fluid is depicted in the peripancreatic (**A,** *arrow*), perihepatic (**B,** arrow), and subpleural spaces (Fl). **C** and **D,** Depiction of a pseudocyst (arrow) at the tail of the pancreas (Pa).

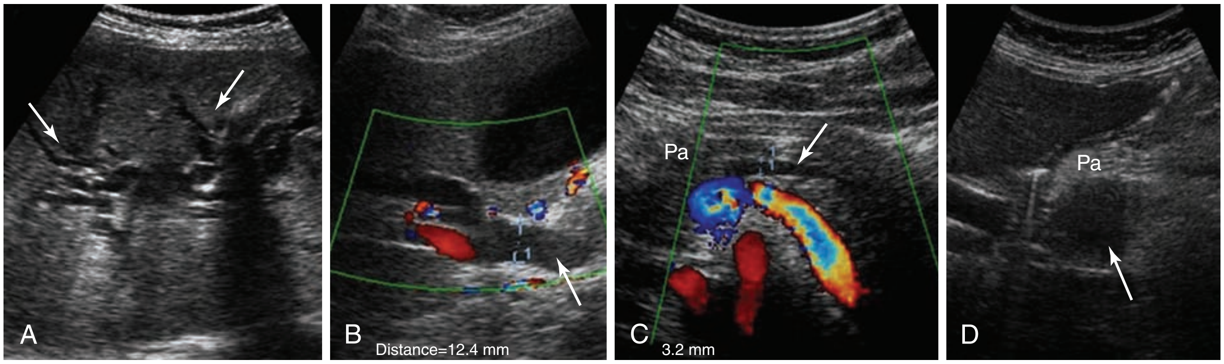

Figure 41 E-11 Pancreatic adenocarcinoma. Dilated intrahepatic ducts (**A,** *arrows*), common bile duct (**B,** *arrow*), and pancreatic duct (**C,** *arrow*). **D,** Depiction of a hypoechoic mass (*arrow*) at the head of the pancreas (Pa).

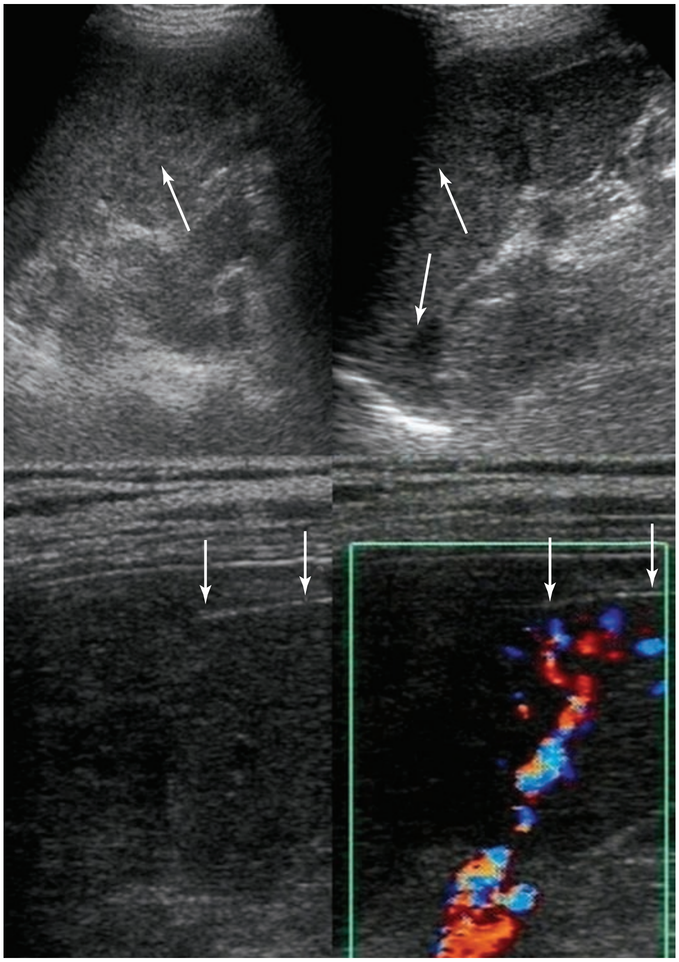

Figure 41 E-12 Splenic rupture caused by blunt abdominal trauma. (*Top*) Heterogeneous echotexture of the splenic parenchyma (*arrows*). (*Bottom*) Rupture of the splenic capsule depicted with a high-frequency transducer (*arrows*).

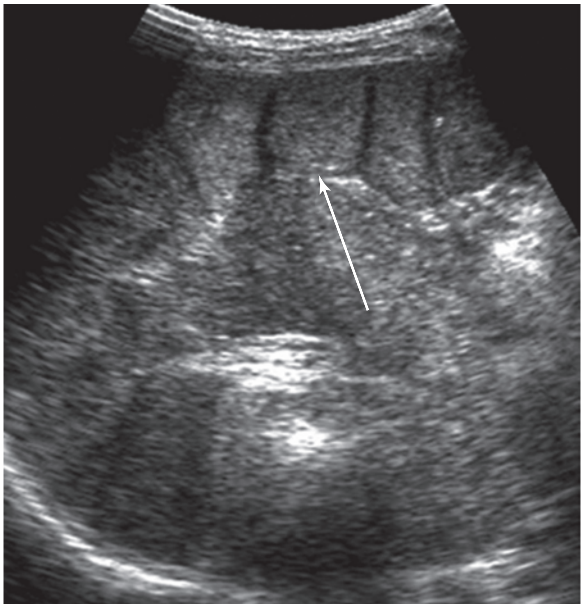

Figure 41 E-13 Incidental detection of a fully regenerated (*arrow*) orthotopic spleen (15 years after splenectomy).

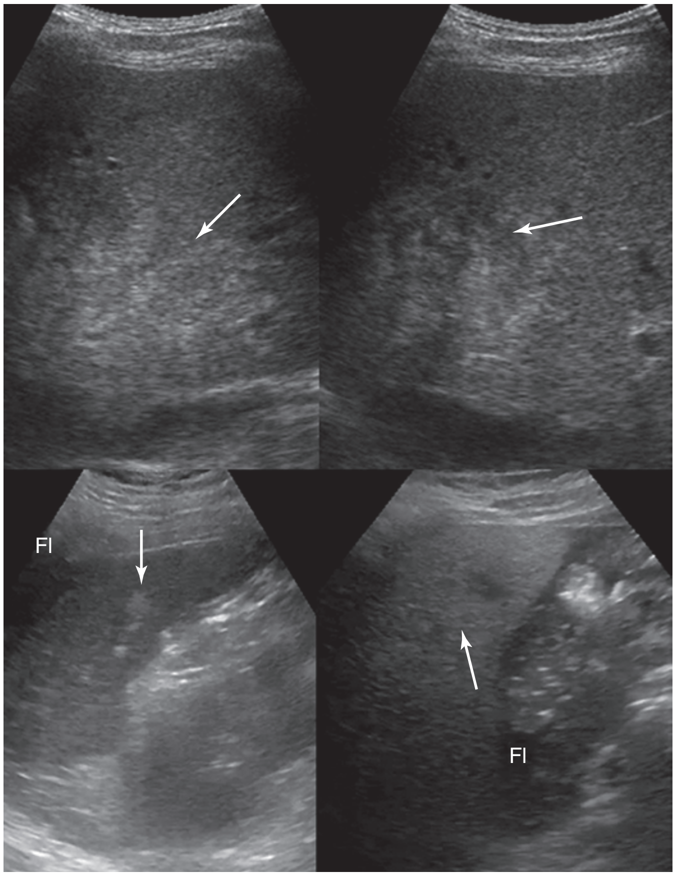

Figure 41 E-14 (*Top*) Liver contusion following blunt abdominal trauma. A diffuse hyperechoic pattern (*arrow*) with associated hypoechoic areas (first day, *left*) can be visualized; the hyperechoic pattern appears to be slightly abated, whereas the hypoechoic regions (*arrow*) appear rather enhanced in follow-up examinations (fourth day, *right*). (*Bottom*) Splenic laceration following blunt abdominal trauma. Perisplenic fluid (Fl) and hypoechoic (*arrow*) areas of the splenic parenchyma (*left*) can be visualized. The heterogeneous splenic parenchyma (*arrow*) with perisplenic fluid (Fl) is seen delineating adjacent bowel loops (*right*).

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42

Approach to the Urogenital System

DIMITRIOS KARAKITSOS | GEORGIOS ANYFANTAKIS | ABRAHAM A. GHIATAS | MICHAEL BLAIVAS

Anatomy

The oval-shaped kidneys, measuring 9 to 15 cm in length and 4 to 6 cm in width, are located in retroperitoneum between the 12th thoracic and 4th lumbar vertebrae, just lateral to the psoas muscles. The kidneys are surrounded by the Gerota fascia (echogenic capsule) and a fat layer of variable thickness. Ultrasound examination, in both longitudinal and transverse planes, is performed using convex or microconvex (2.5-5 MHz) transducers and identifies the hilum, containing renal vessels and ureter; the pelvis, receiving two to three major calyces; and the cortex and the medulla, containing renal pyramids. Normal cortical echogenicity should be less than or equal to the echogenicity of liver (Figure 42-1). The right and left kidneys are visualized in the right (midaxillary line) and left (posterior-axillary line) lower intercostal spaces, respectively. The right kidney is lower than the left one because of the right lobe of the liver. In the intensive care unit (ICU), intercostal ultrasound approaches as well as scans along both hypochondriac regions can be used.[1-4]

The right and left main renal arteries (RAs) originate laterally from the abdominal aorta, inferior to the superior mesenteric artery (SMA). Segmental (lobar) arteries originate before or immediately after entering the kidney, and their branches (interlobar arteries) travel through the kidney parenchyma. The right and left renal veins (RV) originate off the inferior vena cava (IVC). Ureters travel retroperitoneally, crossing over the iliac vessels and along the pelvic sidewalls, before curving anteriorly and medially at the level of ischial spines, and thus entering the bladder at ureterovesical junction. Ureters are not well visualized by ultrasound but, when distended *(hydroureter),* appear as hypoechoic, tubular structures (Figure 42-2). The round-shaped bladder is depicted by ultrasound just above the pubis. When not distended, its wall appears thickened. When fully distended, its wall should measure less than 0.4 cm thick. The trigone is a triangular region of the bladder base, formed by two ureteral orifices and the internal urethral orifice, which are identified by depicting ureteral jets, emanating from the ureters. In critical care patients, the balloon of the Foley catheter should be visible in the bladder (catheter is clamped to avoid bladder emptying, Figure 42 E-1). Inability to visualize the balloon should prompt a search for its location because extravesical inflation may result

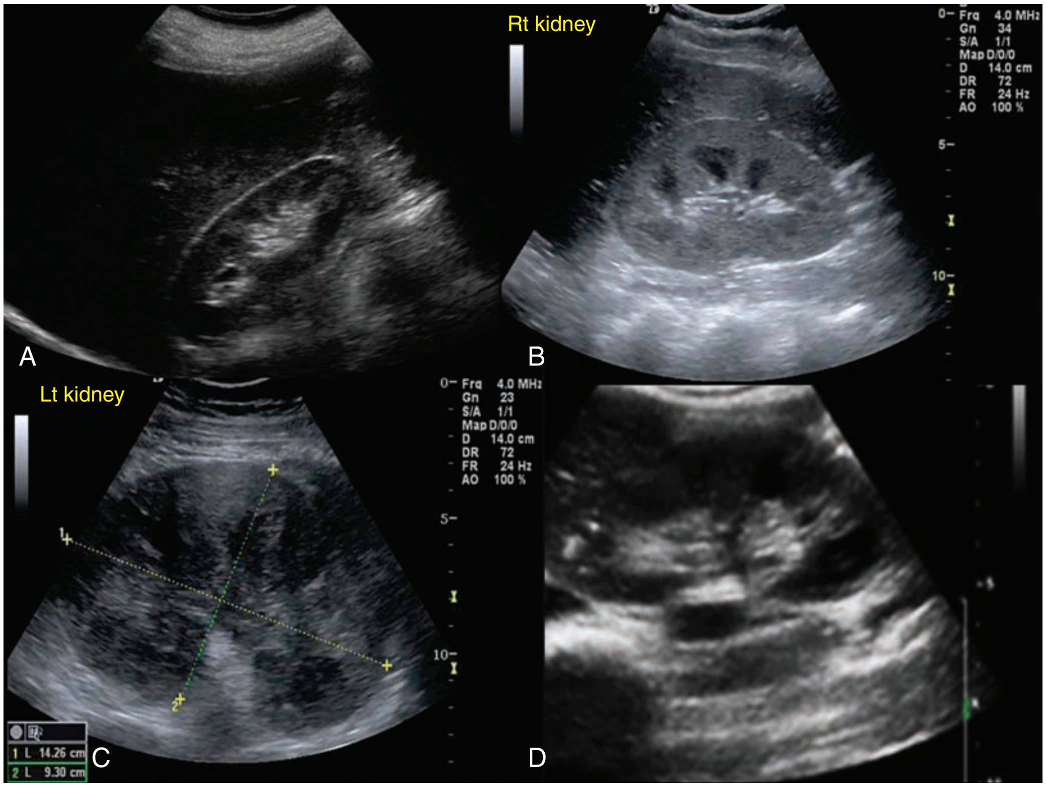

Figure 42-1 **A,** Normal kidney. **B,** Enhanced cortical echogenicity in lupus-related glomerulonephritis. **C,** Kidney enlargement with loss of parenchymal differentiation in a septic patient with acute kidney injury. **D,** Heterogeneous cortical appearance in pyelonephritis.

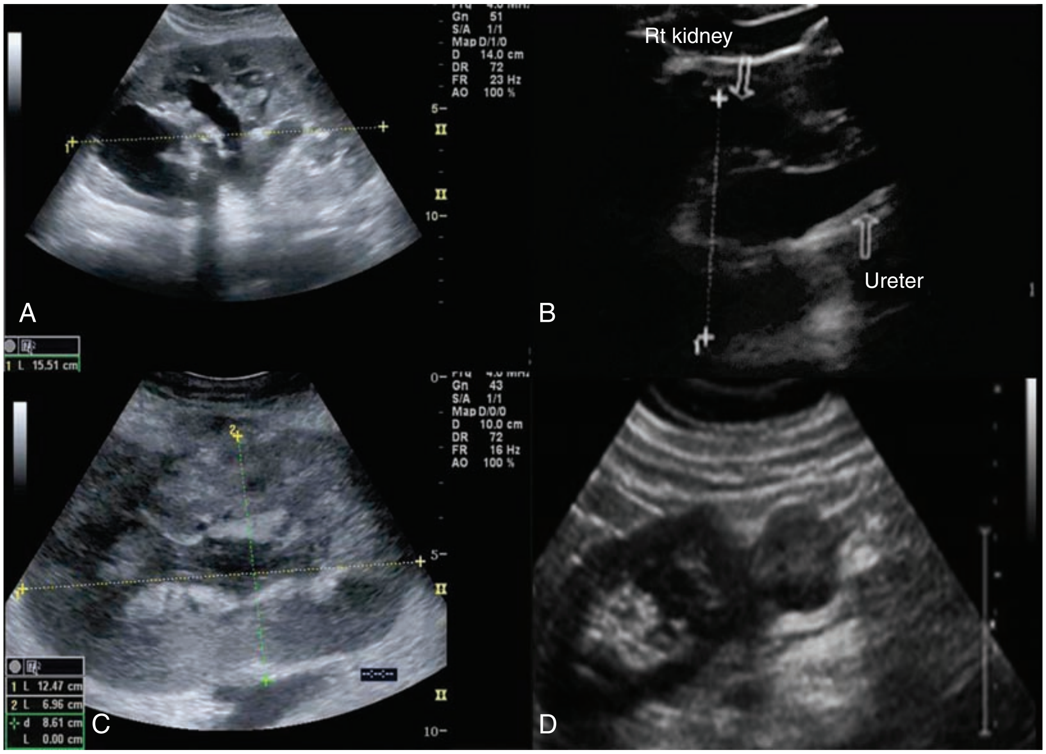

Figure 42-2 Hydronephrosis. **A,** Kidney enlargement with dilatation of the collecting system. **B,** Distended ureter. **C,** Parenchyma of mixed echogenicity (edema-hemorrhage) in renal trauma. **D,** Renal cell carcinoma projecting from the lower kidney pole.

in local trauma and confusing appearances. The normal adult testis measures about 3 to 4 cm (longitudinal section) and is normally hypoechoic. The upper testicular pole is capped with the head of the epidydimis. A thin rim of anechoic fluid may be seen around the testicle.[1-4]

Disorders

KIDNEY

Renal failure resulting from various causes is commonly encountered in the ICU. Ultrasound may depict loss of parenchymal differentiation and rule out obstruction. In acute failure, kidneys may appear normal or increased in size (see Figure 42-1), whereas in chronic failure, kidneys appear small with thin parenchyma and irregular borders. The Doppler-derived *resistive index* [(RI) = (peak systolic velocity − end diastolic velocity)/(peak systolic velocity)] of renal and interlobar arteries has been used to study many different renal diseases. *The normal mean RI value is approximately 0.60, whereas values greater than 0.8 indicate parenchymal disease*. These criteria require further validation, and inaccurate readings may occur, especially in ICU patients. Doppler measurements may be obtained when the sample volume is adjusted to 1.5 to 2 mm and the angle to 0 degrees when evaluating interlobar arteries, whereas the angle should be 60 degrees or less in the RA. Despite its limitations, the above method may be promising in the monitoring of critical care patients with failing renal function (Figure 42 E-2).[4-8]

Pyelonephritis, although difficult to diagnose in the ICU because of blurred clinical picture, may be detected by ultrasound (see Figure 42-1). Ultrasonographic findings are a normal or enlarged kidney, focal or diffuse swelling with decreased echogenicity, loss of corticomedullary differentiation, areas of necrosis (hypoechoic), and microabscess formation (hypoechoic areas with smooth or irregular margins and high-level internal echoes). Renal abscess appears usually as a complex, lobulated cystic mass, whereas hyperechoic foci within indicate presence of gas. Depiction of gas bubbles extended to parenchymal areas, sinus, and perinephric space characterize a severe form of pyelonephritis called *emphysematous pyelonephritis,* which is usually observed in diabetic patients. Another form of severe infection is *pyonephrosis,* which may appear as calyceal dilatation (*hydronephrosis*) with the presence of echogenic material within, consistent with pus or debris formation.[4] *Glomerulonephritis* is a major cause of end-stage kidney disease. In acute and subacute cases, kidneys may appear enlarged because of parenchymal swelling with increased echogenicity and prominent hypoechoic medullary pyramids (see Figure 42-1). In chronic glomerulonephritis, kidneys are small and atrophic with increased echogenicity.[4]

Renal trauma is usually observed after abdominal injury (see Figure 42-2). Although ultrasound can detect hemoperitoneum, its role in evaluating renal trauma is limited compared with computed tomography (CT). Ultrasound may detect presence of parenchymal (mixed echogenicity) or subcapsular hematomas (perirenal fluid collection), segmental corticomedullary dedifferentiation, linear defect consistent with laceration, or a shattered kidney (multiple areas of disorganized tissue with blood and urine collections) (Figure 42 E-3). Trauma may lead to persistent *urine leakage* and development of *urinomas* that manifest as delayed complications (e.g., hydronephrosis, paralytic ileus, etc.). Urinomas have a variety of appearances and may be misdiagnosed as ordinary ascites, abdominal or pelvic abscesses or hematomas, cystic masses, or pancreatic pseudocysts. Urinomas may result from blunt or penetrating trauma, iatrogenic injury, or transmitted back pressure caused by downstream obstruction resulting from a ureteral stone, surgical ligature, or abdominal and pelvic masses. Ureteral urine leaks may be iatrogenic (e.g., surgery or endourologic procedures).[9]

Renal vascular disorders are evaluated by duplex ultrasound techniques. *Atherosclerosis* is the most common disorder, causing either RA stenosis or occlusion. A *renal-aortic Doppler velocity ratio* (RAR = peak systolic RA velocity/peak systolic aortic velocity) less than 2.5 indicates the absence of a flow-reducing RA stenosis (reduced RA diameter < 60%), whereas values greater than 3.5 usually correspond to hemodynamically significant stenosis. In cases of aortic disorders (e.g., aneurysm), often observed in the ICU, using RAR is not reliable; instead, peak systolic velocities in either RA greater than 200 cm/sec, along with confirmed poststenotic Doppler signals, could be used to detect flow-reducing stenosis (Figure 42 E-4).[4,10] Atherosclerosis may cause bilateral stenosis, while it affects the proximal RA segments. A less common disorder causing RA stenosis is *fibromuscular dysplasia,* which affects the middistal RA segments, while a "string of beads" RA appearance (narrowing and then widening of arterial segments) can be observed. Acute arterial occlusion may occur because of abdominal trauma. Doppler findings are absence of renal arterial flow and either absence of endonephric flow or detection of low-velocity Doppler signals resulting from collateral channels. Finally, the risk of renal arterial embolism, which may cause partial or total arterial occlusion, increases in patients with atrial fibrillation, mitral stenosis, or previous RA stenosis. *RV thrombosis* can occur in one or both veins (e.g., nephrotic syndrome) because of extrinsic compression, hypercoaguable states, trauma, or surgery (e.g., posttransplantation). Compression of the left distal RV that may lead to thrombosis between the aorta, and SMA rarely occurs (*nutcracker syndrome*). Ultrasonographic findings of acute thrombosis include kidney enlargement, loss of parenchymal differentiation, diffuse "snow appearance" (central heterogeneous mass with numerous anechoic spaces), thrombus in the RV or in IVC. In chronic thrombosis, kidneys may appear normal or atrophic and calcified.[4,11]

Renal transplant duplex ultrasound evaluation may depict spectral flow patterns and tissue changes characteristic of normal transplants and those undergoing rejection. Ultrasound can detect RA stenosis-occlusion, RV thrombosis, and the presence of arteriovenous fistulas within the transplant. Renal transplants are often placed subcutaneously in the pelvis, whereas transplant RA and RV are usually anastomosed to the external or internal iliac artery and vein (Figure 42 E-5). All anastomotic sites should be checked by duplex ultrasound; however, this is not always technically feasible. Doppler spectral patterns from all inflow, outflow, and organ vessels must be integrated before drawing any conclusions. Apart from B-mode transplant evaluation, the demonstration of a RI greater than 0.8 or an end-diastolic to systolic velocity ratio greater than 0.2 by Doppler ultrasound, in the absence of RV thrombosis and ureteral obstruction, may be indicative of rejection.[12-14]

Hydronephrosis is the dilatation of renal pelvis and calyces and may be due to various causes, such as obstruction (blood clot, sloughed papillae, iliac vessels crossing, strictures, etc.), papillary necrosis, reflux nephropathy, chronic infection, urogenital tumors, benign prostatic hyperplasia, ureter narrowing (infection, injury, surgery), neurogenic bladder, pregnancy, retroperitoneal fibrosis and so forth (see Figure 42-2). Ultrasound can detect kidney stones, especially if stones are greater than 0.5 mm because posterior acoustic shadowing is usually present. If the latter is not present, depiction of the "twinkle artifact," appearing as a quick fluctuating mixture of Doppler signals behind a strongly reflecting interface (stones), might help. A common pitfall is depicting vascular calcifications as renal calculi.[4,5]

Renal cysts are the most common renal lesions. They are usually benign and may be single, multiple, unilateral, or bilateral. If multiple cysts are found, *polycystic kidney disease* must be considered. The latter usually affects both kidneys (unilateral in 17% of cases) and may affect other organs, such as the liver, pancreas, heart, and brain. Ultrasonographically, simple cysts are round, anechoic structures composed of a sharply defined smooth wall with posterior acoustic enhancement. *Parapelvic* cysts may cause hydronephrosis because of pressure; however, in hydronephrosis calyces are usually interconnected with the collecting system. *Complex* cysts usually have thick walls, septations, lobulations, calcifications, internal echoes, fluid-filled or echogenic material and are classified as infectious, hemorrhagic, proteinaceous, calcified, neoplasmatic, and hydatid. Renal *masses* detected by ultrasound, whether cystic or solid, should be further evaluated by other imaging modalities (e.g., contrast-enhanced CT) to make an accurate diagnosis and facilitate surgical treatment (see Figure 42-2). Renal masses are of variable size and may be found at the renal cortex or projecting inside the medulla. Solid tumors are homogeneous or heterogeneous lesions of mixed echogenicity with distinct or irregular borders (Figure 42 E-6). Cystic and hemorrhagic components or evidence of angiogenesis may be found within the tumor.[4,15]

BLADDER

A typical transverse section of the ultrasound examination depicts the bladder behind both rectal muscles and above and behind the rectum. Bladder should be fully filled to achieve a better wall delineation. In males, the prostate gland is visualized under the bladder neck, whereas in females who have not undergone hysterectomy, the uterus may be seen in the midline, posteriorly and superiorly to the bladder. *Bladder wall thickening* (>0.4 cm) may be focal or diffuse. Focal thickening may be due to cystitis, endometriosis and Crohn disease (possible fistula formation), benign and malignant tumors, and benign prostate hyperplasia (Figures 42 E-7 and 42 E-8). Diffuse thickening may be due to infection, inflammation, prolonged catheterization, drugs, and neurogenic bladder (Figure 42-3). Depending upon the underlying cause additional imaging findings may be present (e.g., echogenic mobile blood clots in case of hemorrhagic cystitis). Ultrasound sensitivity is low for detecting bladder injury; however; indirect findings (e.g., free fluid) may be present. Doppler techniques may help differentiate between tumors and clots (e.g., clots do not exhibit flow); *however absence of flow in a bladder mass does not exclude malignancy*. Doppler ultrasound is used to enhance *ureteral jets* (normally apparent within 5-8 minutes) because any asymmetry may indicate obstruction.[4,16]

In the ICU, a catheterized bladder should be checked for any signs of trapped urine or diverticulum. Often, a sedated patient may develop anuria, which prompts a search for "hemodynamic" causes, whereas scanning the bladder first to exclude distention is a more rational approach. *Bladder outlet obstruction* may be due to the presence of calculi, pyuria, or blood clots. *Calculi* can be detected as echogenic foci movable with posterior acoustic shadowing (Figure 42 E-9). Bladder disorders such as *diverticulum* and *ureteroceles* may cause diagnostic confusion. Ultrasound findings consistent with diverticulum include an anechoic out-pouching originating from the bladder

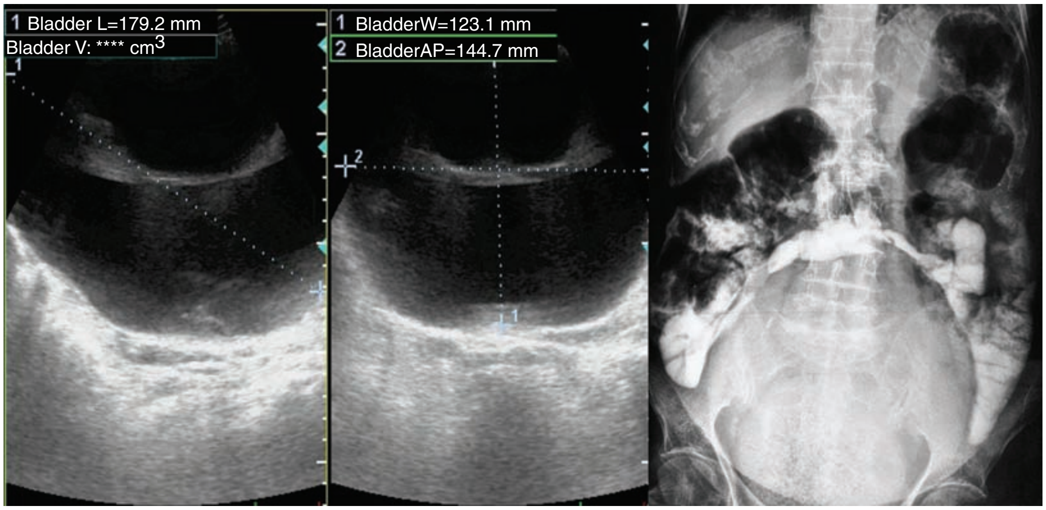

Figure 42-3 Maximally distended (1660 mL) neurogenic bladder (diagnosis of exclusion: co-evaluation with clinical data).

with a narrow or wide neck, which should be differentiated from ureteroceles, which appear as well-defined, thin-walled echogenic masses (see Figure 42 E-9). Ureteroceles are almost always present inferolaterally at the ureterovesical junction, and if ectopic, a duplicated collecting system is present (80%).[17]

SCROTUM

Ultrasound examination of scrotum is performed by high-frequency linear transducers (7-15 MHz). Each testis is examined separately and compared with the other. *Epidydimitis* starts by affecting epidydimis' tail and could develop to *orchitis* in 40% of cases (Figure 42 E-10). Ultrasound findings include edematous enlargement of the gland (the head could measure >17 mm) and thickening of scrotal layers along with increased vascularity. In diffuse orchitis, the testis is enlarged, with a heterogeneous appearance. Seminomas can have the same appearance, as well as testicular torsion. *Testicular torsion* (twisting of testicular spermatic cord), which most commonly affects patients between 12 to 20 years but can occur at any age, is an emergency condition because it results in ischemia and necrosis (testicular tissue is not viable after more than 6 hours of ischemia). In the acute phase, ultrasound findings may be normal, whereas as it progresses, evidence of testicular and scrotal enlargement along with absent testicular blood flow may be found. Confirmation of both venous and arterial flow on pulsed wave Doppler is critical when ruling out testicular torsion. *Scrotal trauma,* resulting usually from blunt injury, has poor prognosis if surgical repair is postponed. Ultrasound may reveal irregular testicular shape, heterogenic testicular lesions, intraparenchymal hematoma, and distorted testicular vascularity with associated hematocele (see Figure 42 E-10). The testicles contours should be scanned closely for any irregularity because this could indicate rupture.[1-4]

Ultrasound-Guided Interventions

Ultrasound-guidance facilitates interventions, such as emergency *percutaneous nephrostomy (PCN)* and *suprapubic bladder*

IMAGING CASE: INTRA-BLADDER HEMATOMA

A trauma victim suffering from multiple injuries (liver laceration, numerous bone fractures) was admitted to the ICU. Bladder ultrasound was urgently performed because of massive hematuria. A solid heterogeneous mass was detected in the bladder. No blood flow was detected within the mass (absence of flow does not exclude malignancy). After multiple bladder irrigation with normal saline, the mass started to dissolve gradually.

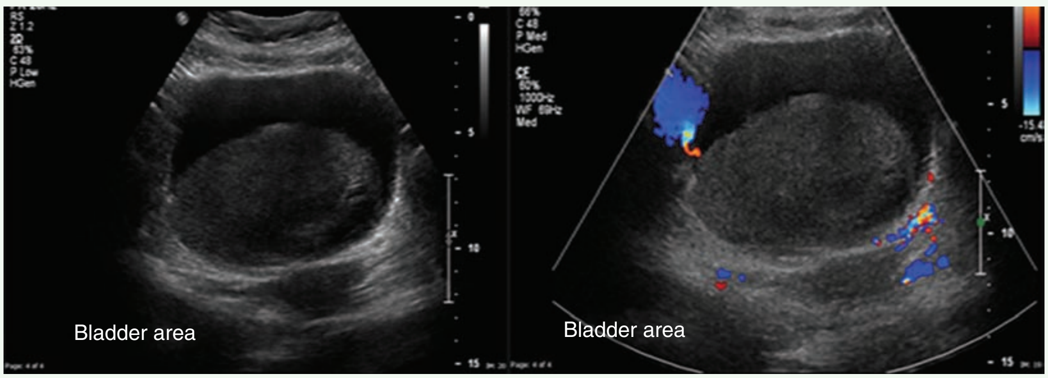

Figure 42-4

catheterization or placement of internal-external nephroureteral stents. Guided PCN is used to treat urinary obstructions in septic and unstable patients who cannot be transferred to the operating room and carries a lower mortality rate (0.2%) compared with surgery. The kidney is punctured via a posterolateral approach to avoid the colon and the pleura, while the needle is targeting the dilating calyces for the subsequent placement of the PCN tube. Persistent postprocedural hematuria may necessitate a change in tube size or obtaining a new access in a different calyx or even ruling out arteriovenous fistula formation. Guided suprapubic bladder catheterization provides the operator with the potential to choose a more cranial penetration point that may decrease the risk of sepsis in prevesical space.[1-4]

Pearls and Highlights

- Ultrasound-detected renal masses should be evaluated by additional imaging modalities.
- Doppler-derived RI greater than 0.8 of the interlobar arteries indicates parenchymal disease.
- Loss of parenchymal differentiation and changes in normal kidney size and cortical echogenicity are nonspecific ultrasound findings.
- Ultrasound is used to monitor renal transplants and guide emergency interventions.
- Sudden development of anuria or hematuria indicates bladder ultrasound evaluation.
- Prompt ultrasound detection of testicular trauma and ischemia facilitates early surgical repair.

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For a full list of references, please visit www.expertconsult.com.

Figure 42 E-1 Balloon of indwelling catheter in fully filled bladder.

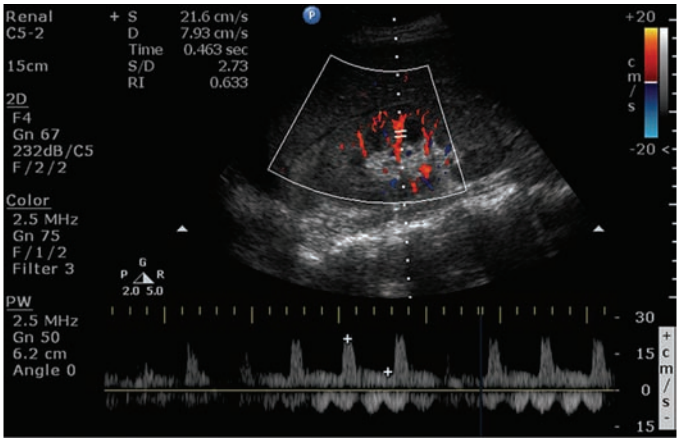

Figure 42 E-2 A septic patient presented with "anuric" acute kidney injury. Doppler-derived resistive index (RI) (0.63 in this image) values ranged from 0.45 to 0.65 in repeated measurements. After supportive therapy, renal function and urine output gradually normalized.

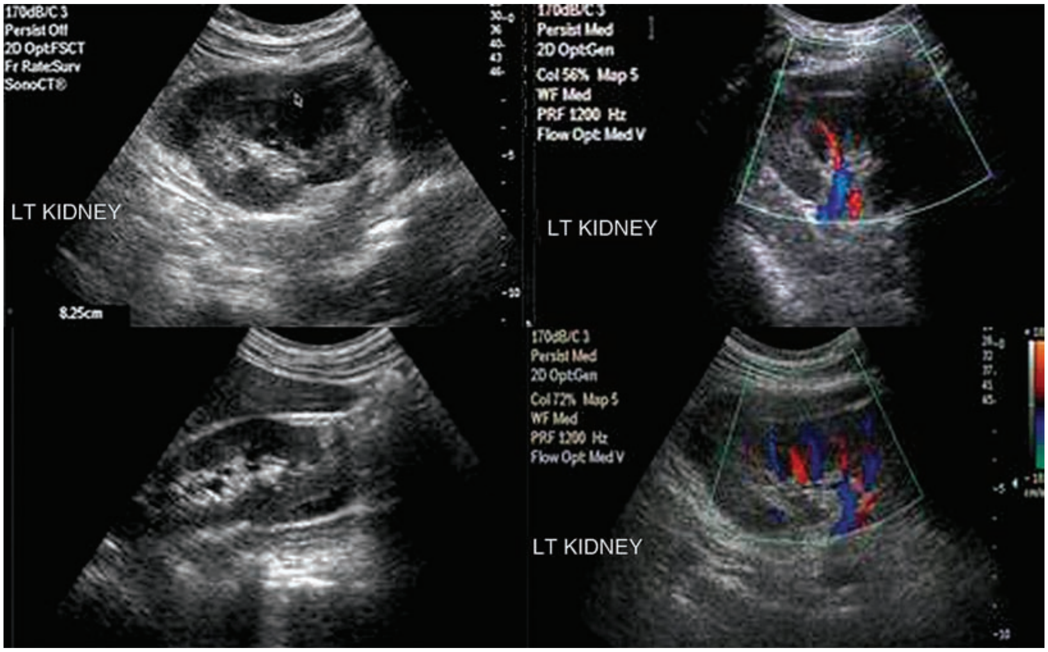

Figure 42 E-3 Renal hematoma in a patient with blunt abdominal trauma.

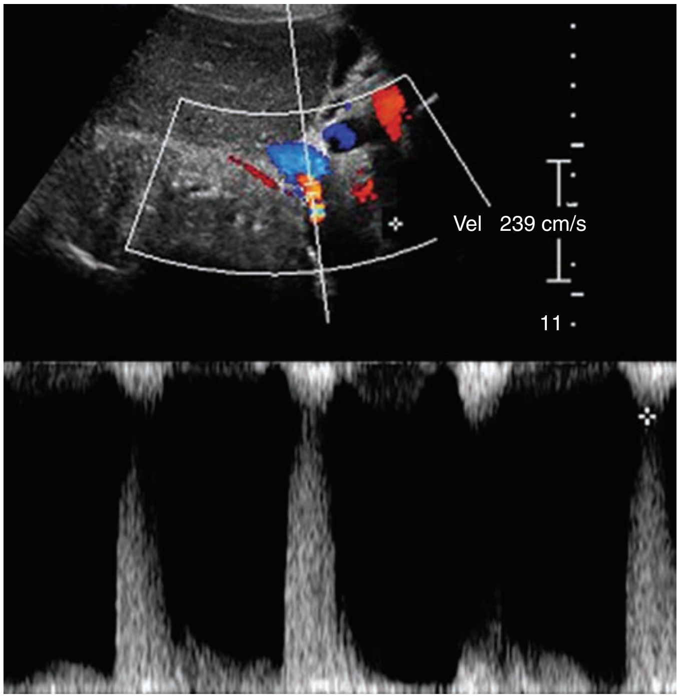

Figure 42 E-4 Color Doppler depicting renal artery (RA) stenosis (peak systolic velocity > 200 cm/sec) in a patient with aneurysmal abdominal aorta.

Figure 42 E-5 Normal renal transplant (power Doppler).

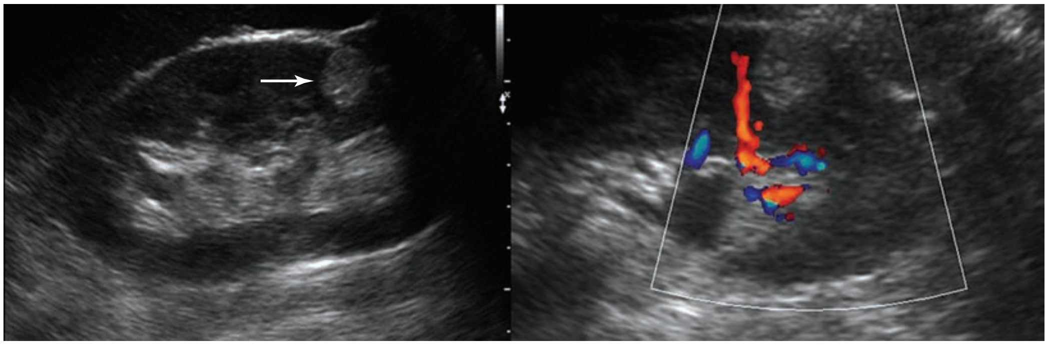

Figure 42 E-6 Kidney angiomyolipoma.

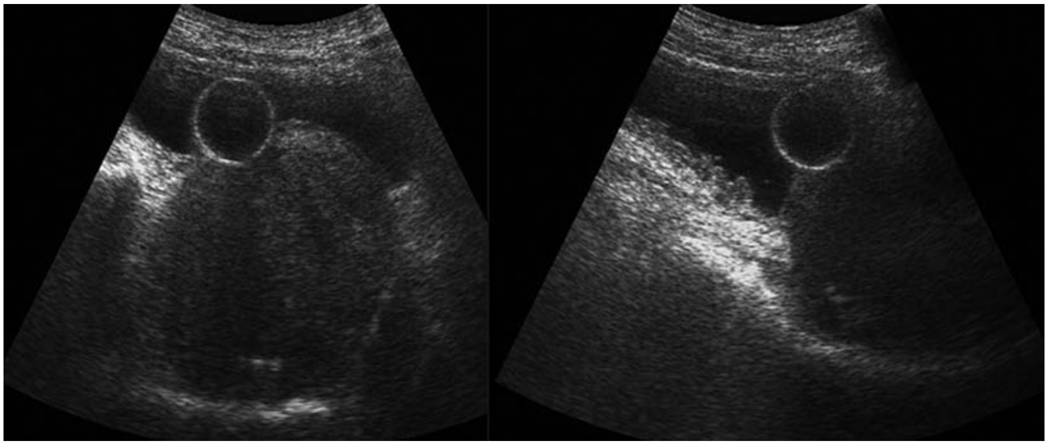

Figure 42 E-7 Bladder wall thickening caused by huge prostatic enlargement.

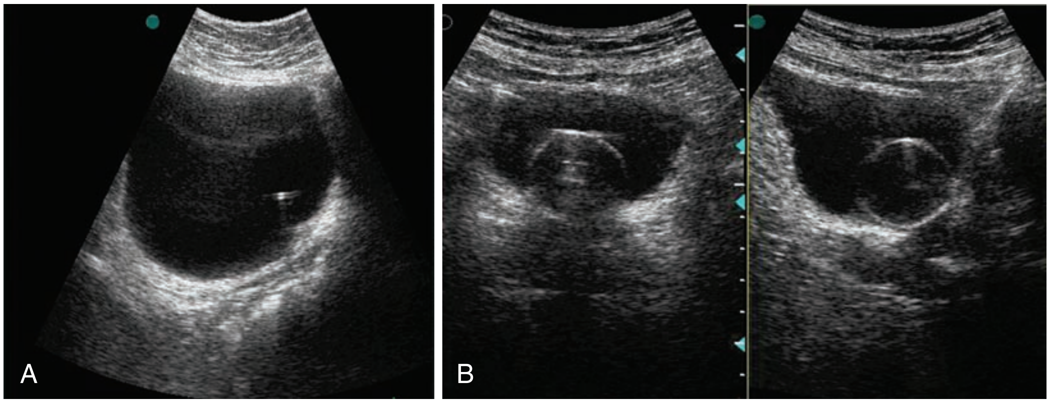

Figure 42 E-8 **A,** Echogenic stent inserted for subpelvic ureteral stenosis. **B,** Indwelling catheter inserted for urinary retention.

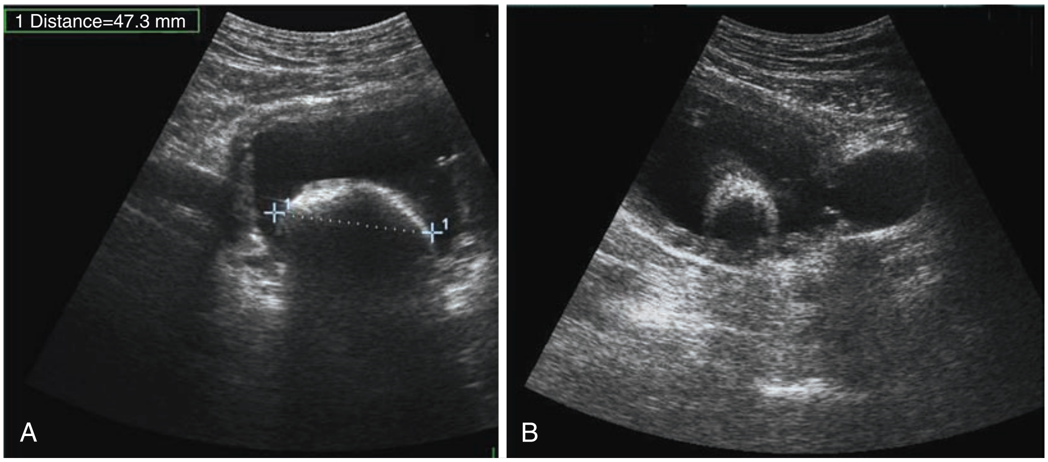

Figure 42 E-9 **A,** Huge echogenic stone in the bladder (note the acoustic shadowing). **B,** Diverticulum depicted as anechoic solitary outpouching of the bladder wall.

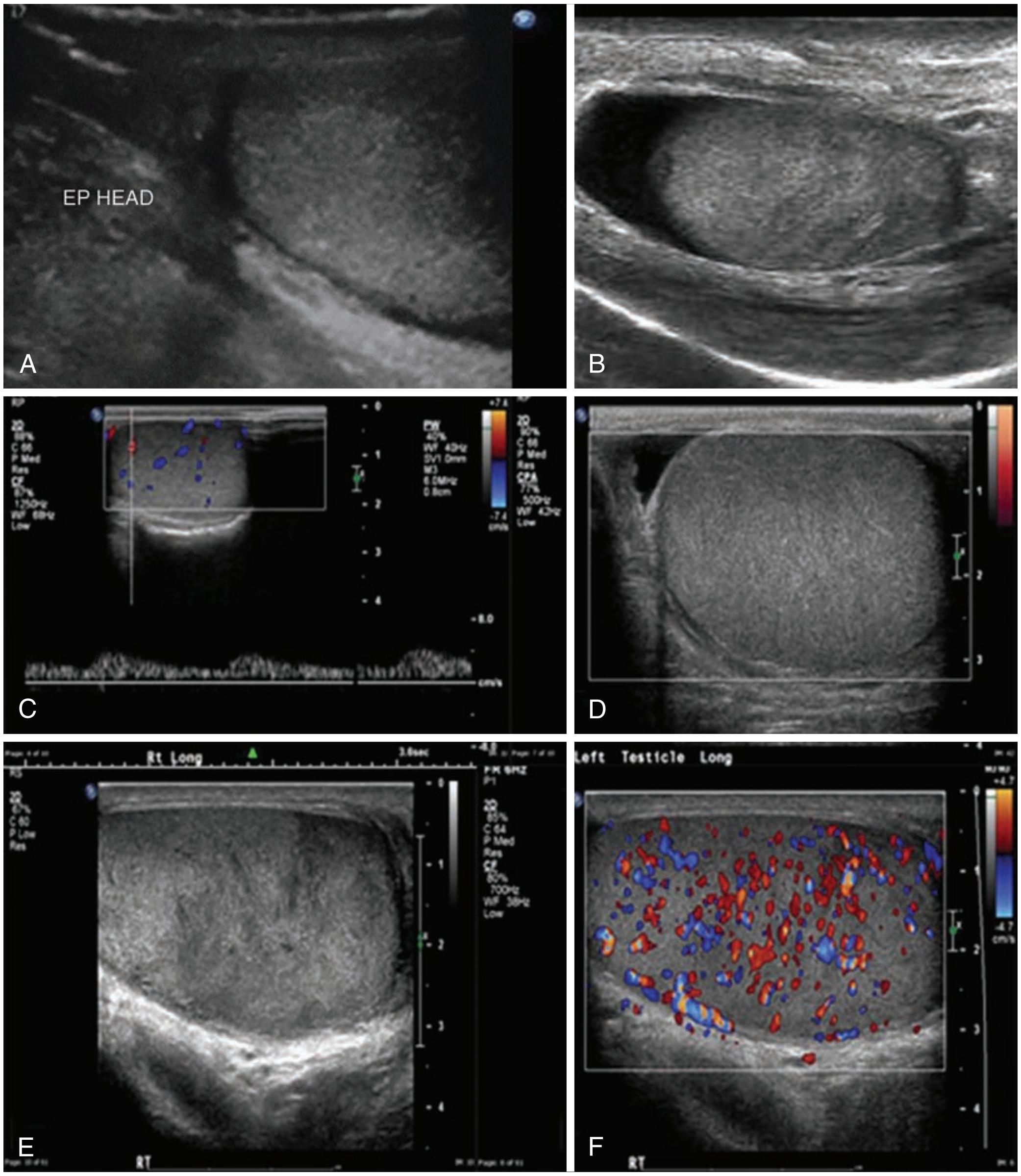

Figure 42 E-10 **A,** Normal testis and head of epidydimis. **B,** Scrotal hematoma. **C,** Normal testicular blood flow. **D,** Absent blood flow in the left testis (acute ischemia). **E** and **F,** Heterogeneous testis with hyperemia (orchitis).

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43

Point-of-Care Pelvic Ultrasound

LORI STOLZ | SRIKAR ADHIKARI

Overview

This chapter illustrates the basic features of *pelvic ultrasound* by outlining the exploration of the *female genital system*, concluding thus the holistic approach (HOLA) ultrasound concept of the abdominal examination (see Chapters 1 and 44). Clinician-performed point-of-care pelvic ultrasound is an integral skill in a growing number of medical subspecialties. History and physical examination are not always reliable in the evaluation of possible pelvic pathology, especially in the critically ill patient. The ability to diagnose life-threatening conditions at the bedside can decrease time to diagnosis. Ultrasonography is the preferred imaging modality for female pelvic anatomy in both the nonpregnant and pregnant patient. The accuracy of clinician-performed bedside ultrasound in identifying pelvic pathology has been well established.

Indications

Abdominal pain, pelvic pain, and vaginal bleeding are common complaints for which pelvic ultrasound is used. Although less common, pelvic ultrasound may also be indicated for syncope, dizziness, abdominal or pelvic mass on physical examination, trauma, fever, and hemodynamic instability. In the setting of pregnancy, the first and foremost use of pelvic ultrasound is in the diagnosis of an intrauterine pregnancy (IUP). Once an IUP has been established, ultrasonography can be further used to document gestational age, fetal heart rate, subchorionic hemorrhage, abnormal pregnancies, pregnancy loss, or to follow normal pregnancy. For the nonpregnant, critically ill patient, other pertinent applications include the evaluation of life-threatening ovarian pathology, such as ovarian torsion, ovarian cyst rupture with associated hemorrhage, and tubo-ovarian abscess. In any female who is hypotensive, septic, febrile, or suffering from severe abdominal pain, pelvic ultrasound is an extremely useful tool to direct appropriate treatment.[1,2]

Technique and Normal Anatomy

Imaging of the pelvic organs is assisted by the use of both transabdominal sonography (TAS) and transvaginal sonography (TVS). Each technique has its own advantages in the assessment of pelvic organs. A transabdominal approach gives the examiner spatial orientation of the pelvis and defines the relationship of the uterus with adjacent pelvic and abdominal structures. It is also helpful to delineate large masses, free fluid, and other pathology extending outside of the true pelvis. A transvaginal approach is useful because of probe proximity to the pelvic organs and the higher frequency resulting in images with superior resolution. This approach provides more anatomic detail of pelvic structures, allowing early identification of intrauterine contents and adnexal abnormalities. In addition, the probe can be used to detect the mobility of the pelvic organs. This can reveal adhesions and highlight pelvic pathology. These two modalities are complimentary, and in the undifferentiated patient, we recommend using both approaches.[1-4]

TRANSABDOMINAL TECHNIQUE

For TAS, scanning starts in the suprapubic area, using a low-frequency curvilinear transducer. The examination is best performed with a full bladder, although an overly distended bladder will decrease image quality. The bladder acts as an acoustic window and also displaces bowel loops from the pelvis for better imaging.[1-4] With the indicator directed cephalad, sagittal images can be obtained by sweeping the transducer slowly from right to left. Transverse images can be obtained with the indicator to the patient's right, by convention. By gently sweeping the transducer caudad and cephalad, all organs can be imaged in all three dimensions. The examiner should first start with an assessment of the uterus in both the sagittal and transverse planes. The position of the uterus, whether it is anteverted or retroverted, should be noted. Obesity and retroverted position can present challenges to the sonographer. The various portions of the uterus are then identified, namely, the cervix, body, fundus, and endometrial stripe. Sonographically, the normal uterus exhibits a low-gray homogenous texture. The endometrial stripe is typically seen as an echogenic line in the middle of the uterus (Figures 43 E-1 and 43 E-2). The appearance of uterine endometrium changes as the thickness of the endometrium changes with different phases of menstrual cycle. The cervix has similar sonographic appearance to that of the rest of the uterus. The thin linear hyperechoic vaginal canal is visualized between the anechoic urinary bladder (anterior) and the echogenic rectum (posterior). The cul-de-sac should be evaluated for free fluid or hematoma or mass, both in long and transverse planes. Next, the operator moves the transducer to the right or left lower quadrants to identify the adnexa. The identification of the ovaries is aided by identifying the iliac vessels, which define the borders of the pelvis. The ovaries are often adjacent to them. Ovaries are identified by their "chocolate chip cookie" appearance of hypoechoic follicles within the ovary. Again, they should be imaged in two planes, sagittal and transverse. Ovarian size can be evaluated by measuring the ovary's dimensions in three planes. Normal ovarian measurements are approximately 5.1 ± 3.1 cm^3 in the preovulation period, 3.2 ± 1.7 cm^3 in the postovulation period, and 1.3 ± 0.6 cm^3 in postmenopausal women. Ovaries may not always be seen on TAS but are visualized 65% to 99% of the time when performed in the radiology suite.[3,4]

TRANSVAGINAL TECHNIQUE

For TVS, consent should be obtained and the procedure explained, if at all possible. A chaperone should also be present.

The patient should be placed in lithotomy position, and the bladder should be decompressed because a distended bladder can distort the normal pelvic anatomy and push the uterus posteriorly.[3,4] The transducer should be prepared with an appropriate cover, with lubricating gel inside and outside of the cover. The endocavitary transducer is directed to different points of interest by using the midpoint on the probe as a fulcrum. *To image anteriorly on the body, the transducer handle should be moved posteriorly, thus bringing the imaging of the probe anteriorly.* This principle is one of the frequent missteps of novice sonographers but can be easily learned and mastered. Just as in TAS, assessment begins with the uterus imaged in two planes. With the indicator facing the ceiling, the sagittal images are obtained, and with the indicator pointed to the right side of the patient, the coronal plane images are obtained. The uterine contents should be screened thoroughly, and the posterior cul-de-sac should be evaluated at the level of the fundus, body, and cervix (Figures 43 E-3 to 43 E-5). The free fluid in the posterior cul-de-sac can be quantified into small (free fluid seen < ⅓ of the way up the posterior wall of the uterus), medium (free fluid seen ⅔ of the way up the posterior wall of the uterus), and large (free fluid seen > ⅔ tracking along the posterior wall of the uterus). The transducer is then angled rightward or leftward to visualize the adnexa. Again, the proximity of the ovaries to the iliac vessels can be used to locate them, and each structure should be imaged in two planes, coronal and sagittal.[3,4] Typically, the ovaries are found lateral to the uterus, medial and anterior to the iliac vessels (Figure 43 E-6).

Major Disorders Encountered

ECTOPIC PREGNANCY

Ruling out ectopic pregnancy is the first step in evaluating a patient with a positive pregnancy test. The β–human chorionic gonadotropin (β-HCG) level at which an IUP can be visualized on TVS (termed the discriminatory zone) has been quoted to be between 1000 and 2000 mIU/mL. However, *use of β-HCG has been shown to perform very poorly as a means of differentiating ectopic pregnancy from IUP, and ectopic pregnancy frequently occurs at very low levels.*[5,6]

The stepwise appearance of the gestational sac (4-5 weeks), the yolk sac (5-6 weeks), the fetal pole (6–7 weeks), and, finally, a fetal heartbeat can be followed sonographically in a normal pregnancy (Figure 43-1). Determining the definitive presence of an IUP requires visualizing the yolk sac, which is a hyperechoic circular structure within the gestational sac. Although the earliest intrauterine sign of pregnancy is the gestational sac, this is not definitive evidence of an IUP. Another early sign of intrauterine pregnancy is the *double decidual sign*. This is characterized by two hyperechoic rings (the decidua capsularis and the decidua vera) separated by a hypoechoic ring that surrounds the gestational sac (Figure 43 E-7). Misinterpretation of this sign is common and may have serious consequences; therefore this is not considered a sign of definitive IUP in the setting of point-of-care ultrasound. Gestational age can be determined by adding 30 to the mean gestational sac diameter (length, width, and height of the gestational sac obtained in two orthogonal planes and divided by three). Between 6 to 12 weeks, crown rump length (CRL) is the most accurate sonographic measurement for determining gestational age. While measuring CRL, the longest measurement of an unflexed fetus should be obtained without including the yolk sac (Figure 43 E-8).

The prevalence of ectopic pregnancy is roughly 2% but has been noted to be significantly higher in patients presenting with symptoms in the acute care setting.[5,7] *Findings highly suggestive of ectopic pregnancy include an empty uterus, extrauterine empty gestational sac, extrauterine gestational sac with yolk sac or embryo with or without cardiac activity, complex adnexal mass, tubal ring, a large amount of free fluid or echogenic fluid in the pelvis* (Figures 43-2, 43-3, and 43 E-9). A tubal ring is a hypoechoic circular structure with a hyperechoic border, clearly separate from the ovary, that is highly suggestive of ectopic pregnancy in the correct clinical setting.[5] Adnexal masses adjacent to the ovary can be difficult to distinguish from a normal corpus luteum cyst. Applying pressure with the probe will help to separate an ectopic mass from the ovary. Identification of a live pregnancy in the adnexa is confirmatory and occurs in roughly 10% of cases.[5] A pseudogestational sac (<10 mm ovoid endometrial fluid collection with poorly defined margins and no double decidual sign) is present in up to 20% of ectopic pregnancies. In a high-risk patient, heterotopic pregnancy must always be considered and ruled-out. The prevalence increases in

Figure 43-1 Longitudinal view of a pregnant uterus by transvaginal sonography (TVS) showing yolk sac and fetal pole within the gestational sac.

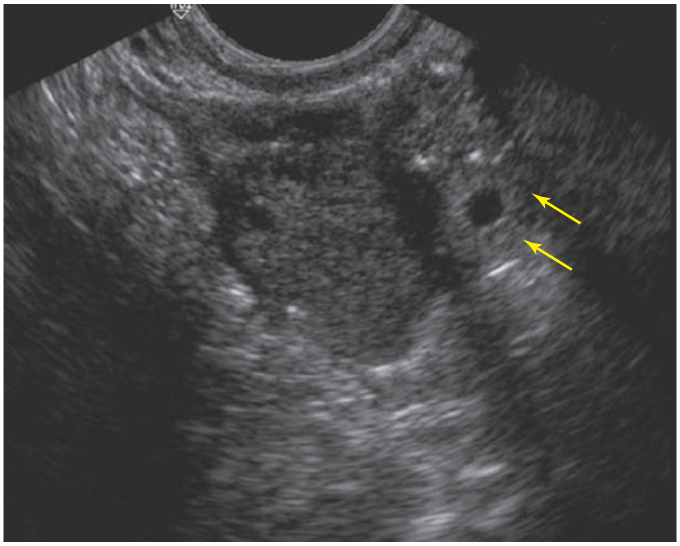

Figure 43-2 Tubal ring *(arrows)* representing an unruptured ectopic seen adjacent to the ovary on transvaginal sonography (TVS)

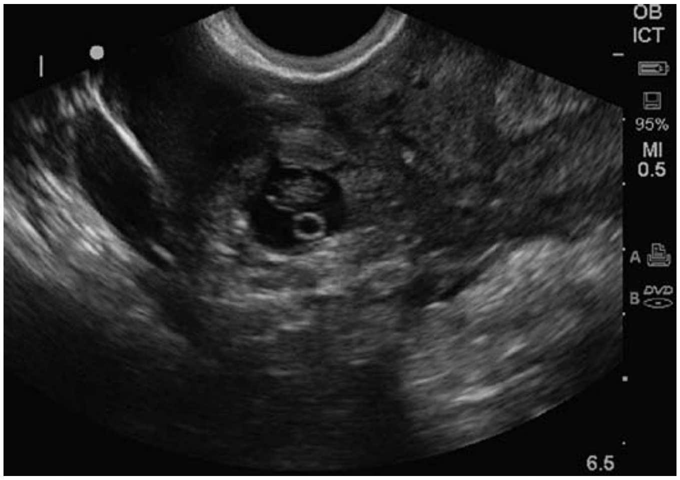

Figure 43-3 Ectopic pregnancy. An intact gestational sac with a yolk sac outside uterus in the left adnexa

patients with a history of pelvic inflammatory disease, fertility treatments, or other risk factors but is also known to occur in the absence of risk factors.

When considering a critically ill patient who is pregnant but does not have an established IUP, an *evaluation of the abdomen for free fluid* is necessary. *An unstable patient, with a positive β-HCG, free fluid in the abdomen, and an empty uterus should proceed directly to the operating room for surgical management. Identification of free fluid in the hepatorenal space is highly predictive of need for surgical intervention.*[8] *Patients with a large volume of pelvic fluid or echogenic fluid are at increased risk of ectopic pregnancy* as well.[9]

PREGNANCY LOSS

There are several sonographic signs of an abnormal pregnancy or impending miscarriage. First, a *large gestational sac without a visualized yolk sac* should alert the sonographer to a possible anembryonic pregnancy. A mean gestational sac diameter (MSD) of greater than 10 mm on TVS or greater than 20 mm on TAS, without a yolk sac visualized, is abnormal. In addition, a MSD of greater than 18 mm on TVS or 25 mm on TAS without a fetal pole, or a gestational sac with an irregular, ragged border or a collapsed gestational sac are considered abnormal (Figure 43 E-10).[10] Once an embryo is visualized, the *fetal heart tones* should be assessed. *M-mode is the preferred method*, given the theoretic risk of thermal injury with the use of Doppler. *Absent heart tones in an embryo of 5 mm in length on TVS is a good indicator of embryonic demise.*[2] *Fetal heart rates less than 90/min when the CRL is greater than 5 mm are also associated with fetal demise.* A patient with an IUP and vaginal bleeding or abdominal pain may be experiencing miscarriage. One quarter of pregnancies will experience vaginal bleeding, and one half of those will go on to have a miscarriage.[11] In patients with an identified yolk sac, miscarriage occurred in 17% of those with pain, 41% with bleeding, and 35% with both pain and bleeding.[12] In cases in which a live IUP was identified, 9.3% of first trimester patients with bleeding went on to have a miscarriage. However, if the patient presented with pain only, 2.5% miscarried.[13] After a complete spontaneous abortion, an empty uterus with a clear midline echo is visualized on ultrasound. With an incomplete abortion, retained products of conception are visualized as a thickened midline stripe (>10 mm wide) or irregular echogenic material within the uterine cavity (Figure 43 E-11).

SUBCHORIONIC HEMORRHAGE

Subchorionic hemorrhage appears sonographically as a *hypoechoic or anechoic area between the placenta and the uterine wall*. The risk of miscarriage, stillbirth, placental abruption, and preterm labor are all increased if a subchorionic hemorrhage is identified on ultrasound.[14] The spontaneous abortion rate is about 9.3% when subchorionic hemorrhage is identified in the first trimester. The rate is further increased with advanced maternal age and gestational age less than 8 weeks.[15] The prognosis is also associated with the size of the bleed. The appearance of acute hemorrhage is hyperechoic or isoechoic. Within 1 to 2 weeks, the hemorrhage becomes hypoechoic or anechoic with liquefaction of the clot (Figure 43 E-12).

OVARIAN CYST RUPTURE

Differentiation of benign versus malignant masses is not within the scope of bedside ultrasound; however, detecting the presence of these masses and the sequelae is within the scope of the bedside clinician. Any ovarian mass encountered should be evaluated for its size, it echogenicity (cystic, solid, mixed, etc), presence of septations, and thickness of the walls.[4] Normal functional ovarian cysts will be 6 cm or less.[3] When hemorrhagic, fibrin strands with a fishnet weave or fine reticular appearance and a retracting clot are generally seen within an enlarged ovary (Figure 43-4). Diagnosis of cyst rupture can be difficult sometimes because the cyst itself is no longer visible sonographically after rupture. Therefore the diagnosis is made in the correct clinical setting of sudden onset pelvic pain and free fluid in the pelvis.[16] With simple ovarian cyst rupture, anechoic fluid is visualized in the pelvis. However, hemorrhagic ovarian cyst rupture results in echogenic fluid in the pelvis or massive hemoperitoneum. This can occasionally precipitate life-threatening hemodynamic instability. The presence of a large amount of abdominal free

Figure 43-4 A hemorrhagic ovarian cyst with fibrin strands and reticular appearance.

fluid should point to the diagnosis with the correct clinical picture.

OVARIAN TORSION

Ovarian torsion is another ovarian emergency for which ultrasound is the first-line diagnostic tool. Rotation of the ovary about its pedicle can impede and totally occlude its blood supply through the uterine artery. There is a progression from venous stasis, ovarian edema, and congestion to complete ischemia. This is often associated with an adnexal mass, but can be idiopathic. Up to 20% of adnexal torsion occurs in the setting of pregnancy.[3] *Ultrasonography has a diagnostic accuracy of 74.6% for ovarian torsion and is highly dependent on operator accuracy.*[17] The sonographic findings are quite variable and are dependent upon the duration of symptoms, degree of torsion, and whether the torsion is intermittent. The ovary is typically enlarged, with prominent heterogeneous central stroma and peripherally displaced small follicles (Figure 43 E-13). An underlying mass, such as a dermoid cyst or hemorrhagic cyst, may be visualized. Other findings include free fluid in the pelvis, an abnormal ovarian position, and a whirlpool sign, which is an enlarged fallopian tube with alternating hypoechoic and echogenic bands representing the twisted vessels within the adnexal pedicle.[2] The absence of blood flow on Doppler in a painful, morphologically abnormal ovary is highly suspicious of ovarian torsion. However, normal arterial and venous pulse Doppler waveforms do not exclude ovarian torsion because of dual blood supply to the ovary from both the ovarian and uterine arteries. In addition, with partial torsion (obstruction to lymphatic and venous drainage before arterial occlusion) and intermittent torsion, normal arterial waveforms are noted.

TUBO-OVARIAN ABSCESS

The sonographic findings of pelvic inflammatory disease (PID) without abscess are varied and are not sensitive for the diagnosis. For the bedside clinician, the findings of *thickened and dilatated fallopian tubes with internal echoes or even air* are the most striking and can lead to the diagnosis.[18] Other sonographic signs may include an enlarged uterus or thickened heterogeneous endometrium and poor mobility of the adnexal structures. Along the spectrum of PID, tubo-ovarian abscess (TOA) is a severe consequence and can be confirmed sonographically. Findings typically include loss of the normal boundaries between the fallopian tube and the ovary (because of the pus-filled, edematous inflamed tissue), complex adnexal mass of varying echogenicity with irregular margins, debris, septations, and loculated or speckled or echogenic free fluid in the cul-de-sac (Figure 43 E-14).[19] Any adnexal mass identified on pelvic ultrasound in the correct clinical setting should raise suspicion for TOA. Pelvic ultrasound has been reported to have a sensitivity of 56% to 94%, with a specificity of 86% to 98% in the detection of TOA.[20] The wide range of reported sensitivities is likely secondary to variation modalities, study populations, and ultrasound interpreters in each of the studies that have been done. Larger TOAs may be difficult to diagnose on TVS because of the limited field of view with this probe and may be more easily imaged on TAS.

The use of pelvic ultrasound to diagnose an intrauterine pregnancy, pregnancy failure, and ectopic pregnancy is considered a baseline examination that can be performed by nonspecialists. However, the diagnosis of *tubo-ovarian abscess*, *ovarian torsion*, and *evaluation of ovarian masses* require advanced scanning skills and hence are considered *consultant level examinations* that should be performed by specialists.

IMAGING CASE

A 25-year-old female was admitted to the ICU after successful emergency department cardiac arrest resuscitation. She remained hypotensive and tachycardic. A bedside ultrasound was performed by the critical care physician, which revealed hemoperitoneum and an empty uterus with a large amount of free fluid in the pelvis. A point-of-care urine pregnancy test was performed, which was positive. The diagnosis of a ruptured ectopic pregnancy was made. The patient was immediately taken to the operating room by the obstetrics service, where a large hemoperitoneum and a ruptured ectopic in right adnexa was found. A right salpingectomy was performed, and the patient recovered uneventfully.

Figure 43-5 Free fluid in Morison pouch.

Figure 43-6 An empty uterus with large amount of free fluid in cul-de-sac.

Pearls and Highlights

- Pelvic ultrasound has become an invaluable adjunct to the clinical evaluation of patients with abdominal pain, pelvic pain, and vaginal bleeding.
- Transabdominal and transvaginal ultrasonography provide complimentary information.
- An intrauterine gestational sac is not definitive evidence of an intrauterine pregnancy until a yolk sac or fetal pole are visualized.
- The spectrum of ultrasound findings of ectopic pregnancy includes empty uterus, pseudogestational sac, complex adnexal mass, extrauterine empty gestational sac, extrauterine gestational sac with yolk sac or embryo with or without cardiac activity, tubal ring, and free fluid in cul-de-sac.
- Ruptured hemorrhagic ovarian cyst rupture can result in echogenic fluid in the pelvis or massive hemoperitoneum.
- Normal ovarian arterial and venous flow on Doppler does not exclude ovarian torsion.

REFERENCES

For a full list of references, please visit www.expertconsult.com.

Figure 43 E-1 Longitudinal view of a nonpregnant uterus by transabdominal sonography (TAS).

Figure 43 E-2 Transverse view of a nonpregnant uterus by transabdominal sonography (TAS).

Figure 43 E-3 Sagittal view of a nonpregnant uterus by transvaginal sonography (TVS).

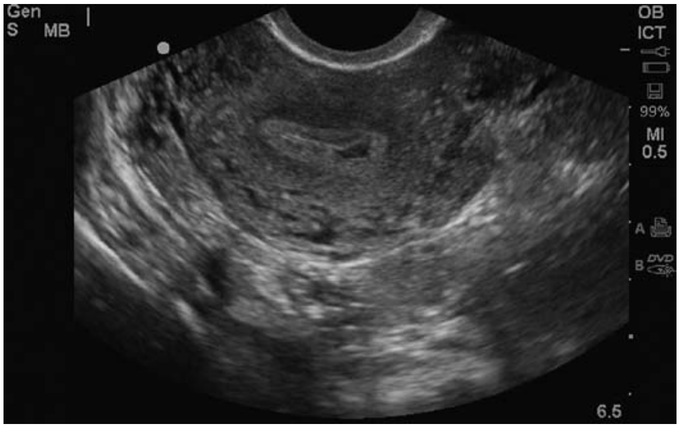

Figure 43 E-4 Coronal view of a nonpregnant uterus by transvaginal sonography (TVS).

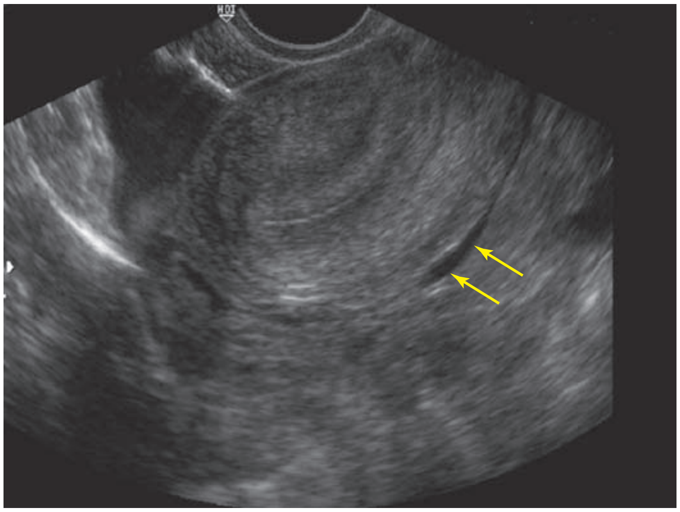

Figure 43 E-5 A small amount of free fluid in pelvis *(arrows)*.

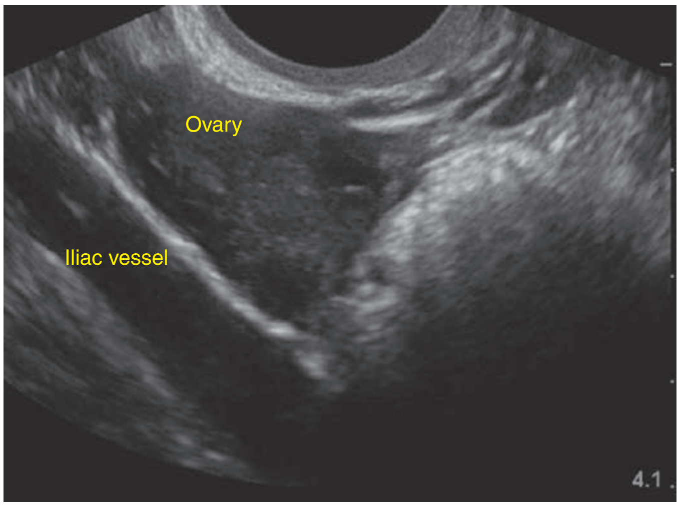

Figure 43 E-6 Normal ovary is seen medial to the iliac vessel on transvaginal sonography (TVS).

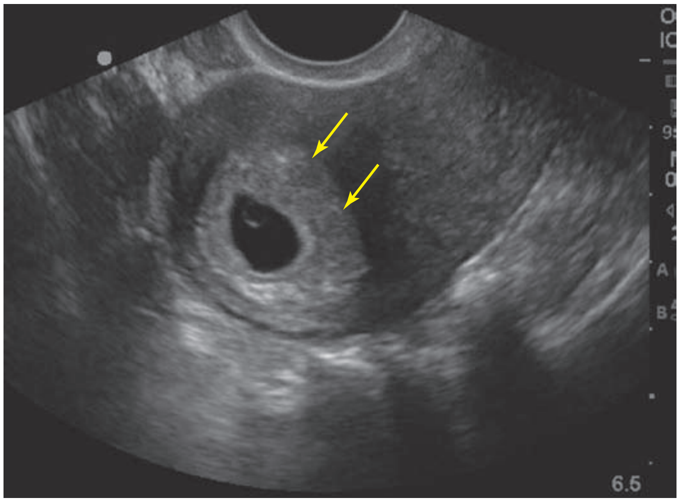

Figure 43 E-7 Sagittal view of a pregnant uterus with double decidual sign *(arrows)* on transvaginal sonography (TVS).

Figure 43 E-8 Crown rump length measured, excluding yolk sac.

Figure 43 E-9 A ruptured ectopic sagittal view of an empty uterus, with large amount of free fluid on transvaginal sonography (TVS).

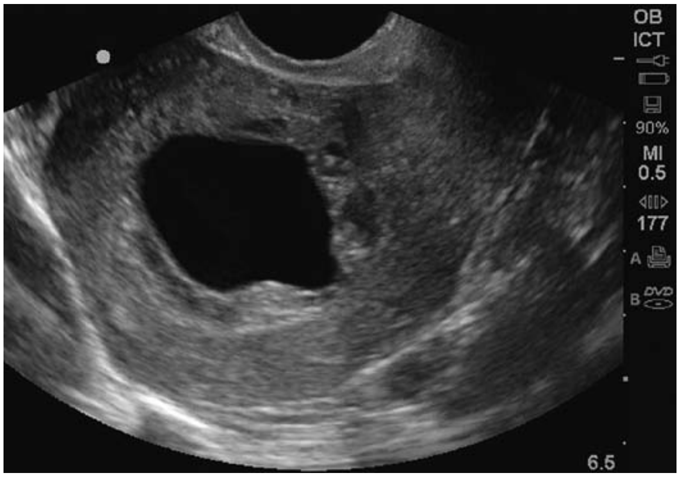

Figure 43 E-10 An irregular gestational sac (sagittal view transvaginal sonography [TVS]) suggesting pregnancy failure.

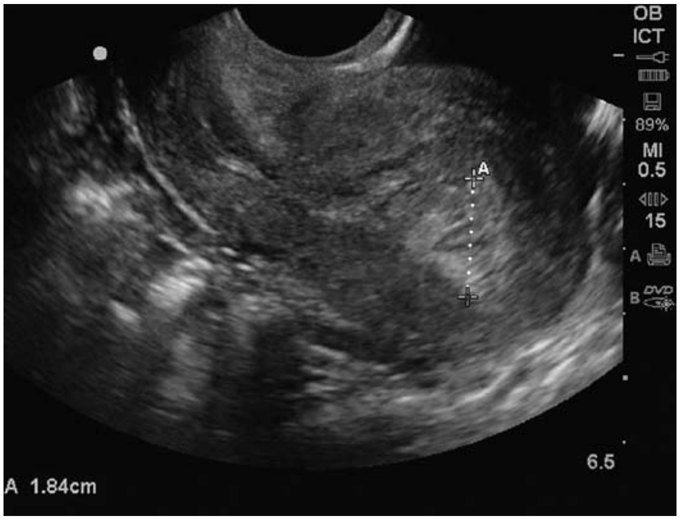

Figure 43 E-11 Sagittal view of a retroverted uterus (transvaginal sonography [TVS]) with thickened endometrial stripe suggesting incomplete abortion.

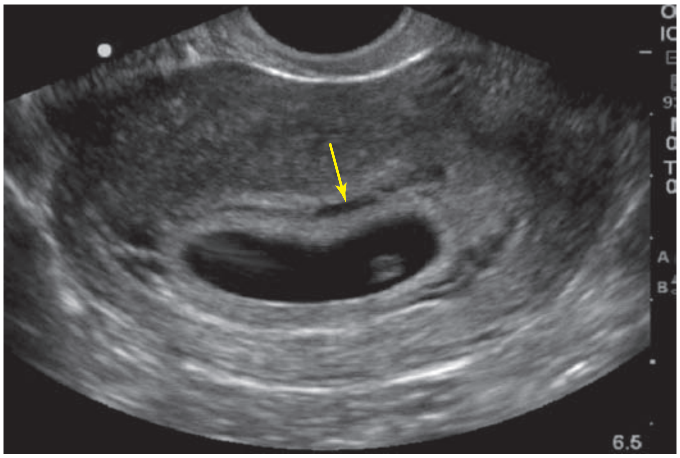

Figure 43 E-12 Longitudinal view of a pregnant uterus (transvaginal sonography [TVS]) showing subchorionic hemorrhage *(arrow)*.

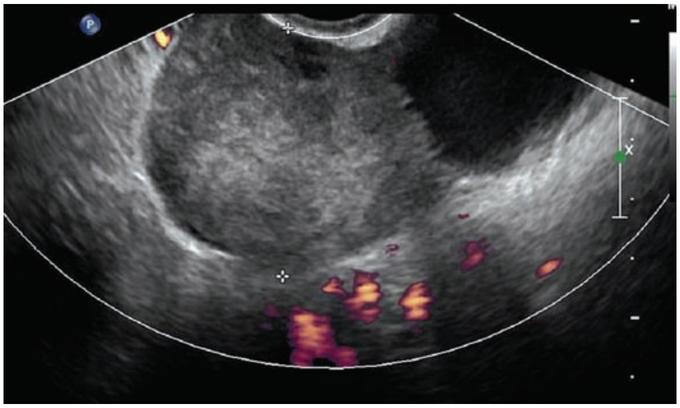

Figure 43 E-13 Enlarged left ovary with cyst and absence of blood flow, consistent with ovarian torsion.

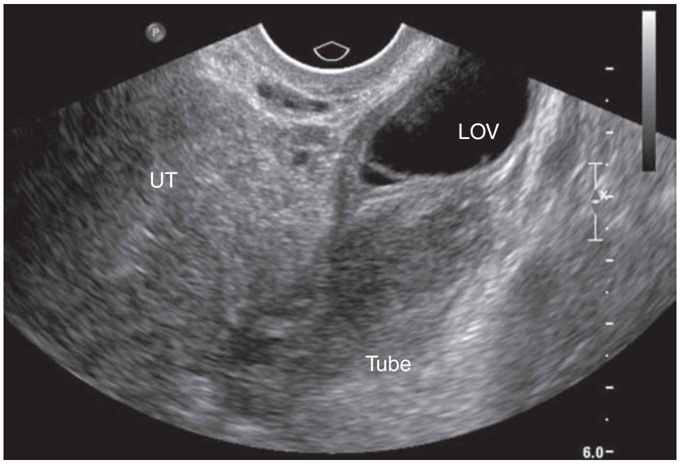

Figure 43 E-14 Tubo-ovarian abscess. Complex adnexal mass seen adjacent to the uterus.

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44

Procedural Ultrasound for Surgeons

JADEN EVANS | SARAH AHMAD | SHARMILA DISSANAIKE

(CONSULTANT-LEVEL EXAMINATION)

Ultrasound (US) has become an indispensable part of the surgeon's armamentarium, useful in both bedside assessment and operative treatment. Because the diagnostic and critical care applications of US are discussed elsewhere, this chapter will focus on intraoperative and US-guided surgical procedures.

Intraoperative Ultrasonography

Intraoperative ultrasonography (IOUS) has been described extensively since the 1980s, and although its main applications are in hepatobiliary and pancreatic surgery, it also has roles in neurosurgery, cardiovascular, and endocrine surgery. In oncologic surgery, IOUS allows identification of lesions not detectable with preoperative imaging modalities and accurate assessment of tumor extension and relationship to critical blood vessels to determine resectability and guide operative planning. By providing real-time data, it enables safe, expeditious, and thorough operative procedures. IOUS helps define the characteristics and location of nonpalpable lesions or structures, such as parenchymal masses (cysts, hemangiomas, and tumors), biliary calculi, dilatated ducts, and space-filling structures in the retroperitoneum, such as pseudocysts and abscesses. IOUS-guided procedures may include biopsy and aspiration, cannulation of structures, and placement of probes for radiofrequency, microwave, and cryotherapeutic ablative technologies. When compared with contrast radiography, IOUS is safer in that it does not expose the patient to ionizing radiation, contrast agents, or complications from cannulation.

Liver

IOUS helps to evaluate undifferentiated hepatic masses for malignancy and resectability. It is frequently used to screen for unsuspected liver metastases in colorectal operations and occult lesions in planned hepatobiliary resections. It reveals deep hepatic sectoral anatomy and, as such, is commonly used to guide parenchymal resections and biopsies and to target intrahepatic lesions during ablation procedures.

Primary hepatocellular carcinoma usually occurs in the setting of dense cirrhosis, which makes visualization and palpation difficult. Furthermore, many hepatomas are smaller than 5 cm and are not fully evident by exploration and palpation alone. IOUS aids with anatomic localization, definition of satellite lesions, and imaging of segmental/subsegmental vascular invasion of the portal or hepatic veins (Figure 44-1).

The same principles apply to hepatic metastases of all tissue types. IOUS has higher (>90%) sensitivity and specificity than preoperative computed tomography (CT), US, or surgical inspection in screening for these lesions, largely because IOUS detects tumors less than 1 cm.[1] When performed as a routine screening procedure during colorectal resections, occult metastases are identified nearly 10% of the time. Likewise, in determining resectability of other intra-abdominal malignancies (pancreas, gallbladder, stomach), identification of occult metastases in the liver dramatically changes the surgical approach from curative to palliative intent. The results of many studies show that IOUS changes the clinical management in up to 50% of patients undergoing hepatic resection for malignancy. Even when intraoperative US does not change surgical management, it results in corrected staging and, consequently, alters postoperative treatment in 11% of patients.[2,3]

Bloed et al[4] showed that despite preoperative triphasic CT, intraoperative US still provided additional useful information in 50% of their patients, which resulted in a change in the surgical procedure in 15%. In a study done at Royal Prince Alfred Hospital, 20 of 30 hepatic resections (67%) were changed or guided by IOUS. IOUS detected 26 more metastases (44%) in 10 of 19 patients (1-5 per patient). Two patients had preoperatively suspected metastases refuted by IOUS-guided biopsy. Eight of the 11 patients (73%) undergoing resection of primary carcinoma of the liver had the planned procedure changed or guided by IOUS.[5]

Gall Bladder

IOUS has equivalent efficacy while providing cost and time savings when compared with cholangiography in biliary disease and has great utility in identifying common bile duct (CBD)

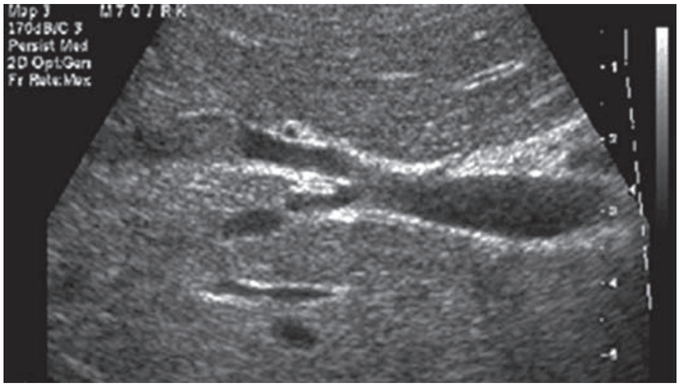

Figure 44-1 Intraoperative ultrasound (IOUS) image of hepatocellular carcinoma invading the right hepatic vein. An isoechoic mass protrudes into the lumen of the vein in a cirrhotic liver.

pathology during open operations, especially because these procedures typically occur amidst inflammation, malignancy, or prior surgery. In cases of unresectable disease, biopsy can be guided by IOUS, and during reconstructive procedures, transhepatic biliary stent placement can be facilitated.

In a recent study, IOUS identified significant biliary abnormalities in 20 patients (40%) undergoing cholecystectomy, including a foreshortened cystic duct (<1 cm) in 7 patients (14%), CBD stones in 4 patients (8%), abnormal cystic duct anatomy in 4 patients (8%), and abnormal vascular anatomy in 8 patients (16%).[6]

Kidney

The relationship of renal tumor to structures deeper within the sinus may be more readily appreciated using IOUS. In a series of patients with hereditary renal carcinoma, IOUS identified tumors that were undetectable by the surgeon in 25% of cases, some as large as 4 cm, of which 50% were pathologically proven renal cell carcinoma (Figure 44 E-1).

Intraoperative real-time renal scanning also displays a cross section of renal tissue and allows accurate, three-dimensional stone localization. This is of value when performing open stone surgery. After mobilizing the kidney, it is scanned in multiple planes until the stone is identified by its characteristic dense echo pattern and the presence of acoustic shadowing. Fine-needle probes are then passed to the stone and a nephrotomy made directly over the stone. With this technique, an experienced ultrasonographer can identify stones 2 mm or more in diameter.

Pancreas

IOUS techniques are particularly useful in the pancreas because of its retroperitoneal location. It augments the staging of pancreatic malignancies, especially neuroendocrine tumors. Perhaps one of the best-defined applications for IOUS is for localization of pancreatic islet cell tumors, both functional and nonfunctional. These tumors are characteristically small (<5 mm) and hypoechoic on US, but more important, preoperative and even intraoperative identification can be unyielding. Intrapancreatic insulinomas can be detected with IOUS between 85% and 100% of the time, and gastrinomas are identified with a 95% frequency, although these rates correlate directly with IOUS experience.[7] In parenchymal-sparing enucleation procedures for tumors or cysts, IOUS helps reveal the relationship of the lesion to the main pancreatic duct in order to protect against the development of a significant pancreatic fistula.

IOUS may be used for pancreatic pseudocyst drainage procedures and can help determine whether multiple pseudocysts are connected, or not, and assess the adequacy of drainage (Figure 44-2). Complications of chronic pancreatitis, such as pseudocysts, dilatated and strictured pancreatic ducts, and portal/splenic venous hypertension, may require surgical intervention but can be difficult to understand anatomically by using visible and tactile exploration alone. IOUS is also excellent for determining the size and characteristics of an obstructed pancreatic duct, an important consideration in choosing a ductal drainage procedure over resection in some cases of chronic pancreatitis. Intraductal papillary projections can occasionally be seen by using IOUS in cases of intraductal

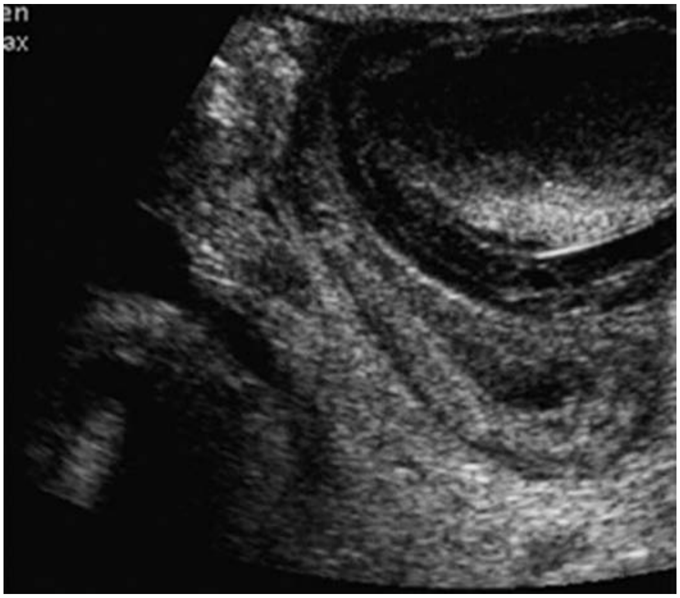

Figure 44-2 Pancreatic pseudocyst. A 5.9 × 3.5-cm cystic lesion with an irregular thick wall contains hyperechoic, heterogenous debris.

papillary mucinous neoplasms, although this is usually unnecessary if the preoperative endoscopic and imaging evaluation was adequate.

Pancreatic adenocarcinoma is an aggressive malignancy that is often unresectable because of local invasion and/or regional metastases. IOUS can help the surgeon determine resectability and whether complex reconstructive maneuvers, such as portal vein reconstruction, will be necessary.

Colon

With the increase in laparoscopic surgery for colorectal neoplasms, there is difficulty encountered in localizing neoplasms without the benefit of tactile feedback. The most commonly used localizing techniques are tattooing with India ink and intraoperative colonoscopy. Although, widely used, these methods are far from perfect. Injected dyes tend to migrate away from the lesion or fail to show it. Intraoperative colonoscopy is cumbersome, and the insufflated gas causes bowel distension that may compromise the operative domain in laparoscopic cases. IOUS has been described as a method to identify these lesions; however, excellent imaging requires the bowel to be filled with saline,[8,9] and this technique has not been widely adopted.

Ultrasound-Guided Percutaneous Surgical Procedures

Ultrasound is also used to facilitate many minor surgical procedures done outside the operating room; several of the most common procedures are discussed below.

SUPRAPUBIC CATHETER INSERTION

Suprapubic catheter insertion (SPC) is indicated in patients with urinary retention after trauma or permanent bladder dysfunction from neurologic conditions.

Ultrasound-guided suprapubic catheter (USSPC) insertion is the safest method, especially in patients with previous abdominal or pelvic surgery, because it reduces the incidence of bowel injury observed in blind SPC while avoiding general anesthesia. The goals of USSPC are to evaluate bladder filling, identify interposed bowel, and guide the needle to the appropriate site (Figure 44 E-2). In patients with sufficient bladder distension and intervening bowel excluded, the puncture site is usually 2 to 4 cm above the symphysis pubis. The position should be confirmed using US before and after balloon inflation to avoid accidental insertion of the catheter tip into the urethra or a diverticulum.

Although the literature on USSPC is sparse, the few studies that have been done show reduced complication rates, improved first-time success rates, and subsequent reduction in infections.[10] As a result, recent British Association of Urological Surgeons guidelines recommend US guidance for SPC insertion whenever possible.[11]

PERCUTANEOUS CHOLECYSTOSTOMY

Percutaneous cholecystostomy (PC) is used as a temporizing measure in critically ill patients with acute cholecystitis who are not candidates for immediate surgical gallbladder removal (Figure 44-3). Once the patient's condition is stable enough for surgery, definite treatment is still cholecystectomy. One exception is acalculous cholecystitis, where percutaneous drainage may be the only treatment required.

PC is performed via a US-guided transhepatic approach through the right lobe to access the gallbladder. A transhepatic is preferred over a transperitoneal approach because of the risk of bile peritonitis in the latter. Bile samples should be collected for Gram staining and cultures. Before catheter removal, ensure patency of the cystic duct by clamping the tube for 48 hours and evaluate for signs of cystic duct obstruction (i.e., fever, pain, or elevated white blood cell [WBC] count).

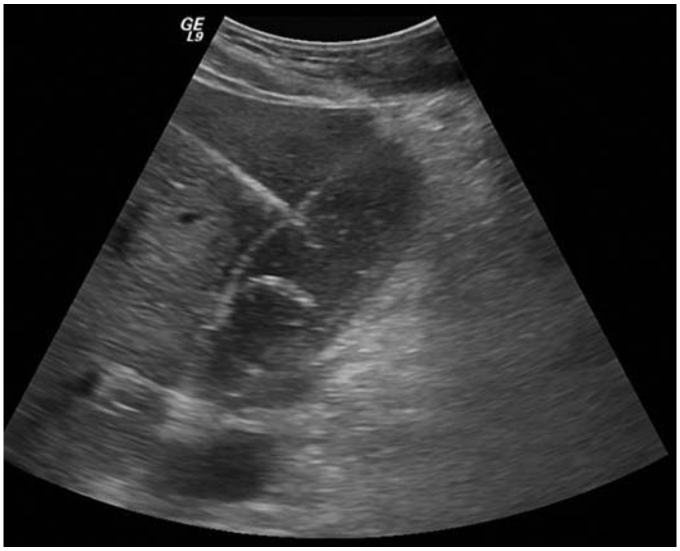

Figure 44-3 Image shows a percutaneous cholecystostomy catheter entering an inflamed gallbladder in a man with acute cholecystitis that complicates renal failure after a necrotizing soft tissue infection.

Surgical gallbladder removal is the best treatment for both acute calculous and acalculous cholecystitis because of its curative nature and low mortality rate of 0% to 0.8%.[12,13] However, the mortality rate in elderly or critically ill patients with comorbid disease skyrockets to 14% to 30%[14,15]; therefore PC provides a safe alternative in the critically ill and elderly.[16,17]

PERCUTANEOUS ABSCESS DRAINAGE

Ultrasound-guided percutaneous abscess drainage (USPAD) is highly effective in treating abdominal and pelvic abscesses, a common surgical problem. It may be used either as a preparatory step or an alternative to open surgery. USPAD offers real-time imaging, reduced radiation, and the option to perform the procedure at the bedside. Multiloculated abscesses should be drained using CT, which may necessitate multiple catheters.

Guidewire selection is extremely important to good outcomes and should be stiff enough to guide dilators and catheters into the abscess but not be so stiff as to prevent easy coiling within the abscess. Once access is gained to the collection, it is critical to maintain guidewire access during the entire length of the drainage procedure. If access is not maintained, reentry may be difficult because of spontaneous decompression of the abscess or difficulties in imaging the disturbed region.

The success of USPAD is well documented and has become the standard of care in treating intraabdominal and pelvic abscesses (Figure 44 E-3).

BREAST CYST DRAINAGE

Breast cysts are a common problem affecting women of all ages. Although asymptomatic stable cysts do not require treatment, larger cysts may cause pain and benefit from aspiration (Figure 44 E-4). In addition, any cyst with a potential solid component should be evaluated to exclude malignancy. Fine-needle aspiration is done using ultrasound to ensure proper placement within the fluid-filled cavity. The procedure is used to both diagnose and treat the cyst. If the aspirated fluid is clear and the mass resolves, malignancy is unlikely. If the fluid is bloody or if there is a residual mass after aspiration, referral for core-needle or excisional biopsy is indicated.

POSTOPERATIVE SEROMA DRAINAGE

A seroma is a collection of clear serous fluid that can develop after surgery. Seromas are differentiated from hematomas by a lack of red blood cells and from abscesses by a lack of pus. Seromas commonly develop after mastectomies, facial plastic surgeries, lymph node removal, abdominal surgeries, and, in some cases, brachytherapy. Most seromas will resolve without intervention, but persistent seromas may require percutaneous drainage with US guidance. The technique is similar to cyst aspiration as discussed earlier.

IMAGING CASE

A 50-year-old woman with nausea, vomiting, and abdominal pain was referred for laparoscopic cholecystectomy. The gallbladder was densely adherent to the liver, prompting IOUS, which revealed a polypoid mass. Open radical cholecystectomy with en bloc resection of the adjacent liver was performed. Pathology revealed a completely resected T2N0M0 cancer.

Figure 44-4 Intraoperative ultrasound (IOUS) image of a polypoid gallbladder lesion.

Pearls and Highlights

- IOUS facilitates identification of occult hepatic lesions and small neuroendocrine pancreatic tumors and determines resectability of larger pancreatic and liver cancers.
- US provides the safest method of suprapubic urinary catheter insertion.
- US-guided cholecystostomy is a safe and effective alternative to surgical gallbladder removal in the critically ill.
- US guidance is standard of care in seroma and breast cyst aspiration.

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For a full list of references, please visit www.expertconsult.com.

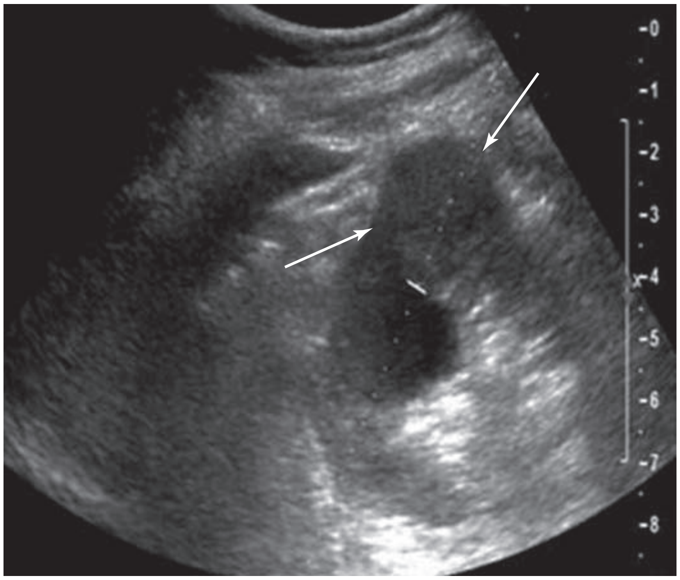

Figure 44 E-1 A renal cell carcinoma is identified as a rounded mass extending off the posterior kidney *(arrows)*. Note the dark area next to the mass, which represents a renal cyst.

Figure 44 E-2 Images (from *left* to *right*) show needle puncture under ultrasound (US) guidance, guidewire confirmed on US, and loop of intervening bowel over bladder. *(Reproduced with permission from Jacob P, Rai BP, Todd AW: Suprapubic catheter insertion using an ultrasound-guided technique and literature review.* BJU Int *110:779-784, 2012.)*

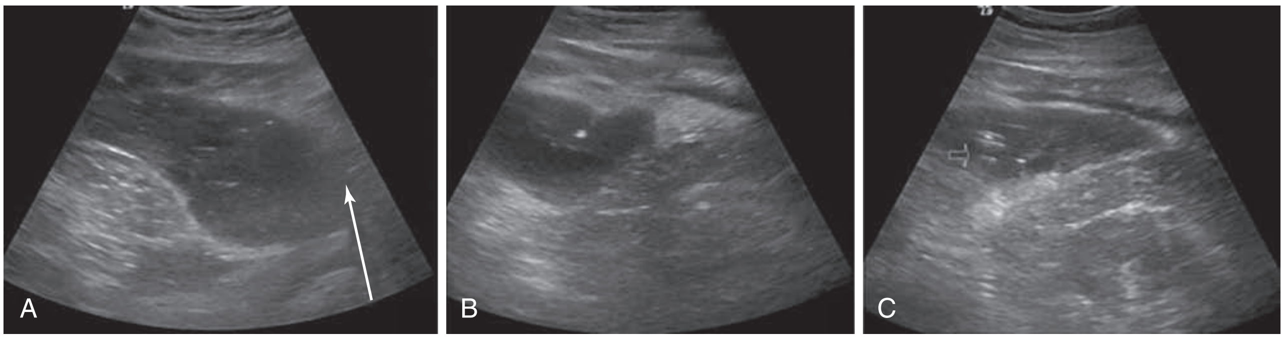

Figure 44 E-3 **A,** Intraabdominal abscess after colon resection for diverticulitis. **B,** Tip of catheter visible within the abscess. **C,** Postdrainage.

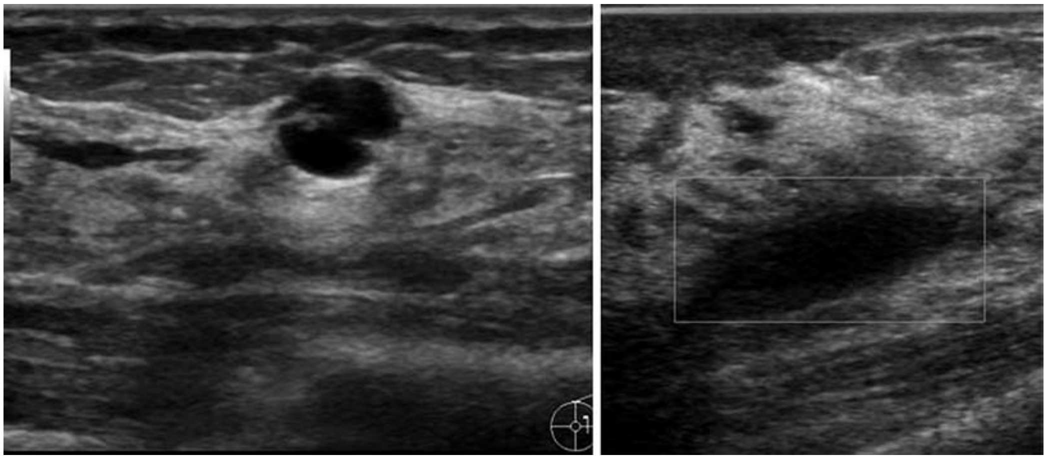

Figure 44 E-4 Lobulated and simple breast cysts from the same 45-year-old woman.

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45

The Extended FAST Protocol

YEKATERINA GREWAL | ARIEL L. SHILOH | LEWIS A. EISEN

Overview

Ultrasound has become a permanent part of the evaluation of trauma patients ever since its first use in the emergency department more than 30 years ago.[1] First used in Europe in the 1970s, abdominal ultrasound ultimately replaced diagnostic peritoneal lavage during the 1980s.[2] Currently, bedside ultrasound is the initial imaging modality of choice for trauma care and is integrated into the Advanced Trauma Life Support protocol developed by the American College of Surgeons.[3]

"*FAST,*" an acronym for the *f*ocused *a*ssessment with *s*onography in *t*rauma, was first described by Rozycki and Shackford[4] in 1996. The basic four-view examination consisting of perihepatic, perisplenic, pelvic, and pericardial views has become the foundation of FAST. The ability to be performed rapidly and safely during resuscitative measures makes it an ideal initial imaging modality in trauma patients. Ultrasound is reliably sensitive in diagnosing free fluid and free air in peritoneum, allowing the rapid recognition of hemoperitoneum and perforated viscera in hypotensive patients and traumatic injuries.[5-8] Previous work demonstrated that ultrasound has a higher sensitivity (49%-99%) than standard chest radiography (27%-75%) in the identification of hemothorax or pneumothorax.[9-12] The *extended FAST (e-FAST) protocol,* which includes the assessment of the lung and pleura bilaterally and the subcostal cardiac view, has been developed as point-of-care ultrasound for assessing and treating thoracic pathology in the intensive care environment. Its use has increased considerably over the last decade.[13]

Ultrasound has been recognized as a powerful diagnostic tool in many clinical settings beyond trauma and has proliferated through a variety of medical specialties. Although pioneered in emergency medicine, e-FAST has now become an important part of critical care evaluation of medical and surgical patients.[14,15]

Limitations of e-FAST

As an operator-dependent test, the learning curve, which is correlated with the results, has been studied. The literature describes variable outcomes related to different operators (radiologists vs. emergency medicine doctors). In addition, e-FAST is limited by technical factors that affect image acquisition, which include, but are not limited to, obesity and deep tissue structures, subcutaneous emphysema, bandages, or barriers to adequate transducer contact. Also, although sensitive for the detection of free fluid or air, ultrasound is not as adept in isolating the associated parenchymal injuries.[5,16-19] Once free air or fluid is identified, additional imaging modalities, such as computed tomography (CT), are usually required to further isolate a parenchymal injury.

Application of e-FAST in the Intensive Care Unit

e-FAST is applicable in medical and surgical populations in the intensive care unit (ICU). The most practical applications concern hemodynamically unstable or shock patients in whom rapid diagnostic imaging, resulting in focused therapies, could potentially prevent catastrophic outcomes.

Learning to perform the e-FAST examination involves learning how to visualize the heart, diaphragms, liver, spleen, and bladder.[20] Interpretation of the e-FAST examination involves learning where free fluid commonly collects adjacent to these structures.

At this time, there is still lack of agreement on recommendations for e-FAST training. It appears that most investigators find that sensitivity and specificity begin to plateau after 25 to 50 examinations.[18,21] Current guidelines recommend performing 200 e-FAST examinations.[22]

Thorax

KEY FINDINGS

- Pneumothorax
- Free fluid

Of note, it has been demonstrated that 30% to 50% of pneumothoraces are missed by chest radiography.[23] This diagnostic inaccuracy is partially due to the fact that hemothoraces settle out posteriorly and pneumothoraces anteriorly. In the trauma setting, the e-FAST examination has a sensitivity of 81% to 100% and specificity of 100% for the diagnosis of free fluid in the thoracic cavity.[24] About 200 mL of free fluid in the thoracic cavity need to be accumulated to be detected by a plain chest radiography.[25] However, ultrasound is much more sensitive and is able to detect as little as 20 mL of free fluid in the same settings.[26] The time required for ultrasound versus radiography, in one study, was 1 minute versus 14 minutes, highlighting the potential for rapid diagnosis and intervention.[27] Although no similar studies are done for ICU patients, our clinical experiences fully support the time savings associated with bedside ultrasound.

Structures to be identified during the thoracic examination are the pleural line (the combination of the visceral and parietal pleura) and the costal arcs. Chest examination consists of defining "pleural sliding," A-lines, B-lines, and free fluid (these specific findings are extensively detailed in previous chapters).

Anterior pneumothorax can often be undetected on a supine portable chest radiograph due to underlying normal lung tissue. However, it can easily be detected with ultrasound as air rises to the highest point within the chest cavity. Therefore, in a supine patient, free intrathoracic air will likely be detected in an anterior examination unless pleural loculations are present. Furthermore, presence of a lung point will be diagnostic of pneumothorax.[28]

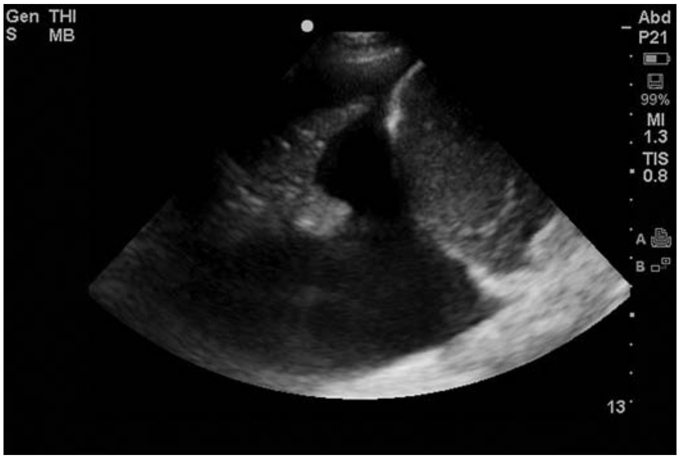

Figure 45-1 Right pleural effusion. Atelectatic lung can be seen compressed within the pleural effusion. All fluid is confined to the space above the diaphragm.

Detection of fluid in the thoracic cavity should promote acute interventions, such as rapid bedside thoracentesis, to determine the gross presence of blood and can facilitate chest tube placement in efforts to resuscitate an unstable patient (Figure 45-1).

Abdomen

KEY FINDINGS

- Free fluid
- Free air

The initial investigations with e-FAST examination focused primarily on the use of bedside ultrasound in the detection of free peritoneal fluid. Sites of evaluation consist of the hepatorenal and splenorenal spaces, paracolic gutters bilaterally, and posterior to the bladder. Although ultrasound is inferior to abdominal CT in the detection of parenchymal injury, it is greater than 95% sensitive and specific for the presence of hemoperitoeum.[29,30] It is generally accepted that 250 mL of fluid in the peritoneal cavity is the minimum volume that can be sonographically detected. Of note, large amounts of free peritoneal fluid can be sonographically detectable even by inexperienced operators, whereas small amounts of peritoneal fluid may be missed, especially when located in areas in between structures (e.g., the Morison pouch; Figures 45 E-1 and 45 E-2). To optimize sensitivity to detect the smallest amount of free fluid possible, it is important to obtain images of good quality at multiple intraperitoneal sites.[15,31]

In a multicenter prospective trial, Rozycki et al[5,7] found that the hepatorenal interface was the most common location for free fluid collection and was associated with significant parenchymal injuries. Although a single hepatorenal view has been advocated by some, a multiple-view e-FAST examination is still recommended because the sensitivity for identification of free fluid is increased and the additional time required is minimal.[32-35]

Intraabdominal parenchymal injury is harder to detect when the organ capsule remains intact. The most common sonographic finding associated with splenic rupture is a diffuse pattern of mixed echogenicity within the spleen (Figure 45 E-3). This can be difficult to identify because the stomach overlies the acoustic window of the spleen and can give a hyperechoic signal that appears to be within the spleen.[29] The liver has a greater volume than the spleen; thus small intraparenchymal lesions may be missed with the rapid e-FAST technique (Figures 45 E-4 and 45 E-5). Retroperitoneal injuries are also difficult or impossible to detect with ultrasound. e-FAST can yield negative findings or fail to help detect signs of retroperitoneal injury, even in the presence of significant injury, because ultrasound can mainly assess the peritoneal space (see Chapter 41).[36,37]

Detection of free fluid in the peritoneal cavity, in a hemodynamically unstable patient, usually necessitates immediate laparotomy. Ultrasound cannot reliably distinguish acute bleeding from simple ascitic fluid or urine because all appear hypoechoic (Figure 45-2). However, ultrasound-guided paracentesis can quickly make this differentiation (Figure 45 E-6). In case conservative management is followed, repeated ultrasound examinations can evaluate possible alterations in the amount of fluid. As blood coagulates, a "hematocrit sign" may be observed as the more echogenic particles of blood precipitate to dependent areas (Figure 45-3).[38]

A free-flowing effusion seeks a dependent position in the abdomen by gravitational effect. Free fluid is usually seen in the hepatorenal recess or along the lower edge of the liver and around the lower tip of the liver.[39] Placing a patient in the Trendelenburg position improves the sensitivity for detecting free

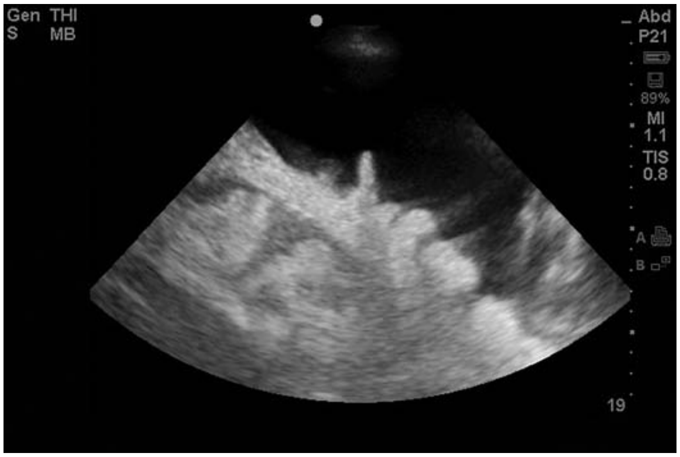

Figure 45-2 Free fluid in the abdominal cavity. Bowel loops can be identified. The fluid can be described as nonechogenic simple fluid.

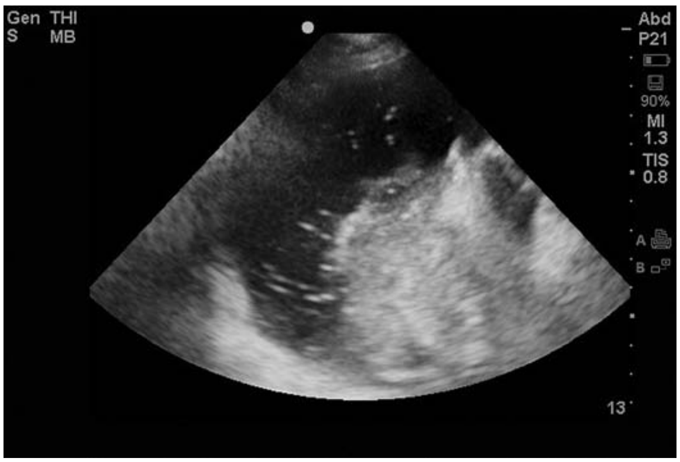

Figure 45-3 The hematocrit sign. As blood coagulates, a "hematocrit sign" may be seen as the more echogenic particles of blood precipitate to dependent areas.

fluid.[34] Trendelenburg positioning can be also applied when the pelvic view is indeterminate or difficult to visualize. Overall, the e-FAST examination is 90% sensitive for detecting any amount of intraperitoneal free fluid (Figure 45-4).[36]

Swirling echoes, strands, fronds, or septations may be visible in exudative collections. Effusions with these findings are described as being heterogeneously echogenic. Echogenic effusions with septations often indicate infectious peritonitis or empyema.[40,41] Ultrasound may be superior to a CT scan in revealing septations.

Bowel injuries in the acute settings are notoriously difficult to diagnose, even with CT. Ultrasound is inaccurate for detecting bowel injuries, and the most common associated finding is free fluid.[42] Abdominal ultrasound is useful in detection of free peritoneal air during emergent assessment. Similar to lung sliding, "gut sliding" of the intact visceral and parietal peritoneal layers has been described. The absence of gut sliding with an associated horizontal air pattern arising from the peritoneal line (similar to A-lines) can be highly indicative of free intraabdominal air.[43] The scanner should look for a splanchnogram sign indicating that the major abdominal organs (such as liver and spleen) are visible. The absence of the splanchnogram sign coupled with the absence of sliding gut predicted pneumoperitoneum with 100% sensitivity (Figure 45-5).[43]

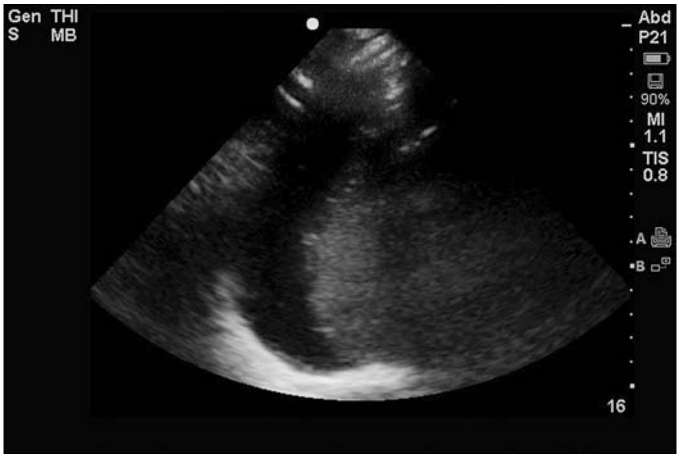

Figure 45-4 Perihepatic fluid. Free fluid is localized between the diaphragm and liver.

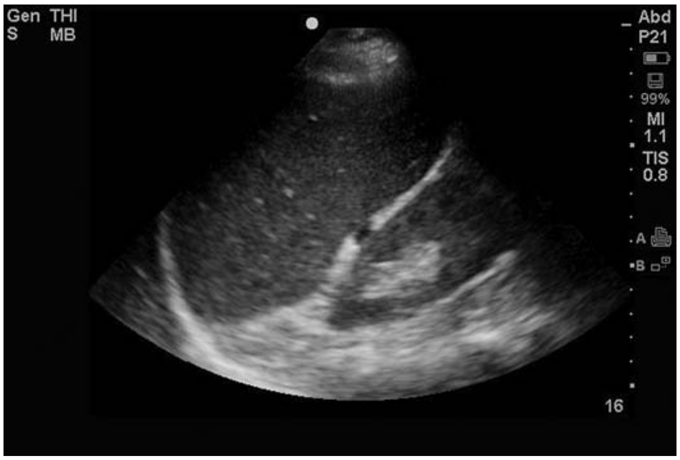

Figure 45-5 The splanchnogram sign—clear visualization of the visceral organs. This image demonstrates the normal hepatorenal space (Morison pouch).

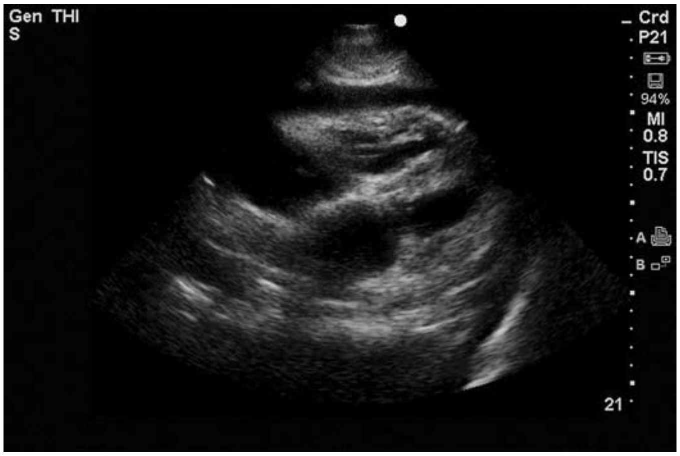

Figure 45-6 Pericardial effusion. A subcostal view of the heart demonstrates an encapsulating pericardial effusion.

Cardiac

KEY FINDINGS

- Global ventricular function
- Pericardial effusion
- Cardiac tamponade
- Inferior vena cava (IVC) analysis (diameter and collapse)

As part of the e-FAST, a subcostal (subxiphoid) cardiac view is obtained. Work done by Plummer[44] demonstrated the value of bedside ultrasound in the evaluation of cardiac injuries. In this study, the ultrasound group had a significantly faster rate of diagnosis and disposition and higher survival rates (100% vs. 57%).[44] Although e-FAST visualization of the heart consists mainly of a subcostal view, ideally, imaging in multiple views (using several windows) provides the most accurate detection of pericardial effusion.

Cardiac function can be quickly estimated, and pericardial fluid can be identified (Figure 45-6). Signs of pericardial tamponade are described in detail in previous chapters. However, in a hemodynamically unstable patient, significant fluid should be drained via ultrasound guidance. From the subxiphoid view, the IVC can be visualized adjacent to the right atrium, where it can be analyzed (diameter and collapse). IVC analysis can be used as a measure of volume responsiveness (detailed in previous chapters).[31,32]

Pearls and Highlights

- e-FAST is a rapid tool for detection of cardiac, intrathoracic, and intraabdominal pathology.
- Detection of free fluid or air on e-FAST should prompt immediate further investigation or intervention.
- Ultrasound can be used to follow patients managed conservatively or to guide diagnostic procedures.

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For a full list of references, please visit www.expertconsult.com.

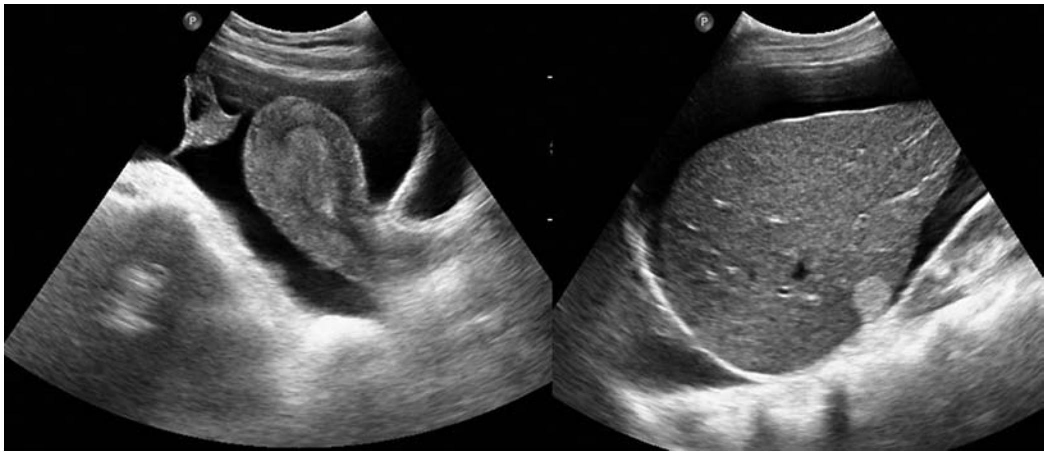

Figure 45 E-1 Large amounts of free peritoneal fluid can be detected even by novice operators. *(Courtesy Dr. D. Karakitsos.)*

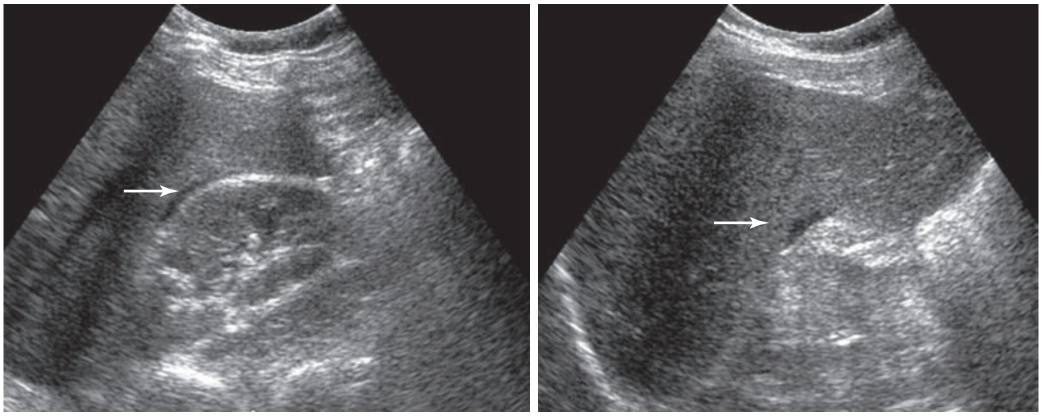

Figure 45 E-2 Small amounts of peritoneal fluid *(arrows)* may be missed especially when located in areas in between structures, such as the Morison pouch, in this example. *(Courtesy Dr. D. Karakitsos.)*

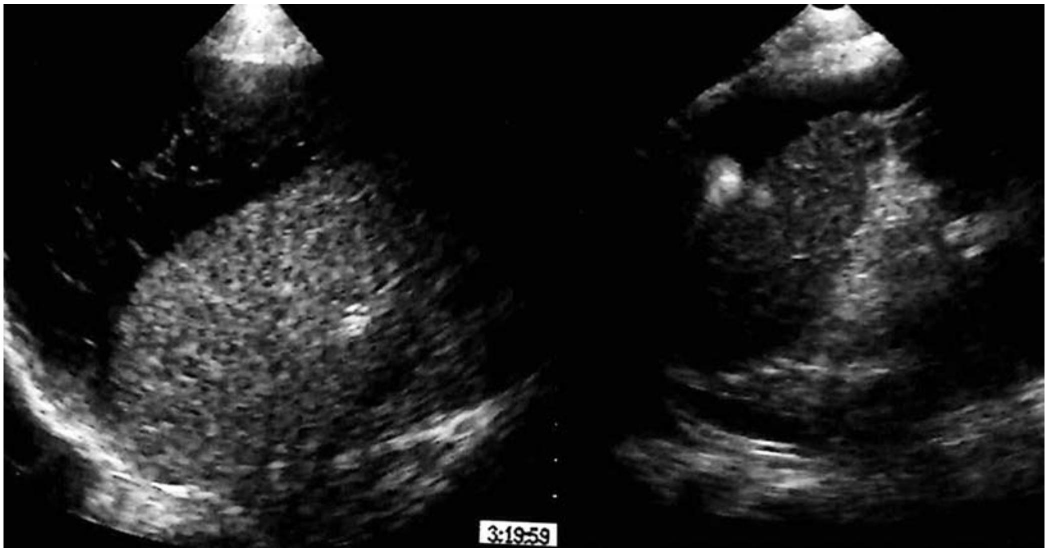

Figure 45 E-3 Visualization of a diffusely heterogeneous splenic parenchyma of mixed echogenicity and perisplenic fluid, whereas the capsule appears not to be intact (splenic rupture). *(Courtesy Dr. J. Poularas.)*

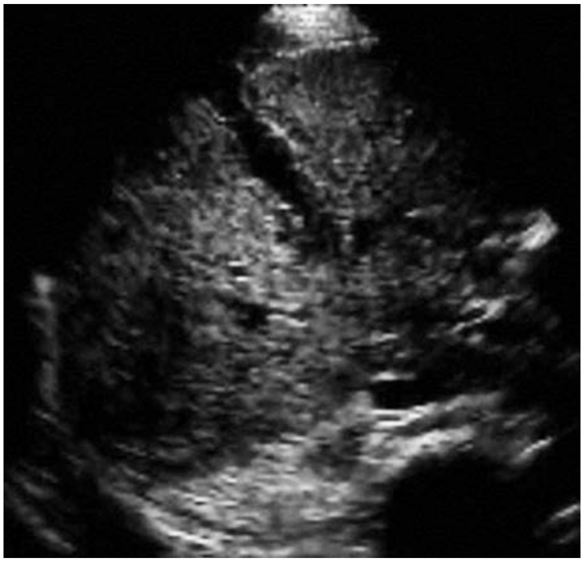

Figure 45 E-4 Visualization of a diffusely heterogeneous hepatic parenchyma of mixed echogenicity and perihepatic fluid, whereas the Glisson capsule appears not to be intact (hepatic rupture; zoom image). *(Courtesy Dr. D. Karakitsos.)*

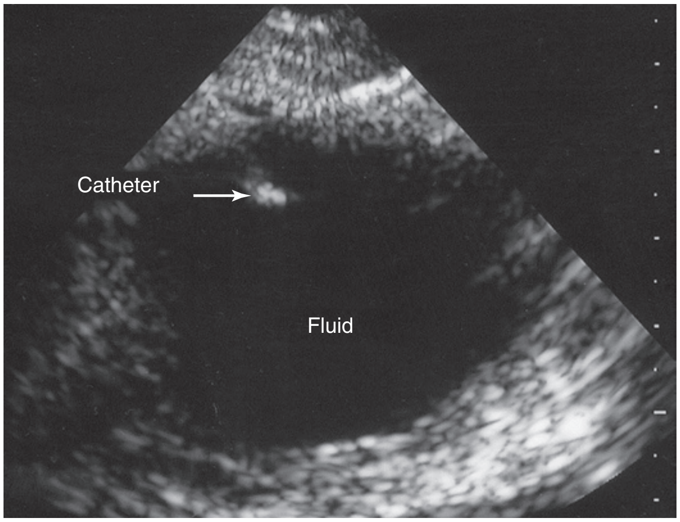

Figure 45 E-6 Transverse view of an ultrasound-guided paracentesis of free peritoneal fluid. *(Courtesy Dr. J. Poularas.)*

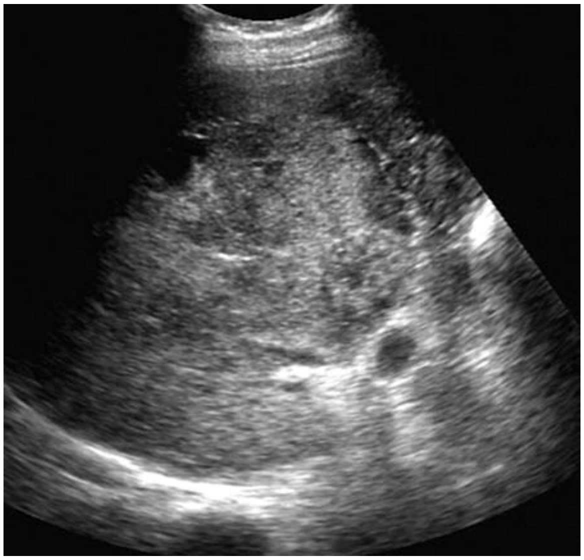

Figure 45 E-5 Visualization of a diffusely heterogeneous hepatic parenchyma of mixed echogenicity and partially intact Glisson capsule (hepatic rupture). *(Courtesy Dr. J. Poularas.)*

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46

Use of Ultrasound in the Evaluation and Treatment of Intraabdominal Hypertension and Abdominal Compartment Syndrome

KHANJAN H. NAGARSHETH | HEIDI LEE FRANKEL

Overview

Intraabdominal hypertension (IAH) and abdominal compartment syndrome (ACS) are well-documented causes of morbidity and mortality in the critically ill. IAH and ACS may affect almost every organ system.[1] The World Society of the Abdominal Compartment Syndrome (www.wsacs.org) has set forth a number of definitions based on clinical evidence and expert opinion. Intraabdominal pressure (IAP) is normally 5 to 7 mm Hg in adults. IAH is defined as sustained or repeated pathologic evaluation of IAP greater than or equal to 12 mm Hg. This is further subdivided into four grades based on pressure value. ACS is sustained IAP greater than 20 mm Hg, associated with new organ dysfunction/failure.[1] Usual causes of IAH and ACS include intraabdominal hemorrhage, pneumoperitoneum from perforated viscus, and third spacing of fluid during massive resuscitation (Figure 46-1).

Pathophysiologic Effects

CARDIOVASCULAR

Cardiac dysfunction occurs in patients with IAH and ACS because of increased intrathoracic pressure (ITP) resulting from upward diaphragm displacement. This increased ITP causes a significant decrease in venous return, thereby reducing cardiac output. There is a clear association between IAP and ITP. Fifty percent of the IAP is transmitted and affects the ITP.[2] Cheatham et al[3] point out that catheter-based hemodynamic measures, such as pulmonary artery occlusion pressure and central venous pressure, therefore have significant limitations as indexes of volume status in the face of IAH. They proposed the idea of using volumetric measurements, such as end-diastolic volume index, in directing adequate resuscitation in these patients. Anticipating the relationship between IAP and ITP and possibly using volume indexes for estimation of preload could help to prevent inadequate resuscitation and inappropriate use of vasoactive agents in patients with IAH. Several ultrasound (US) methods are used to guide therapeutic strategies in the face of IAH. Resuscitation efforts geared toward a right ventricular, end-diastolic volume index, goal-directed model have been shown to reduce the incidence of multiple organ failure and death.[4]

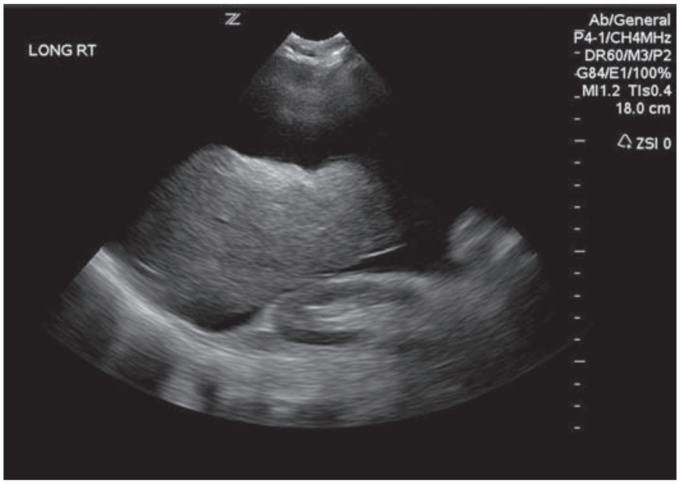

Figure 46-1 Free abdominal fluid in the right upper quadrant.

RESPIRATORY

IAH results in increased ITP by pulmonary parenchymal compression and reduced chest wall compliance. Parenchymal compression leads to pulmonary hypertension. To overcome the alveolar compression and atelectasis, positive end-expiratory pressure (PEEP) is increased or added to maintain oxygenation and ventilation. Aggressive PEEP can result in not only opening up atelectatic areas of the lung but also overdistending normal lung and inhibiting adequate ventilation.[1,5]

RENAL

An early sign of end-organ hypoperfusion resulting from IAH and/or ACS is decreased urine output. Renal dysfunction usually occurs with oliguria at 15 mm Hg and anuria at 30 mm Hg in euvolemic patients with no underlying kidney disease.[6] This may occur at lower IAP in those who are already hypovolemic or in those with baseline pathology. Dysfunction may be due to compression of the renal parenchyma and vein, along with decreased renal perfusion pressures, leading thus to microcirculatory alterations and decreased urine output.[7] Urine output is dependent on the renal filtration gradient (FG) or the glomerular filtration pressure (GFP) minus the proximal tubular pressure (PTP), which can be estimated as mean arterial pressure (MAP) minus two times the IAP [$FG = GFP - PTP = MAP - (2 \times IAP)$].[1,6]

Ultrasound and Other Diagnostic Adjuncts

INTRAVESICULAR PRESSURE

Measurements are performed at the end of expiration in a supine position with the transducer zeroed at the iliac crest in the midaxillary line by using 25 mL of saline instilled into the bladder. The measurement is taken in mm Hg between 30 to 60 seconds after the saline is instilled and catheter clamped. All abdominal muscle contractions should be absent during measurements.[8,9]

INTRAGASTRIC PRESSURE

Intragastric pressure (IGP) monitoring has been used, in place of bladder pressure monitoring, in several experimental models to obtain abdominal pressure readings.[10,11] There is a close relationship between IAP and IGP, with potential for inaccuracy in patients with ileus and in those who are being enterally fed.[11]

ABDOMINAL ULTRASONOGRAPHY

Recently, abdominal US has been used to identify patients with IAH and ACS. Cavaliere's group[12] examined the ultrasonographic detection of changes in the dimensions of abdominal veins—in the setting of simulated increased IAP in normal volunteers—as a marker of ACS. They used a pelvic binder to create external compression, inducing mild IAH. Dimensions of multiple abdominal veins were estimated by B-mode, while pulsed wave Doppler measured peak blood flow velocities at the end of expiration. The inferior vena cava (IVC) below the renal veins, the right suprahepatic vein, the portal vein (PV), the right external iliac vein, and the segmental branches of the right renal artery were measured. Significant changes in IVC and PV diameters were noted. Diameters were noted to be decreased about 10%, whereas the cross-sectional area of the IVC was decreased about 25%. No significant changes were evident in peak Doppler velocities of the studied vessels, but significant variability between individuals existed. Studies using computed tomography scans revealed distorted IVC shape and decreased diameter as well as flattening of renal vasculature in ACS.[13] Further research should include ultrasonographic analysis of IVC and PV in patients with IAH and ACS.

RENAL DUPLEX ULTRASOUND

Duplex US of the renal arteries and their branches has been used in patients with various kidney diseases to estimate their renal resistive index (RI).[14] RI is defined as [(peak systolic velocity − end-diastolic velocity)/(peak systolic velocity)] and correlates with renal function. Pulsed wave Doppler measurements are obtained with the sample volume adjusted to 1.5 to 2 mm and the angle to 0 degrees when evaluating interlobar arteries, whereas the angle should be 60 degrees or less when scanning renal arteries. Signals are obtained from the interlobar arteries along the border of the medullary pyramids (Figure 46-2).[15] Several measurements at multiple points in the organ are obtained, whereas average values are used to calculate the RI (Figure 46-3). The RI method is technically demanding and has many limitations (e.g., optimization of Doppler signals and pertinent waveforms, proper identification of arcuate and intramedullary arteries, etc.).[14] The normal mean RI value is approximately 0.60 (in patients without underlying kidney disease), whereas values greater than 0.8 usually indicate parenchymal disease.[16] Of note, in the above-mentioned Cavaliere et al[13] study, subjects with mild IAH had increased renal RI values. Although the role of RI role in the evaluation of vascular-interstitial abnormalities is debatable, the method may aid in identifying ACS at the renal microvascular level.

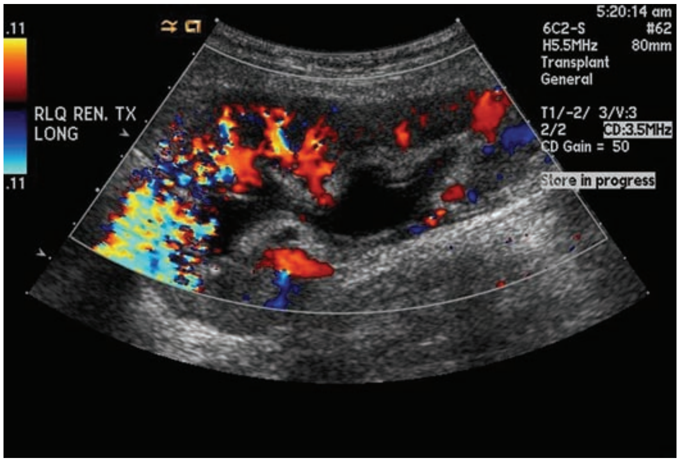

Figure 46-2 Doppler flow within the kidney, used to calculate renal resistive index.

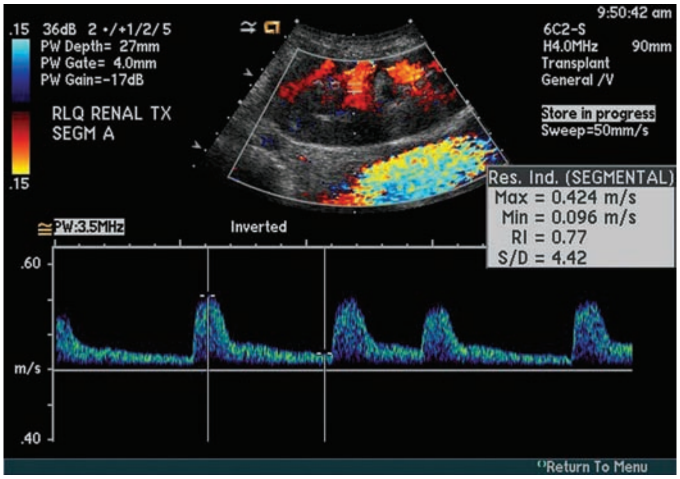

Figure 46-3 Renal resistive index and renal Doppler flow.

FOCUSED TRANSTHORACIC ECHOCARDIOGRAPHY

Significant cardiovascular alterations occur with IAH and ACS. Transthoracic echocardiography (TTE) is used in patients with IAH and ACS to assess cardiac function, intraventricular filling, and intravascular volume status. TTE aids clinicians in garnering information and then basing resuscitation efforts on volumetric measurements.[4] Invasive methods of assessing cardiac function and fluid status include the use of pulmonary artery catheters, although no survival benefits have been documented.[17,18] TTE is a noninvasive and safe alternative to invasive measures of volume status.

Ultrasound in the Treatment of Abdominal Compartment Syndrome

Decompressive laparotomy (DL) has long been the definitive treatment of ACS. A meta-analysis of 18 studies published between 1972 and 2004 analyzed the effects DL on patients with ACS.[19] These 18 studies yielded a total of 250 patients who had been treated for ACS with DL. Of the 250 patients noted, 161 were found to have before and after IAP recorded in relation to their DL. As expected, there was a statistically significant drop in IAP from a mean of 34.6 mm Hg to a mean of 15.5 mm Hg. The mortality in these studies, after DL, ranged from 22% to 100%, with a mean of 49.2%, although some improvements were noted in cardiac output, urine output, and respiratory function, as evidenced by improved partial pressure of arterial oxygen/fraction of inspired oxygen (PaO_2/FiO_2).

With treatment protocols (e.g., Surviving Sepsis Campaign[20]) encouraging aggressive resuscitation, IAH is increasingly observed by intensivists. To avoid the morbidity of a laparotomy, there has been a renewed interest into minimally invasive treatments for significant IAH and ACS, particularly in those in whom a laparotomy is not otherwise indicated. Nonoperative management of IAH and ACS includes five alternate therapies, all aimed at reduction of IAP: (1) evacuation of intraluminal contents, (2) evacuation of intraabdominal space-occupying lesions, (3) improvement of abdominal wall compliance, (4) optimization of fluid administration, and (5) optimization of systemic and regional tissue perfusion.[21,22] Each of these therapies consists of escalating interventions, from noninvasive to more invasive, with the final step consisting of DL.

To facilitate the evacuation of intraabdominal space-occupying lesions, Cheatham advocated performance of a diagnostic abdominal ultrasound to identify the space-occupying lesion or fluid collection.[21] Hemoperitoneum, ascites, intraabdominal abscess, retroperitoneal hemorrhage, and free air can all be space-occupying lesions that can raise the IAP.[20] Many studies examined the utility of percutaneous drainage of these fluid collections and the resultant decreased IAP.[15,23-26] These studies have shown a significant decrease in IAP and resolution of IAH/ACS (without DL) in many of the patients studied. Also, many intensivists (nonsurgeons) are more willing to attempt ultrasound- or CT-guided percutaneous drainage as an initial treatment of ACS.

Case

A 57-year-old African-American male with a history of hypertension, hyperlipidemia, and alcohol abuse was admitted to the surgical intensive care because of necrotizing pancreatitis for 2 days prior. He required significant fluid resuscitation plus vasopressor and ventilatory support, because he received more than 12 L of fluids, including intravenous medications and blood products in the last day. During the last 4 hours, his urine output has dropped to less than 0.5 mL/kg/hr, and he became anuric. His bladder pressure is measured (24 mm Hg), while US evaluation detects significant fluid in bilateral upper quadrants and the pelvis. TTE shows a hyperdynamic left heart with a 65% ejection fraction. The inferior vena cava appears deformed, with a diameter of 1.6 cm, and collapses more than 50% with respirations. US-guided percutaneous drainage of the ascites is conducted (3 L removed) under close monitoring for fluid shifts and hemodynamic changes. Bladder pressure is now 12 mm Hg, and urine production is restored.

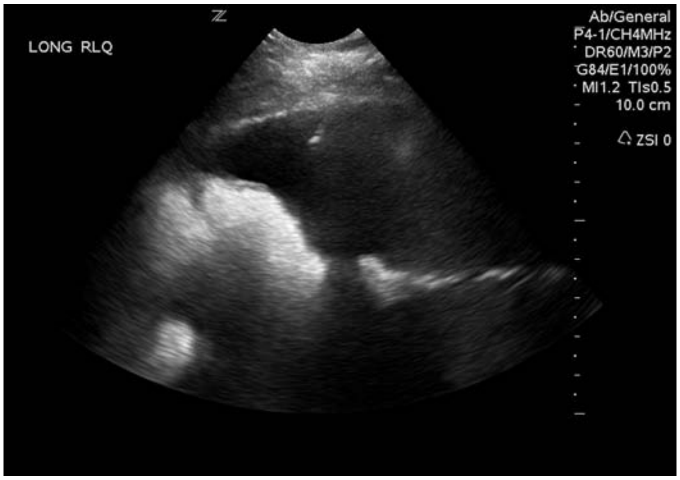

Figure 46-4 Ultrasound guided drainage of intraabdominal fluid.

A recent study of percutaneous drainage for the treatment of ACS revealed success rates of 81% (25/31) in avoiding DL.[24] In this study, successful management of IAH/ACS with percutaneous drainage was associated with drainage greater than or equal to 1000 mL of fluid or decrease in IAP greater than or equal to 9 mm Hg in the first 4 hours after drain placement. The authors recommended that in patients with significant IAH or patients with ACS, ultrasound should be performed to confirm the presence of free intraabdominal fluid or blood. If a sufficient fluid pocket is identified that would allow safe placement of a drainage catheter, this should be performed (Figure 46-4). A caveat is when using US to decompress someone who is actively bleeding and who would be more safely treated in the operating room or in an interventional radiology/angiography suite.

Pearls and Highlights

- Normal IAP is between 5 and 7 mm Hg. IAH is defined as a sustained elevation of IAP greater than or equal to 12 mm Hg. ACS is defined as IAP greater than 20 mm Hg with signs of new organ dysfunction/failure.
- Although ACS is a clinical diagnosis, multiple diagnostic adjuncts exist.
- Abdominal US detects space-occupying lesions and/or fluid collections, leading thus to more conservative therapeutic strategies by avoiding a possible DL.
- TTE evaluates fluid status and guides resuscitation based on cardiac volumetric indexes. Inferior vena cava deformability with respiration may represent a sign of poor volume status or increased IAP.
- The definitive treatment for ACS is DL.
- Minimally invasive techniques (e.g., US-guided percutaneous drainage) are suggested to be effective at lowering IAP and avoiding the morbidities associated with an open abdomen. We would recommend this approach in patients with pancreatitis and liver failure, where accumulation of ascites leads to increased IAP and organ failure.

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SECTION VIII

Specialized Settings

47

Ultrasound in the Neonatal and Pediatric Intensive Care Unit

MAHMOUD ELBARBARY | DIMITRIOS KARAKITSOS

Overview

Children and neonates are ideal candidates for the implementation of the holistic approach (HOLA) critical care ultrasound concept (see Chapter 1). This is mainly due to their small body size, which permits the fast application of all possible ultrasound techniques from head to toe. However, in the individual pediatric patient, only a part of the available ultrasound techniques will be clinically indicated, and many sites of generic scanning will need to be omitted. Ultrasound is safe in imaging pediatric patients if used when clinically indicated and with the minimally necessary energy exposures, based on the ALARA (*a*s *l*ow *a*s *r*easonably *a*chievable) principle. In the pediatric intensive care unit (PICU), HOLA ultrasound is easily scaled down to specific application profiles; some of those require expert input to interpret findings that should be processed under the light of clinical judgment or require special expertise. Elective and repetitive ultrasound scanning is often necessary for diagnostic and monitoring purposes, whereas goal-directed therapies can be guided by means of ultrasonography.[1,2] This chapter briefly outlines the role of ultrasound in the neonatal intensive care unit (NICU) and PICU.

Hemodynamic Monitoring

Ultrasound is an essential tool in the evaluation of nontraumatic, symptomatic, undifferentiated hypotension in NICU and PICU patients. It is a useful adjunct to the physical examination, which may be inconclusive, and aids in bedside hemodynamic monitoring and management of pediatric patients. Cardiovascular morphology and function as well as volume status are basic parameters in the hemodynamic monitoring of both adults and children (see Chapter 36).[3,4] Bedside ultrasound can facilitate the assessment of the above-mentioned parameters and guide therapeutic interventions (e.g., administration of fluids or vasoactive agents).

Echocardiography is an essential tool of pediatric hemodynamic monitoring. The assessment of left ventricular (LV) global systolic function is mainly performed by means of LV fraction shortening (FS) and ejection fraction (EF), either by global visual assessment or objective numerical measurement. In pediatric patients, global eye assessment of LVEF is usually an easily applied and reproducible method. When the LV empties more than half of its volume, the EF is considered to be normal (EF > 55%). Mild (EF = 45%-55%), moderate (EF = 30%-44%), and severe (EF < 30%) impairment can be estimated accordingly. Color Doppler imaging and tissue Doppler indexes of transmitral flow, reflecting LV end-diastolic pressure (and thus left atrial pressure), can be also applied in the evaluation of cardiac function as analyzed in the echocardiographic section of this book. Echocardiography can be used in almost all emergency situations, including cardiac arrests.[5]

Vena cava and global ventricular volume analysis, along with lung ultrasound, can be used in the evaluation of volume status in pediatric patients. By implementing the HOLA ultrasound concept in hemodynamic monitoring (see Chapter 36) and using echocardiography as a core tool, a simple four-step algorithm can be applied in the evaluation of pediatric patients in *shock states.*

1. *Gross ruling out of preexisting cardiac disease* (dilatation or hypertrophy of the left and right ventricle or valvular abnormalities) or genetic cardiovascular abnormalities (e.g., ventricular septal defect, aortic coarctation, right-sided aneurysmal aorta).
2. *Vena cava analysis.*[6] A small inferior vena cava (IVC) with spontaneous collapse suggests hypovolemia (e.g., inspiratory collapse > 50% in spontaneous ventilation). Hypovolemia can be considered as "absolute" (hemorrhage) or "relative" (e.g., sepsis, anaphylaxis, third spacing). A distended and fixed IVC may suggest pulmonary hypertension or tamponade when associated with pertinent right ventricular (RV) echocardiographic signs (see step 3). The presence of an A-line profile in lung ultrasound usually rules out pulmonary edema at this stage. Cautious volume loading therapy can therefore be attempted.
3. *Evaluation of RV function.* In the presence of a fixed and distended IVC, a small and hyperkinetic right ventricle is suggestive of tamponade (especially if combined with the rapid accumulation of pericardial fluid), whereas a dilatated and hypokinetic right ventricle may signify pulmonary hypertension. The assessment of RV volume is rather difficult by usual two-dimensional echocardiography. However, RV end-diastolic area (EDA) can be easily assessed. Thus we should underline the effect of positive end-expiratory pressure (PEEP) in the hemodynamic equation. With increasing PEEP, RV EDA progressively increases, and thus this phenomenon should be co-evaluated when assessing RV function in a shocked mechanically ventilated pediatric patient (Figure 47-1). Additional echocardiographic signs suggestive of tamponade are right atrial inversion/collapse in late systole, RV inversion/collapse in early diastole, swinging heart (clockwise rotation), and presence of fluids or clots around the heart. Additional Doppler echocardiographic signs suggestive of pulmonary hypertension are analyzed in detail in Chapter 33. At this stage, other causes of obstructive shock, such as a pneumothorax, can be ruled out by lung ultrasound (see Chapters 19-21).

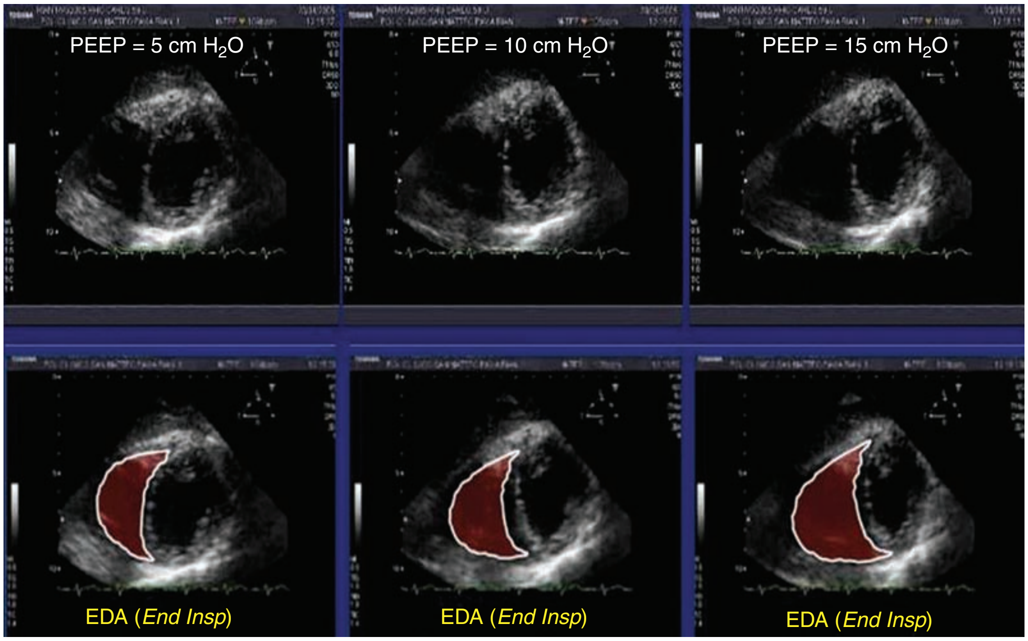

Figure 47-1 Effects of positive end-expiratory pressure (PEEP) of 5, 10, and 15 cm H_2O, respectively, on the right ventricular end-diastolic area (EDA) in a mechanically ventilated pediatric patient (*bottom*, measurements performed at end inspiration).

4. *Assessment of LV function.* A hypokinetic LV and a B-line profile depicted by lung ultrasound in a hypotensive pediatric patient with low blood oxygen saturation are suggestive of cardiogenic pulmonary edema, indicating thus the administration of diuretics and inotropes. Of note, the typical appearance of adult lung ultrasound signs, such as A-lines and B-lines may differ in pediatric patients, especially in neonates. In general, fluid administration in such cases should be done extremely cautiously.

The implementation of the above-mentioned *four-step approach* could guide therapy (vasoactive agents vs. volume loading) and monitor its results (e.g., improvement of LV function) in pediatric shock states.

Lung-Pleural Ultrasound and Mechanical Ventilation

Lung ultrasound pediatric applications are similar when compared with the applications of the method in adult patients. Hence diagnosis and management of lung disorders, especially lung interstitial syndrome, pneumothorax, lung consolidation, and pleural effusions, by means of lung ultrasound are routinely performed in the NICU and PICU. Regular follow-up lung ultrasound examinations facilitate the early detection of lung and pleural disorders and enhance their therapeutic management. When using lung ultrasound as a routine diagnostic and monitoring tool, children and neonates are largely spared the detrimental ionizing effect of repetitive chest radiography or computed tomography scans.[7] Such ultrasonography also may be used in periendotracheal intubation procedures.[8]

Sometimes, lung ultrasonographic findings may be difficult to interpret in the NICU because their appearance is slightly different compared with the usual one known in adults.[9] For example, the hyperechoic B-lines in neonates and infants may be confluent (not comet tail–like), which makes counting them impossible. A global assessment of the percentage of white (hyperechoic)/black (hypoechoic) areas in the ultrasound screen divided by 10 usually gives a correspondent number of B-lines. This may aid in guiding diuretic or positive-pressure ventilation (PPV) therapy in cardiogenic pulmonary edema.

In general, PPV supports the function of an impaired LV by reducing the transmural pressure across the LV free wall (LV afterload is reduced). In contrast, PPV is usually a functional burden on an already impaired RV function because of the reduction of preload and increase of afterload, respectively (see Figure 47-1). Ultrasonography can help in optimizing PPV to achieve the maximal benefit in oxygenation, while avoiding its side effects on cardiac function. *An advanced HOLA protocol would be combined lung and cardiac ultrasound to estimate the optimum level of PEEP.* Optimization of PEEP could facilitate the recruitment of collapsed alveoli, and the improvement in pulmonary functional residual capacity thus reduces the pulmonary vascular resistance. In turn, this could minimize the burden on RV function. Thus general chest ultrasound (lung and cardiac ultrasound) evaluation could guide both ventilatory and circulatory support. The optimization of heart-lung interaction could enhance the *therapeutic effect of mechanical ventilation* and also facilitate the *weaning* process (see Chapter 34).

In pediatric patients, *diaphragmatic and vocal cord paralysis* can lead to extubation failure. Ultrasound can easily detect the above disorders in the PICU. The *ultrasound examination of the vocal cords* is performed while the child is breathing spontaneously, in a supine position with minimal neck extension, to allow a space for the transducer to be placed and gently manipulated on the cricoid cartilage and trachea.[10] A high-frequency linear or curvilinear probe is used. The *diaphragm* normally moves downward on inspiration and upward on expiration. When paralyzed, the diaphragm either remains *immobile in a fixed position* (upward) or may exhibit *paradoxic movement* (moves upward during inspiration). When paretic, the diaphragm is moving in the right direction; however, the excursion is limited. Fluoroscopic examination is the gold standard in assessing diaphragmatic motion. Recently, ultrasound examination has been successfully integrated in the study of diaphragmatic motion. Both hemidiaphragms of the child should be ultrasonographically assessed (on both longitudinal and transverse planes) during quiet respiration by pleural ultrasound. High transverse scans must be undertaken, with both diaphragms in view, for movement comparison. Important technical points follow.

1. In children older than 2 years, a 3- to 5-MHz frequency transducer is preferred, whereas a 5- to 8-MHz frequency curvilinear transducer is used for children younger than 2 years.
2. *Subcostal transverse views* with the transducer pointer oriented at 9:00 o'clock are not ideal for the visualization of the ipsilateral hemidiaphragm but do aid in a general preview (the pointer should be oriented in the right side of the screen, the posterior aspect of the diaphragm is usually visualized, stomach air prevents the clear visualization of the hemidiaphragm).
3. *Longitudinal views* with the transducer pointer oriented at 12:00 o'clock (cephalic) are usually applied for visualizing the ipsilateral hemidiaphragm (coronal plane at the midaxillary line (diaphragmatic level) and axial plane at the subcostal position).
4. Next, *M-mode* recordings (Figure 47-2) are performed when the cursor is almost vertical on the hemidiaphragm (while moving with a maximum deviation of 20 degrees from the vertical position). M-mode tracings are obtained, in the axial subcostal or in the coronal midaxillary views on either side with the transducer pointer oriented at 12:00 o'clock (cephalic).[11] The amplitude of the movement of the hemidiaphragmatic copula should be greater than 4 mm and oriented toward the transducer (during inspiration).

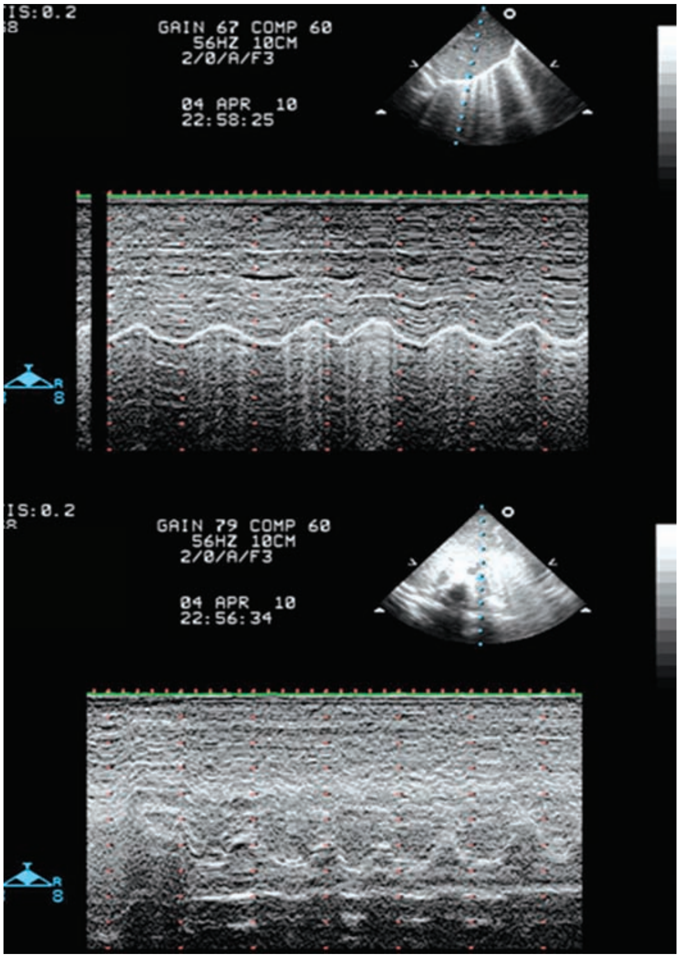

Figure 47-2 Ultrasound assessment of diaphragmatic motion by M-mode.

Procedural Ultrasound

Common procedures (e.g., ultrasound-guided vascular access) are accomplished in the emergency room/ICU with ultrasound guidance.[12] Additional ultrasound-guided procedures can be performed in the NICU and PICU, such as lumbar puncture (Figure 47-3), paracentesis of fluid collections, pericardiocentesis (Figure 47-4), and placement of peripherally inserted central venous catheters. Finally, abscess, gall bladder and suprapubic drainage, or the placement of transhepatic lines can also be performed with ultrasound guidance in pediatric patients.

Ultrasonographic Evaluation of Newborn Emergencies

ABDOMINAL SURGICAL EMERGENCIES

Necrotizing enterocolitis (NEC) is an acquired disorder that is characterized by diffuse necrotic injury of the mucosal and submucosal layers of the bowel wall. It is the most serious gastrointestinal disorder that occurs during the neonatal period. NEC affects mostly the extremely-low-birth-weight (ELBW) infants but can occur in full-term infants as well. The mortality rate for NEC is estimated to be 11.5 to 12.3 per 100,000 infant deaths, greatly exceeding that of other gastrointestinal (surgical) disorders. Radiographic findings are essential in the staging of NEC and determine the need for surgical intervention. *Ultrasonography may detect air bubbles moving through the wall of the intestine* (*pneumatosis intestinalis* Figure 47-5). Accordingly, color Doppler imaging may detect hyperemia or decreased blood flow in the intestinal wall.[13] Ultrasonographic detection of air in the portal system can also be indicative of NEC (see Chapter 41). The above ultrasound findings, along with other clinical signs, aid in the diagnosis of NEC before bowel perforation and development of peritonitis.

Neonatal bowel obstruction is a serious disorder that can be complicated by intestinal perforation. Early radiologic studies in cases of neonatal bowel obstruction are needed to rule out intestinal malrotation with midgut volvulus. Up to 40% of patients with malrotation present within the first week of life. It is often difficult to differentiate malrotation from other causes of intestinal obstruction, such as intestinal atresia. Ultrasonography may aid in diagnosing intestinal obstruction (see Chapter 41). The diagnosis of a dilatated intestinal loop with liquid content adjacent to a very narrow atrophic loop may indicate the diagnosis of *intestinal atresia.* The identification of the superior mesenteric vein to the left of the superior mesenteric artery is highly suggestive of *malrotation.*

CENTRAL NERVOUS SYSTEM EMERGENCIES

Intraventricular Hemorrhage

Extremely-low-birth-weight preterm infants are at high risk of many of the complications of prematurity. Sudden deterioration

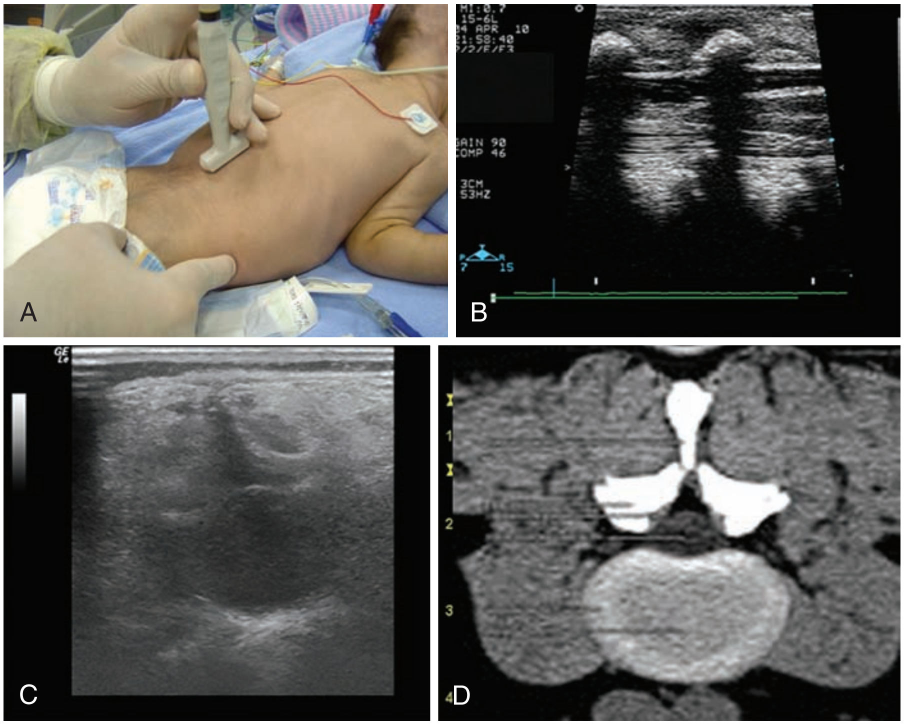

Figure 47-3 **A** and **C,** Ultrasound-guided lumbar puncture in an infant. **B** and **D,** Ultrasound and computed tomography (CT) scan views of the lumbar area in the same case.

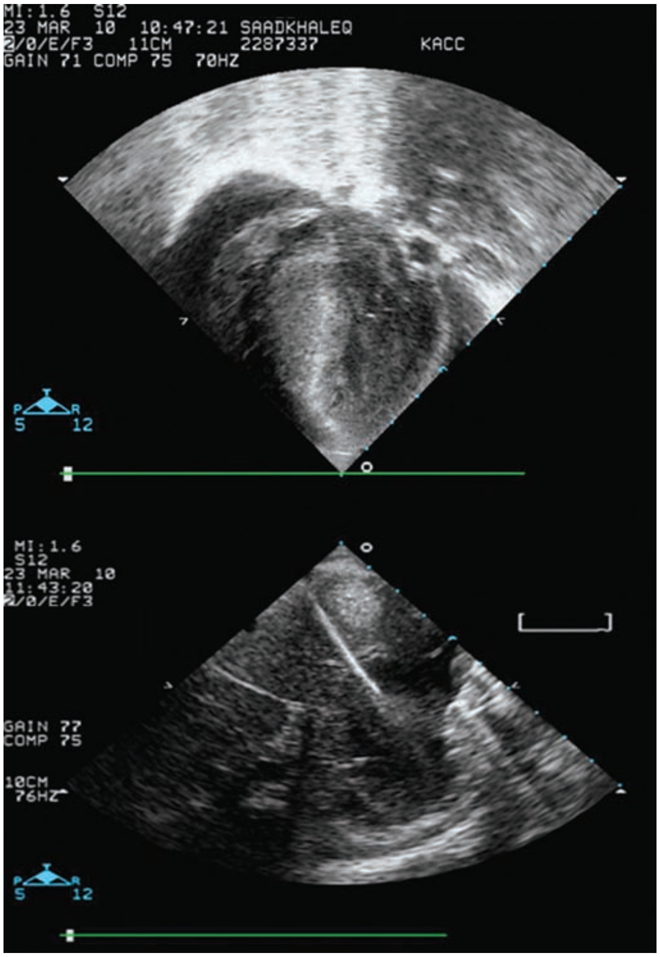

Figure 47-4 Identification *(top)* and drainage *(bottom)* of a pericardial effusion by ultrasound.

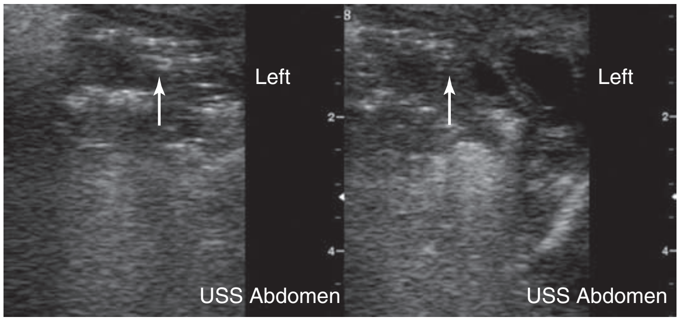

Figure 47-5 Ultrasound detecting hyperechoic punctiform lesions *(white arrow)* casting acoustic shadows, which are indicative of air bubbles in the intestinal wall (pneumatosis intestinalis).

of their clinical status may occur in the first few days of life because of various causes. Severe intraventricular hemorrhage (IVH) is a detrimental complication that occurs in ELBW infants because of impaired cerebral autoregulatory ability. The latter may result in rapid alterations of cerebral blood flow and large changes in cerebral blood pressure. Subsequently, these sudden changes can result in hemorrhage inside the lateral ventricles and hemorrhagic infarction in the adjacent brain parenchyma (grade IV IVH). Grade IV IVH is usually manifested as a neonatal shock state accompanied by metabolic acidosis, hypotension, apnea, and bradycardia (differential diagnosis: pneumothroax, patent ductus arteriosus, etc.). Correct diagnosis would impact decisions for further management and support as well as avoidance of unnecessary therapy. An ultrasound transducer (5-10 MHz) that fits in the infant's open anterior fontanel can easily yield the diagnosis (Figure 47-6).

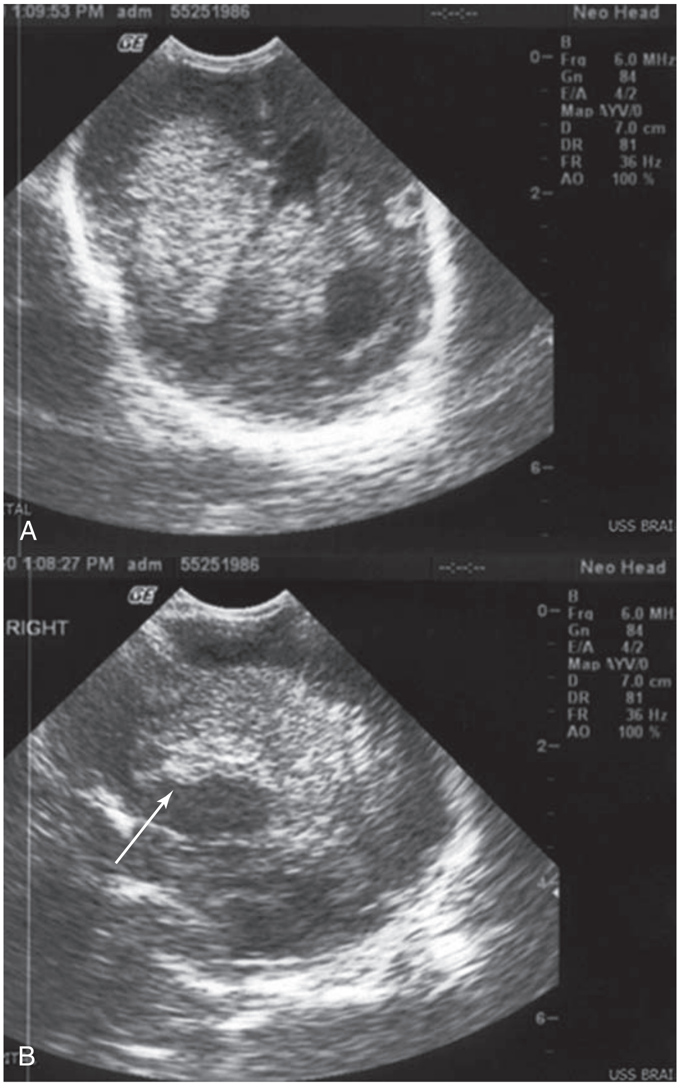

Figure 47-6 Coronal **(A)** and sagittal planes **(B)** of two-dimensional ultrasound showing hyperechoic densities *(arrow)* in the area of the right lateral ventricle and adjacent brain parenchyma, indicative of right intraventricular and periventricular hemorrhage, respectively (grade IV IVH).

RESPIRATORY EMERGENCIES

Transient Tachypnea of the Newborn

Transient tachypnea of the newborn (TTN), also called "wet lungs" or type II respiratory distress syndrome, usually can be diagnosed in the first hours after birth. TTN can occur in both premature (because their lungs are not yet fully developed) and full-term babies. Newborns at higher risk for TTN include those who are

1. Delivered by cesarean section (CS)
2. Born to mothers with diabetes
3. Born to mothers with asthma
4. Small for their gestational age (small at birth)

Copetti et al[3] described a peculiar lung ultrasound sign, called the *double lung point,* in newborns with TTN. In the latter case, lung ultrasound showed a difference in lung echogenicity between the upper and lower lung areas. Specifically, coalescent B-lines were observed in the inferior lung fields, whereas those were rare in the superior fields (Figure 47-7). Of note, this ultrasonographic finding was not observed in healthy infants or in infants with respiratory distress syndrome, atelectasis, pneumothorax, pneumonia, or pulmonary hemorrhage. Thus sensitivity and specificity of the double lung point were 100% in the diagnosis of TTN.

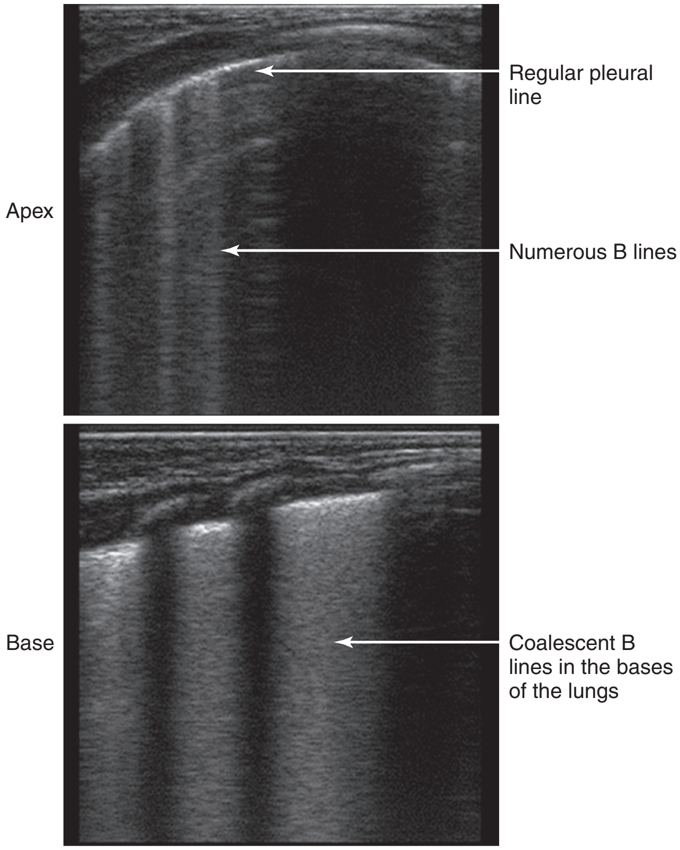

Figure 47-7 The double lung point in transient tachypnea of the newborn (TTN) of the newborn. *(Courtesy Dr. R. Copetti.)*

Of interest, in normal babies delivered by CS, multiple B-lines can be found soon after birth, bilaterally. These eventually disappear after a few days. Finally, the application of mechanical ventilation in neonates can result in several complications, such as *bronchopulmonary dysplasia,* which can be ultrasonographically detected as small multiple subpleural consolidations underlining an irregular and rather coarse pleural line (Figure 47-8). Thus it is worth mentioning that the classic "bat sign," which is formed by the acoustic shadows of the ribs, in lung ultrasound is rather obscure in neonates, because their ribs consist of very soft cartilaginous components.

CARDIOVASCULAR EMERGENCIES

Analyzing all possible cardiovascular emergencies of the newborn is beyond the scope of this chapter. However, we briefly outline one of the most common causes of neonatal shock—*a patent ductus arteriosus (PDA)*. Neonatal shock may be due to the closure of the ductus arteriosus in some ductal-dependent cardiac lesions, such as severe aortic coarctation, pulmonary atresia, and transposition of great arteries. Ultrasound PDA examination aids in establishing a diagnosis and monitors the effect of prostaglandin infusion. Identification of the blood

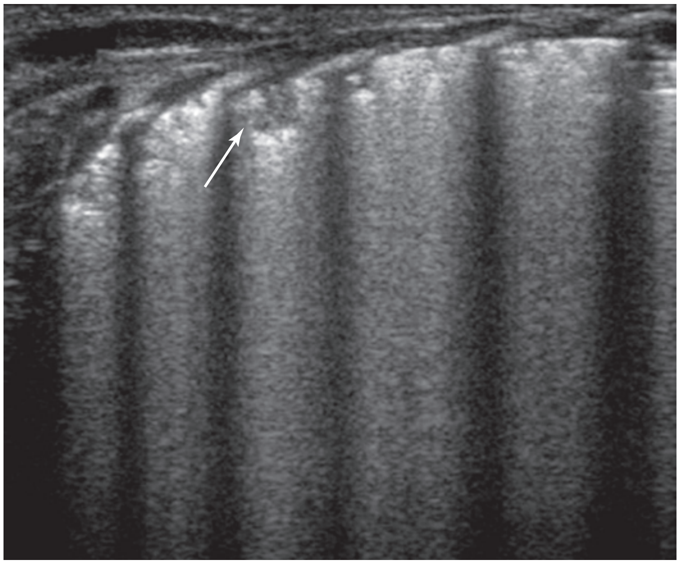

Figure 47-8 Broncopulmonary dysplasia: small multiple subpleural consolidations *(arrow)*. Please note the irregularly thickened and coarse pleural line, whereas the lung parenchyma appears diffusely hyperechoic (white lung).

flow direction (by color Doppler imaging) in the PDA aids in the diagnosis of pulmonary hypertension (right–to-left shunt). Another scenario is a neonate who suffers from heart failure and becomes inevitably ventilator dependent, in the absence of intracardiac lesions, mainly because of the presence of a large PDA with a left-to-right shunt. Intracardiac thrombi can also be the cause of neonatal shock status.[14] In all the above clinical scenarios, ultrasound examination of the heart and the PDA is essential in determining the correct diagnosis and monitoring therapy.[15]

Pearls and Highlights

- Children and neonates are ideal candidates for the implementation of the HOLA critical care ultrasound concept. This is mainly due to their small body size, which permits the fast application of all possible ultrasound techniques from head to toe.
- Echocardiography has a pivotal role in the investigation of cardiovascular structure and function and in the assessment of volume status in PICU and NICU patients.
- Lung and pleural ultrasound can detect and monitor various pulmonary abnormalities as well as mechanical ventilation side effects. However, their findings should be interpreted with caution because the typical appearance of adult lung ultrasound signs may differ in pediatric patients, especially in neonates.
- Ultrasound can evaluate diaphragmatic and vocal cord paralysis, which may lead to extubation failure in PICU and NICU patients.
- Combined lung and cardiac ultrasound can estimate the optimum level of PEEP in mechanically ventilated pediatric patients. The optimization of PEEP could improve the respiratory status while minimizing the burden on RV function in these patients. The subsequent optimization of heart-lung interaction could further enhance the therapeutic effect of mechanical ventilation and also facilitate the weaning process.
- Several newborn emergencies, such as necrotizing enterocolitis, neonatal bowel obstruction, brain intraventricular hemorrhage, transient tachypnea (type II respiratory distress syndrome), and patent ductus arteriosus can be ultrasonographically identified and monitored in the NICU.

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48

Integrating Ultrasound in Emergency Prehospital Settings

MANSOOR KHAN | SARAH MURTHI | HEIDI LEE FRANKEL | THOMAS M. SCALEA

As previous and future chapters will attest, ultrasonography (US) is an indispensable modality in assessing patients in the hospital and outpatient setting. In the past few years, compact, robust, and portable US machines have been developed for use in various prehospital settings. Recent technologic advances have led to the development of battery-powered, light, handheld portable devices. In addition, ease of use, simplification of technology, and facilitated connectivity allow allied providers to perform US in a variety of austere settings.

Unlike computerized tomography (CT) and magnetic resonance imaging (MRI), US represents a more mobile diagnostic tool. However, unlike the aforementioned modalities, US operation requires the operator, or the person guiding the operator, to have an intimate knowledge of the anatomy of the region they are scanning and the ability to interpret pathology on the US image. Nonetheless, if a focused question is asked or if the images can be shared via telemedicine while the operator is proctored through the examination, US can be of great value in the austere setting of disaster medicine.

There are now several pocket US scanners weighing substantially less than 2 pounds. The GE V SCAN Portable Ultrasound weighs less than 1 pound and is about the size of a smartphone and can be used for torso imaging. The Acuson P10 (Siemens Medical Solutions, Malvern, PA) is also pocket sized and is used for similar applications. The SonoSite 180 (SonoSite, Bothell, WA) is slightly larger, but can be used for both vascular and torso imaging. Additional portable technology is on the horizon.

A prospective evaluation in a hospital environment, determined that handheld focused assessment sonography in trauma (HHFAST) examination was equivalent to the FAST examination, using more conventional equipment. HHFAST had a sensitivity of 78%, specificity of 100%, positive predictive value (PPV) of 100%, and negative predictive value (NPV) of 97%.[1,2] HHFAST can detect intraperitoneal fluid with high degrees of accuracy. It will miss some injuries, but the majority of injuries missed do not require therapy.[3] In addition, field US, using the HHFAST, can also be performed by nonphysician providers. With close supervision, paramedics can adequately obtain and interpret FAST and abdominal aortic US images under protocol.[4]

Remote Location Imaging

Popov et al[5] set out to demonstrate both the simplicity and robustness of existing US technologies in a remote location. They evaluated telementored resuscitative extended FAST (e-FAST) US examination. An expert interpreter guided a first responder located midmountain at a commercial ski resort. The test subject was a healthy volunteer. US images were obtained on a first-generation SonoSite 180 machine and were converted to digital video using a readily available video converter. A head-mounted camera provided a macroscopic view of the examination, allowing the remote examiner to view both the patient and examiner's hands, while simultaneously viewing the US results (Figures 48-1 and 48-2).[6-8]

Remote US has also been evaluated and tested aboard Aquarius, an underwater habitat off the Florida Keys, as part of the NASA Extreme Environment Mission Operations (NEEMO). The life sciences mission NEEMO 7 investigated the role of US examination of the abdominal organs and structures. US-trained and untrained aquanaut crew members conducted a series of diagnostic and interventional procedures with remote guidance from experts more than 3000 km away. Researchers demonstrated that mean efficiencies were slightly higher with telementoring than with the use of a procedure manual.[9]

Disaster and Prehospital Medicine

The role of US in disaster medicine has not been well established and is generally limited to case reports and case series. A report by the Disaster Medical Assistance Team (DMAT), responding to the aftermath of a cyclone in Western Australia, demonstrated that US-competent physicians were able to use portable US on casualties to exclude intraabdominal hemorrhage, pericardial

Figure 48-1 Remote imaging on a mountainside. *(Image courtesy Dr. Paul McBeth.)*

Figure 48-2 EFAST on a mountainside. *(Image courtesy Dr. Paul McBeth.)*

fluid, pneumothoraces, and hemothoraces. The US machine had a weight of 3.7 kg (MicroMaxx, SonoSite, Bothell, WA). It was powered by using a self-contained, rechargeable battery. A 60-mm, 5-2-MHz curvilinear probe and a 38-mm, 10-5-MHz linear probe were selected as most appropriate for the likely requirements. Information obtained using US made initial patient management and subsequent decisions regarding triage for transport safer and based on more detailed clinical information.[10,11]

Sarkisian et al[12] reported from the Armenian earthquake of 1988, in which US was performed as a primary screening procedure in 400 of 750 mass casualty patients with trauma who were admitted to a large hospital within the first 72 hours after the earthquake. Two real-time sector scanners were used in the reception area of the hospital, and the average time spent on one patient was 4 minutes. More than 130 follow-up ultrasonographic examinations were required. Impressively, trauma-associated pathology of the abdomen and retroperitoneal space was detected in 12.8% of the patients, with 1% false negatives and no false positives.

In the Marmara earthquake, which occurred on August 17, 1999, 639 people had renal complications and 477 needed hemodialysis treatment because of acute renal failure caused by crush injury. This led Keven et al[13] to undertake a study using renal US, in which resistive indexes were measured, and it was demonstrated that in crush injury, measurement of renal resistive indexes can be useful for the prognosis of recovery from acute renal failure.

Thoracic Imaging

In addition to the potential role as FAST, field medics are using US to detect abnormalities in other anatomic regions. Studies have demonstrated that US scanning, in the right hands, is extremely accurate in determining the presence of pneumothoraces.[14,15] In a normal individual, there is visible sliding of the pleura on ultrasonography[16] and comet tails.[17] However, the presence of a pneumothorax will eliminate the presence of both. Use of M-mode ultrasonography also allows the detection of pneumothoraces. This can be of great advantage in the field environment or disaster relief situations because chest radiographs are not readily available.

US has also shown promise in detecting medical problems in austere settings. It has been successfully used in demonstrating adequate endotracheal tube positioning (which is especially useful if there is suspicion that the tube is malpositioned and radiography is not available),[18] diagnosis of cerebrovascular accidents,[19] differentiating between pulmonary edema and chronic obstructive pulmonary disease,[20] and the diagnosis and treatment of myocardial infarction with wall hypokinesis.[21]

Airway Imaging

Currently, the role of US in anesthesia-related airway assessment and procedural interventions is encouraging, although it is still ill defined. US can visualize anatomic structures in the supraglottic, glottic, and subglottic regions. The floor of the mouth can be visualized by both transcutaneous views of the neck and also by transoral or sublingual views. However, imaging the epiglottis can be challenging because it is suspended in air. US may detect signs suggestive of difficult intubation, but the data are limited. Other possible applications in airway management include confirmation of correct endotracheal tube placement, prediction of postextubation stridor, assessment of subglottic diameter for determination of pediatric endotracheal tube size, and percutaneous dilational tracheostomy.[22,23]

Transtracheal or transcricothyroid placement of a cannula is a practice used in a number of aspects of airway management in anesthesia and intensive care. If a difficult intubation scenario occurs in a patient with unidentifiable anterior neck airway anatomy, at a location where an US machine is immediately available, it is recommended that consideration be given to the use of US-guided cannula tracheotomy as the first-line rescue technique.[24]

Cardiovascular Imaging

Experimental studies have shown that some US contrast agents actually enhance the effectiveness of thrombolytic agents in the presence of US in vitro and in vivo. Recent "sonolysis" studies have been undertaken to study this effect in patients with ST-elevation myocardial infarction, based on proximal lesions of the infarct-related artery,[25-27] which theoretically could be initiated in the field.

There are case series that suggest that abdominal aortic aneurysm and e-FAST emergency US examinations can be performed in the stationary or moving land/air ambulance environment to a standard consistent with those performed in the hospital emergency department.[28, 29]

Other Regions

A recent study[30] demonstrated that US-trained personnel can correctly detect, with a high degree of sensitivity and specificity, the presence or absence of simulated long bone fractures.

CASE

During the Haitian crisis, US was a modality available to disaster relief workers. One of the cases highlighted was that of an 8-year-old boy who was seen with a history of several weeks of fevers and chills, general malaise, and increasing abdominal girth. The deployed personnel used a Philips portable US with a 12-MHz linear array and 5-MHz curvilinear probe and confirmed the diagnosis of advanced schistosomiasis.[31]

CASE

The organization Partners in Health,[32] working in Rwanda, reported a case of a 50-year-old man who presented with dyspnea on exertion, fevers, weight loss, and weakness. Physical examination was notable for cachexia and signs of physiologic distress. Bedside ultrasound revealed a significant pericardial effusion, with collapse of the right ventricular and atrial free walls during diastole, indicating life-threatening cardiac tamponade, which was drained when he arrived at the receiving hospital.

Pearls and Highlights

- There are several extremely portable US scanners that afford imaging in remote locations. Imaging can be performed by nonphysicians, with images downloaded to more experienced providers. This has been successfully accomplished in space and at high altitude. The absence of gravity in space makes traditional FAST imaging challenging.
- Portable US has been used successfully in disaster mass casualty situations to prioritize care of the injured patients. In addition to trauma applications, portable US can be used to image the airway and to assess cardiac and pulmonary function in the face of hypotension and hypoxia.

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Use of Ultrasound in War Zones

JASON D. HEINER | ERIC J. CHIN

Overview

War zones are unpredictable and austere environments that present unique challenges to medical providers. The hazards of combat as well as common nontraumatic pathology must be cared for in a diverse range of settings, from the combat medic caring for a wounded casualty while under enemy fire to the physician caring for critically ill patients in a forward-deployed temporary field hospital.

During previous conflicts, as recently as the late 20th century, medical diagnostic imaging on the battlefield was mostly limited to sparsely available plain radiography. The introduction of ruggedized handheld ultrasound devices in the late 1990s transformed the diagnostic capability on the modern battlefield.[1,2] Although still vulnerable to the harsh environment of war zones, these lightweight portable units now enhance medical care for diverse battlefield settings and medical providers. The use of ultrasound in war zones often reflects its use in traditional hospital environments; however, the unique challenges and constraints of the battlefield give rise to unique applications.

Deployable Ultrasound Devices and Technology

Ultrasound imaging for field military use became feasible in 1999 with the release of the SonoSite 180 machine (SonoSite, Bothell, WA), which was developed with a grant from the United States government for military use, with specifications that it be "a field device, hand-held by soldiers or medics, producing high quality images which could be downloaded via satellite to physicians at base hospitals" (Figure 49-1).[1,2] To achieve these goals and be practical for field use, designers of this and subsequent ultrasound machines have sought to be lightweight and easy to transport, rugged, and versatile in their power source.

Modern battlefield ultrasound machines with a transducer attached typically weigh 2.5 to 3.5 kg, with durable and/or flip-top screens as well as a carrying handle incorporated into the body of the device. High image quality and multiple modes and applications enable replication of typical sonographic capabilities. Screens must be able to ensure that images are viewable in varying degrees of ambient lighting. Transport in a durable case aids in protecting the elements of both the device and its transducers. Users should consider their anticipated working environment and size/weight requirements when acquiring an ultrasound machine for use in a war zone and must modify their method of machine transport to their setting. A medic in the field needs to ensure device protection and rapid accessibility when injury occurs, whereas a physician in a combat hospital may be able to establish more permanent locations for the device. Ultrasonography often occurs in unique situations, such as medical evacuation via ground transport by armored vehicle or air transport by helicopter, but requires providers to be prepared to adapt their equipment to their situational requirements.

Transport for accessories, in addition to the primary ultrasound machine, must also be planned. Experience with ultrasonography in war zones has demonstrated the usefulness of low-frequency curvilinear probes, high-frequency linear probes, and endocavitary transducers for applications mirroring the civilian hospital setting. Consistent access to external electrical power needed to run the device is rarely guaranteed in many of the austere settings of war, and access to reliable device-compatible battery power is imperative. Over time (particularly in extreme conditions), battery life is expected to wane. Additional batteries for extended missions are a prudent precaution when timely access to more batteries or compatible sources of electrical power is uncertain.

War zone ultrasonographers may be equipped with capable technology and basic image acquisition and interpretation training but may lack the expertise to interpret some aspects of the images obtained. Via telesonography, electronic communication tools allow the transmission of ultrasound images

Figure 49-1 The portable SonoSite 180 machine first developed for use in the battlefield.

from the point of care to specialists for further image interpretation. Several battlefield methods have been described.[2-5] Image file capture can be achieved by the ultrasound machine or a secondary device, such as a camera or camera-equipped phone. Image file transmission has been described by phone, landline, and by wireless relay from a portable vest-mounted transmitter to a receiving antenna and then to a satellite.[6] The clinical impact of telesonography depends on the speed of image transmission, clarity of the final received image, and the timeliness of pertinent image interpretation.

Settings of Patient Care during War

Medical care is delivered to battlefield casualties in several unique settings, from the point of injury to care during evacuation out of the war zone. Each of these settings can pose exceptional challenges to a unique combination of care providers with varying medical skills and familiarity with ultrasound (Table 49-1). These variations allow diverse opportunities for ultrasound to impact the care of injured or ill patients.

During war, the prehospital medical setting is typically characterized by simple and unpredictable resources amidst exposure to harsh environmental conditions and the danger of enemy engagements. Patient care may take place without shelter, while under enemy fire, and with limited oversight. In such situations, ultrasound imaging can be used by soldiers, typically combat medics, to guide patient care. Ultrasound imaging can act as a triage tool to identify those most needing evacuation to a combat hospital or those patients who can be adequately cared for in smaller rapidly deployed and highly mobile aid stations.[7] In this dynamic environment, ultrasound imaging may be the only method of diagnostic imaging available. Ultrasonographers in this field setting may rely only on prior ultrasound instruction or may also have telesonography resources available to assist in image interpretation and patient care.

Evacuation from the battlefield to the combat hospital by armored vehicle or helicopter is often hazardous and not conducive to patient care. Physical space during transport is cramped, vehicle movement impairs patient assessment, environmental noise makes clinical assessments by auscultation unfeasible, and the rush of evacuation can leave traumatic injuries largely undifferentiated. In these confined settings, a portable ultrasound machine can be used by paramedical personnel as a dynamic adjunct to patient assessment and stabilization.

Field hospitals during war can provide a considerable degree of consistency in medical care, but availability of medical supplies can be unpredictable, and medical specialty staffing can be variable. Physicians, nurses, and medics may all use ultrasound for applications often mirroring that in noncombat settings. Ultrasound use may assist with triage during mass casualty events and help to guide resuscitation of the critical patient, procedural ultrasound may optimize patient safety, and detailed studies for medical or surgical pathology may influence patient care and ultimately their disposition. Ultrasonographers are often radiologists and emergency physicians—specialists likely to be familiar with the use of ultrasound for a variety of traumatic and medical indications. In the combat hospital, platforms for telesonography are generally available when images need further analysis. Ultrasound may also be used by medical providers to dynamically assess patients, who are often critically ill, during loud and extended transport times while being medically evacuated from a field hospital or out of the war zone.

TABLE 49-1 Characteristics of Different Settings of Care in the War Zone

Setting	Potential Ultrasonographers Providing Care	Challenges to Medical Care
Point of injury	Medics Soldiers	Enemy fire Noise Lack of resources Lack of medical expertise Mass casualty events
Prehospital transport	Medics	Enemy fire Noise Uncertainty of injuries
Field aid station	Medics Physicians Midlevel providers, such as physician assistants	Enemy fire Uncertainty of injuries Lack of resources Lack of medical specialists
Field hospital	Physicians Midlevel providers, such as physician assistants Nurses Medics	Mass casualty events Variable resources and medical specialists
War zone evacuation	Physicians Nurses Medics	Noise Long transport times

Current Uses and Applications

Although portable ultrasound devices were partly developed for use by the United States military in the battlefield, the applications used there are not generally novel. However, the use of and unique reliance on ultrasonography in war zones often reflects the exceptional constraints and needs of providing medical care during combat. These limitations and the extreme circumstances experienced by field ultrasonographers have resulted in some highly effective and well-described applications of ultrasound imaging in a war zone (Table 49-2).

TABLE 49-2 Commonly Reported and Less Frequently Described Uses of Ultrasound in War Zones

Well-Described Uses of Ultrasound	Other Reported Uses of Ultrasound
FAST (and e-FAST) Fracture detection Abdominal Foreign body detection or related soft tissue applications Pelvic ultrasound for female abdominal pain and first trimester bleeding Echo Procedural ultrasound	Optic nerve sheath diameter assessment after head injury Thoracic ultrasound to detect pneumonia Assistance of peripheral and regional nerve blocks DVT Renal Assistance of intubation confirmation and cricothyroidotomy

DVT, Deep venous thrombosis; *e-FAST,* extended focused assessment with sonography in trauma; *FAST,* focused assessment with sonography in trauma.

Combat casualties are often critically ill and occur in multicasualty or mass casualty incidents, with hemorrhage being the most common cause of death.[8] The FAST (*f*ocused *a*ssessment with *s*onography in *t*rauma) examination evaluating for potential blood in the peritoneal, thorax, and pericardial space, and the e-FAST (*e*xtended *f*ocused *a*ssessment with *s*onography in *t*rauma) examination, which includes an additional thoracic window to evaluate for a pneumothorax, are frequently used as a triage tools during combat casualty arrival.[2,4,5,9] Operating room capabilities are often limited, and advanced imaging, such as computed tomography, may be absent in a war zone; a portable ultrasound device can triage patients in these resource-scarce zones. Both the FAST and e-FAST examinations also provide an ability to assess and reassess for life-threatening injuries during periods of loud and otherwise challenging helicopter or armored vehicle patient evacuation.[10]

Lack of advanced or alternative methods of diagnostic imaging in the presence of a portable ultrasound device has produced a number of case reports describing additional ultrasound applications, such as ultrasonographic fracture detection, soft tissue foreign-body detection, and ultrasonographic ocular assessment of the optic nerve sheath diameter for evidence of increased intracranial pressure.[2,11-13] Radiography machines, which are significantly easier to transport than computed tomography, are not easily portable compared with handheld ultrasound devices, which can be transported in a medic's equipment bag without location barriers. In the absence of radiography, combat medics and physicians have relied on ultrasound to detect, with high accuracy, the presence of underlying pathology requiring limited transportation resources to transfer patients to a higher level of medical care or evacuation from the war theater.

In the war zone, ultrasound (often used by nonradiologist physicians) is frequently used for nontraumatic and procedural indications. Abdominal imaging for medical complaints, such as gallbladder pathology, is common, and female pelvic and obstetrical/gynecologic ultrasound imaging for applications such as ovarian and pregnancy-related pathology is prevalent.[2,4,9,14] Simple procedural applications, such as assistance with central line insertion, are used in a similar manner as in nonwar settings. More advanced ultrasonographic procedural applications, such as imaging of fracture reduction and assistance with complicated regional and peripheral nerve blocks, are also used when operator expertise is sufficient.[15,16] The use of complex nerve blocks in the combat hospital setting can be a particularly valuable method of achieving excellent and long-lasting anesthesia and pain control in patients with complex traumatic injuries.

The Future of Ultrasound in War Zones

Although the needs of the battlefield have influenced ultrasound technology with the development of small devices, these devices have quickly become popular in civilian hospital settings because of their excellent performance, portability, and affordability. The future of ultrasound use in war zones will largely reflect the current and future clinical uses of ultrasound in civilian settings. Advances in targeted training with nonphysicians, such as physician assistants, nurses, and field medics, and new technology, such as the development of software to automate the interpretation of ultrasound images, may allow more reliable clinical analysis by novice operators. Moreover, other advances leading to more rugged and durable machines, smaller devices and accessories, and longer battery life will enhance the feasibility of ultrasound use on the battlefield. Future research and reports will help guide the forward movement of both ultrasound technology and the translation of clinical ultrasonography to the war zone.

CASE

An otherwise healthy 22-year-old male soldier suffered severe blast injuries to the torso after the nearby detonation of an improvised explosive device. He was quickly placed on a medical evacuation helicopter in the care of a flight medic for transport to the nearest military surgical hospital, 50 km away. The patient was secured within the helicopter, intravenous access was obtained, and he was given analgesia as the helicopter exited the combat zone amidst enemy fire.

The patient's initial in-flight vital signs were normal as his wounds were assessed, but after several minutes of flight, he began to complain of marked abdominal and chest pain. The flight medic asked for more details of this pain, but the patient's words were incomprehensible in the noisy environment of the helicopter. Within minutes, the patient became progressively tachycardic and hypotensive, with little response after a bolus of intravenous fluid. His oxygen saturation began to fall, in addition to his blood pressure, as his heart rate continued to rise.

The flight medic performed an e-FAST examination with a portable ultrasound device. His abdominal and pericardial ultrasonographic windows were negative for the presence of intraperitoneal or pericardial fluid. As the patient's vital signs continued to deteriorate, ultrasound imaging of the thoracic fields revealed the presence of a large right-sided pneumothorax. Right pleural-space needle decompression, followed by placement of right-sided tube thoracostomy, placed to suction, was immediately performed, with the resulting normalization of all vital signs.

Pearls and Highlights

- The needs of medical care on the modern battlefield have influenced advancements in ultrasound technology through the development of the first portable ultrasound units.
- To be feasible for use in war zones, ultrasound devices must be portable and lightweight, small, rugged, and able to be safely transported in varying environmental conditions, locations, and settings. Ultrasound kits must possess enough battery power to sustain use between anticipated electrical sources and have a variety of transducers to facilitate desired field applications.
- Battlefield ultrasound imaging can achieve clinical impact when performed by ultrasonographers of varying skills—from soldiers with little medical background to medics to physicians. Targeted training can facilitate the ability of novice ultrasonographers, and telesonography can enable accurate interpretation of images when specialists are not available for image interpretation at the point of care.
- Medical care in war zones occurs in unique locales and situations, such as in the battlefield, during medical evacuation in an armored vehicle or helicopter, in field

aid stations, the combat hospital, and during evacuation from the war zone. Environmental conditions, enemy fire and noise, special constraints, and unpredictable resources and access to specialty medical care are some challenges that ultrasonographers face in these settings.

- Portable ultrasound has proven to be uniquely adaptable in war zones as an imaging modality and adjunct to patient care. Although most applications are similar to the noncombat setting, ultrasonography in combat is often heavily relied upon as the only diagnostic tool to guide patient triage, patient treatment, and evacuation to higher levels of patient care.

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For a full list of references, please visit www.expertconsult.com.

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Ultrasound Imaging in Space Flight

ASHOT E. SARGSYAN | DIMITRIOS KARAKITSOS

Throughout the 5 decades of human space flight, the space medical support systems provided for onboard treatment of minor medical events and evacuation of the seriously ill or injured to Earth. In the absence of adequate objective information, however, it may be difficult to weigh the risks of onboard management against those of emergency return. A case of substantial trauma or illness would pose a serious challenge even to the most advanced human space flight program—the International Space Station (ISS). Failure of treatment onboard and evacuation with adverse outcome being the worst developments, unnecessary return to Earth is also a major problem because of its enormous financial and programmatic costs.

Between the 1970s and mid-1990s, eight different ultrasound imagers were flown on National Aeronautics and Space Administration (NASA) and Russian spacecraft and successfully operated for research purposes. These successes justified the installation of the first permanent ultrasound system (HDI-5000, ATL/Philips, Andover, MA) for the ISS Human Research Facility (2002). After serving for 10 years, the ISS Ultrasound-1was replaced by a new unit with advanced research and clinical capabilities (Figure 50-1).

Significant efforts were needed before space-based ultrasound imaging could be recognized for clinical use, with no medical expertise onboard and little evidence on the imaging representations of disease in microgravity.[1] The successful implementation of clinical ultrasound in space flight is a great testament to the essential universality and versatility of ultrasound imaging. We hope this chapter will motivate more physicians to seek and promote imaging solutions in their areas of practice.

Scope of Diagnostic Ultrasound in Space

Ultrasound imaging is uniformly recognized as a highly accurate and nearly universal diagnostic tool in myriad conditions; a diverse variety of those, such as urolithiasis; eye, abdominal, and soft tissue trauma; pneumothorax; localized infections; and complications of toxic inhalation, have been encountered in space or are believed to be more likely to occur in space flight conditions.

The health care system of a spacecraft heavily depends on communications and remote provision of specialized expertise; the mere presence of technology onboard is insufficient. A medical procedure may be conducted by crew members without assistance (e.g., periodic health evaluation), with assistance drawn from onboard computers (e.g., a laboratory test), or using telemedicine mechanisms (most procedures requiring specialized expertise). Although ultrasound technology is permanently available, the crew is trained only in equipment operation; specific imaging guidance is provided in real time by ground-based experts using "privatized" video downlink and a private voice connection.

Space medicine depends on ultrasound imaging more than most other clinical disciplines because of the absence of other diagnostic imaging modalities and the operational nature of the setting with limited resources and the very limited ability to safely and quickly evacuate the ill or injured crew member. Depending on the clinical and operational circumstances, a focused diagnostic examination in space with a single binary clinical question *(emergency medicine model)* can evolve into a broader, multitarget assessment and monitoring *(critical care model)* or into a comprehensive and specific imaging application *(radiology model)*. The current medical requirements for the International Space Station foresee a possibility of advanced life support of a seriously ill or injured crew member for up to 72 hours, which, regardless of the initial offending factors, essentially includes close monitoring of the hemodynamic parameters, pulmonary physiology, airway management, intracranial pressure, and so forth, without the trained personnel and resources taken for granted in any terrestrial hospital. Therefore space medicine experts have great interest in both established and emerging ultrasound applications, and they monitor the recently accelerating implementation of bedside ultrasound approaches and techniques in terrestrial emergency medicine and intensive care.

Figure 50-1 The International Space Station (ISS) Ultrasound System (Vivid Q, General Electric, Waukesha, WI) is ready for use. The box underneath the machine is a data and power interface. Note the oversized water drop on the 12-MHz linear array transducer, to be used for acoustical coupling instead of gel. Also note the multicolor keyboard overlay specially designed for remote guidance purposes. *(Image courtesy National Aeronautics and Space Administration.)*

Implications of Microgravity

PATIENT AND OPERATOR POSITIONING

In the absence of gravity, the patient must often be physically restrained by using elastic cords or fabric belts to ensure positional stability; in general, the mutual positioning of the operator, patient, and imaging hardware must be globally compatible with the medical equipment setup for emergency medical treatment and life support activities. Thus a seriously ill patient would be scanned on the special electrically isolated restraint system designed for advanced life support procedures (Figure 50-2). The operator should also be restrained in a comfortable and sustainable position to consistently exert a contact force on the transducer and have both hands available for the imaging procedure.

Self-scanning is also possible with minimal foot restraint, except for patients in distress or when a more experienced operator is available. Furthermore, some crews use creative ways of positioning in microgravity for specific applications (Figure 50-3).

NORMAL AND PATHOLOGIC ANATOMY

In the lack of gravity, the position of an object or the shape and distribution of a fluid collection are determined by the combined effect of weaker physical forces, such as properties of the fluid; surface interaction forces; tissue and organ compliance; random pressure fluctuations and gradients, such as peristalsis; and small accelerations. The absence of gravity may thus require significant modifications of imaging techniques as well as data interpretation. A terrestrial "gold standard" imaging procedure may not work in microgravity, whereas a previously unexplored technique may be the method of choice. Animal models of internal bleeding[2-4] in simulated microgravity strongly suggest high diagnostic accuracy of ultrasonography if performed and interpreted using microgravity-based evidence and considerations. Intrathoracic hemorrhage and pneumothorax, maxillary sinusitis, lung abscess, ileus with dilatated bowel loops, and urinary calculi are examples of the many imaging situations influenced by the gravity vector or its absence.

Figure 50-2 Astronaut Peggy Whitson (International Space Station [ISS]-5 expedition, 2002) developing the optimal setup for ultrasound examinations on the ISS by using the Crew Medical Restraint System (CMRS). Note the use of foot restraints. This position was found unacceptable because applying force on the transducer would make the operator position unstable. The CMRS was moved closer and was used for restraining both the subject (using straps) and the operator (inserting one knee into the space under CMRS). *(Image courtesy National Aeronautics and Space Administration.)*

Figure 50-3 International Space Station (ISS) Commander Gennady Padalka and Flight Engineer E. Michael Fincke (ISS-9 Expedition, 2004) using a creative positioning solution for a musculoskeletal procedure development (Achilles tendon). *(Image courtesy National Aeronautics and Space Administration.)*

LACK OF IMAGING EXPERTISE ONBOARD

Even with a comprehensive set of standardized scanning protocols, the variability of normal and affected structures and random factors, such as imaging conditions and acoustical artifacts, require knowledge and experience. Space medicine experts agree that the expertise necessary to independently perform an ultrasound examination in space cannot be expected because most crew members have no medical background and receive only basic medical training. To make the crew ultrasound operators, three measures are currently used: (1) limited preflight training in equipment use and general scanning technique, (2) preprocedure multimedia-based performance enhancement,

Figure 50-4 The remote guidance team conducting an imaging session aboard the International Space Station (ISS). In this experimental session, cardiac preload changes were assessed in response to thigh cuffs (2007). *(Image courtesy National Aeronautics and Space Administration.)*

and (3) real-time remote guidance by an expert from the ground.

Real-time remote guidance is essential for adequate data acquisition and confident interpretation. NASA has conducted numerous ground-based simulations, which have involved inexperienced operators of various backgrounds, including astronauts, and have uniformly resulted in image sets of acceptable quality. Having completed the preflight ultrasound training and practice, the astronaut is cognitively prepared to perform an imaging study in continuous real-time communication with a ground-based expert. The "guiders," in their turn, have been able to provide confident, constructive direction for an efficient imaging procedure. The crew comfortably relies on the provided expertise without frustration or doubts regarding the effectiveness of this unique and highly professional interaction.

A very important component of remote guidance is the convention among all participants on the exact language used in training, multimedia materials, and real-time discourse, including transducer positioning and manipulation terms, anatomic landmarks, and instrument controls. As of the end of 2012, NASA medical personnel and the research community had conducted hundreds of successful remote guidance sessions in all areas of adult ultrasound imaging (Figure 50-4).

Selected Medical Problems and Ultrasound Imaging Solutions

Ultrasound imaging is expected to assist in the management of more than 50% of the medical conditions considered possible in conditions of space flight. The below-listed examples are chosen to illustrate the unique features of imaging techniques, interpretation, and impact on patient management in the space flight environment.

Urolithiasis, urinary obstruction, and retention are very common emergencies terrestrially and are among the recognized risks for human space flight. In some crew members, renal colic has been observed during space flight and shortly after landing. Urinary tract imaging was conducted on at least eight healthy crew members in space for procedure development purposes by using terrestrial techniques, which retain validity in microgravity[5,6]; notwithstanding a usually favorable prognosis for small stones, it is easy to foresee a scenario leading to patient evacuation, especially if urinary tract infection is present. Prognostic determination would be a prime focus of imaging in such cases because the size and location of the calculus help forecast the course of the obstruction.

Urinary retention has been observed in space, mainly in the initial phase of adaptation to microgravity; certain medications may contribute to its development. Ultrasound imaging can easily assess the bladder volume and the state of antireflux mechanisms, thus determining the need for catheterization. Ultrasound imaging would also be used to guide suprapubic or renal drainage should such a need arise.

Peritoneal fluid and gas are principal imaging targets in abdominal trauma and in a number of systemic and localized pathologies. Free blood in microgravity does not localize to the *f*ocused *a*ssessment with *s*onography in *t*rauma (FAST) sites as readily as on Earth.[3] Small quantities of blood remain in the place of origin, slowly spreading over adjacent mesothelial surfaces by means of surface interaction and capillary action. As bleeding continues, localized collections form and slowly spread according to the peritoneal anatomy. Although the basic FAST locations remain valid, additional non-FAST locations must be added to the FAST examination.[5,7,8]

Acute appendicitis would be difficult to rule out or confirm clinically in a space crew member, and direct visualization of the vermiform appendix will be necessary. An inconclusive report in a right lower quadrant (RLQ) pain, including a failure to identify the appendix or otherwise resolve the diagnostic problem should warrant repeated imaging sessions. The imaging conditions in the RLQ change over time because of the intestinal dynamics, bladder filling, guarding, patient cooperation, and available time. For these reasons, follow-up ultrasound imaging must be scheduled in positive cases to monitor the course of disease and, in inconclusive or negative results, to continue the diagnostic workup.

Decompression sickness (DCS) is caused by rapid transition to a lower ambient pressure. The rate of gas bubbles in the lower extremity venous return is easy to assess but not as important as the "bubble crossover" (e.g., penetration of the bubbles into the left circulation).[9] Although the ISS program invested primarily in the prevention of DCS during extravehicular activity with low in-suit pressure, the capability is still important for accidents resulting in the drop of ambient pressure inside the vehicle.

Eye trauma can be caused by airborne objects, cluttered environment, elastic cords, and pressurized gases; it can be assessed in the field by scanning through closed eyelids. A comprehensive ocular protocol has been tested in several space crew members.[10] In addition, a novel method of ultrasound pupillometry was also proposed and tested on the ISS, with a subsequent terrestrial validation.[11]

Intracranial hypertension may develop in a small subset of crew members if the overall adaptive capacity to microgravity-related cephalad fluid redistribution is saturated. Responding to this concern, since early 2010, ISS astronauts undergo eye and orbit ultrasonography before, during, and after flight as part of an occupational monitoring program. Eye and orbit ultrasonography has thus become the single most practiced clinical imaging modality in human space flight (Figure 50-5). The quantitative and qualitative parameters include the *optic nerve sheath diameter (ONSD), globe flattening, optic disk protrusion,* and others. Eye and orbit ultrasonography is thoroughly addressed in Chapter 6.

Pneumothorax (PT) is either idiopathic or associated with chest trauma, positive-pressure lung damage, or other identifiable causes. NASA investigators studied the potential of ultrasonography in PT first in a microgravity animal model[12] and then in a prospective human trial; ultrasonography was 98% sensitive and 100% specific.[13] In September 2002, for the first time in history of space flight, NASA scientist Peggy A. Whitson, assisted from the Mission Control Center (author A.S.), demonstrated the normal pleural interface in microgravity.[5] The same procedure was routinely repeated in several subsequent expeditions.

Free pleural fluid would present a diagnostic challenge in space even to a skilled physician, primarily because of its unusual distribution. Animal studies in parabolic aerial flight (20- to 25-second microgravity periods) have shown pleural separation by fluid throughout the pleural cavity, rather than in dependent locations only. Microgravity ultrasound reliably detected as little as 50 mL of pleural blood in a 50-kg porcine model by using then-current multipurpose equipment.[3] Even higher sensitivity is expected in human pleura in continuous microgravity when using modern equipment and proper imaging technique.

Pulmonary pathology, in the absence of radiographic and meaningful auscultation capability may be easily overlooked. Evidence corroborates the relevance of ultrasound imaging in chemical pneumonitis or infectious processes, congestive lungs, pulmonary embolism, or atelectasis in previously healthy lungs. In 2011, evidence-based consensus statements were published to guide implementation, development, and standardization of lung ultrasound in all relevant clinical settings.[14]

Figure 50-5 International Space Station (ISS) Flight Engineer Dr. Donald Pettit (ISS-31 expedition, 2012) is about to begin an eye and orbit ultrasound procedure required for all crew members as part of the occupational surveillance program. Note the small amount of water placed over the orbit area for acoustical coupling purposes. The use of water allows conserving gel (an available but expensive commodity in space) and gaining additional advantages of convenient, pressure-free standoff, time saving, and ease of cleanup. *(Image courtesy National Aeronautics and Space Administration.)*

Bone fractures: The clinical utility of ultrasonography in fractures is widely recognized and of interest to space medicine. Besides identifying a fracture, ultrasonography reveals mutual mobility of fragments, proximity and condition of vascular trunks, tendons and nerves, and can aid in reposition and monitoring of healing. NASA investigators have reported a high accuracy of ultrasonography in long-bone fractures in an emergency room setting.[15]

Because of the differences in the background physiology, serious conditions occurring in microgravity will differ in their pathophysiology as well from their intensive care unit (ICU) analogues. However, most medical problems encountered in space could still be interpreted in terms of critical care medicine (e.g., the occurrence of PT on the grounds of barotrauma in space resembles usual side-effects of positive-pressure mechanical ventilation). Space medicine experts therefore use critical care medicine concepts and solutions in the planning of mission medical support, design of the onboard medical kits, and training programs. Elements of advanced ICU diagnostics and therapeutics will continue to influence the design of future space medicine systems, especially those for the future exploration-class space flights.

Future Challenges and Conclusions

As the required degree of clinical autonomy increases with mission duration, size of the crew, and distance from Earth, so will increase the medical support demands. Health-related concerns will probably dominate the agenda for interplanetary missions, rather than engineering challenges. Therefore great attention to the medical support of future missions is necessary, including the use of the ISS as a test bed for technology development.

Ultrasound imaging will likely be part of interplanetary missions, without the luxury of on-demand guidance from the ground. The imaging expertise will have to reside onboard, possibly including automated image recognition for procedure guidance and image interpretation. Also note that the emergency return from flights to remote planets, such as Mars, will most certainly take longer than the natural course of any acute illness. The engineering community and space medicine experts will have to respond to the challenges of new mission designs. The ultrasound systems of interplanetary missions can be foreseen as small, radiation-stable, and compatible with the vehicle's shared computing and communication resources.

Thus, in its continuous efforts to refine the preventive and clinical care capabilities in space flight, the international space medicine community routinely uses ultrasonography as the sole imaging modality for monitoring human adaptation to space travel and for clinical decision-making in the limited-resource environment of space travel.

Pearls and Highlights

- Ultrasound imaging is a permanent research capability aboard the International Space Station, as well as the sole diagnostic imaging capability for crew medical support.
- The space program–affiliated experts contribute to the development and promotion of novel diagnostic solutions, including pleural and lung ultrasound, trauma imaging, and others.

- Imaging representations of normal states and especially disease in microgravity may differ from those on Earth, and may require modifications of both imaging technique and interpretation.
- Patient positioning in microgravity is used only for convenient scanning setup and to ensure stability upon transducer pressure.
- The current paradigm of ultrasonography in space includes real-time ultrasound video downlink with verbal remote guidance of the crew-member operator. Telemedicine solutions developed by the space program have important terrestrial applications.
- Future missions outside the low Earth orbit will eliminate the ability for real-time guidance and rapid evacuation to Earth, requiring increased medical autonomy. Ultrasound expertise will have to reside aboard the vehicle, along with automated image recognition and other solutions.
- Medical results of the space program can improve the well-being of people on Earth, including expansion of ultrasound applications and development of advanced telemedicine techniques.

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SECTION IX

Special Techniques and Applications

51

Soft Tissue, Musculoskeletal System, and Miscellaneous Targets

ASHOT E. SARGSYAN | GLYKERIA PETROCHEILOU | SERAFIM NANAS | ARIEL L. SHILOH | HEIDI LEE FRANKEL | DIMITRIOS KARAKITSOS

Overview

Besides encompassing specific focused techniques, the holistic approach (HOLA) ultrasound concept, introduced in Chapter 1, promotes generic scanning of any body part (head-to-toe ultrasound imaging) as modulated by current clinical indications. Any ultrasound view obtained through the skin contains some information about *soft tissues.* While serving as an *imaging window* and as anatomic reference structures in focused techniques (e.g., the chest wall in lung scanning), soft tissues per se are often a *primary target* (e.g., in extremity crush injury). Therefore mastery of fine anatomy is essential for the HOLA-level ultrasound operator, both in terms of tissue type (e.g., fascia, tendon, peritoneum), and in terms of named structures (e.g., basilic vein, gracilis muscle, median nerve). This chapter reviews nonspecific (generic) soft tissue and musculoskeletal (MSK) imaging and miscellaneous intensive care unit (ICU)-relevant HOLA targets.

Soft tissue and skeletal scanning may be indicated in many clinical situations, including the following:

- Visible bruising, swelling, deformity, redness, pulsation, or asymmetry
- Palpable mass, warmth, pulsation, crepitus, or other focal abnormality
- Known or suspected foreign body, including indwelling access devices
- Known or suspected MSK injury or history of a relevant event, such as a fall
- Traumatic or surgical wounds
- Spontaneous, traumatic, surgically placed, or postsurgical fistulas
- Ruling out pathologic lymph nodes
- Planning interventional procedures (e.g., vascular access)
- Known or suspected vascular pathology or access devices, including status post difficult vascular access

Equipment and Technique

Any modern multipurpose system with a high-frequency (7-15 MHz) transducer is appropriate for most superficial targets. Lower frequencies (2-5 MHz) are used for deeper tissues in large subjects or large body parts (e.g., the thigh). More than one transducer can be used on the same region of interest (ROI) to exploit advantages of each. Some experts recommend *broadband microconvex transducers* (usually 5-8 MHz) for most soft tissue targets because they offer a good balance of resolution and penetration in a wide-angle view through a small footprint. With any transducer, both B-mode and color Doppler mode are often used. Although *elastography*, an emerging method to map elasticity of tissues, currently has limited use in the ICU, every superficial tissue scanning procedure includes elements of "visual elastography" (see Pathology section later).

Commercially available gel pads or a thick layer of gel (probe "floating" technique) are used for imaging the most superficial tissues or lesions, especially when an adequately high-frequency probe is not available.

Normal Patterns

The uppermost layer of the image is a thin hyperechoic line that corresponds to the *skin*. *Subcutaneous adipose tissue* underneath is relatively hypoechoic, with linear echoes (septa). *Fascia* is a brightly echogenic line (perceived as a contiguous layer during scanning). *Muscles* appear as hypoechoic structures with organized echogenic fibroadipose septa between fasciculi; the septa merge as the transducer is moved toward a tendon (Figure 51 E-1). *Tendons* appear hyperechoic and fibrillar when scanning along their course and granular in cross sections; however, even a small deviation from the 90-degree orientation of the ultrasound beams relative to the fibers results in the loss of the echogenic pattern, mimicking a tear or defect. This feature is known as *anisotropy* (Figure 51-1)—dependence of the imaging pattern on the beam orientation. In tendons, the smooth type-1 collagen fiber bundles are good reflectors (direction dependent) but poor scatterers (direction independent). *Peripheral nerves* also have a fascicular appearance, but with less anisotropy, and are surrounded by loose connective tissue (see Figure 51-1). *Vessels* appear as anechoic (black) stripes across the image when the scanning plane aligns with their course. In transverse orientation, *arteries* are circular and may visibly pulsate. *Veins* have a near-circular appearance with less prominent walls, easily compress with transducer pressure, but fail to collapse entirely in case of thrombosis (see Figure 51-1). The *bone* surface is normally depicted as a brightly echogenic line with acoustic shadowing. The *joint space* is identified by a V-shaped discontinuity in the cortical line from adjacent bones, usually representing *fibrocartilaginous tissue* (e.g., *meniscus* or a *labrum*). Random collagen fiber orientation in these structures determines their high, nonanisotropic echogenicity.[1-3] *Hyaline cartilage*, on the other hand, looks like a thin hypoechoic rim over the bone (see Figure 51-1).

Pathology: High-Level Considerations

Ultrasound imaging allows observing the instantaneous anatomy of body parts with reasonably consistent normal patterns for each type of tissue, each area, and each named structure. The ability of the operator to recognize the normal anatomy

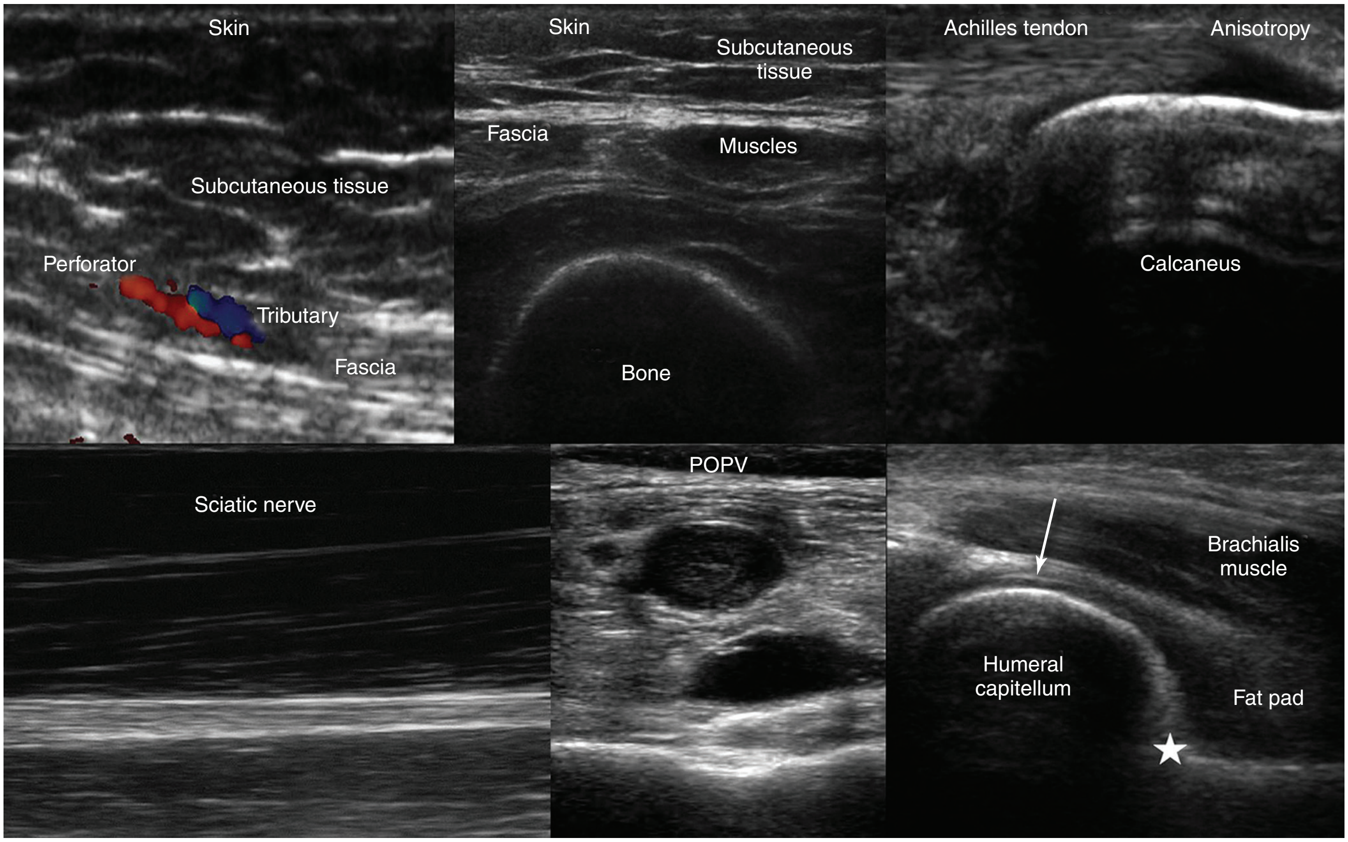

Figure 51-1 *Top, left-to-right,* Visualization of the skin, subcutaneous tissue, perforator (artery) and tributary (vein) exiting from the hyperechoic abdominal fascia (longitudinal plane); transverse view of the anterior thigh demonstrating the skin, subcutaneous tissue, fascia, muscles, and bone (femur); longitudinal view of the calcanear insertion of the Achilles tendon demonstrating anisotropy. *Bottom, left to right*, Longitudinal view of the sciatic nerve coursing the posterior thigh; incompressible popliteal vein (POPV) caused by thrombosis; medial sagittal plane of the anterior elbow joint showing the coronoid fossa (*star* = anterior coronoid recess) and the articular cartilage of the distal humeral epiphysis *(arrow).*

and any deviations from the norm grows fast with scanning experience. Most physicians learn quickly to correlate the real-time, two-dimensional (tomographic) visual information with their knowledge of topographic anatomy and to interpret the data in the clinical context. The following *high-level criteria* are used to a varying extent in each scanning procedure to discriminate between the normal and pathologic topography and structure:

- Change in the relationships, shape, echostructure, or echogenicity of an anticipated (recognized) structure
- Focal change within an anticipated structure or its discontinuity
- Unexpected response of the structure(s) to transducer compression
- Appearance of an extraneous (unanticipated) structure within or between normal structures
- Consistent difference between the suspected pathologic area and the presumably normal contralateral site
- A trend in any of the above criteria relative to prior examinations

The shape and the response of a structure to transducer pressure are two interconnected criteria that are important for the following reason: elastic structures with fluid content (gas, liquid, loose tissue) assume a more spheric shape and become less compressible as the pressure within that space (compartment) increases. Experienced operators consider shape and use compression intuitively as part of the scanning scrutiny of both anatomic and pathologic structures.

Extraneous structures include cysts, abscesses, hematomas and pseudoaneurysms, hernias, tumors, enlarged lymph nodes (most of which do not stand out if normal), and foreign bodies (including devices), among others.

Pathology: Specific Types

Hematomas are collections of extravascular blood caused by common and iatrogenic trauma, coagulation disorders, necrosis, and other mechanisms. They usually appear as poorly demarcated but structurally differing areas within or between anatomic structures, often distorting them (*mass effect*). A hematoma shows serial changes over time (Figure 51-2). Fresh blood initially looks anechoic and then becomes finely echogenic when clotted. After clot liquefaction, hematomas regain anechoic or hypoechoic appearance with diffuse internal echoes that may form a layer by sedimentation. Most hematomas resolve, but some organize into a chronic hyperechoic mass with echogenic inclusions or concentric layers from repeated bleeds.[2-4] Color Doppler ultrasound helps demonstrate deviations of adjacent vessels; it is also helpful in distinguishing between a hematoma and a pathologic tissue.

Ultrasound imaging is valuable in *musculotendinous injuries* as part of the physical examination in trauma. Acute muscle contusion and hemorrhage appear hyperechoic, whereas later

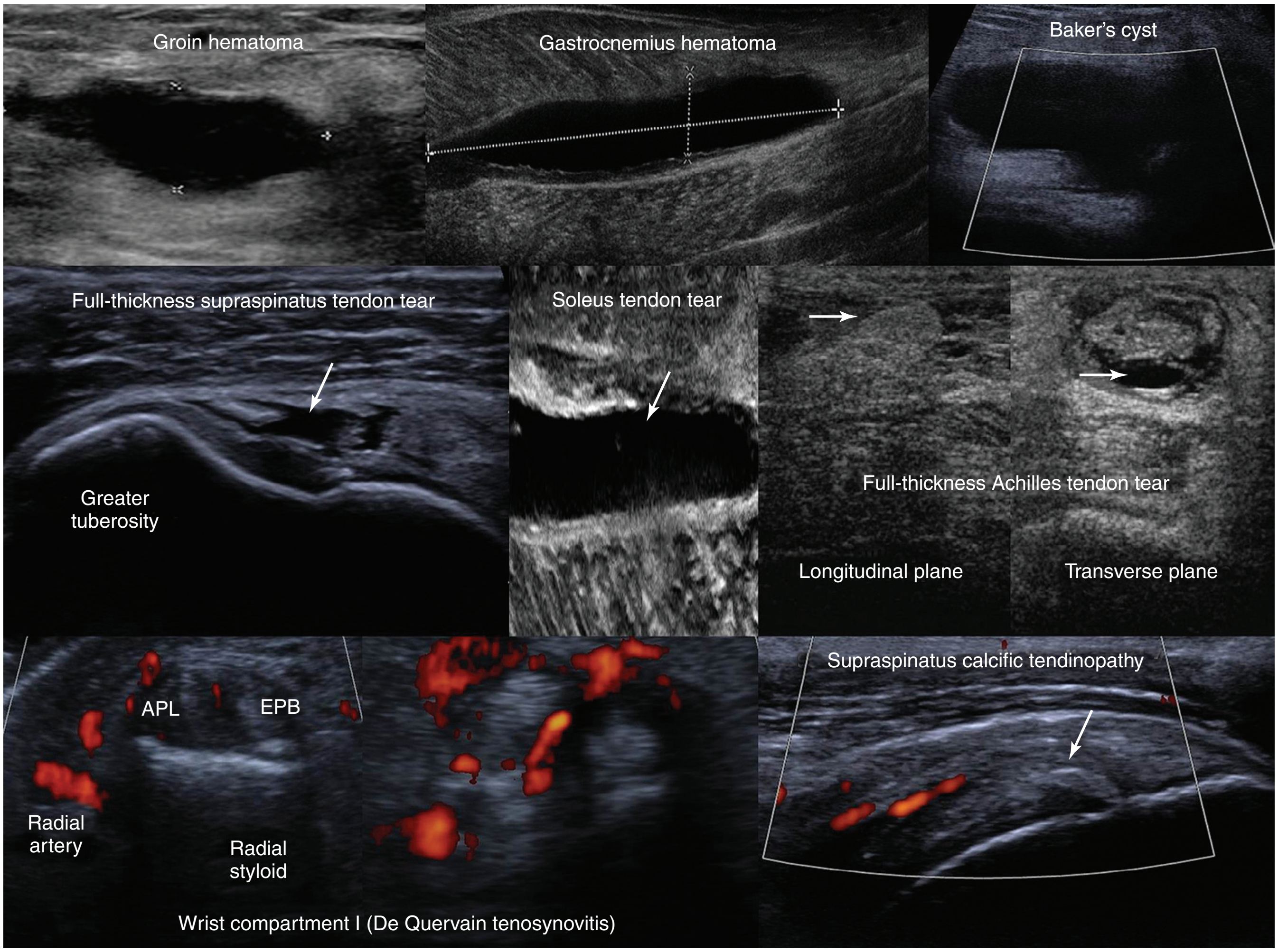

Figure 51-2 *Top, left-to-right,* Anechoic groin hematoma; gastrocnemius muscle hematoma after clot liquefaction; visualization of a cystic structure (no blood flow is evident) between the medial gastrocnemius and semimembranosus tendon in the popliteal fossa (Baker cyst). *Middle, left-to-right,* Visualization of a hypoechoic area in the supraspinatus tendon corresponding to a full-thickness tear *(arrow);* zoom image of a soleus muscle tear *(arrow);* longitudinal and transverse planes of a full-thickness Achilles tendon tear demonstrating Kager fat pad herniation *(arrow)* and a hypoechoic hematoma enhancing the conspicuity of the tear *(arrow),* respectively. *Bottom, left-to-right,* Focal thickening and increased vascularity surrounding the de Quervain tendons at the level of the radial styloid process (de Quervain tenosynovitis); anterior view of the shoulder depicting a thickened and heterogeneous supraspinatus tendon with a focus of calcification *(arrow)* and increased vascularity (calcific tendinopathy). *APL,* Abductor pollicis longus; *EPB,* extensor pollicis brevis. *(Images of soleus muscle tear* (middle) *and de Quervain tendons* (bottom) *courtesy Dr. K. Stefanidis.)*

stages of injury exhibit mixed patterns. Partial or complete muscle tears with or without retractions are usually obvious (see Figure 51-2). Intramuscular hematomas may later evolve into seromas or intramuscular cysts (anechoic fluid collections) that may require aspiration or surgical drainage. Heterogeneous, grainy muscular patterns with a hypoechoic appearance of septa and fasciae are described in *malignant hyperthermia*. Hypoechoic muscular swelling with architectural disorganization may be observed in traumatic *rhabdomyolysis*.

In *crush injuries,* ultrasound imaging can assist in critical decision-making and have significance for the extremities and be lifesaving because a buildup of pressure within the fascial compartment disrupts tissue perfusion (compartment syndrome) with dire consequences, unless fasciotomy is emergently performed. *An advanced HOLA protocol in extremity crush injuries* would therefore include assessment of (1) the shape and structure of all the fascial compartments (looking for outward convexity of the normally flat fascial partitions between compartments), fractures, tears, hematomas, and hypoechoic areas of potential fluid collection or necrosis; (2) color and pulsed wave Doppler monitoring of the vessels within the compartment and the main artery feeding the compartment; (3) renal imaging (monitoring size/volume, renal arterial spectral Doppler, and parenchymal differentiation); and (4) search for free abdominal fluid if the thigh and pelvis areas are involved.

Partial and complete tendon tears can be identified by dynamic ultrasound evaluation assessing the tendon's integrity through the respective range of motion. Hypoechoic-to-anechoic intratendinal regions indicate partial tearing. Full-thickness tears may appear as tendon discontinuity with or without retraction and acoustic shadowing, whereas defects may be filled by hematomas or fat pad herniation (see Figure 51-2). An anechoic fluid cuff around a thickened, hyperechoic tendon with increased vascularity suggests *tenosynovitis*. *Tendinopathy* may appear as an intratendinous, hypoechoic patchy or hyperechoic calcific area with increased vascularity and loss of anisotropy and fibrillar pattern (see Figure 51-2). *Ganglion cysts* arise from the joint capsule or tendon sheaths and appear anechoic. The *Baker cyst*, first described by Dr. William Baker in 1877, is the most common mass in the popliteal fossa, which represents a fluid-distended gastrocnemio–semimembranosus bursa (see Figure 51-2).[3]

A cortical discontinuity with step-off deformity is the diagnostic hallmark of a *bone fracture* that is best seen in a plane perpendicular to the fracture line (Figure 51-3). Intensivists rarely deal with fracture diagnosis because patients arrive with a full set of radiographic imagery or after orthopedic surgery. Ultrasound imaging is relevant for monitoring adjacent soft tissue damage, such as hematomas or joint effusions (hemarthrosis). Monitoring can detect fracture nonunion and other complications (e.g., osteomyelitis) because ultrasound imaging depicts callus formation earlier than radiography, particularly in open injuries.[2,3] *Heterotopic ossification (HO)* is usually observed in periarticular muscles of the limbs, mainly in neurologic states (spinal cord injury, hemiplegia after stroke, or traumatic brain injury) or after burns, trauma, and joint arthroplasty, and it can severely affect the joint's range of motion. Early clinical features (pain, swelling, erythema, warmth) may resemble skin infection, deep vein thrombosis (DVT), or acute arthritis. Mineralization is detected by ultrasound earlier than in radiography as an inner hypoechoic core surrounded by a peripheral hyperechoic band of mineralized islands ("zone phenomenon") with increased vascularity. In cases when calcifications have not yet occurred, HO may be confused with sarcomas (see Figure 51-3).

Recently, ultrasound has been used to determine the type and extent *of traumatic nerve injuries*. In cases of nerve entrapment,

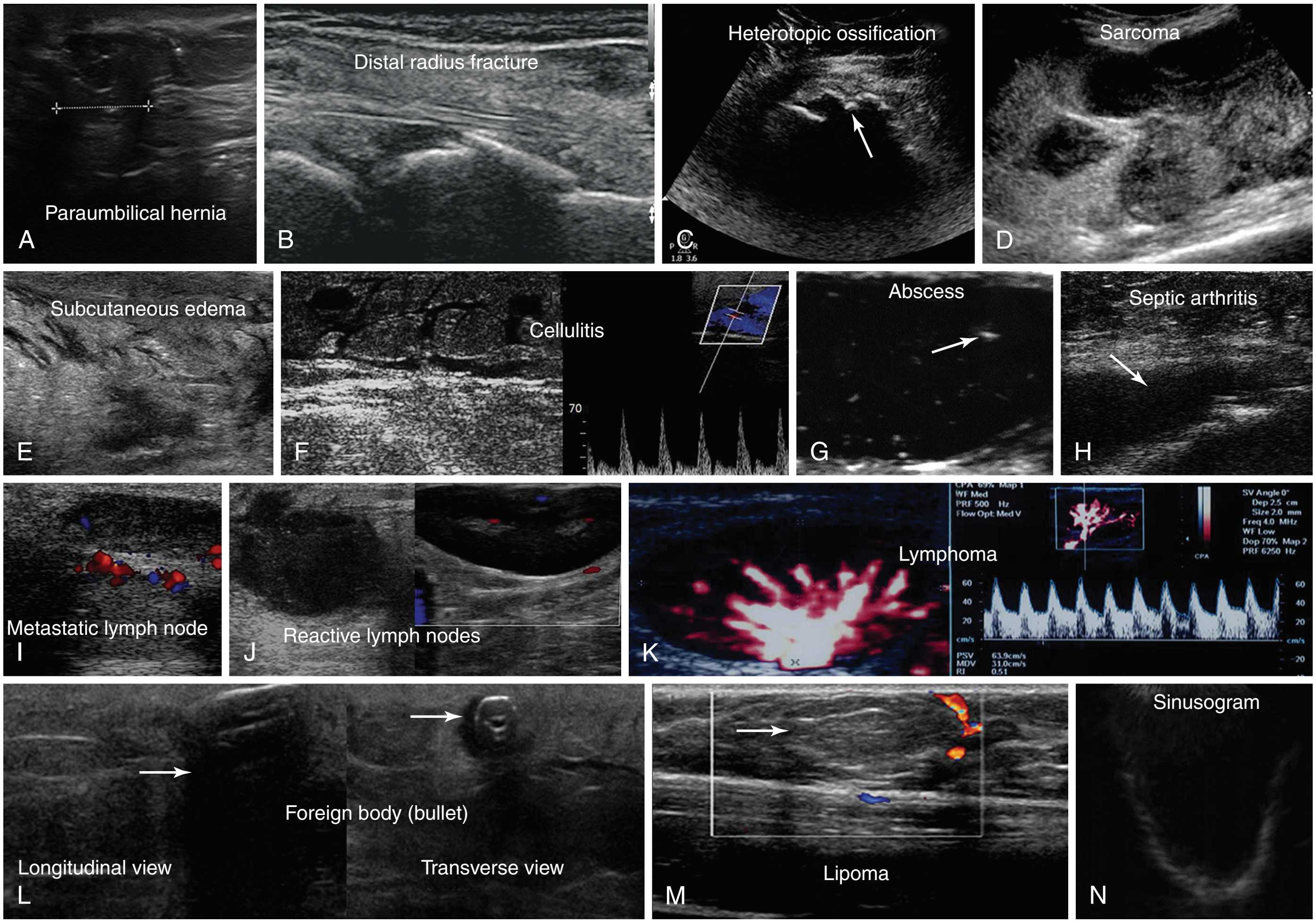

Figure 51-3 **A,** Longitudinal view of a paraumbilical hernia containing omentum (12-mm defect). **B,** Lateral/coronal long-axis scan of the distal forearm in a trauma patient. Note a comminuted distal radius fracture: four distinct segments of bone with mutual misalignment, with a hypoechoic area of a likely hematoma (note the extensor pollicis brevis tendon across the screen, parallel to the skin, and the general axis of the fractured bone). **C,** Visualization of the "zone phenomenon" in heterotopic ossification: an inner hypoechoic core is surrounded by hyperechoic mineralized islands *(arrow)* within the iliopsoas muscle adjacent to the hip joint. **D,** Heterogeneous groin mass with ill-defined borders (sarcoma). **E,** Cobblestone appearance of the subcutaneous tissue resulting from generalized interstitial edema in a heart failure patient. **F,** Cobblestone echotexture of the subcutaneous tissue in a region of the gastrocnemius muscle and depiction of unusually high flow (increased peak systolic Doppler velocity) in a local perforator (cellulitis). **G,** Zoom image of a subcutaneous hypoechoic abscess with hyperechoic punctiform material. **H,** hypoechoic knee effusion with echogenic material (*arrow,* septic arthritis). **I,** Hypoechoic metastatic arm lymph node in a patient with thyroid cancer. **J,** Reactive round- and oval-shaped groin lymph nodes. **K,** Oval-shaped groin lymph node with a Doppler-derived resistive index (RI) 5 0.51 (power Doppler mode), which was initially characterized as reactive, but eventually proved (biopsy) to be malignant (lymphoma) with cystic necrosis. **L,** Longitudinal and transverse planes of the thigh depicting a bullet casting an acoustic shadow *(arrow)* and the formation of "halo" *(arrow)*, respectively. **M,** Longitudinal view of superficial lipoma *(arrow)* over the xiphoid process. **N,** Visualization of a totally fluid-filled sinus that appears hypoechoic, with its posterior and lateral walls delineated (sinusogram). *(Images in* ***A,*** *courtesy Dr. K. Stefanidis;* ***D, L,*** *and* ***M*** *courtesy Dr. K. Shanbhogue;* ***G,*** *courtesy Dr. J. Poularas.)*

associated changes in nerve contour and echotexture and causative extrinsic abnormalities may be depicted.[5] The role of ultrasound in guiding regional anesthesia techniques is well established (see Chapter 53).

Ultrasonographic evaluation of *infections* in the ICU is another important application. Local spread of infection (e.g., involvement of muscles, joints, etc.), thrombophlebitis, causative factors (e.g., foreign bodies), or occult abscesses can be detected. *Cellulitis* is a diffuse infection of skin and subcutaneous tissue that may progress to abscess formation if left untreated. Initially, swelling with increased echogenicity of the involved area is depicted. Progressively, fluid-filled regions of hypoechoic edema create a cobblestone pattern. Detecting hypervascularity may be helpful to differentiate cellulitis from other causes of *interstitial edema* (e.g., congestive heart failure), which may also appear as anechoic, fluid-filled zones dissociating the connective septa (see Figure 51-3). *Subcutaneous fat necrosis* resulting from panniculitis or trauma resembles an ill-defined hyperechoic mass containing hypoechoic areas related to infarcted fat. *Necrotizing fasciitis* is a rapidly progressing and life-threatening infection involving deep fascia and muscle (usually located in the limbs, abdominal wall, or perineum). Thickened fascia with cloudy fluid collection (>4 mm in depth) and muscle swelling indicate the diagnosis, whereas *subcutaneous gas* can be identified as "dirty""acoustic shadowing with a reverberation artifact.[2,6]

Abscesses may exhibit a wide range of ultrasonographic patterns but are usually surrounded by an irregular rim that represents edematous soft tissue or cellulitis. An abscess cavity typically appears hypoechoic, although debris, septa, or bacterial gas can sometimes result in an isoechoic or hyperechoic appearance, making recognition difficult (see Figure 51-3). The increased through transmission effect and the movement of purulent material (induced with gentle transducer pressure) confirm the fluid nature. Color Doppler may depict hypervascularity within the abscess wall and in surrounding tissues while showing no Doppler signal within the abscess cavity. Abscesses and associated edema in skeletal muscle layers indicate *pyomyositis* (usually found in immunocompromised patients). Hypoechoic fluid collections adjacent to bone cortex (subperiosteal location in children), along with cortical irregularity, raise suspicion of *osteomyelitis*. Septic tenosynovitis may be encountered after penetrating injury and often shows fluid around the tendon and flow on color Doppler. Septic arthritis may be suggested by the presence of irregular internal echoes in a joint effusion (see Figure 51-3).[2,6]

Normal and reactive *lymph nodes* are usually oval shaped (short-to-long–axis ratio < 0.5); hypoechoic at the periphery compared with adjacent muscles, with echogenic medulla and hilum; and usually show low-resistive Doppler waveforms from the feeding artery (see Figure 51-3). Features favoring malignancy include larger size, rounded shape, eccentric versus concentric cortex thickening, heterogeneous echotexture with loss of identifiable medulla/hilum, presence of microcalcifications or cystic necrosis, and ill-defined borders. Malignant lymph nodes usually have high-resistance Doppler waveforms (resistive index [RI] > 0.8, pulsatility index [PI] > 1.5), but low-resistance flow patterns may be encountered in case of necrotic changes or advanced neovascularization (see Figure 51-3). The differential diagnosis of lymph node pathology (e.g., lymphoma, metastases) therefore requires an ultrasound-guided fine-needle aspiration (FNA) or excisional biopsy.[2,4]

Retained *foreign bodies* in soft tissues may lead to severe infections and disability. Ultrasound imaging detects even radiolucent foreign bodies (e.g., wood, plastic) and guides their removal. Most materials appear hyperechoic. Posterior acoustic shadowing or reverberation and comet-tail artifacts may be observed, depending on the size, shape, and structure; over time, edema, pus, or granulation tissue create a hypoechoic "halo" around the foreign body, enhancing its identification (see Figure 51-3).[7] When searching for superficial foreign bodies in soft tissues of hand or foot, it is practical to scan the area immersed in saline bath to improve acoustical transmission and avoid pressure on the sensitive area.

Ultrasound can identify *soft tissue tumors* and assist in guided biopsy. Differentiating benign from malignant lesions may be facilitated by assessing size, border echogenicity, structure, adjacent tissues, vascularity, and Doppler-derived RI. Superficial *lipomas* usually do not require additional imaging or biopsy when demonstrating characteristic features (spindle shaped in cross sections; ovoid in the plane parallel to the skin; well-defined, elastic-compressible, with linear striations). *Invasive tumors* are typically hypoechoic heterogeneous masses with ill-defined borders; adjacent malignant lymph nodes may also be present (see Figure 51-3).[4]

Miscellaneous Scanning Targets

The HOLA ultrasound examination approach has a general head-to-toe sequence (see Chapter 1) and includes various tissue types and specific targets as modulated by the clinical circumstances. The examination may begin with *facial* structures, to assess soft tissues and facial bones as indicated. Eyelid, eye, and orbit scanning is discussed in Chapter 6. Ultrasound imaging is a valuable screening tool in intubated patients with *maxillary bacterial sinusitis,* which could be an occult cause of fever, nosocomial pneumonia, and meningitis.[8,9] Radiography is unreliable in recumbent patients, whereas the costs and effort associated with computed tomography (CT) or magnetic resonance imaging (MRI) are not necessarily justified. The maxillary sinuses are scanned in sagittal and transverse planes just below the orbital rim (see Chapter 1). Normal air-filled sinuses elicit a reverberation artifact with parallel, evenly spaced echo lines. Totally fluid-filled sinuses allow a brightly echogenic line of the posterior wall and occasionally the two lateral walls to be seen, producing a pattern known as the "*sinusogram*" (see Figure 51-3). In partially fluid-filled sinuses, scanning with the patient in a more upright position results in periodic resonance artifact (as in a normal sinus) in the upper half (above the air-fluid level) and a posterior wall line in the lower, fluid-filled part of the image.[8,9] Differentiation between tissue hypertrophy (significant mucosal thickening, nasal polyps) and fluid-filled sinus is achievable, but mucoid cysts or blood resulting from facial trauma (e.g., sinus wall fractures) are not easily differentiated. Other facial targets of interest are the parotid and submandibular glands. *Parotitis* is a rare complication of mechanical ventilation; the gland is easily identified in the preauricular area as hypoechoic and heterogeneous tissue with increased vascularity. Infection affecting the submandibular gland can also be ultrasonographically investigated. The mutual proximity of these two glands allows their side-by-side comparison; the pathologic gland is almost always relatively hypoechoic (darker). This side-by-side comparison of echogenicity is also highly useful in other anatomic sites such as testicular imaging.

Neck scanning zones are imaged in midsagittal and lateral planes, suprasternal views, as well as supraclavicular and infraclavicular approaches (Figure 51 E-2). Neurovascular structures, thyroid gland, extrathoracic trachea, lymph nodes, and soft tissues can be assessed. Ultrasound is useful in *tracheal imaging* and *airway management.* The longitudinal midline view shows tracheal rings as small well-aligned structures with a "string of beads" appearance (Figure 51 E-3). Beneath the cartilages, visualization of a brightly echogenic line and periodic resonance artifact correspond to the tracheal lumen. Additional oblique views may illustrate the entire tracheal anatomic configuration (see Figure 51 E-3). *Preintubation* scanning measures tracheal diameters (applied mainly in children), and aids in evaluating tracheal compression (e.g., diving goiter, lymph node) or stenosis (e.g., pharyngeal or laryngeal pathology). Landmarks (e.g., cricoid cartilage) that may be difficult to palpate (e.g., in obese patients, etc.) are depicted along with adjacent structures, such as the thyroid gland (e.g., thyroid isthmus, goiter, etc.) or vascular structures (e.g., aberrant brachiocephalic artery, innominate vein). This helps choose the tracheostomy and/or cricothyroidotomy site (see Chapter 52). Midline transverse planes can be used to depict the *anterior jugular veins* and *tributaries of the venous jugular arch* that remain major sources of hemorrhage when performing percutaneous tracheostomy in the ICU (see Figure 51 E-3). *Postintubation* scanning depicts the endotracheal tube and/or its cuff's position in the midtrachea (suprasternal view). The tube is depicted as parallel echogenic lines with acoustic shadowing (see Figure 51 E-3), whereas the air-filled cuff is recognized by its curved contour and associated comet-tail artifacts (filling the cuff with saline improves visualization). Correct tube placement is also confirmed by its absence in the esophagus, presence of bilateral diaphragmatic motion (B-mode and M-mode) and bilateral lung sliding (pleural line movement) at the lung–chest wall boundary (see Chapters 1 and 19). Right mainstem bronchus intubation can be determined by the lack of motion of the left hemidiaphragm and a nonsliding left lung. Bilateral absence of lung sliding and paradoxic diaphragm motion during inspiration would indicate "esophageal intubation."[10] The tube will then be clearly seen in the esophagus and best approached in a transverse plane from the left side.

Thyroid gland ultrasound is a routine, highly revealing procedure and, in the ICU setting, is invaluable for screening for autoimmune thyroiditis, which is highly prevalent and underdiagnosed. The typical pattern is irregular, small, and hypoechoic and requires a certain level of experience to recognize. A normal pattern allows ruling out the condition, whereas positive or indeterminate results warrant laboratory assessment. The occasional detection of parathyroid tumors (homogeneously hypoechoic to the overlying thyroid gland) in acute hypercalcemia aids in prompt surgical intervention. CT is the preferred imaging modality for examining the retropharyngeal space; however, branchial cleft cysts, abscesses or hematomas can be evaluated by ultrasound. Supraclavicular and infraclavicular views (see Figure 51 E-2), which are extended laterally toward the axilla, may be used to evaluate tissues and structures, or plan and perform guided procedures (e.g., cannulation of central veins).

Scanning is extended to the *upper limbs by using generic scanning approaches* (applying longitudinal and transverse views bilaterally). Upper limb exploration uses *MSK landmarks,* such as shoulder, elbow, and wrist joints (Figures 51 E-4 and 51 E-5).[1] Anterior and lateral dynamic shoulder views (Figure 51 E-6) are applied to detect the biceps tendon, tendons of the rotator cuff, and adjacent muscles. Scanning can then proceed to the arm to examine the brachial artery and vein (see Figures 51 E-4 and 51 E-7). The brachial artery can be followed distally to the anterior elbow, where it lies next to the median nerve. Anterior, lateral, and posterior views (see Figure 51 E-7) may assess the elbow and adjacent structures (e.g., effusion, tenosynovitis, muscle and tendon tears, etc.). Next, forearm exploration effectively reaches the wrist and the hand. By sweeping the transducer medially to examine the Guyon tunnel, the pisiform is detected adjacent to the ulnar artery, whereas lateral wrist exploration is facilitated by identifying the radial styloid adjacent to the radial artery (Figure 51 E-8). The latter view may evaluate the first wrist compartment (e.g., de Quervain disease). Moving the transducer distally from the level of the Lister tubercle, the scaphoid, the scapholunate ligament, and the fourth compartment of extensor tendons can be evaluated, whereas the median nerve is identified within the carpal tunnel, where it can be entrapped (see Figure 51 E-8). In the ICU, hand scanning has limited applications; however, it may be performed to evaluate traumatic injuries or other abnormalities (Figure 51 E-9 and see Figure 51 E-5). The veins of the upper extremity are often used for vascular access and may be evaluated for signs of phlebitis and/or thrombosis as clinically indicated.

Surface ultrasound imaging of the *thoracic and abdominal wall* may reveal comet-tail vertical lines that start at a level external to the ribs and hide underlying structures. This finding signals parietal subcutaneous emphysema, a possible sign of pneumomediastinum or esophageal rupture. A focal region of abdominal tenderness and swelling may be due to a *rectus sheath hematoma* (e.g., bleeding disorders, postprocedural). Ultrasound delineates the entity within the abdominal wall and may guide its percutaneous drainage. Other abdominal wall abnormalities include hernias, lipomas, tumors, pseudoaneurysms, or dilatated superficial veins (Figure 51 E-10).[2,4] A recanalized left umbilical vein is possible to follow to the teres ligament from the umbilical area in many patients with portal hypertension.

Scanning is extended to the *lower limbs via the groin* (Figure 51 E-11). Several abnormalities may be encountered in the *inguinal area,* such as DVT, pseudoaneurysms, vascular bypass grafts, inguinal and femoral hernias, reactive and metastatic lymph nodes, lymphomas, abscesses, hematomas, tumors, and so forth (Figure 51 E-12). The exploration of lower limbs is facilitated by using MSK landmarks, such as hip, knee, and ankle joints. A low-frequency transducer (convex) is used when scanning the hip joint. By rotating the transducer between 45 to 60 degrees, and translating slightly forward, a longitudinal scan of the femoral neck can be obtained, and the femoral head can be identified Figure 51 E-13). *Examination of deep veins to exclude DVT is a required examination in many intensive care units* (see Chapter 9). Assessing other abnormalities that can mimic DVT (Baker cyst, hematomas, cellulitis, lymph nodes, heterotopic ossification, etc.) is equally important (see Figure 51 E-10). Dynamic MSK scanning in the lower limbs can be facilitated by a two-person technique as previously described. Scanning starts from the hip joint and continues caudally. The anterior and posterior aspects of the thigh are investigated (e.g., muscles, bones, neurovascular structures). The *sciatic nerve* can be depicted as it courses the posterior thigh (Figure 51 E-14). A microconvex, or even a convex probe, may be chosen for this area because of depth penetration challenges and the large structures that a linear probe may fail to adequately show. By sweeping the transducer toward the knee (anterior plane), the quadriceps tendon "anchoring" at the patella is depicted (see Figure 51 E-14). Anterior and lateral views (see Figures 51 E-14 and 51 E-15) may be used to evaluate the *knee* (e.g., effusions); posterior views access the popliteal fossa to evaluate major neurovascular structures (see Figure 51 E-15) or depict other abnormalities (e.g., popliteal cysts, etc.). As scanning advances distally toward the *ankle*, muscles (e.g., gastrocnemius muscle) and vessels (anterior tibial and peroneal veins) are accordingly explored. In supine ICU patients, midline longitudinal planes over the ankle dorsum identify the anterior recess of the *tibiotalar joint*. By sweeping the transducer medially and laterally, the *talar dome* is seen in 60% to 70% of cases (Figure 51 E-16).[1] Lateral ankle planes evaluate the anterior talofibular ligament; medial ankle scanning is performed by rotating the foot slightly laterally, thus allowing visualization of medial malleolus and posterior tibial vessels (see Figure 51 E-16). Dorsal foot scanning offers a view of the small and tortuous dorsalis pedis artery, which may be used for placing an arterial line. Finally, the *Achilles tendon,* the most commonly injured ankle tendon, should be examined along its full course by using both longitudinal and transverse planes; using two or three operators and lateral positions may permit dynamic scanning (passive dorsal and plantar flexion to distinguish partial from complete Achilles tendon tears (see Figure 51-2).

The HOLA concept facilitates the evaluation of various abnormalities in the upper and lower limbs, including the limited use of the common MSK landmarks. With experience, this approach enhances the ability of the operator to perform various applied techniques, such as ultrasound-guided cannulations of arteries and veins and peripheral nerve blocks. Once the operator becomes skillful in identifying all structures in the ROI, specific targets such as nerves or vessels are found quickly and confidently. Of note, this is not only easier but may prove to be safer too, as the operator learns to concurrently rule out other potential changes in the ROI. Discovering unsuspected DVT, for example, alters therapy and facilitates urgent interventions (e.g., placement of an inferior vena cava filter).

Pearls and Highlights

- Any ultrasound view obtained by placing the transducer on the skin includes potentially useful anatomic information.
- According to the HOLA concept, soft tissues may be a primary scanning target (e.g., in extremity crush injury) or may serve as an anatomic reference during imaging of deeper structures (e.g., skin, fat and fascia are identified over the vessel to be cannulated).
- Correct identification of anatomy is essential in both generic sense (types of tissues and layers) and site-specific sense (named vessels, muscles, nerves, bundles, compartments, joints).
- Ultrasound can greatly augment the physical examination of a conscious as well as sedated ICU patient and reliably identify soft tissue and MSK abnormalities.
- Hematomas usually appear as collections of extravascular fluid, showing serial changes in echogenicity over time (anechoic in acute phase and/or after clot liquefaction).
- An advanced HOLA protocol in crush injuries, accompanied by compartment syndrome can include assessment of the shape of the fascial compartment for outward

IMAGING CASE: HETEROTOPIC OSSIFICATION

A 55-year-old male patient was hospitalized in the ICU after severe traumatic brain injury. Fifty days after admission, he still required intermittent continuous positive airway pressure ventilation. He suffered from hemiplegia, and during physiotherapy sessions, pain and warmth adjacent to the hip and over the inguinal area were located. Physical examination and radiography were unrevealing. DVT was excluded by ultrasound imaging. Scanning adjacent to the hip depicted an inner hypoechoic core surrounded by hyperechoic mineralized islands (*arrow* = "zone phenomenon") within the iliopsoas muscle (left panel, top). Power Doppler detected increased vascularity adjacent to the mineralized islands (left panel, bottom). Radiography confirmed HO, 15 days after its ultrasonographic detection (right panel) and while the patient was already under therapy (indomethacin, disodium etidronate, methylprednisolone).

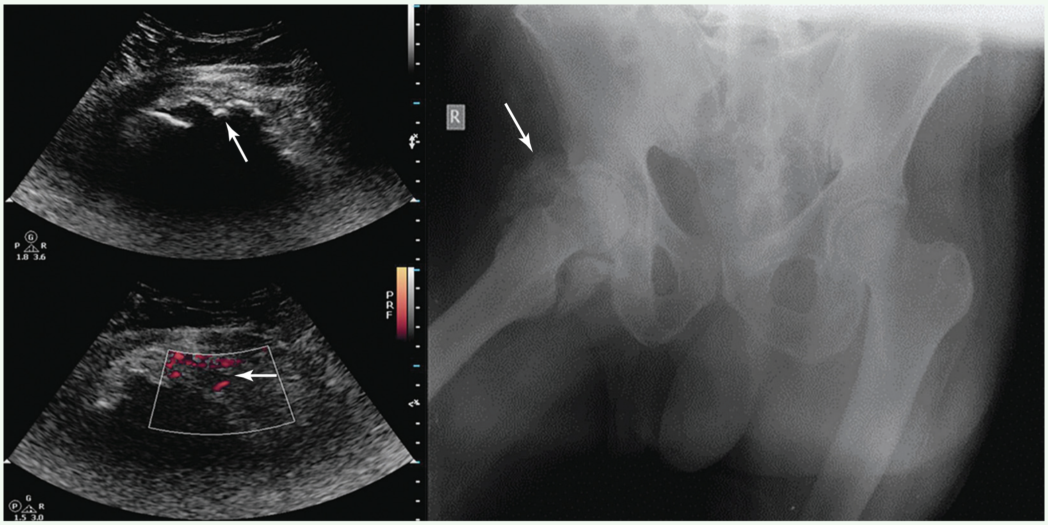

Figure 51-4

convexity of the normally flat fascial borders, color and pulsed wave Doppler monitoring of the vessels feeding the compartment, renal imaging, and search for free abdominal fluid if the thigh and pelvis areas are involved.

- In the ICU, ultrasound is rarely used for the diagnosis of bone fractures, although ultrasonographic monitoring of fractures and their traumatic sequelae (e.g., hematomas, hemarthrosis, osteomyelitis) is useful.
- Heterotopic ossification can be detected by ultrasound imaging in its earliest stages.
- Ultrasound imaging detects local spread of infection (e.g., involvement of skin, muscles, joints), thrombophlebitis, potential causative factors (e.g., foreign bodies), or occult abscesses.
- Several ultrasound features may aid in differentiating malignant from benign lymph nodes and/or tumors of soft tissues, although biopsy is still required for definitive diagnosis.
- Ultrasound imaging detects maxillary sinusitis and aids in airway management.
- Ultrasound scanning of the upper and lower limb can be used to guide interventions, such as vascular access, placement of nerve blocks, or drainage of fluid collections. However, by applying the HOLA scanning concept, operators learn to appreciate all the structures in a ROI and thus avoid missing abnormalities during site-specific scanning.

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For a full list of references, please visit www.expertconsult.com.

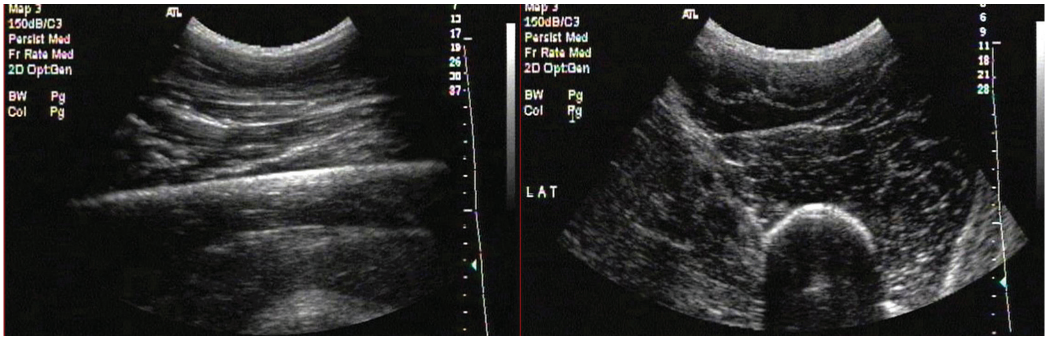

Figure 51 E-1 Longitudinal and transverse anteroposterior images of the thigh. Note the typical structure of a large skeletal muscle in the transverse view. Fascial borders of individual muscles and the compartment can be seen. Note the bright cortical reflection from femur. The hard bony cortex strongly reflects an ultrasonic wave, producing a bright, readily detectable curve or line on the image. This reflection is due to the large acoustic impedance gradient between bone and the overlying soft tissue. Although this makes the internal structure of bone difficult to visualize, it provides a very clear picture of the surface itself and therefore is a sensitive means of fracture detection. Because of the large size of the region of interest (ROI), a low-frequency convex transducer is used.

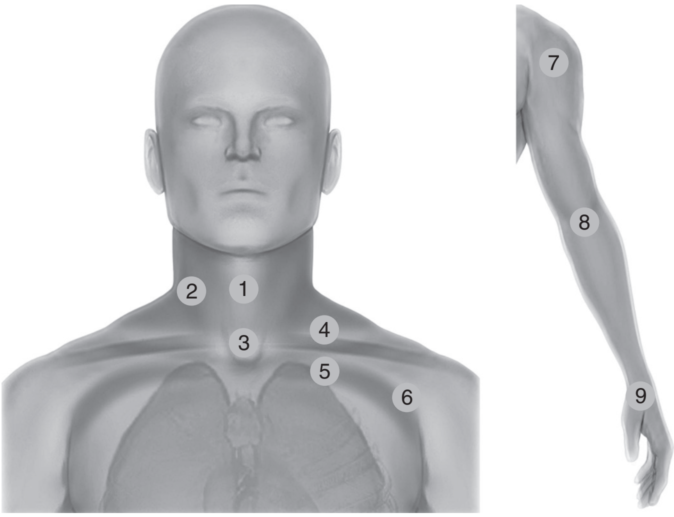

Figure 51 E-2 Neck scanning zones *(left):* Median line *(1)* and lateral *(2)* scanning zones; suprasternal view *(3);* supraclavicular *(4)* and infraclavicular *(5)* scanning approaches extending laterally *(6);* exploration of the upper limb *(right)* using the shoulder *(7),* elbow *(8),* and wrist joints *(9)* as landmarks.

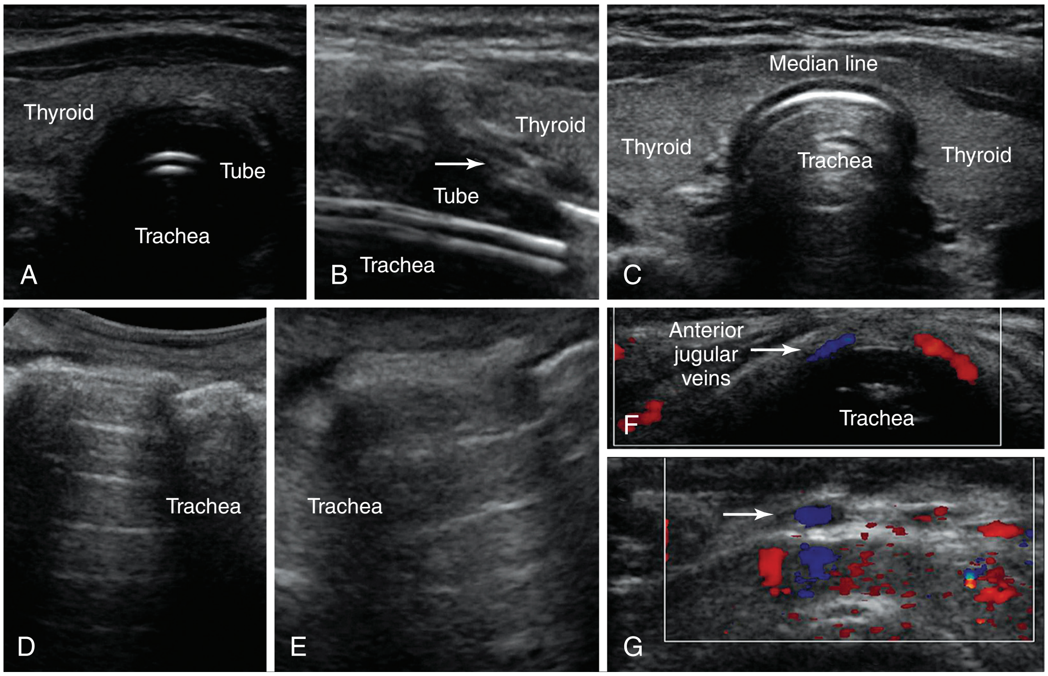

Figure 51 E-3 Median line plane: Transverse **(A)** and longitudinal **(B)** views of the intubated trachea depicting its rings as small hypoechoic structures with a "string of beads" appearance *(arrow)* and an endotracheal tube (series of echogenic parallel lines); transverse view at the level of the thyroid gland (median line) **(C);** oblique views of a normal trachea (**D** = median line, **E** = lateral); median-line transverse views depicting the anterior jugular veins **(F)** and tributaries *(arrow)* of the venous jugular arch, which may be helpful to identify when selecting optimal sites for performing percutaneous trach

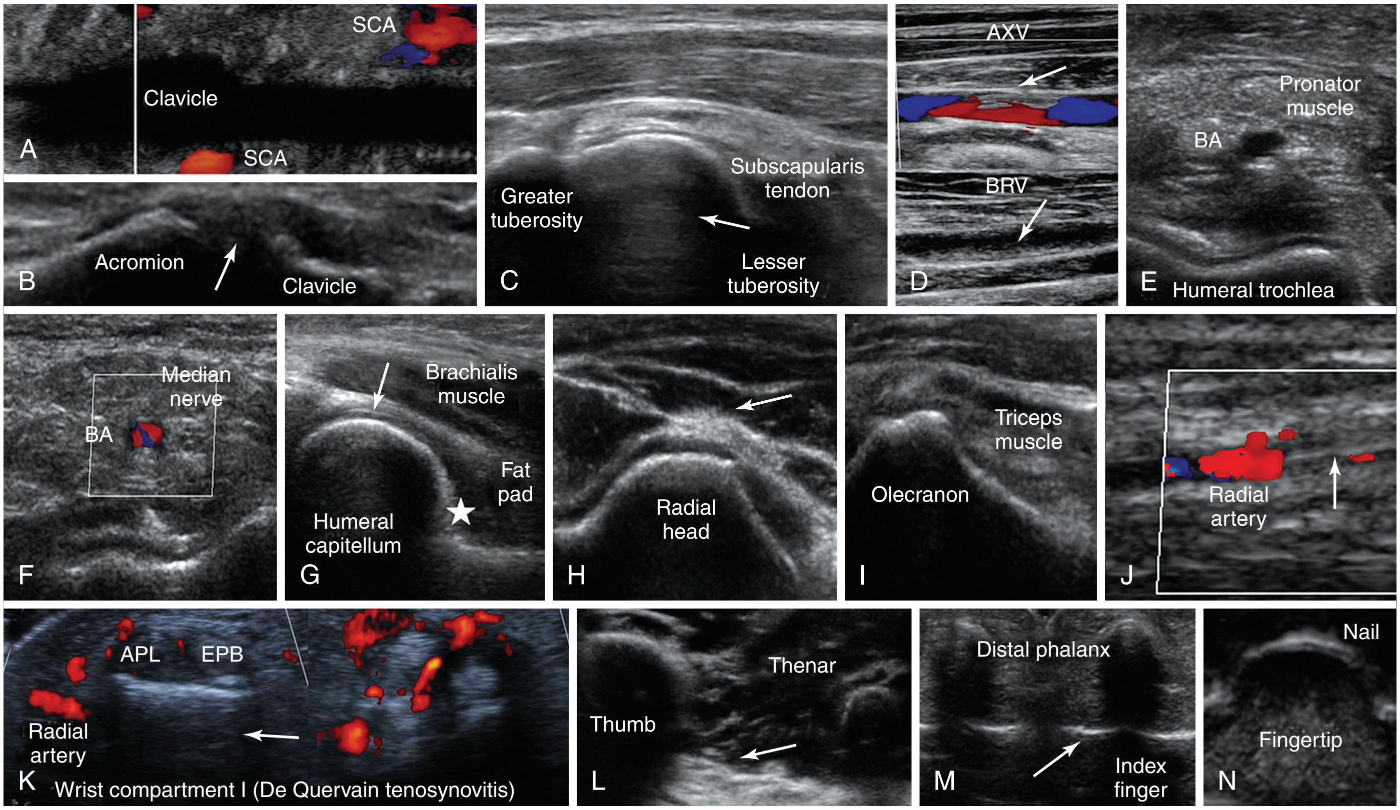

Figure 51 E-4 **A,** Oblique lower neck view depicting the subclavian artery *(SCA)* at the borders of the clavicular acoustic shadow. **B,** Coronal plane view over the acromioclavicular joint (*arrow* = joint space). **C,** Transverse view of the anterior shoulder depicting the biceps tendon's long head *(arrow)* between the lesser and greater tuberosities. **D,** Partial flow in the axillary vein (AXV) resulting from thrombosis *(arrows),* which extends to the brachial vein (BRV). Transverse views of the anterior elbow depicting the humeral trochlea **(E)** and the brachial artery accompanied by the median nerve **(F). G,** Medial sagittal plane of the coronoid fossa (*arrow* = articular cartilage of distal humeral epiphysis, *star* = anterior coronoid recess). **H,** Lateral elbow view of radial head and posterior interosseous nerve *(arrow).* **I,** Posterior elbow (in flexion) view depicting the olecranon fossa. **J,** Longitudinal view of the lateral wrist depicting an arterial line *(arrow)* in the radial artery. **K,** Focal thickening and increased vascularity surrounding the de Quervain tendons abductor pollicis longus *(APL)* and extensor pollicis brevis *(EPB)* at the level of radial styloid process (de Quervain tenosynovitis). **L,** Oblique ventral view of the proximal palm showing the thenar eminence (*arrow* = fascia), **M,** Transverse view of the interphalangeal joints *(arrow)* of the index and middle fingers. **N,** Transverse inverted view of the index finger's tip ("sonographic fingerprint").

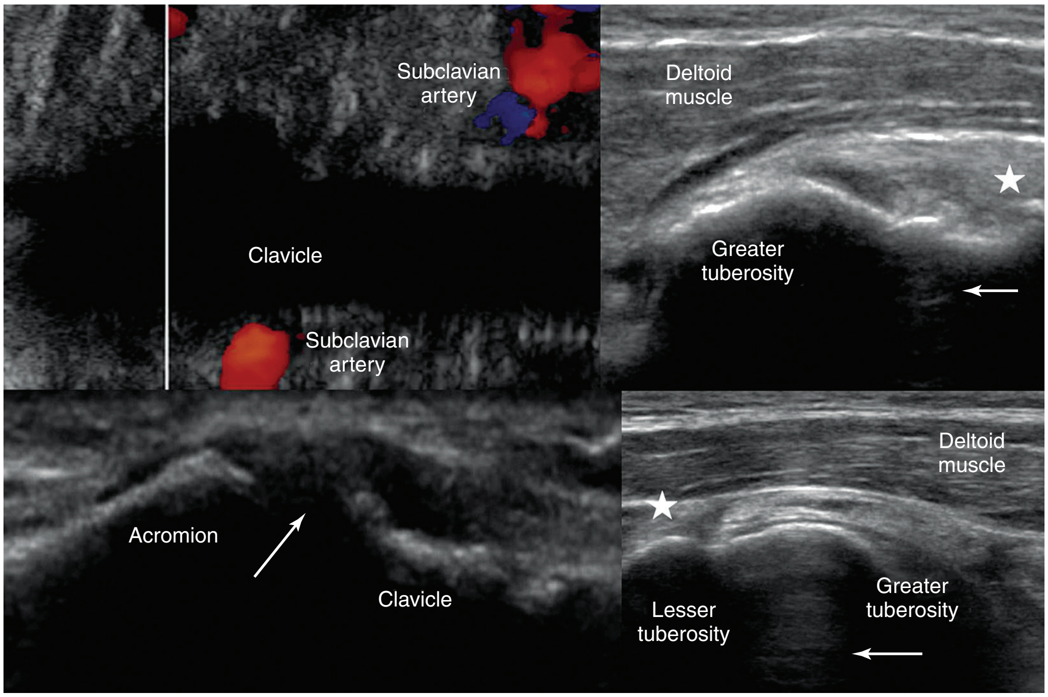

Figure 51 E-5 Longitudinal dorsal views of the second digit, which demonstrate minor trauma of the distal phalanx *(top)* and a normal phalanx *(bottom)*, respectively. *(Courtesy Dr. Hasmik Berberyan.)*

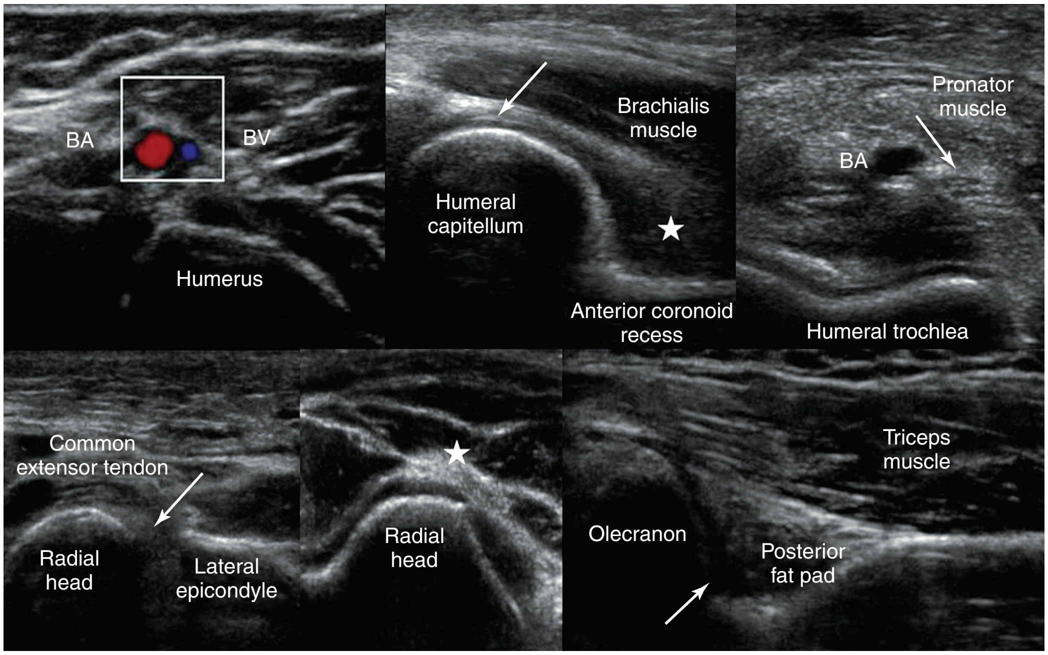

Figure 51 E-6 *Top*, Oblique lower neck views demonstrating that a vessel (subclavian artery) can still be visualized at the borders of a bone's (clavicle) acoustic shadow *(left);* anterior shoulder view depicting the biceps *(arrow)* and supraspinatus *(star)* tendons adjacent to the greater tuberosity *(right). Bottom*, Coronal plane view over the acromioclavicular joint (*arrow* = joint space). By sweeping the transducer from this position anteriorly and posteriorly over the joint, the presence of an os acromiale may be demonstrated *(left);* anterior shoulder view with the arm in slight internal rotation (directed toward the contralateral knee) and the elbow flexed 90 degrees (palm up) depicting the biceps tendon between the lesser and greater tuberosities (*star* = subscapularis tendon; *right*).

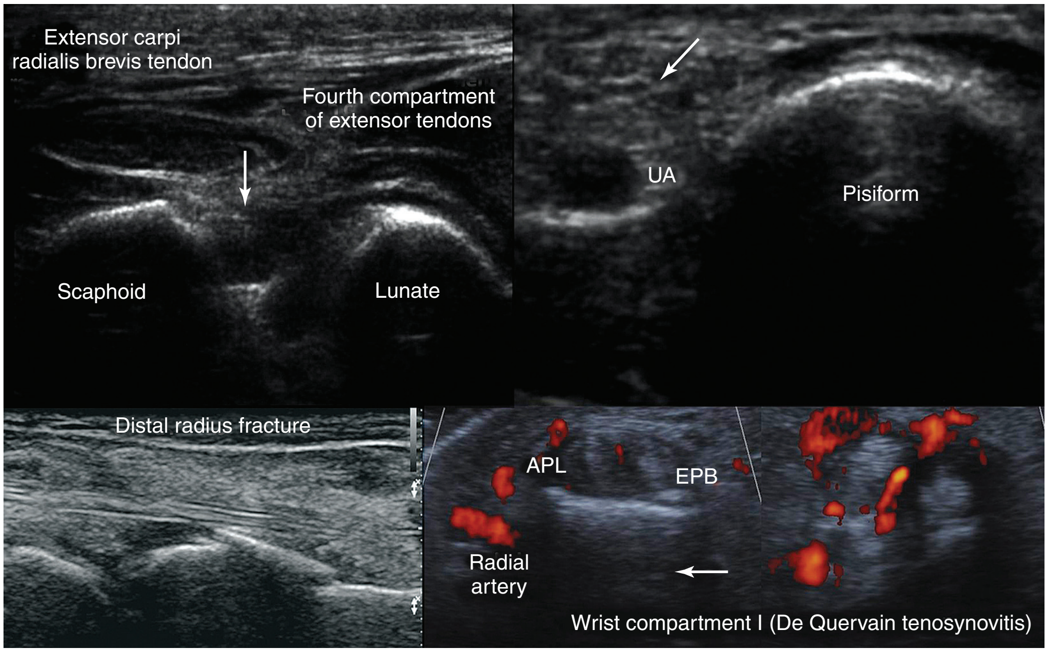

Figure 51 E-7 *Top, left-to-right*, Medial transverse view of the arm depicting the brachial artery and vein; anterior elbow views: medial sagittal plane of the coronoid fossa where a small amount of fluid may be normally seen between the fat pad *(star)* and the humerus (*arrow* = articular cartilage of distal humeral epiphysis); and transverse view depicting the pronator muscle, the brachial artery, and the median nerve *(arrow)* over the trochlea. *Bottom, left-to-right*, Lateral elbow planes depicting the lateral synovial fringe *(arrow)*, between the radial head and the lateral epicondyle, and the posterior interosseous nerve *(star);* posterior view of the elbow (partial flexion) depicting the olecranon fossa, the triceps muscle, and the posterior olecranon recess *(arrow)*.

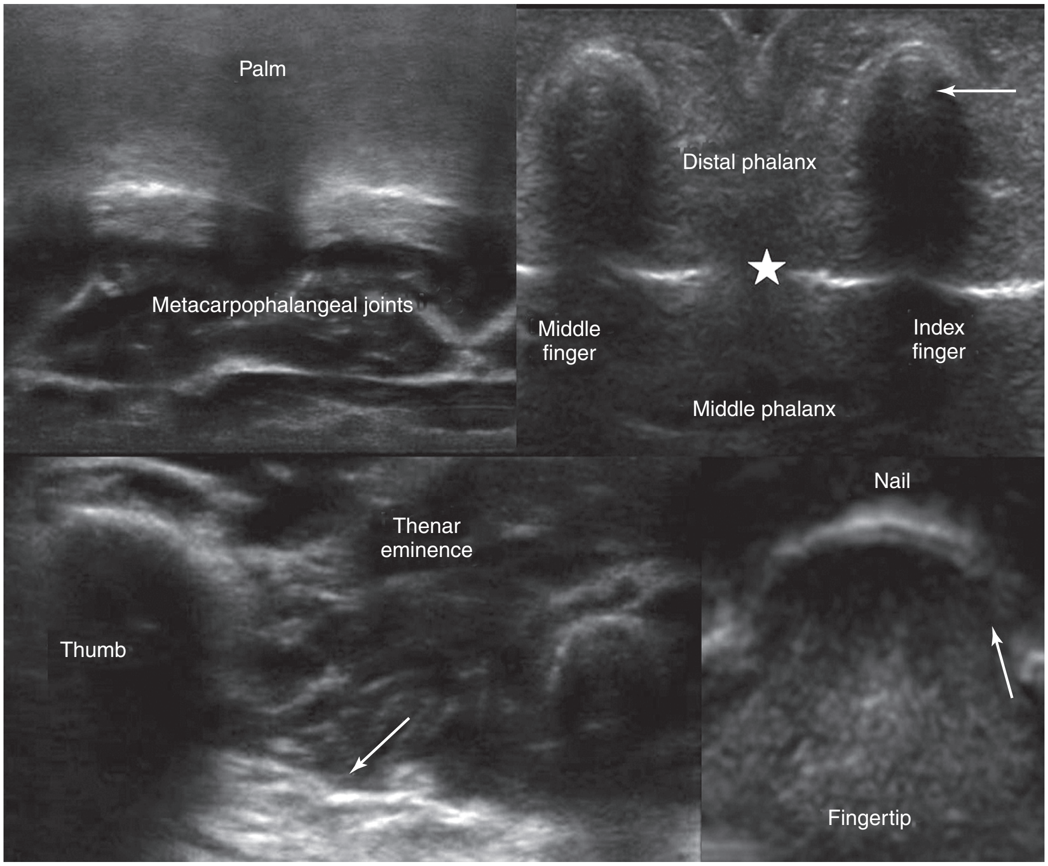

Figure 51 E-8 *Top, left-to-right,* Transverse dorsal view of the scapholunate ligament *(arrow);* medial wrist view of the ulnar artery *(UA)* and nerve *(arrow)* adjacent to the pisiform. *Bottom, left-to-right,* Distal radius fracture and de Quervain tenosynovitis.

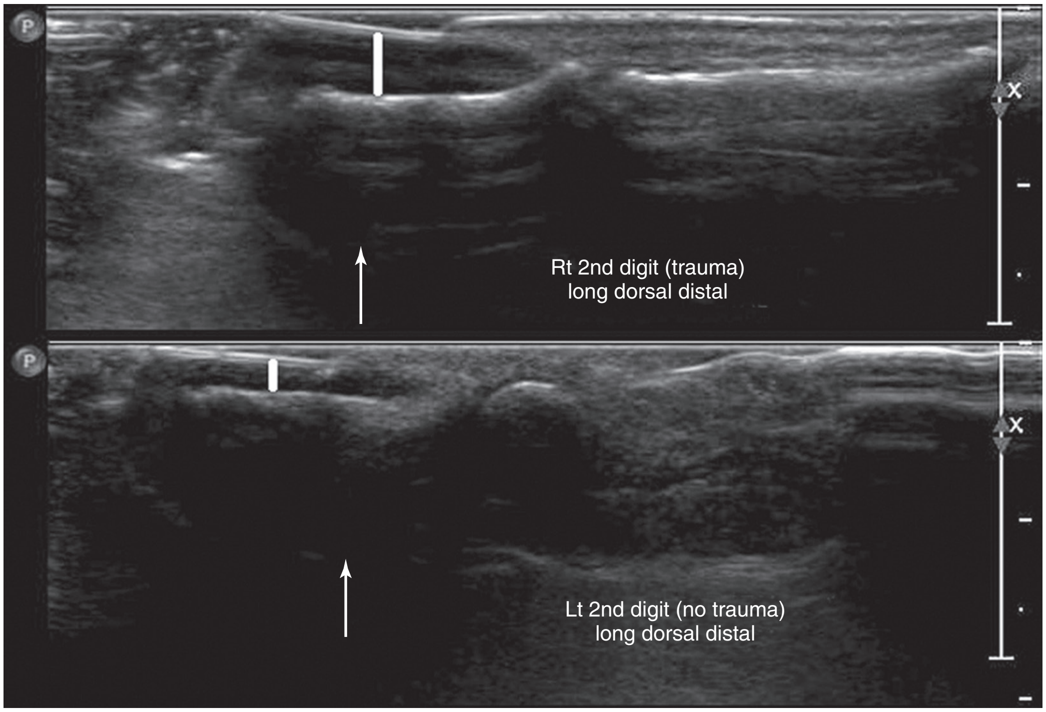

Figure 51 E-9 Suggested "fast" hand exploration by D. Karakitsos (the "*h-scan*"): *Top*, Transverse palmar view of metacarpophalangeal joints *(left);* transverse view of index and middle fingers (*arrow* = vincula tendinum and *star* 5 interphalangeal joints, *right). Bottom,* Oblique proximal palmar view of the thenar eminence (*arrow* = fascia, *left);* transverse inverted view of index finger's (*arrow* = eponychium) distal phalanx (fingertip) and nail ("sonographic fingerprint", *right*). Using these transverse planes as reference views, the operator can extend scanning accordingly to include longitudinal planes and detect thus even minor injuries (see Figure 53 E-5).

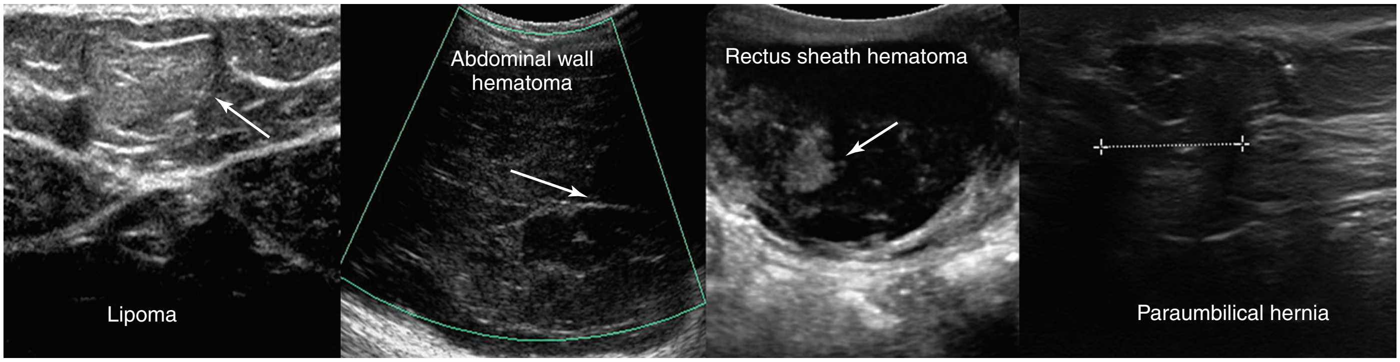

Figure 51 E-10 *Left to right,* Superficial lipoma *(arrow);* absence of flow in a superficial abdominal wall hematoma; depiction of a rectus sheath hematoma with mixed echogenicity pattern because of fibrin organization *(arrow);* longitudinal view of paraumbilical hernia containing omentum (12-mm defect).

Figure 51 E-11 Lower limb exploration: *(1)* Inguinal area and hip joint investigation that is extended distally using the knee *(2)* and ankle *(3)* joints as landmarks.

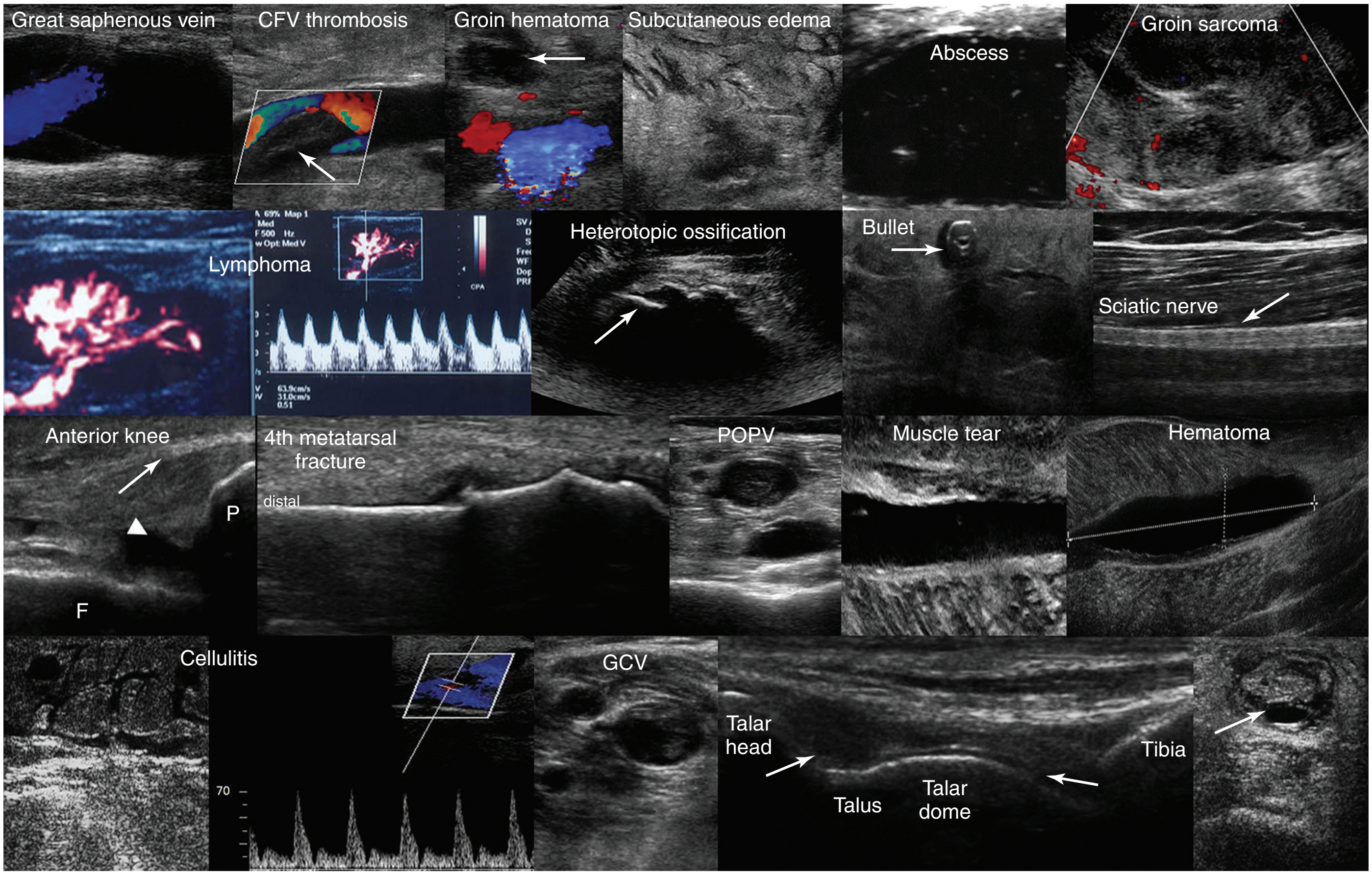

Figure 51 E-12 *Top, left-to-right,* Normal venous flow in the great saphenous vein; fresh thrombus in the common femoral vein; groin hematoma *(arrow)* over the common femoral artery and vein; cobblestone appearance of soft tissues (groin) resulting from generalized edema; hypoechoic cyst filled in with hyperechoic punctiform material (abscess); groin tumor of mixed echogenicity (sarcoma). *Second line, left-to-right,* Reactive groin lymph node; visualization of the "zone phenomenon" of heterotopic ossification: the inner hypoechoic core is surrounded by several hyperechoic mineralized islands *(arrow)* within the iliopsoas muscle; depiction of a bullet in the anterior thigh casting an acoustic shadow; posterior aspect of the thigh illustrating the sciatic nerve *(arrow)*. *Third line, left-to-right*, Longitudinal view of the anterior knee depicting the femur *(F)*, the patella *(P)*, the suprapatellar synovial recess *(arrowhead)* and the distal third of the quadriceps tendon *(arrow);* longitudinal image (dorsal approach) of the fourth metatarsal bone depicting a cortical discontinuity with step deformity and adjacent tissue damage and edema (fracture). The thickness of overlying soft tissue can be compared with the contralateral side to appreciate the degree of edema (note the domelike curvature of the dorsal fascia and the curved tendon above the fracture); visualization of a popliteal vein thrombosis; zoom image of a soleus muscle tear; liquefying hematoma in the gastrocnemius muscle. *Bottom line, left-to-right*, Cobblestone appearance of the subcutaneous tissue and unusually high flow in a local perforator (cellulitis); visualization of a gastrocnemial vein thrombosis; midlongitudinal plane over the dorsum of the ankle depicting the anterior recess of the tibiotalar joint *(arrows);* transverse view of a ruptured Achilles tendon. (Top line *image of groin hematoma courtesy Dr. K. Stefanidis; image of hyperechoic cyst courtesy Dr. J. Poularas; image of groin tumor courtesy Dr. K. Shanbhogue;* second line *image of bullet in anterior thigh courtesy of Dr. K. Shanbhogue.)*

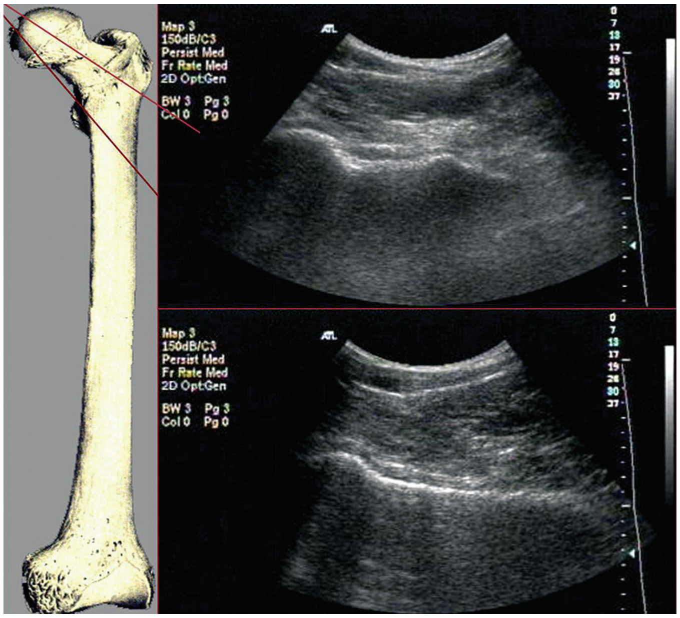

Figure 51 E-13 A low-frequency transducer (convex) is used to achieve a wide field of view and excellent penetration when scanning the hip joint. By rotating the transducer between 45 to 60 degrees and translate slightly forward, a longitudinal scan of the femoral neck can be obtained, and the femoral head can be identified. There is a range of possible transducer positions that covers the entire anterior aspect of the neck and should be explored if a fracture is suspected but not obvious. There are some irregularities of the normal femoral neck cortex that correspond with the tendinous insertions of the hip capsule. These may be confused with the cortical discontinuity of a hip neck fracture.

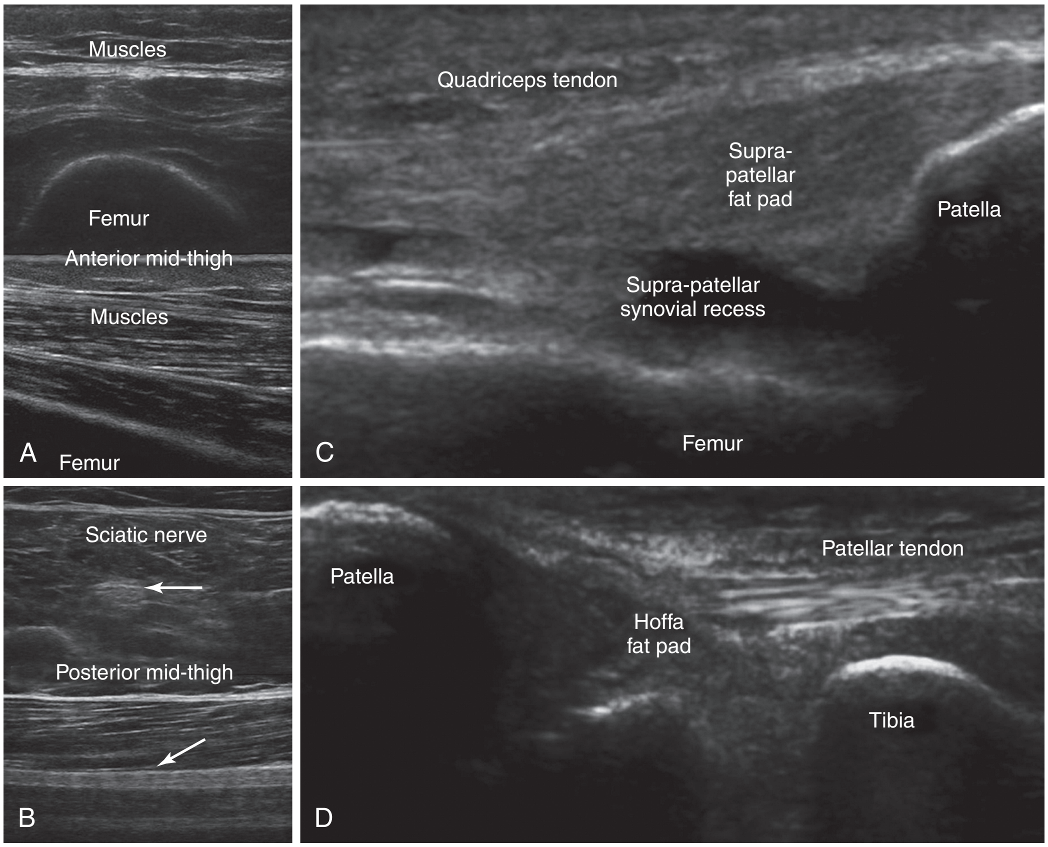

Figure 51 E-14 **A,** Transverse and longitudinal anteroposterior views of the thigh demonstrating the skin, subcutaneous tissue, muscles, and the underlying acoustic shadow of the femur. **B,** Transverse and longitudinal views of the sciatic nerve *(arrows)* coursing the posterior thigh; anterior knee views (longitudinal plane) depicting the femur, patella, suprapatellar synovial recess, and the distal third of the quadriceps tendon (proximal to the patella) **(C),** and as scanning is extended distally, permitting visualization of the patella, tibia, Hoffa fat pad, and the patellar tendon **(D).**

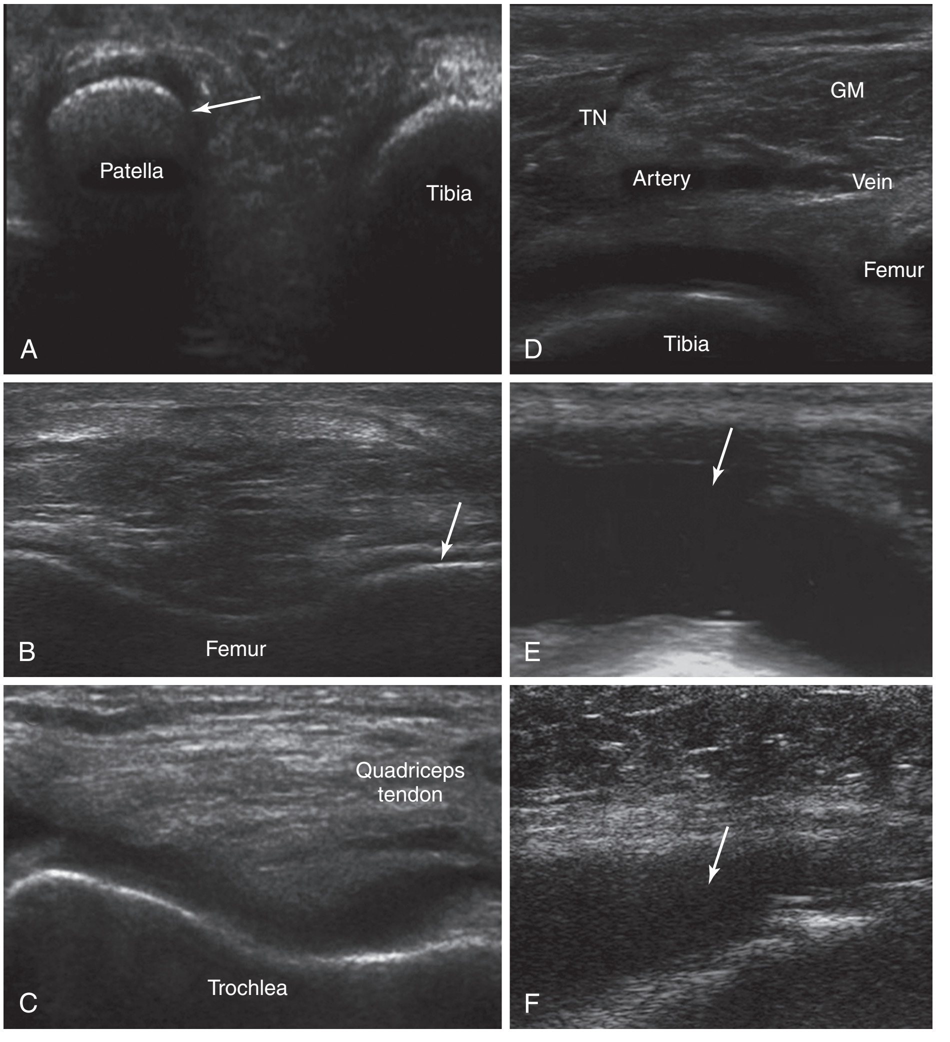

Figure 51 E-15 **A,** Medial knee (partially flexed) view demonstrating the medial facet of the patella *(arrow)*. **B,** Depiction of the hyaline cartilage at the right lateral condyle. **C,** Transverse view of the V-shaped trochlea (knee partially flexed). **D,** Transverse view of the popliteal fossa demonstrating the gastrocnemius muscle and the popliteal vessels adjacent to the tibial nerve *(TN)*, which appears rather blurred because of a recent guided nerve block. **E,** Posttraumatic knee joint effusion *(arrow)*. **F,** Septic knee arthritis *(arrow)*.

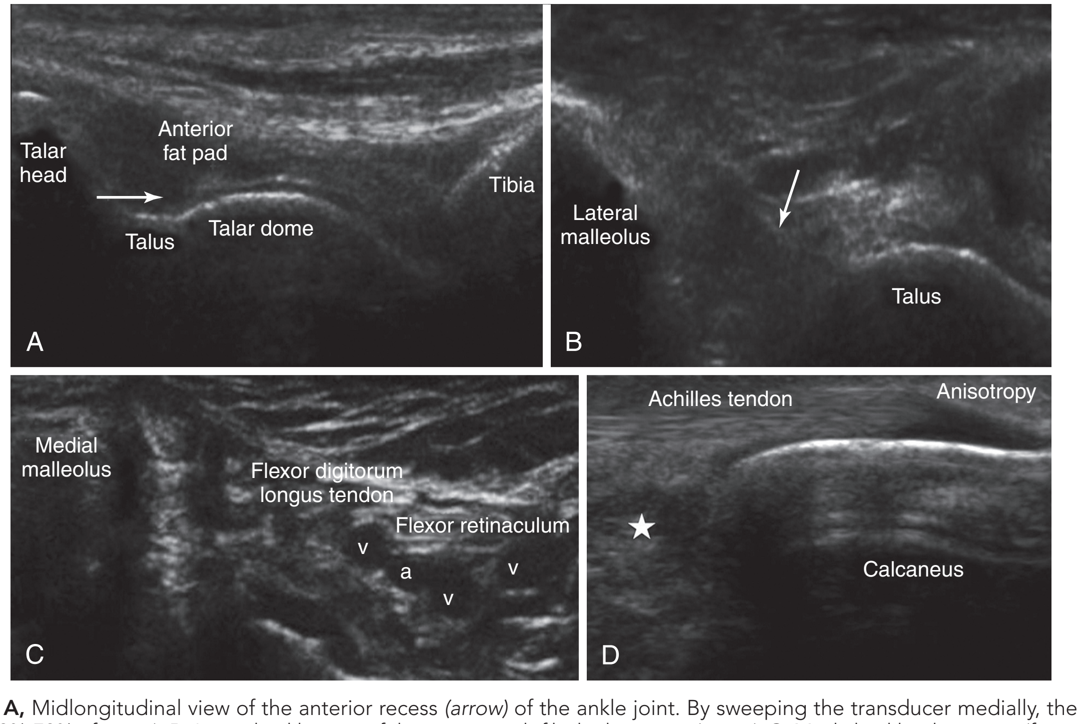

Figure 51 E-16 **A,** Midlongitudinal view of the anterior recess *(arrow)* of the ankle joint. By sweeping the transducer medially, the talar dome can be visualized (in 60%-70% of cases). **B,** Lateral ankle view of the anterior talofibular ligament *(arrow)*. **C,** Medial ankle plane view (foot rotated laterally) depicting the medial malleolus and the posterior tibial vessels (*a* = artery, *v* = vein). **D,** Longitudinal view of the calcanear insertion of the Achilles tendon overlying the Kager fat pad *(star)*.

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52

Ultrasound-Guided Percutaneous Tracheostomy

AHMED LABIB | ANDREW BODENHAM

Overview

Percutaneous tracheostomy (PT) is a common bedside procedure in the intensive care unit (ICU). Successful outcome requires midline needle puncture between the second and fourth tracheal rings and avoidance of posterior wall and vascular trauma.

Kearney et al[1] reported rates of perioperative morbidity of 6% and procedure-related mortality of 0.6%. Placement complications include hemorrhage, accidental extubation, pneumothorax, formation of a false passage, damage to tracheal rings, and perforation of the posterior tracheal wall. Delayed bleeding is typically seen a few days after PT and is due to either minor vessel damage or erosion into high or aberrant mediastinal vessels. The latter can be life-threatening and necessitates immediate surgical input. The most important late complications are tracheal stenosis, tracheomalacia, and vocal cord dysfunction, which could adversely affect the quality of life of ICU survivors.[1,2]

Point-of-care ultrasound (US) is increasingly being used for the management of critically ill patients. Despite wide application, US-guided percutaneous tracheostomy (USGPT) is not yet routine practice in many centers. Preprocedural, real-time US can reduce some of the complications just mentioned, morbidity, and possibly the occasional mortality associated with PT.[3-8] This chapter focuses on the role of US for PT, the sonographic anatomy of the anterior neck region, and the evidence available for USGPT.

Sonographic Anatomy of the Anterior Neck Region

Typically, a high-frequency (5- to 10-MHz), high-resolution, small-footprint, vascular-type linear probe is used for US scanning of the trachea and paratracheal area. Because air within the larynx and trachea has very high acoustic impedance, which results in high reflectance of the sound waves, US has limited ability to depict the inside of the air-filled airways and generates a characteristic acoustic shadow. Despite this shortfall, the superficial location of the larynx and trachea allows delineation and visualization of the anterior and lateral walls. Both the thyroid and cricoid cartilage are clearly visible as midline echogenic structures separated by the echolucent cricothyroid membrane with characteristic acoustic shadow underneath.[4,5] Below, the cartilaginous tracheal rings, which are characterized by a thin acoustic shadow, are easily visible along with pretracheal tissue and vessels.

In the longitudinal view, the thyroid, cricoid cartilage, and individual tracheal rings can be seen anterior to the hyperechogenic line formed by the air-tissue interface at the anterior tracheal wall. The longitudinal view allows identification of the intercartilaginous spaces and selection of the most appropriate needle puncture site, which can be performed in real time with a sterile probe cover. However, the need for a probe with a small physical footprint and the inability to visualize the posterior wall of the trachea and paratracheal structures may limit the usefulness of this approach (Figure 52-1A).[4,5]

The transverse view enables simultaneous visualization of nearby tissue and blood vessels, including the thyroid lobes, isthmus, and major vessels. PT through the thyroid isthmus is permitted as long as vulnerable vessels are avoided.[4,5] In a large proportion of PT procedures the thyroid isthmus is traversed, and this may be unavoidable.[4,5] The diameter and location of the anterior jugular veins (midline or near midline) can be delineated and vulnerable vessels can be electively ligated or avoided to reduce the risk for intratracheal bleeding (Figure 52-1B).[5]

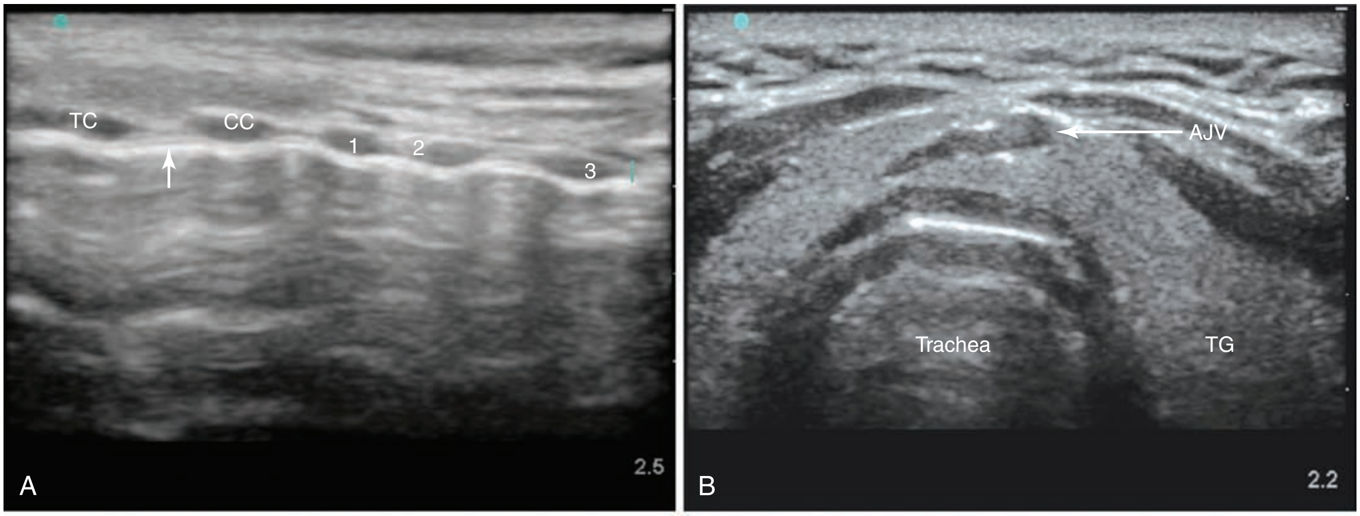
Life-threatening hemorrhage can arise from unintended damage to the carotid, brachiocephalic, and subclavian arteries. The immediate paratracheal carotid arteries are vulnerable to such injury from placement of the needle and dilator in a nonmidline position. A major advantage of US is the ability to depict and delineate abnormal anatomy (e.g., a high-riding brachiocephalic trunk) and aberrant vessels (Figure 52-1C), including thyroid arteries near the midline, for example, the thyroidea ima artery, which occurs in 3% to 10% of the population.

Real-time tracheal puncture is characterized by an acoustic shadow ahead of the advancing needle, displacement of pretracheal tissue, and indentation of the anterior wall of the trachea associated with a palpable change in resistance as the needle passes through the anterior tracheal wall. This technique may be particularly useful in patients with limited neck movement, a potentially unstable cervical spine, suboptimal anatomy, and morbid obesity.[9]

With the head in a neutral position, the thickness of the soft tissue between the skin and trachea can be measured, as well as the internal diameter of the trachea. Such measurements will help in making decisions regarding the need for an extended-length tracheostomy tube and appropriate size of tube. The need for longer tracheostomy tubes has been reported.[10] Postprocedural US examination of the chest is useful to check for pleural complications.[4]

Evidence for Ultrasound-Guided Percutaneous Tracheostomy

Most of the current literature on the use of US before or during PT is derived from small observational studies and case series. However, a substantial body of high-quality evidence



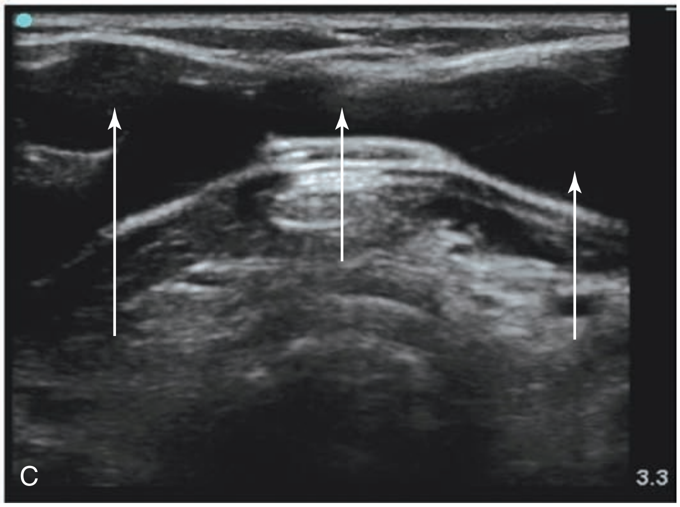


Figure 52-1 **A,** Longitudinal ultrasound (US) scan of the neck. The anterior tracheal wall is indicated by the *white arrow*. *CC*, Cricoid cartilage, first, second, and third tracheal cartilages; *TC*, thyroid cartilage. **B,** Transverse view of the trachea showing the joined anterior jugular veins (AJV). *TG*, Thyroid gland. **C,** Extensive venous plexus depicted on US examination (*white arrows*) in an elderly patient with severe tricuspid regurgitation.

recommends US guidance for various other diagnostic and therapeutic interventions, and it is likely that application of US before PT will become routine practice.

Kollig et al[6] reported a change in the planned tracheostomy site in 24% of patients after US scanning of the anterior neck region. In another study, significant bleeding occurred in 24 of 497 (5%) patients after PT, and in 6 of 24, PT was converted to a surgical procedure. The authors concluded that bleeding could have been avoided had US been performed before PT.[7]

The anterior jugular vein was vulnerable in 8 of 30 patients, and 4 had potentially vulnerable arteries requiring a change in puncture site, elective ligation of vulnerable vessels, and modification of the procedure.[5]

A postmortem report revealed cranial misplacement in a third of patients who underwent PT without US guidance, whereas satisfactory tube placement was confirmed in all patients who underwent US scanning before PT.[8] In a recent study, real-time US guidance facilitated safe and successful PT in 13 patients with head injury and allowed less frequent endoscopic guidance.[9]

Pearls and Highlights

- Routine US scanning of the anterior neck region before PT enables visualization and identification of airway structures and the midline of the trachea, selection of the most appropriate stoma site, and depiction of vulnerable blood vessels and associated structures. This information can help in formulating the most appropriate procedure for individual patients.
- Tracheal depth and diameter and the skin-to-trachea distance can be measured and the appropriate size and length of tube chosen.
- Real-time USGPT can increase the safety and accuracy of the procedure, particularly in patients with morbid obesity or suboptimal anatomy, and avoid some of the drawbacks associated with endoscopy.

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Ultrasound-Guided Regional Anesthesia in the Intensive Care Unit

BETTINA U. SCHMITZ | MARIA MATUSZCZAK | MARCO A. FONDI | SARA GUZMAN-REYES | LUDWIG H. LIN | SAMER NAROUZE

Overview

Peripheral regional anesthesia and neuraxial anesthesia are well established in postoperative pain management following major orthopedic, thoracic, and abdominal procedures. Benefits include pain control superior to that achieved with systemic opioids, improved lung function after thoracic and abdominal procedures, and decreased stress/inflammatory responses.[1-6] Ultrasound (US) guidance for regional anesthesia has been used increasingly over the last decade because it allows precise positioning of the catheter and local anesthetic (LA) and thus decreases the amount of LA required to achieve a complete block. In addition, the incidence of vascular puncture is lower with US guidance, thereby increasing the safety of the procedure. Fewer needles passes and replacement of nerve stimulation and subsequent muscle contraction with US visualization minimize procedural pain in patients.

Patients are frequently admitted to the intensive care unit (ICU) with neuraxial or peripheral regional anesthesia catheters placed in the operating room (OR) for postoperative pain management; less commonly, regional anesthesia is initiated in the ICU or implemented on ICU patients in the OR.

In critical care patients, pain can originate from multiple sites, and even though regional anesthesia will not eliminate the need for systemic opioids in most patients, inclusion of regional anesthesia in the pain management regimen can nonetheless result in a significant decrease in overall opioid and sedative requirements. Additionally, these advantages are attractive in the context of the recent paradigm shift toward less sedation in ICU patients.[7]

This chapter outlines the advantages of US-guided regional anesthesia techniques, the benefits of and indications for neuraxial and peripheral regional anesthesia for ICU and non-ICU patients, concerns associated with and contraindications to regional and neuraxial anesthesia, and a brief description of various US-guided regional anesthesia procedures (detailed descriptions of these procedures for adult and pediatric patients are available online).

Advantages of Ultrasound Guidance for Regional Anesthesia

Recent data suggest that US guidance improves the success rate and quality of regional anesthesia procedures.[8-11] It allows visualization of the neural and surrounding structures in the region of interest (ROI), and real-time US guidance can demonstrate and be used to optimize spread of LA. This is presumably why US-guided nerve block techniques shorten procedure time, hasten onset of the block, and result in fewer needle passes and a decreased incidence of vascular puncture.[12] Moreover, the volume (dose) of LA required to achieve a complete block is decreased under US guidance.[13,14]

The decreased incidence of accidental vascular puncture and the lower volumes needed to achieve an effective block can lessen the risk for LA toxicity. Additionally, US-guided regional anesthesia can replace functional (nerve stimulation) localization of the targeted neural structures, which can result in significant discomfort and pain in patients with injuries and fractures.

Conditions in which the ability to visualize target structures with US may be restricted include very deeply located neural structures, such as the lumbar plexus, and the presence of bones partially obscuring the neural structures, such as the epidural space.

Benefits of Ultrasound-Guided Regional Anesthesia in Patients in the Intensive Care Unit

US-guided regional anesthesia has a number of confirmed and potential benefits in critical care patients:

1. *Better pain control.* Multiple studies have documented the superior pain control in patients receiving epidural analgesia or paravertebral analgesia after rib fractures, thoracotomy, and major abdominal surgery. Superior pain control is also achieved by the implementation of regional anesthesia in patients undergoing surgery on the extremities.[4,6,15]

   In the ICU, trauma patients often have multiple injuries. Use of regional anesthesia techniques for all injuries at the same time might be not feasible in most trauma cases. Sequential regional anesthesia, according to the surgical interventions, can reduce baseline and procedural pain and the need for opioids in this population.[16] Bolus injections of LA instead of continuous infusion, as well as a lower concentration and volume of the LA solution, can reduce the overall amount of LA used per day and thereby enable performance of regional anesthesia in more than one location in the same patient.
2. *Lower requirement for systemic opioids and sedation.* Multiple studies have documented better outcomes and decreased levels of sedation in ICU patients. The American College of Critical Care Medicine addressed these results in practice guidelines published in 2013 in which lighter sedation was recommended for most ICU

patients.[7] However, decreasing the level of sedation in ICU patients without sacrificing good pain control can be challenging. Regional anesthesia provides excellent pain control without affecting the mental status of patients.

3. *Improved pulmonary function after thoracic or abdominal surgery and rib fractures.* Nishimori et al documented in a Cochrane review that epidural anesthesia improves pulmonary function and reduces the duration of mechanical ventilation in patients undergoing abdominal aortic surgery.[15]
4. *Possible decrease in the development of chronic pain through better management of acute pain.* Chronic pain as a sequela of severe undertreated acute pain is well described. However, data supporting the fact that regional anesthesia for the treatment of acute pain can reduce the incidence or severity of chronic pain are still scant. In a retrospective study, Salengros et al documented a higher incidence of allodynia and chronic pain in patients undergoing thoracotomy with high-dose remifentanil anesthesia than in those with epidural anesthesia and low-dose remifentanil.[17-19]
5. *Sympathicolysis.* Sympathicolysis is a well-described effect of regional anesthesia that can be beneficial for patients with impaired perfusion of the extremities because of vascular disease or trauma.[19]
6. *Possible impact on recurrence of cancer.* Surgical stress and opioids are known to suppress the immune system. Some retrospective studies have shown a lower recurrence rate of cancer in patients treated with regional anesthesia and propofol infusion than in those undergoing anesthesia with opioids and inhalational anesthetics. However, other studies could not confirm these statements, and prospective studies are in progress. Whether better postoperative pain control with regional anesthesia and less use of opioids postoperatively have an influence on tumor recurrence is not certain.[20,21]
7. *Impact of regional anesthesia on mortality and duration of hospital stay.* Currently, the overall evidence showing improved mortality and reduced duration of hospital stay after regional or neuraxial anesthesia is insufficient (Box 53-1).

BOX 53-1 BENEFITS OF REGIONAL ANESTHESIA

PROVEN BENEFITS

Better pain control than with systemic opioids for extremity surgery, thoracic and abdominal surgery, and rib fractures
Decreased requirements for postoperative systemic opioids
Improved pulmonary function after thoracic surgery, abdominal surgery, and rib fractures
Decreased stress response (thoracic epidural)
Sympathicolysis

POSSIBLE BENEFITS

Decreased requirement for opioids and sedatives in patients in the intensive care unit
Decreased severity and incidence of chronic pain syndromes
Decreased metastasis and recurrence rate in cancer patients

Concerns and Problems Related to Neuraxial and Peripheral Regional Anesthesia in Patients in the Intensive Care Unit

PATIENT-RELATED CONCERNS AND PROBLEMS

1. *Coagulopathy and systemic infection.* Coagulopathy and systemic and local infection are contraindications to regional anesthesia; moreover, these conditions are prevalent in ICU patients. The American Society of Regional Anesthesia (ASRA) guidelines regarding patients receiving antithrombotic or thrombolytic therapy should be followed. When regional anesthesia procedures are performed in patients with borderline coagulation status, more peripheral approaches (axillary, femoral, fascia iliaca compartment, and popliteal sciatic) should be considered. However, finding a window of appropriate coagulation to safely remove indwelling catheters can be challenging.[22]
2. *Regional anesthesia under deep sedation or anesthesia.* Decreasing sedation to facilitate communication with patients during regional anesthesia procedures is not always possible. Deep sedation or anesthesia abolishes the ability of the patient to report symptoms pertinent to LA toxicity or nerve damage. Accordingly, the ASRA recommendations (2008) do not support the routine performance of neuraxial or interscalene blocks in anesthetized or heavily sedated patients. However, the group acknowledged that the risk-benefit ratio can be favorable for regional anesthesia under the aforementioned conditions in selected cases. Neuraxial and peripheral regional anesthesia in pediatric patients under heavy sedation or anesthesia is considered more applicable, mainly because of the inability of pediatric patients to communicate symptoms of toxicity or nerve injury and the potential harm associated with patient movement.

   Systemic LA toxicity and nerve damage have been reported even after US-guided peripheral nerve blocks. Meticulous needle control, observation of LA spread, verification of the position of the tip of the catheter with hydrodissection, avoidance of intraneural injection or catheter placement, use of a test dose, and slow injection of LA in small increments can reduce risk for the aforementioned complications.[23]
3. *Risk for compartment syndrome.* Compartment syndrome is a complication of extremity trauma. Regional anesthesia itself does not increase the risk for compartment syndrome, but it could mask the associated pain and delay detection. Thus, the lowest effective concentration of LA solution should be infused. Whether this consideration is relevant for an intubated and sedated ICU patient can be questioned. However, because compartment syndrome is a limb-threatening complication, regional anesthesia in patients with high-risk injuries such as tibial and distal radial fractures should be discussed with the orthopedic surgeon, and measurement of compartment pressure should be considered.[24,25]
4. *Positioning.* Positioning of traumatized patients for regional anesthesia can be challenging.

ORGANIZATION-RELATED CONCERNS AND PROBLEMS

1. *Training.* ICU personnel caring for patients with neuraxial or peripheral regional anesthesia catheters in place need to be adequately educated regarding regional anesthesia and its benefits, possible adverse effects, and complications.
2. *Implementation of care protocols.* Detailed protocols for the care and follow-up of patients who receive neuraxial or peripheral regional anesthesia should be implemented.
3. *Color marking of different access lines.* Adding another line to the already numerous lines inserted and attached to patients in the ICU increases the risk for misidentification of neuraxial/regional infusion and intravenous infusion lines. Judicious color marking of the different lines and their connections can reduce this risk.
4. *Infection.* The risk for infection with an indwelling catheter is higher in ICU patients. The insertion site of the neuraxial or regional anesthesia catheter should be inspected at least once daily for signs of infection and the findings documented.
5. *Catheter dislocation.* Accidental dislocation or removal of neuraxial or regional anesthesia catheters during mobilization and transportation is a potential problem. The integrity of all indwelling catheters should be checked routinely after mobilization and transport of patients.
6. *The future of LA catheters.* Extended-release LA formulations might decrease the need for insertion of catheters for continuous LA infusion in the near future.

Table 53-1 lists common indications for neuraxial and peripheral regional anesthesia, whereas Box 53-2 outlines barriers and contraindications to US-guided regional anesthesia in critical care patients.

BOX 53-2 BARRIERS AND CONTRAINDICATIONS TO ULTRASOUND-GUIDED REGIONAL ANESTHESIA IN THE INTENSIVE CARE UNIT

PATIENT RELATED

Infection (local or systemic)
Coagulopathy
Antithrombotic, fibrinolytic therapy
Sedation status
Multiple injuries
Positioning problems for a regional anesthesia procedure

SYSTEM RELATED

Lack of knowledge regarding the benefits of regional anesthesia
Lack of knowledge/inexperience regarding side effects and complications of regional anesthesia
Catheter-related problems: infection, dislocation, confusion
Lack of protocols for patients with regional anesthesia

Timing of Regional Anesthesia

Regional anesthesia procedures are most commonly performed perioperatively in the OR suite, and patients are subsequently admitted or readmitted to the ICU for further management. However, such procedures can just as well be performed in the ICU, depending on the individual circumstances and condition of patients.

In either location, equipment for airway management and resuscitation and for intralipid infusion, as well as a local anesthesia toxicity checklist, should be available at the bedside of patients. All blocks should be performed with standard American Society of Anesthesiology monitoring in place and patients supervised by trained personnel after injection of the LA.

TABLE 53-1 Indications for Neuraxial and Peripheral Regional Anesthesia in ICU and non-ICU patients

Indication	Non-ICU patient	ICU Patient
Upper extremity analgesia	Joint replacements (shoulder, elbow, hand) Fractures Tendon and muscle repair Vascular surgery Arteriovenous grafts Reimplantation of the finger, hand, and arm	Joint replacements (shoulder, elbow, hand) Fractures Tendon and muscle repair Vascular surgery Arteriovenous grafts Reimplantation of the finger, hand, and arm
Upper extremity sympathicolysis	Ischemia Reimplantation Vascular surgery	Ischemia Reimplantation Vascular surgery
Lower extremity analgesia	Joint replacements (hip, knee, ankle) Fractures Tendon and muscle repair Vascular surgery	Joint replacements (hip, knee, ankle) Fractures Tendon and muscle repair Vascular surgery
Lower extremity sympathicolysis	Ischemia Vascular surgery	Ischemia Vascular surgery
Trunk	Thoracotomy/thoracoscopy Rib fractures Abdominal wall incision	Thoracotomy/thoracoscopy Rib fractures Abdominal wall incision
Neuro-axial	Rib fractures Thoracic surgery Abdominal surgery	Rib fractures Thoracic surgery Abdominal surgery Ileus Pancreatitis

ICU, Intensive care unit.

Ultrasound Technique for Regional Anesthesia

ULTRASOUND SCAN

According to the HOLA concept of US scanning, a preprocedural scan facilitates the visualization of anatomic structures in an ROI, such as nerves, vessels, bones, muscles, and fascia layers (see Chapters 1 and 51). Nerves have a fascicular hyperechoic appearance and are obviously the primary targets during guided nerve blocks. Transverse and longitudinal US views can identify the nerve and confirm spread of the LA along single nerves. Transverse views are less technically complex and used mainly during real-time LA injection. Two-dimensional scanning can be extended (proximally and distally) to identify the location and track the course of neural structures. Such tracking may optimize identification of the target nerve by visualization of adjacent anatomic structures or landmarks (e.g., musculoskeletal, vascular) and their two-dimensional alignment in relation to the former in an ROI.[12]

ULTRASOUND-GUIDED NEEDLE TECHNIQUES

In-plane and out-of-plane techniques are used for US-guided regional anesthesia procedures. An out-of-plane approach does not allow real-time visualization of the penetrating needle but is technically less complex than in-plane techniques, which enhance perpetual visualization of the needle. Our group favors the latter approach because it is a real-time technique that enables control of the needle's trajectory and tip. Another technique is hydrodissection, which refers to the injection of small volumes of normal saline as the needle advances through various tissues. Hydrodissection may aid in identifying the needle or tip of the catheter. It is used routinely in US-guided pediatric regional anesthesia procedures.

A circumferential or crescent-like spread of LA around the nerve is favored for most blocks. This can be accomplished by real-time observation of the spread and fine adjustments of the tip of the needle to achieve it. Nerve stimulation may enable nerves to be identified, especially at sites in which US detection is difficult. However, nerve stimulation may also fail to identify the target nerve even in US-guided procedures in which correct positioning of the tip of the needle has been confirmed (e.g., sciatic nerve blocks). All nerves blocks described in this chapter can be performed as single-shot or continuous blocks with catheter placement, although continuous techniques are preferred in patients in the ICU.

INSTRUMENTATION

High-frequency transducers are used for superficially located neural structures and low-frequency transducers for deeper structures (see Chapters 1 and 53). Enhanced needle visualization software, echogenic material (needles, catheters), or needle guidance systems may be used for optimization of the procedure.

Regional Anesthesia of the Upper Extremity

Anesthesia of the brachial plexus can be performed in the interscalene groove (interscalene approach), directly above the clavicle (supraclavicular approach), under the clavicle (infraclavicular approach), and in the axilla (axillary approach). *The different approaches are not equally suitable for ICU patients.* An interscalene brachial plexus block provides good analgesia for the shoulder, arm, and forearm, but the phrenic nerve is usually blocked as well, which results in paralysis of the ipsilateral diaphragm (Figure 53-1). This effect can aggravate respiratory problems and lead to respiratory failure in compromised, spontaneously breathing patients. Severe complications (i.e., injection of LA into the spinal cord) have been reported after interscalene blocks performed under deep sedation or general anesthesia, and the ASRA guidelines strongly recommend against performing this block under these conditions.[22] Hematoma formation in this area can lead to airway compromise and compression of the neck vessels. Paralysis of the ipsilateral diaphragm is less common with the supraclavicular approach. The supraclavicular approach offers good analgesia to the entire arm, forearm, and hand (Figure 53-2). US-guided techniques can reduce the risk for pneumothorax by meticulous control of passage of the needle and observation of the anatomic structures: artery, rib, and pleura. However, US-guided techniques cannot entirely prevent the typical complications of these two blocks (i.e., pneumothorax, intraneural injection).[27-30] With both approaches (interscalene and supraclavicular), the plexus is close to the skin, and dislocation of a regional anesthesia catheter occurs easily with movement. Tunneling of the catheter can reduce this risk.

The infraclavicular approach provides good analgesia to the lower part of the upper arm, elbow forearm, and hand. In this area the brachial plexus is more distant from the skin than with the other approaches (Figure 53-3 A,B). The needle passes in a relatively steep angle under the US probe, which makes visualization of the needle more difficult, but the use of echogenic needles or needle guidance systems is effective in minimizing this challenge. Apart from this technical issue, the infraclavicular approach is excellent for ICU patients because it provides good analgesia and catheter dislocation is less likely than with the aforementioned approaches.

The axillary approach provides the most peripheral access to the brachial plexus, and it results in good analgesia to the elbow, forearm, and hand. With this approach the plexus is located just under the skin, and the surrounding vessels can easily be compressed and thus be subject to accidental vascular puncture. Despite this technical challenge, the axillary approach is an excellent option for ICU patients (Figures 53-3 C,D). Technical details regarding the aforementioned blocks in adult and pediatric patients are presented later.

The brachial plexus innervates the shoulder and the entire arm. It is formed by the anterior rami of nerves exiting the spinal cord (C5-T1 with contributions from the C4 and T2 roots). The usual indications for performing brachial plexus blocks are surgical anesthesia, postoperative analgesia (catheter techniques) and sympathetic blockade for various chronic types of pain, and vascular insufficiency syndromes.

TIPS FOR PEDIATRIC PATIENTS

In pediatric patients, sonographic detection of the superficially located brachial plexus is relatively easy. However, their musculoskeletal anatomy is less well defined, and thus US images should be interpreted carefully. Real-time visual control of the tip of the needle is crucial to avoid accidental puncture of vessels, pleura, or the spinal cord. Needle trajectory should be

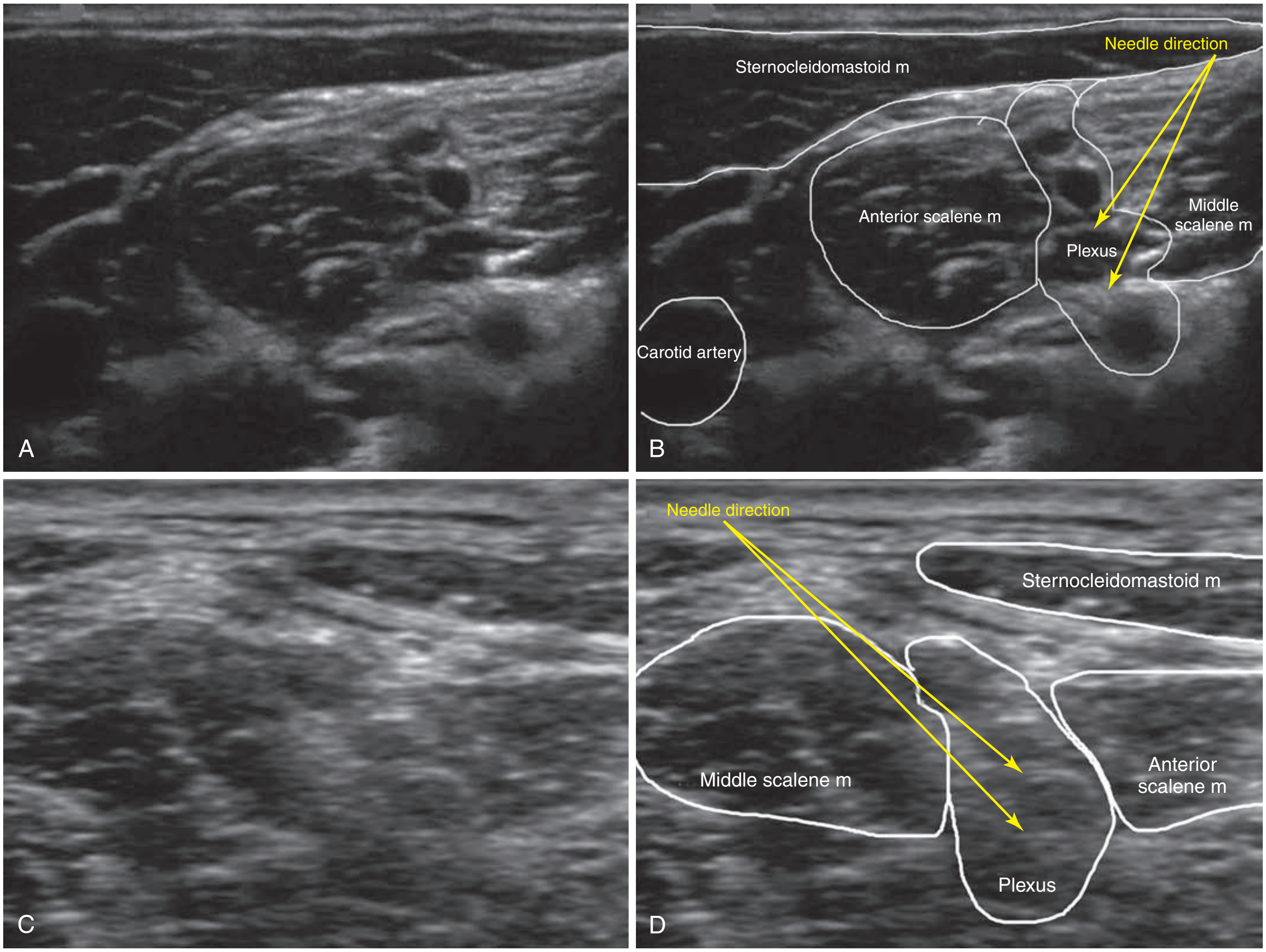

Figure 53-1 Brachial plexus block via an interscalene approach.

adjusted according to the distance needed to reach the brachial plexus (volumes of LA used are 0.2 to 0.4 mL/kg, depending on the concentration and spread needed).

INTERSCALENE BRACHIAL PLEXUS BLOCK

The classic interscalene approach is performed at the level of the cricoid cartilage, in the groove between the anterior and middle scalene muscles, and it provides excellent anesthesia of the shoulder and arm. The transducer is placed lateral to the cricoid cartilage (transverse plane), along the sternocleidomastoid muscle toward the interscalene groove. At this level the plexus is visualized as either roots or trunks with three or more hypoechoic structures in a "traffic light configuration" between the scalene muscles and under the end of the tapering sternocleidomastoid muscle, no deeper than 1 inch under the skin. Anatomic variations may be observed in individual cases.[10]

A 50-mm needle is advanced in plane in a posterior-to-anterior direction; a small roll placed under the shoulder and thorax facilitates this approach. An out-of-plane approach with the tip of the needle aimed cranially is not advisable because of the possibility of malposition of the needle and delivery of LA into the spinal canal. With the tip of the needle positioned in the center of the plexus (between the C5/6, C6/7, or C7/8 roots or the superior and middle trunks), an LA volume of 10 to 20 mL is usually injected after negative aspiration. Because the lower roots or trunk of the brachial plexus may be spared with the interscalene technique, an approach at or below the clavicle is generally recommended for anesthesia or analgesia in the distribution of the ulnar nerve. Though not always predictable in individual patients, lower LA volumes may reduce the incidence of the typical adverse effects associated with the interscalene approach: Horner syndrome, recurrent laryngeal nerve paresis, and phrenic nerve paralysis (Figure 53-1).[14]

Tips for Pediatric Patients

Pediatric patients are rarely seen with shoulder injuries, and although the approach is similar, this type of block is seldom performed in small children. Because the distance between the interscalene and the supraclavicular approach in a small child can be less than half an inch, LA volumes of 0.2 to 0.3 mL/kg or a maximum of 10 to 20 mL for children over 40 kg may provide sufficient anesthesia of the shoulder and entire arm irrespective of the approach used.

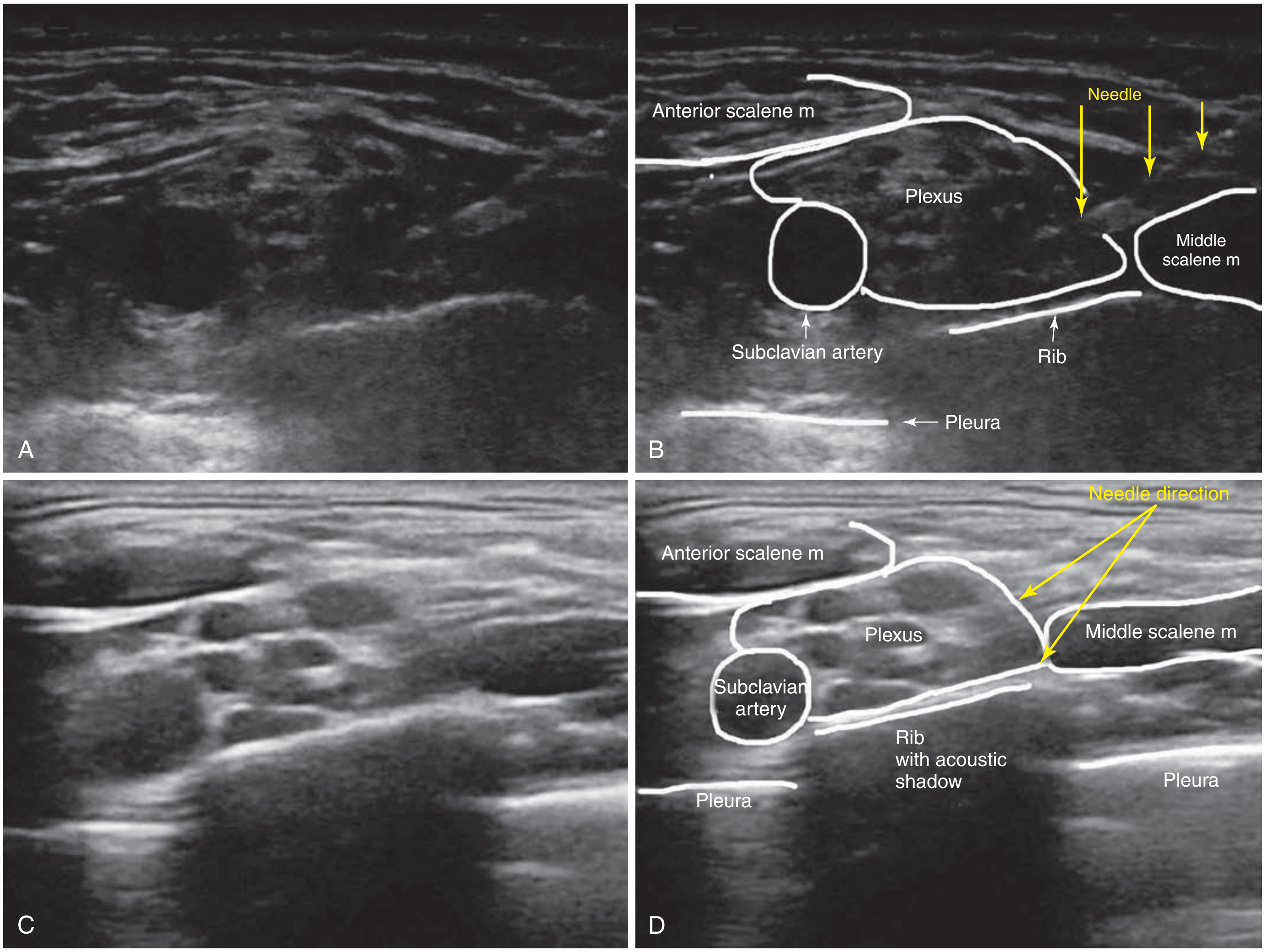

Figure 53-2 Brachial plexus block via a supraclavicular approach.

SUPRACLAVICULAR BRACHIAL PLEXUS BLOCK

The supraclavicular approach has experienced a renaissance since the introduction of US-guided techniques. In the supraclavicular area the plexus nerves are organized in trunks or divisions and can be visualized as a cluster of hypoechoic structures in a corner posterolateral to the subclavian artery, just above the first rib. The subclavian artery, the first rib, and the pleural line should be identified to perform this block safely. A 50-mm needle can be advanced in either a lateromedial or mediolateral direction. The needle is advanced in plane in the corner between the subclavian artery and the first rib. An LA volume between 15 and 25 mL is generally injected. The same adverse effects of an interscalene block can occur with the supraclavicular approach, but the incidence rate is significantly lower (Figure 53-2).

Tips for Pediatric Patients

In small children the brachial plexus at the supraclavicular level lies immediately under the skin, and thus the smallest available needles should be used (LA volumes are adjusted to 0.1 to 0.2 mL/kg). A block at this level provides excellent anesthesia for the entire arm.

INFRACLAVICULAR BRACHIAL PLEXUS BLOCK

An infraclavicular block provides anesthesia and analgesia below the midhumerus region. In the infraclavicular area the plexus is organized in hyperechoic cords around the axillary artery, usually with the lateral cord at the 8- to 10-o'clock position, the posterior cord (under the artery) at the 6-o'clock position, and the medial cord at the 2- to 3-o'clock position. Because the brachial plexus lies under both pectoral muscles, the infraclavicular approach is rather deeper (from the skin surface) than the other two previously discussed approaches (Figure 53-3 A,B).

The transducer is placed in a parasagittal plane to the coracoid process under the clavicle. The pectoral muscles, axillary artery and vein, and the cords (if seen) are identified. An 80-mm needle is inserted in plane below the inferior clavicular border. The tip of the needle is advanced under the artery toward the location of the posterior cord, and an LA volume of 20 to 30 mL is typically injected.[31]

Tips for Pediatric Patients

This approach is ideal for US-guided placement of a catheter for continuous regional analgesia of the arm below the shoulder. The tip of an introducer needle is positioned adjacent to

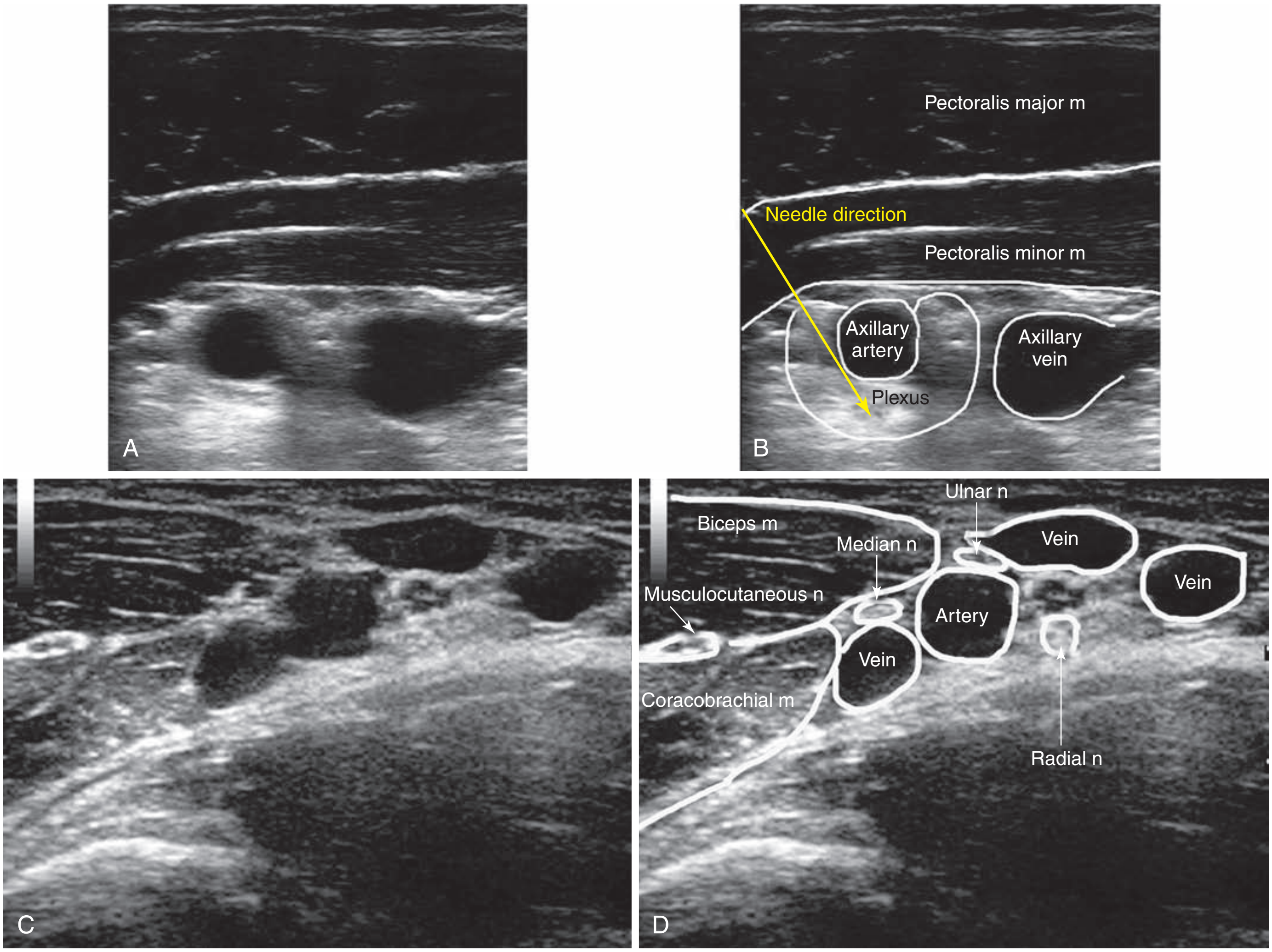

Figure 53-3 Infraclavicular (*top row*) and axillary (*bottom row*) approaches to a brachial plexus block.

the posterior cord; hydrodissection will facilitate the appropriate placement of the catheter. Spread of LA adjacent to the artery may enhance the analgesic effect.

AXILLARY BRACHIAL PLEXUS BLOCK

The axillary approach provides sufficient anesthesia and analgesia for the elbow and the entire lower part of the arm. The US-guided technique provides better block qualities than do the traditional transarterial or nerve stimulator–guided approaches. Specifically, the musculocutaneous nerve, often missed with the traditional approaches, can readily be visualized and anesthetized under US guidance. With the arm abducted, externally rotated, and flexed 90 degrees at the elbow, the transducer is placed in a sagittal/oblique plane across the axilla. The axillary artery is usually visible at a depth of 1 to 2 cm. The hyperechoic nerves are located around the artery and can be identified in the majority of patients: the median nerve at 10 o'clock; the ulnar nerve between 1 and 3 o'clock; and the radial nerve, posterior to the artery, between 3 and 6 o'clock.[28] The musculocutaneous nerve is located between the biceps and coracobrachial muscles. A 50-mm needle is inserted in plane, with the axillary artery used as a landmark in the ROI. The musculocutaneous nerve can then be approached anterior to the artery, the median nerve adjacent to the artery, and the radial nerve posterior to the artery in a continuous procedure by making sequential adjustments in the trajectory of the needle. The ulnar nerve can be injected above or below the artery. An LA volume of 5 to 7 mL is sufficient for each nerve. Alternatively, a volume of 10 to 12 mL can be injected both above and below the artery in an effort to achieve a circumferential LA spread pattern around the vessel (Figure 53-3 C,D).

Tips for Pediatric Patients

In children the axillary approach of the brachial plexus has the shortest learning curve because sonographic detection of the neurovascular bundle is easy. The transducer is positioned perpendicular to the axillary artery with the arm in abduction. The needle is then advanced in plane and redirected accordingly to access each target nerve as previously described, with 1 to 2 mL of LA being delivered at each location.

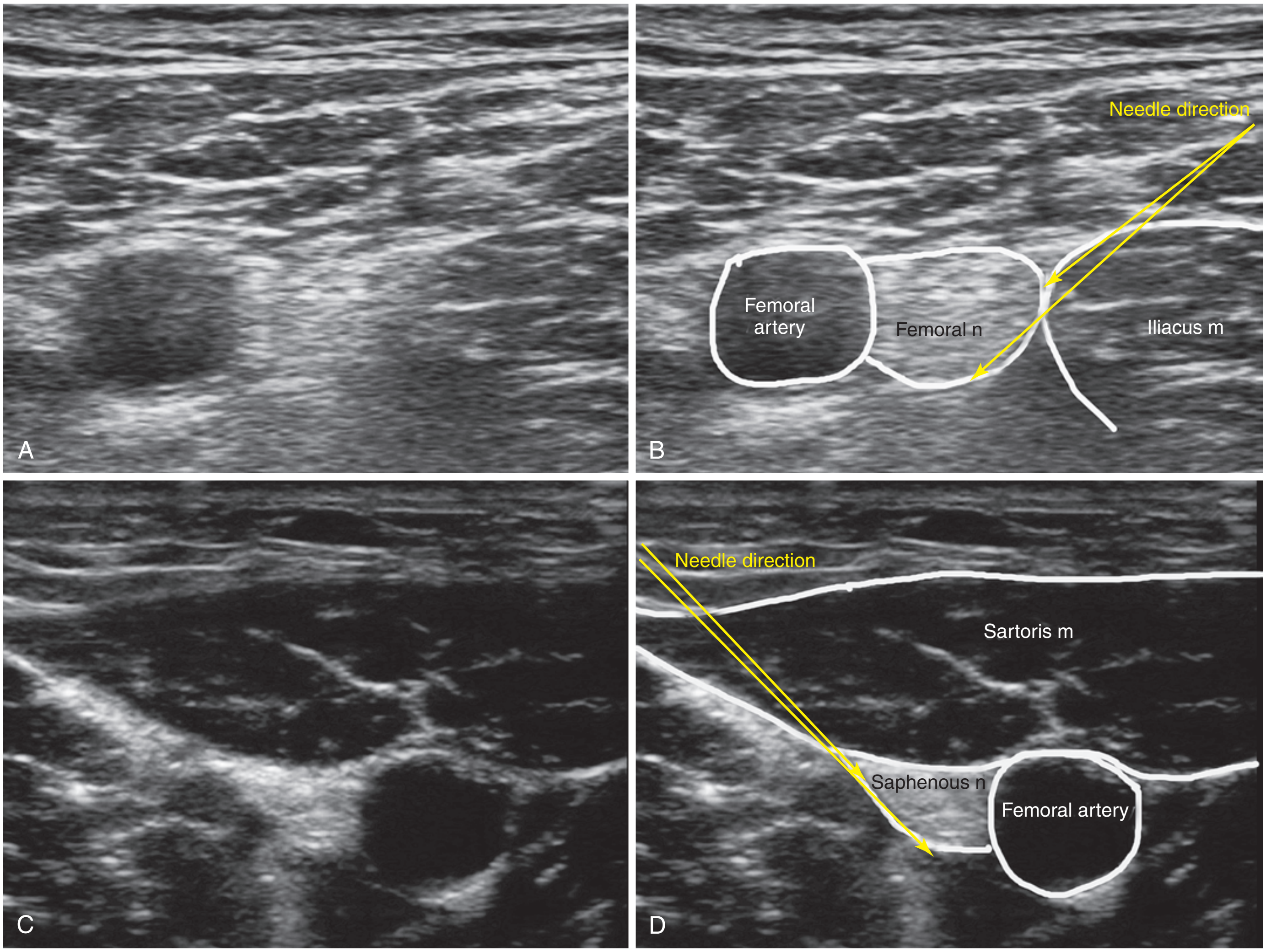

Figure 53-4 Femoral (*top row*) and saphenous nerve (*bottom row*).

Regional Anesthesia of the Lower Extremity

The lumbosacral plexus is formed by the anterior divisions of the lumbar, sacral, and coccygeal nerves and provides innervation to the lower limbs. The femoral artery is the landmark structure for identification of the femoral nerve (FN) in the groin by means of sonography. An FN block provides good pain reduction in the hip joint, thigh, and knee. Notably, a fascia iliaca compartment block can provide additional analgesia to the lateral cutaneous FN. Both blocks do not require complicated positioning and are easily performed in ICU patients. Lateral needle insertion and tunneling of the catheter may reduce infectious complications (Figure 53-4 A,B).

The sciatic nerve (ScN) provides innervation to the lower part of the leg and foot; analgesia of the entire lower extremity can be achieved when combined with a femoral or fascia iliaca compartment block.

The lateral popliteal approach can be performed with the patient in a supine position by elevating the lower part of the leg so that the US probe can be positioned on the posterior aspect of the thigh. The infragluteal approach is usually performed with lateral positioning. Catheters can easily be inserted in both locations. Technical details of the aforementioned blocks are included later (Figure 53-5 and 53-6).

FEMORAL NERVE BLOCK/FASCIA ILIACA COMPARTMENT BLOCK

Femoral Nerve Block

An FN block provides anesthesia to the anterior aspect of the thigh and knee. It is used for postoperative pain management after total knee arthroplasty and other surgical knee procedures. The FN is located under the fascia iliaca lateral to the femoral artery and medial to the iliacus muscle in the inguinal crease. A high-frequency transducer is placed on the inguinal crease to identify the femoral vein, artery, and nerve (in a medial-to-lateral order); the iliacus muscle, fascia lata (above the femoral artery), and fascia iliaca (separating the artery from the nerve) are also visualized. An 80- to 100-mm needle is inserted in plane 1 to 2 cm lateral to the transducer. The needle perforates the fascia lata and then the fascia iliaca and is advanced to the lateral

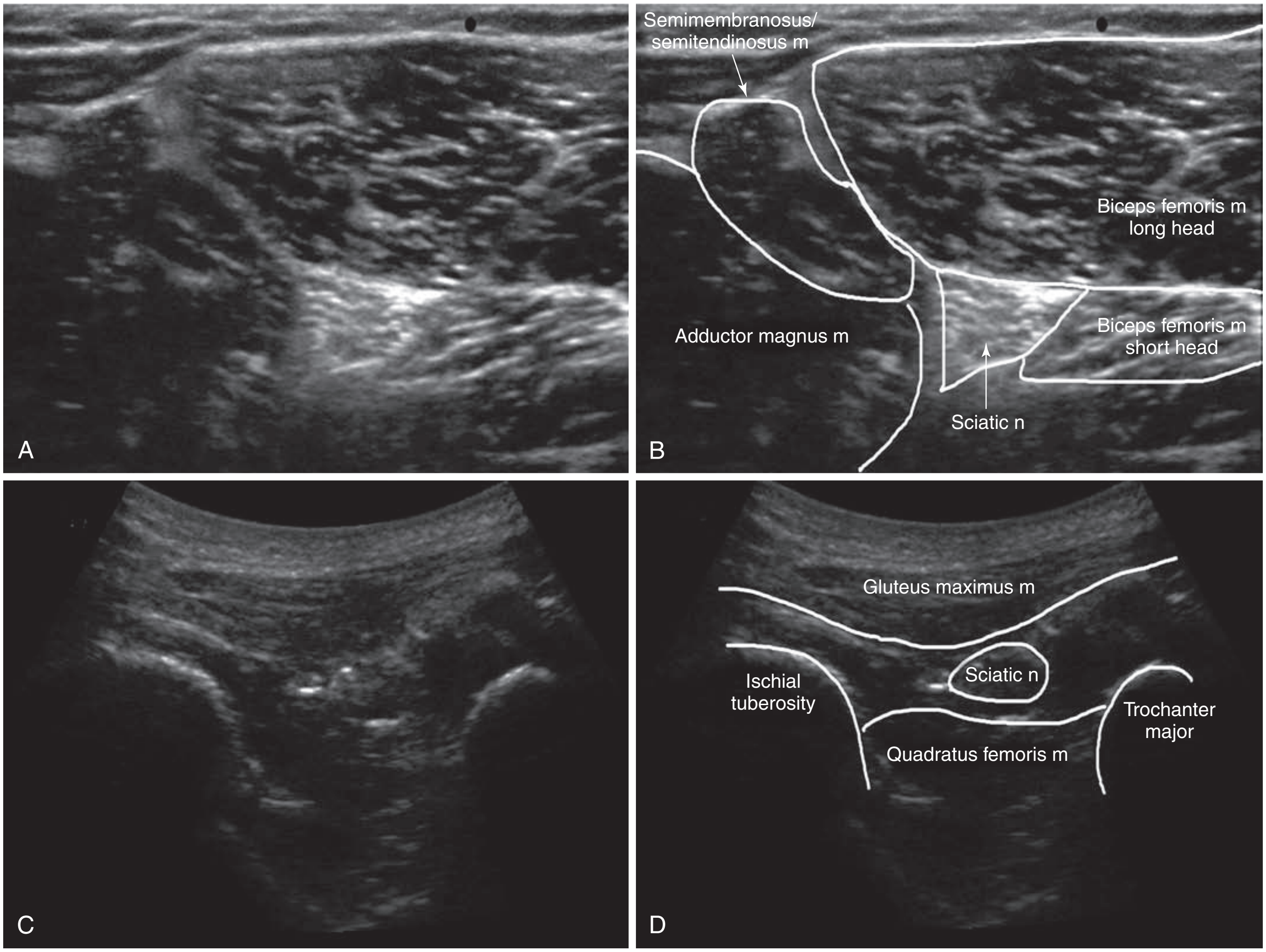

Figure 53-5 Sciatic nerve block: midthigh (*top row*) and subgluteal (*bottom row*) approaches.

FN border or just below the nerve, and an LA volume of 10 to 20 mL is usually injected. Spread of LA above the fascia iliaca results in incomplete anesthesia/analgesia (Figure 53-4 A,B).[26]

Tips for Pediatric Patients. The technique just described is used accordingly in children because this location is ideal for placement of a catheter. The tip of the catheter is best placed posterior to the FN to avoid spread of LA anterior to the fascia iliaca.

Fascia Iliaca Compartment Block

This diffusion block provides anesthesia in the distribution of the FN and lateral cutaneous FN. It is performed with the patient in a supine position and provides excellent results either in the emergency department or in the perioperative setting for patients with hip or femoral fractures and after knee surgery.[33] The US technique is similar to the FN block technique just described; however, the needle is inserted more lateral to the transducer (in comparison to the FN insertion point), and a higher LA volume of 30 to 40 mL is injected within or right below the fascia iliaca. Thus, a block of both the FN and lateral cutaneous FN can be achieved.

Tips for Pediatric Patients. Although in children the fascia iliaca block can indeed be performed successfully with traditional techniques, the US technique can be applied equally. This is a diffusion block and higher LA volumes of 0.5 mL/kg are needed.

SAPHENOUS NERVE BLOCK

The saphenous nerve (SN) is the major sensory branch of the FN. When used in conjunction with an ScN block, it provides anesthesia of the entire leg below the knee. In the midthigh region, the SN is located adjacent to the femoral artery under the sartorius muscle ("adductor canal"). A high-frequency transducer is placed 10 to 15 cm above the knee in a transverse orientation. The SN is not visible in all cases and adjacent structures can be used as landmarks. The femoral artery is visualized deep under the sartorius muscle, which in turn can be detected sonographically as a triangularly shaped muscle just medially to the quadriceps muscle. A 100-mm needle is inserted in plane 1 to 2 cm anterior to the transducer. The tip of the needle is positioned under the sartorius muscle, adjacent to the artery in the fascial plane, and an LA volume of 5 to 10 mL is injected after negative aspiration. As the femoral artery travels distally,

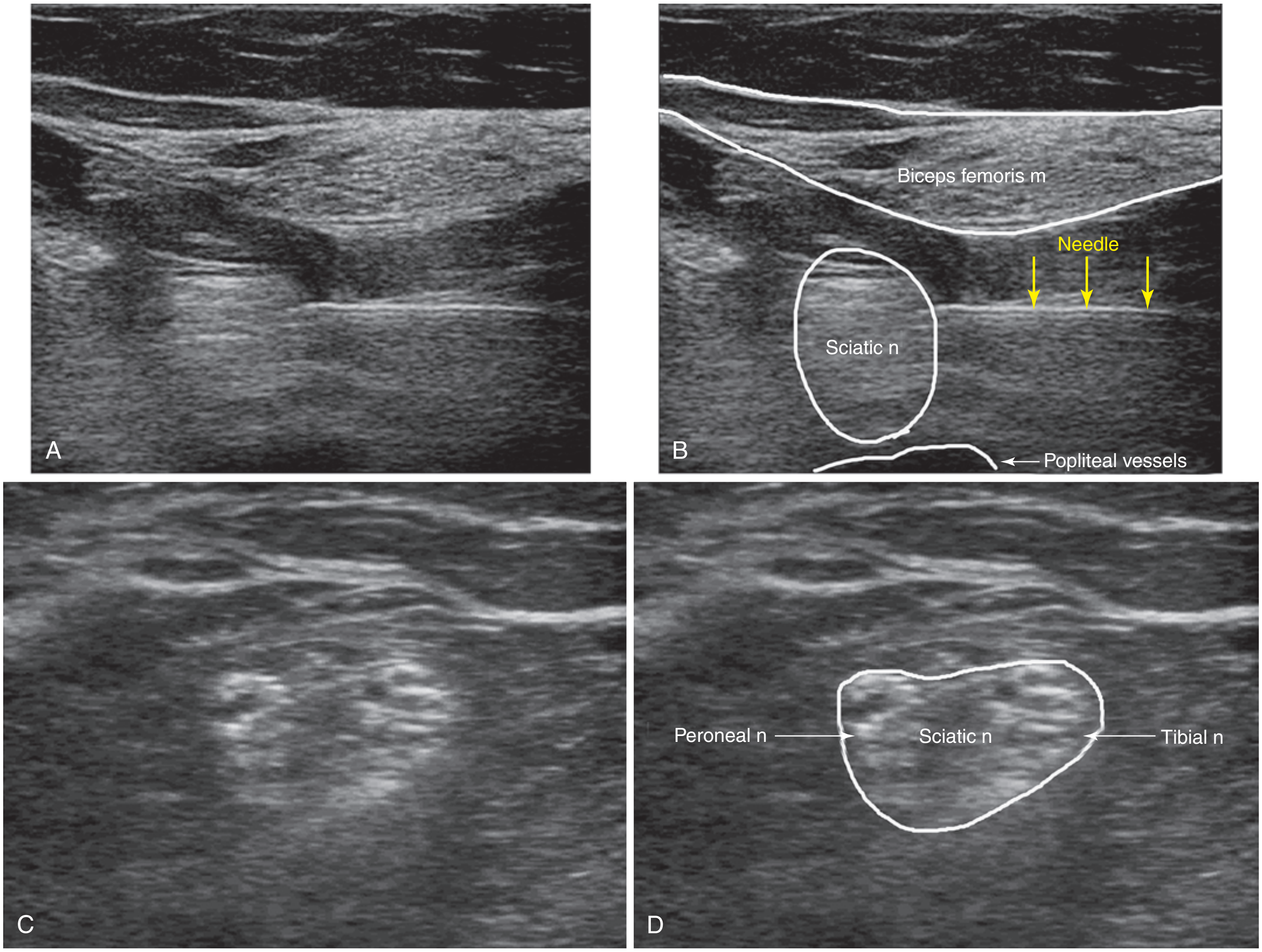

Figure 53-6 Sciatic nerve block: popliteal approach before the bifurcation (*top row*) and at the bifurcation (*bottom row*).

it dives deeper, and its superficial branch (the superficial geniculate artery) accompanies the SN. Hence, this technique should be used for blocking the SN at a level above the bifurcation of the femoral artery (Figure 53-4 C,D).

Tips for Pediatric Patients. In children the SN is approached via the medial aspect of the thigh about 2 to 5 cm above the knee. The small neurovascular bundle can be identified and 1 to 2 mL of LA injected by means of an in-plane US-guided technique.

SCIATIC NERVE BLOCK

The ScN innervates the lower part of the leg and can be blocked along its posterior thigh course by either the infra- gluteal or the popliteal approach.

Infragluteal Approach

The patient is positioned laterally (hip and knee joints flexed) while the target leg is placed in an upright position. This facilitates palpation and US detection of the bony landmarks used with this block: the greater trochanter and ischial tuberosity. Low-frequency transducers are commonly used for scanning in the infragluteal area (in thin subjects, high-frequency transducers may be used). The ScN is usually located below the midline of an imaginary hammock formed by the greater trochanter and ischial tuberosity. The nerve appears as a triangulated or wedge-shaped hyperechoic structure overlying the quadratus femoris muscle. A 100-mm needle is inserted in plane either lateral or medial (about 1 to 2 cm) to the transducer. When the tip of the needle approaches the nerve, 15 to 20 mL of LA is injected after negative aspiration (Figures 53-5 and 53-6 A,B).[34]

Popliteal Approach

The popliteal approach can be performed with the patient in the prone, lateral, or supine position. The transducer is placed in a transverse plane in the popliteal fossa, between the tendons of the semimembranosus/semitendinosus muscle medially and the biceps femoris muscle laterally. The rather superficially located tibial nerve (TN) can be visualized just adjacent to the popliteal vessels, whereas the peroneal nerve (PN) is not always visible in the fossa. However, when the transducer tracks the TN cephalad, the PN can usually be detected. At a variable distance, usually about 3 to 4 inches, proximal to the fossa the two nerves merge to form the ScN. At the level of the ScN bifurcation, an 80- to 100-mm needle is inserted in plane, and 10 to 20 mL of LA is injected after negative aspiration (Figure 53-6 C,D).

Tips for Pediatric Patients. In children, the aforementioned US-guided techniques can also be used. However, for catheter placement and ease of daily catheter examination we prefer the lateral subgluteal approach (when a high approach to the ScN is needed) or the lateral popliteal approach (when a more distal location is applicable). For both approaches the leg is elevated and the transducer is placed on the posterior aspect of the thigh. The nerve is identified and the introducer needle advanced in plane in a lateral-to-medial direction. The tip of the catheter is best placed anterior to the ScN. For both lateral approaches the child does not need to be moved to evaluate the insertion site of the catheter during pain rounds.

Regional Anesthesia of the Trunk

Trunk blocks (paravertebral, transversus abdominis plane [TAP], and rectus sheath) provide anesthesia to the thoracic and abdominal wall and offer an alternative analgesic solution in patients in whom a neuraxial block is not recommend or is contraindicated, such as deeply sedated ICU patients. In contrast to neuraxial analgesia, trunk blocks do not provide analgesia to visceral structures. Pain originating from these structures needs to be addressed with systemic pain medication. Nonetheless, trunk blocks can significantly reduce the amount of pain medication required by allowing the use of less systemic analgesia and lighter sedation, thus facilitating spontaneous breathing and weaning from mechanical ventilation.[35]

The TAP block and rectus sheath block provide analgesia to the anterior abdominal wall and can reduce the pain after any open abdominal surgery. Performed under US guidance, the fascia layer between the internal oblique and transversus abdominis muscles or the posterior rectus sheath can easily be identified in most patients. Catheters for continuous analgesia can be inserted unilaterally or bilaterally, depending on the location of the incision, under US guidance by using the hydrodissection method. Insertion of two catheters (i.e., one at a lower level and one at a higher level from the incision on each side) might be necessary to provide adequate distribution of LA for long incisions (Figure 53-7).

Paravertebral regional anesthesia provides analgesia to the chest, abdominal wall, or both. The pain relief achieved with a paravertebral block is comparable to that with a thoracic epidural

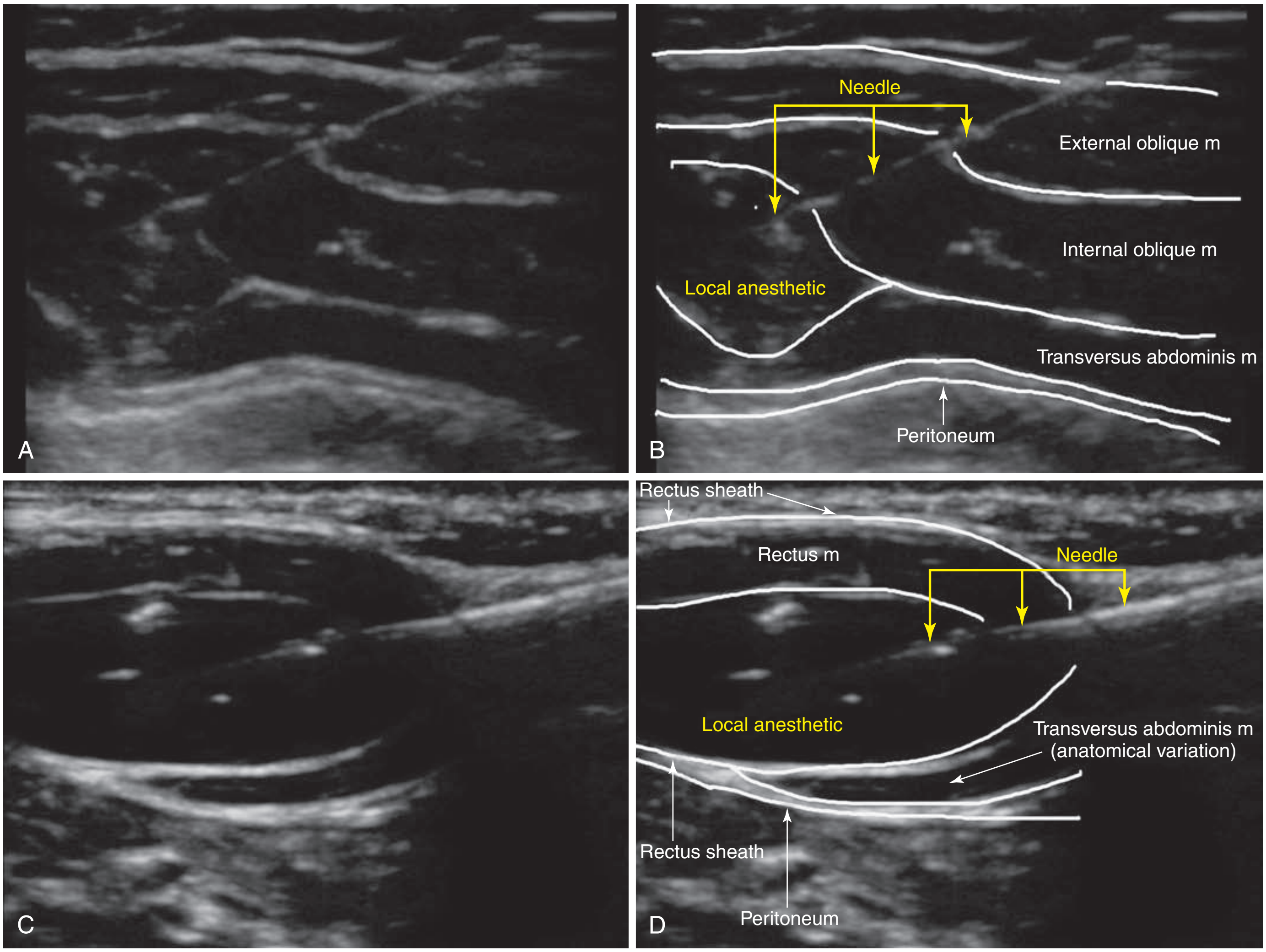

Figure 53-7 Transversus abdominalis plane (*top row*) and rectus sheath (*bottom row*) blocks.

in patients with rib fractures or after thoracotomy with the benefit of a superior safety profile. (Figure 53-8).[36]

The paravertebral space, bordered by the transverse process, the vertebral body, the pleura, and the costotransverse ligament, can be identified with US. An in-plane approach allows good control of the tip of the needle and reduces the risk for accidental perforation of the pleura. Performed unilaterally or bilaterally, a paravertebral block provides pain control after thoracotomy, thoracoscopy, rib fracture, flank incision for nephrectomy, and open cholecystectomy. Catheters can be placed for continuous LA infusion (Figure 53-8).[37]

Technical details of the aforementioned blocks are included in the following sections.

TRUNK BLOCKS

Transversus Abdominis Plane, Rectus Sheath, and Ilioinguinal/Iliohypogastric Blocks

The anterior divisions of the thoracolumbar nerves (T6-L1) innervate the abdominal wall. The former travel between the fascia of the internal oblique and transversus abdominis muscles toward the anterior abdominal wall and continue to the midline in the posterior rectus sheath.

Transversus Abdominis Plane Block. The TAP block reaches the thoracolumbar nerves in the layer of fascia between the internal oblique and transversus abdominis muscles. Different approaches have been described: an approach at the triangle of Petit, subcostal and midaxillary line approaches, and an approach just lateral to the rectus sheath (in children). The triangle of Petit is located at the lateral abdominal wall and is bordered by the costal margin cephalad, the iliac crest caudad, the external oblique muscle anteriorly, and the latissimus dorsi muscle posteriorly (Figure 53-7 A,B).

In all the aforementioned approaches the three muscles of the abdominal wall (external and internal oblique and transversus abdominis) are identified with high-frequency transducers. Next, an 80- to 100-mm needle is advanced (in plane) in the fascia layer, between the internal oblique and transversus abdominis muscles, and 15 to 20 mL of LA is injected after negative aspiration. A TAP block provides sufficient analgesia to the abdominal wall and can be performed unilaterally or bilaterally, depending on the surgical approach. A TAP block can be considered a valuable alternative in patients with a contraindication to neuraxial anesthesia/analgesia and for ambulatory procedures, surgery restricted to the abdominal wall (e.g., hernia), and control of postoperative pain in the ICU (Figure 53-7 A,B).[38]

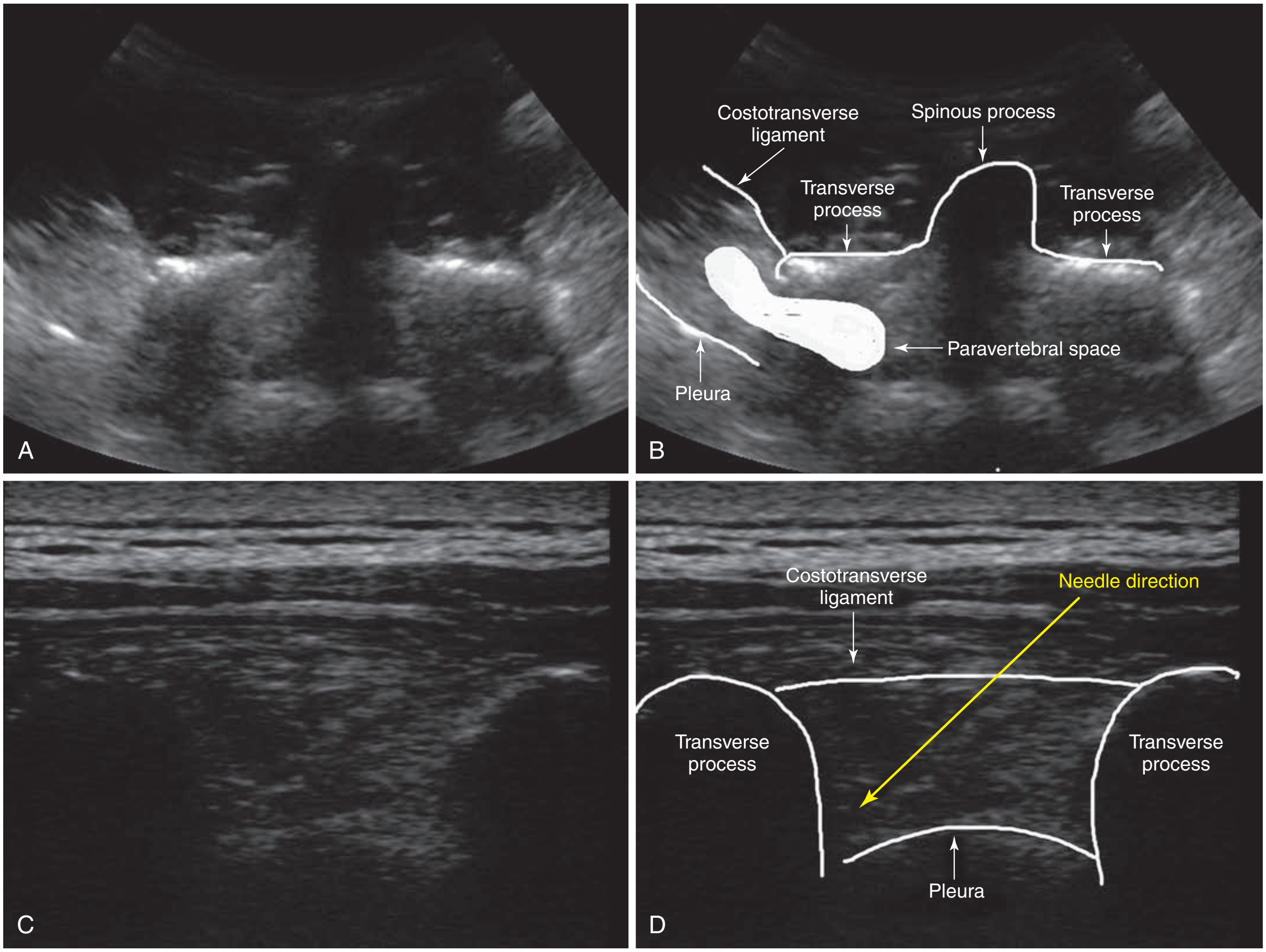

Figure 53-8 Paravertebral nerve block.

Tips for Pediatric Patients. In children the three abdominal wall layers are very thin but easily identifiable. The technique can be challenging because of excursion of the abdominal wall with every respiratory cycle when the child is breathing heavily. A TAP block can provide excellent analgesia for many abdominal surgical procedures. However, current experience with pediatric continuous TAP blockade is limited.[38]

Ilioinguinal/Iliohypogastric Nerve Block. The ilioinguinal and iliohypogastric nerves arise from the lumbar plexus and travel in the fascial plane between the internal oblique and transversus abdominis muscles. A high-frequency transducer is positioned (transverse plane) just medially and above the anterior superior iliac spine (ASIS), and the nerves are visualized within the fascia layer. A 50- to 100-mm needle is advanced (in plane) between the internal oblique and transversus abdominis muscles, and 10 to 15 mL of LA is injected into the fascia layer adjacent to the nerve. This block provides sufficient analgesia for lower abdominal incisions.

Tips for Pediatric Patients. In children the ilioinguinal and iliohypogastric nerves are easily identified as they lay together just medial and cranial to the ASIS. The transducer is positioned on the ASIS and is directed toward the umbilicus. The needle is advanced in plane and along a medial-to-lateral course toward the transversus abdominis muscle; an LA volume of 0.2 mL/kg is injected. *This block is the standard of care for all inguinal hernia repairs at our institution.*

Rectus Sheath Block. A rectus sheath block provides good analgesia to the midline or paramedian abdominal wall. The transducer is placed lateral to the midline at the level of the umbilicus (transverse plane). The rectus, external and internal oblique, and transversus abdominis muscles, as well as the aponeurosis, are identified. A 50- to 100-mm needle is advanced (in plane) in the posterior rectus sheath, and delivery of LA produces a hypoechoic lens-shaped space deep to the rectus muscle. The procedure is repeated on the other side of the abdomen; a total LA volume of 30 to 40 mL is generally required. The indication for a rectus sheath block is analgesia for midline incisions above the arcuate line (e.g., umbilical hernia) (Figure 53-7 C,D).

Tips for Pediatric Patients. This block is frequently used in pediatric patients for repair of an umbilical hernia and for all midline incisions when an epidural is too invasive or contraindicated. After injection of LA into the posterior aspect of the rectus muscle, the anesthesiologist can slide the transducer along the lateral border of the rectus muscle and evaluate whether spread of the LA has been sufficient to cover the entire incision; otherwise a second infiltration may be necessary.

The TAP, ilioinguinal/iliohypogastricus, and rectus sheath blocks do not provide analgesia to visceral structures, and therefore additional analgesics are usually needed when postoperative visceral pain is imminent (e.g., abdominal surgery). Placement of an intraabdominal needle carries a risk for bowel injury with all abdominal wall blocks. Optimal needle visualization under US guidance is essential in preventing this complication.

Paravertebral Block

This block delivers LA to the spinal nerves just after their exit from the spinal canal. The wedge-shaped paravertebral space is located adjacent to the spinal column bilaterally. It is bordered anterolaterally by the parietal pleura (thorax), anteriorly by the psoas muscle (abdomen), medially by the transverse process and vertebral body, and posteriorly by the costotransverse ligament. The thoracic paravertebral space is a continuum (in the cephalad-caudad orientation), and thus a single LA injection can result in multiple levels of anesthesia. The patient is placed in a sitting or lateral position, and blocks can be attempted at any level of the thoracic and lumbar spine (depending on the level of anesthesia desired). High- or low- frequency transducers are used (depending on block level and patient size). The transducer is placed (cephalad-caudad orientation) over the spinous processes. By sweeping the transducer laterally, deep structures such as the transverse processes and parietal pleura can be visualized delineating the costotransverse ligament. A 100-mm needle is inserted in plane and advanced through the ligament between two consecutive transverse processes. Loss of resistance can be felt when the tip of the needle perforates the ligament. An LA volume of 5 mL per level for multiple injections or 20 mL for a single one is required. Higher LA volumes may cause anterior pleural displacement or spread of LA into the spinal canal (or both). An epidural hematoma occurring after this block is rare in comparison to epidural anesthesia techniques.[24] Indications for a paravertebral block include breast, thoracic, and abdominal wall surgery; multiple rib fractures; thoracotomy; and thoracoscopy (Figure 53-8).

Tips for Pediatric Patients. The technique is similar to the one just described; however, this block is not frequently used in children except in specific clinical scenarios (e.g., thoracoscopy, one-sided rib fractures, open cholecystectomy).

EPIDURAL ANALGESIA

The benefits of epidural analgesia after thoracic and abdominal surgery are widely recognized.[15] For most patients, preoperative insertion of the epidural catheter in the OR is preferred. Possible indications for epidural catheter placement in the ICU include postoperative analgesia after emergency thoracic and abdominal surgery, unilateral or bilateral rib fractures, and pancreatitis. US-guided epidural catheter placement is an emerging technique that is not widely used yet. The key structures for epidural anesthesia—ligamentum flavum, dura, and epidural space—are partially obscured by the surrounding vertebrae in the US evaluation but can be identified in most patients. Notably, identification of the aforementioned landmarks by US facilitates epidural catheter placement, especially in patients with poorly defined surface landmarks, previous back surgery, and difficult anatomy.[32] Most commonly, US is used preprocedurally to determine the midline and depth of the epidural space because the epidural anesthesia itself is performed with loss of resistance technique. Real-time US-guided epidural anesthesia has been described mainly in infants.[39]

Pearls and Highlights

- US-guided neuraxial and regional anesthesia is underused in the ICU setting.
- In selected ICU patients, US-guided neuraxial and regional anesthesia can decrease the need for systemic opioids and sedation.
- Epidural anesthesia provides analgesia after thoracic or abdominal surgery that is superior to that provided by systemic opioids.

- Thoracic epidural analgesia and paravertebral anesthesia achieve better pain control and result in improved pulmonary function after rib fractures.
- US-guided peripheral nerve block techniques shorten the procedure time, hasten the onset of analgesia, result in fewer needle passes, and decrease the incidence of accidental vascular puncture.
- Hydrodissection with small amounts of normal saline facilitates visualization of the needle and tip of the catheter during US-guided nerve blocks.
- Preprocedural US scanning can facilitate epidural anesthesia in patients with poorly defined surface landmarks and anatomic variation of the spine.
- The ASRA guidelines regarding the performance of regional anesthesia in situations in which anticoagulation and antiplatelet agents are being administered should be followed in routine practice.
- The ASRA recommendations concerning regional anesthesia in anesthetized or heavily sedated patients should be followed when regional anesthesia is administered in the ICU.

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Ultrasound in Reconstructive Microsurgery

ANDREAS GRAVVANIS | DIMOSTHENIS TSOUTSOS | APOSTOLOS E. PAPALOIS | DIMITRIOS KARAKITSOS

(CONSULTANT-LEVEL EXAMINATION)

Overview

Recent innovations in local tissue rearrangement and free tissue transfer have altered surgical approaches from simple wound care or amputation to optimal functional and aesthetic repair.[1] Survival of transferred tissue remains a concern in trauma patients.[2,3] Apart from the surgical technique, various factors may influence microsurgical operations, such as defect location and size, functional characteristics and underlying disorders, types of affected tissue, anatomic variants, and the presence of trauma or infection. The surgical focus is underlined by an effort to maximize the functional and aesthetic results, although safety remains a paramount requirement. Careful preoperative design, decision-making, and postoperative management in the intensive care unit (ICU) are as critical as the operation itself. Designing reconstructive microsurgical operations is challenging and cannot rely solely on clinical criteria. Ultrasound has been used to study blood flow in free flaps by means of implantable Doppler probes or by surface scanning with high-frequency transducers.[4-6] Ultrasound techniques have increasingly been assimilated in surgical planning of flaps during the last decade.[7-9]

Ultrasound Applications in Microsurgery

Ultrasound examination of free flaps is achieved with standard two-dimensional and color Doppler techniques.[9] Portable ultrasound devices equipped with high-frequency (20-MHz) linear transducers are used for imaging of the small and medium-sized vessels used in microsurgical reconstructions. Ultrasound provides real-time information about arterial and venous conduits (patency, diameter, flow) in both the donor and recipient sites. Doppler spectral waveforms (DSWs) of perforator arteries and accompanying venous tributaries facilitate vascular mapping. Ultrasound has effectively been integrated into free flap design by several microsurgical teams.[4-9] According to a German survey, which included 121 plastic surgery institutions, ultrasound was the predominant technique for preoperative perforator mapping in flap surgery (48% of institutions used ultrasound techniques).[10] Hence ultrasound is the most frequent imaging modality used in reconstructive microsurgery, followed by computed tomographic angiography (CTA) and magnetic resonance angiography.[4-11]

Sonography depicts vessel diameter, course, and branching patterns and facilitates preoperative discrimination between septocutaneous and musculocutaneous perforators.[12] DSW analysis identifies vascular flow characteristics and can be used as an adjunctive tool for selecting between perforator vessels of the same caliber and value in cases in which perforators might have been damaged. In addition, exploring the patency of accompanying venous tributaries is important since dynamic evaluation of venous drainage affects the design of certain flaps (venous congestion might lead to flap failure).[4,9] Perforators are small in size, but their anatomy and vascular network are highly complex and variable. Ultrasound can accurately visualize perforators with a diameter of at least 0.18 mm at the fascia level (Figure 54-1). It is a reliable method for estimation of caliber if its spatial resolution of 0.18 (axial) and 0.35 mm (lateral) is compared with CTA's axial (0.68 to 0.78 mm) and z resolution (0.65 mm).[4,13] Although sonography demonstrates two-dimensional footprints of the perivascular anatomy as opposed

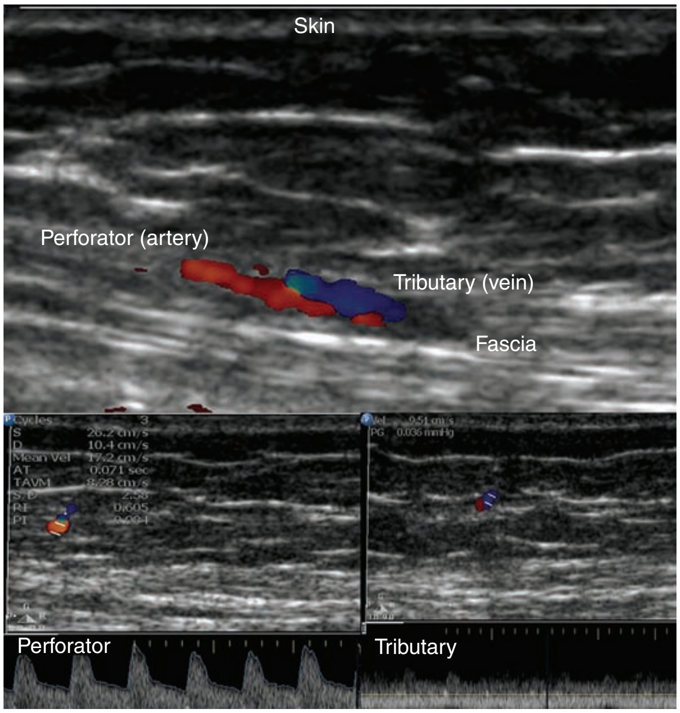

Figure 54-1 (*Top*) Ultrasound depicting a small perforator with accompanying tributary exiting the abdominal fascia and their Doppler spectral waveforms (*bottom*).

to three-dimensional views with CTA, it provides additional information about the condition and thickness of the subcutaneous fat layer along with anatomic characteristics and the status of underlying muscles and fascia.[9] Therefore, sonographic data enable preoperative flap design. Intraoperative ultrasound applications include real-time perforator mapping and evaluation of microsurgical anastomoses and flap perfusion.[9] In the ICU the method can be used for flap monitoring given its ability to evaluate changes in blood flow.[9]

In our practice, ultrasound is used to determine the suitability of vessels as recipients by measuring their diameter and assessing their flow characteristics, as well as the level at which safe anastomosis could be performed (outside the zone of injury).[9] The recipient site is evaluated for possible effects of radiation (e.g., actinonecrosis) or scarring from previous surgery. In head and neck reconstructions, the ipsilateral facial and superior thyroid vessels are the recipients of choice.[14] Nevertheless, all native common carotid artery branches and jugular vein tributaries are investigated in both the ipsilateral and contralateral regions of the neck. For breast reconstruction, the internal mammary vessels are the recipients of choice. Apart from evaluating the arterial circuits, assessment of the flow, diameter, and patency of the venous tributaries is mandatory (Figure 54-2). Moreover, the width of the second and third intercostal spaces is measured to decide whether a rib-sparing technique will be used for exposure of the vessel. A width of 2 cm is required for easy access and safe, comfortable anastomosis. Ultrasound is effective in detecting preexisting vascular disorders or posttraumatic vascular abnormalities after lower limb reconstruction.[4] In cases of pedicled flaps, recipient vessel selection, level of safe anastomosis (e.g., outside the zone of injury), and pedicle length requirements are evaluated regularly. Intraoperatively, sonography is used, under strict sterilization measures, in cases in which recipient vessel or perforator flow appears to be problematic (see Figure 54-2). In the ICU, ultrasound is used to monitor buried flaps or flap perfusion whenever the latter is uncertain based on clinical criteria (see Figure 54-2).

The flexibility of the ultrasound techniques used in reconstructive microsurgery could prove decisive, especially in trauma patients, in whom time between diagnosis and surgery may be crucial. The method is operator dependent, and its results cannot be interpreted by microsurgeons without previous training. Visualizing small vessels by means of sonography is challenging. Experienced operators are using high-frequency and broadband transducers with continuous adjustments to improve spatial resolution and recorded Doppler waveforms. Because image quality is easily affected (scarred tissue, presence of subcutaneous air, edema, obese patients), transducer pressure should be applied with care (e.g., excessive pressure on thin patients with atrophic thighs can interrupt perforator blood flow). Microsurgeons could provide input and guide well-trained operators to facilitate optimal vascular mapping.

Figure 54-2 (*Top*) Microsurgical breast reconstruction: preoperative evaluation of the internal mammary vessels as recipients (*left*) and intraoperative evaluation of the recipient vein (*right*). (*Bottom*) Monitoring of a buried fibula flap in the intensive care unit.

Pearls and Highlights

- Ultrasound provides two-dimensional and color Doppler details of the recipient and donor sites in microsurgical operations. It evaluates perforators and the accompanying venous tributaries to provide dynamic vascular mapping, which is crucial in microsurgical planning.
- Sonographic assessment of medium-sized and small vessels is technically demanding and has many limitations.

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55

Ultrasound in Animals

GREGORY R. LISCIANDRO

Overview

In 2004, in the first historical translational study of focused assessment with sonography for trauma (FAST) from humans to small animals, 101 dogs with severe blunt trauma after being hit by cars were evaluated.[1] The authors reported that intraabdominal injury, specifically, hemoperitoneum, was more common than previously identified (pre-FAST rate of 12% to 23% versus a post-FAST rate of 45%).[2] By imaging the thorax via the subxiphoid site, intrathoracic injury was detected, as well as pleural and pericardial effusions; moreover, proficiency by nonradiologists was documented.[1] Since 2004, the abdominal FAST examination (AFAST) has been modified by naming sites based on target organs rather than external sites and by developing an abdominal fluid score (AFS) as a semiquantitative measure of the volume of effusions. In hemoperitoneum, the AFS was found to predict the anticipated degree of anemia and the need for blood transfusion and emergency laparotomy in dogs.[3] Accordingly, a thoracic FAST examination (TFAST) and a lung survey (Vet BLUE Lung Scan) have been developed. These thoracic and lung ultrasound techniques appeared to be effective in the evaluation of blunt and penetrating trauma inasmuch as nonradiologist veterinarians were able to diagnose thoracic trauma (median time, <3 minutes), including pneumothorax, hemothorax, thoracic wall trauma, pulmonary contusions, and cardiac trauma, and discrimination among various causes of respiratory distress in nontrauma cases was facilitated as well.[2,4]

Abdominal Focused Assessment with Sonography for Trauma and Abdominal Fluid Score

The initial veterinary FAST scan has been refined, including naming the original four sites by target organ and incorporating a fluid scoring system for initial and serial examinations (Figure 55-1)[3]. By emphasizing the target organ approach, veterinarians could appreciate the animal's internal anatomy and enrich their ultrasound skills. Development of the AFS enabled progressive assessment of animals' hemodynamic status (e.g., occult hemorrhage [negative AFS turned positive], continued hemorrhage [increasing AFS], resolving hemorrhage [decreasing AFS]).[2,3]

The *semiquantitative AFS* (AFS 0, negative at all sites; AFS 1 to 4, score of 1 with a maximum of 4 for each positive site) correlated with the degree of anemia when dogs were placed in lateral recumbency (unequal gravity-dependent sites, in contrast to human hemorrhage scoring systems in the supine position, in which all sites are equally gravity-dependent), and such positioning served as an inherent depth gauge (Figure 55-2).[3]

In previously healthy dogs, anemia uncommonly developed in lower-scoring dogs (AFS 1, 2 = *small bleeders*), as opposed to higher-scoring dogs (AFS 3, 4 = *big bleeders*), which as expected became anemic. Big bleeders predictably incurred a minimal decrease of 20% from their baseline packed cell volume (PCV), and approximately 20% became severely anemic (PCV <25%).[3] AFS evaluations facilitated clinical management by anticipating the need for transfusion products or emergency laparotomy.[3] Small bleeders that result in anemia should alert the clinician to look for other sites of hemorrhage such as the thorax (hemothorax), retroperitoneal space, or fracture sites.[2,3] Serial AFS assessments enable monitoring of the evolution of anemia. However, the AFS has not proved to be effective in cats hit by cars (lack of case numbers, big bleeders, or both) because most bleeding cats, intolerant of blood loss, probably expire before reaching a veterinarian.[5,6]

The AFS is also used for *nontraumatic causes of hemoperitoneum*. The latter are usually caused by bleeding tumors and warfarin-based rodenticide toxicosis. Postoperative (e.g., ovariohysterectomy, splenectomy, liver lobectomy) and postinterventional (e.g., percutaneous biopsy, laparoscopy) cases at risk for hemorrhage could be monitored with the AFS since the latter could guide decisions on blood transfusion and definitive care (e.g., interventional radiology, exploratory laparotomy).[2]

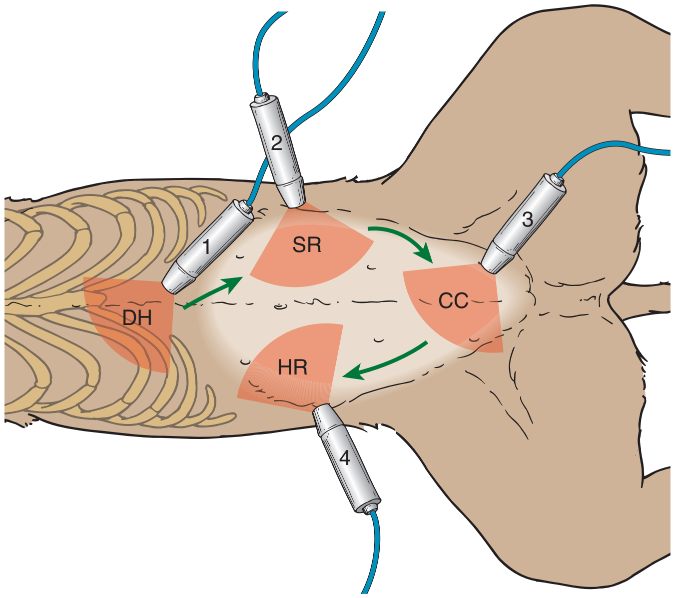

Figure 55-1 Abdominal focused assessment with sonography for trauma examination. Key: DH, diaphragmatico-hepatic view; SR, splenorenal view; CC, cysto-colic view;HR, hepato-renal view. *(Used with permission from Lisciandro GR, Lagutchik MS, Mann KA, et al: Evaluation of an abdominal fluid scoring system determined using abdominal focused assessment with sonography for trauma in 101 dogs with motor vehicle trauma*, J Vet Emerg Crit Care *19[5]:426-437, 2009.)*

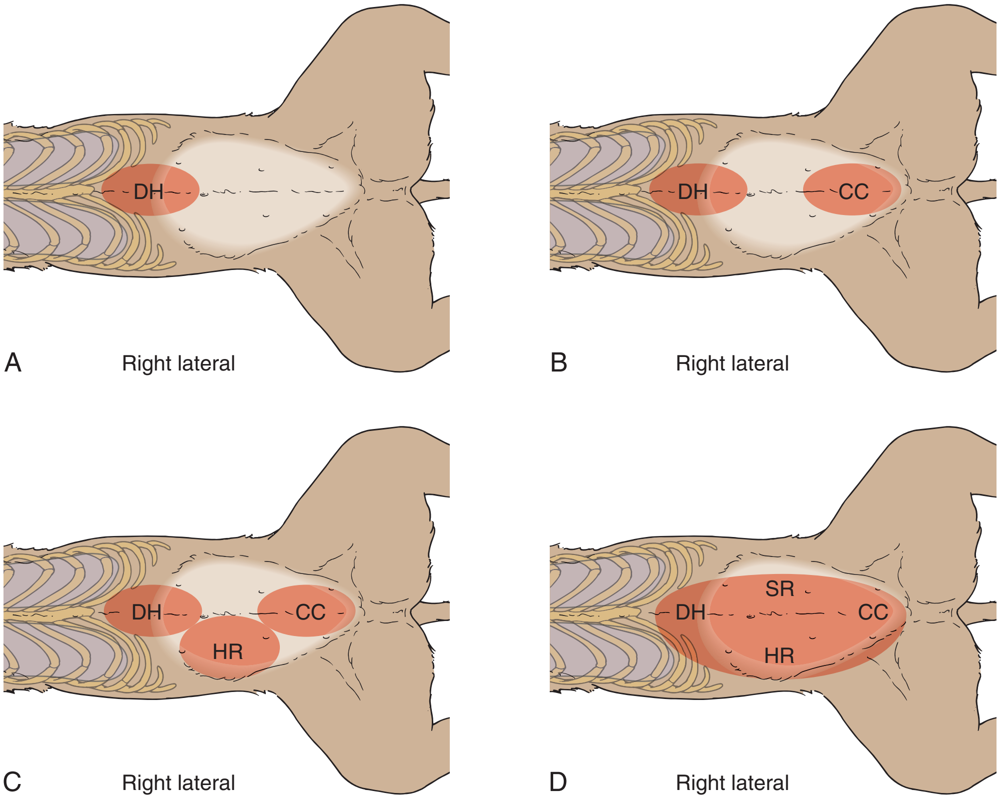

Figure 55-2 Abdominal focused assessment with sonography for trauma–applied abdominal fluid scoring system. *DH*, diaphragmatico-hepatic view; *SR*, spleno-renal view; *CC*, cysto-colic view; *HR*, hepato-renal view. *(Used with permission from Lisciandro GR, Lagutchik MS, Mann KA, et al: Evaluation of an abdominal fluid scoring system determined using abdominal focused assessment with sonography for trauma in 101 dogs with motor vehicle trauma,* J Vet Emerg Crit Care *19[5]:426-437, 2009.)*

In the AFAST study,[3] all dogs exhibited normal PCV and were evaluated with AFAST soon after their trauma (median time, 60 minutes from trauma to AFAST) and following admission (median time from initial evaluation to AFAST, <5 minutes). Prompt AFAST examination aids in modifying resuscitative efforts accordingly and can guide management toward more conservative therapeutic end points and thus lower transfusion rates.[2,3] Initial and serial AFAST and AFS should be integrated into veterinary trauma algorithms because of their potential to affect the clinical course as shown in human medicine.[7,8] Past studies comparing abdominal radiographic (AXR) findings with AFAST-positive and AFAST-negative dogs reported that 24% of dogs with decreased AXR serosal detail (suggesting the presence of free abdominal fluid) were in fact AFS negative whereas 34% of dogs with normal AXR serosal detail (suggesting the absence of free abdominal fluid) were AFS positive. Hence, AXR findings are rather unreliable in comparison to AFAST, which is in accordance with human studies.[3,9]

The use of AFAST for *penetrating trauma* such as bite wounds was hypothesized to be helpful. However, it was found that AFAST performed in many of the 145 dogs in the TFAST study often missed serious intraabdominal injury. This discrepancy probably resulted from the nature of each type of trauma (e.g., blunt versus penetrating) since blood is rapidly “defibrinated” in blunt trauma and appears anechoic and conspicuously as free fluid. In penetrating trauma there is a different initiation event in the coagulation cascade because the crushed and torn tissue results in clotted blood, and thus AFAST misses isoechoic (shades of gray) areas (similar to soft tissue). No extensive data on the role of AFAST for penetrating trauma[2,3] are available. Its ability to detect injury probably has low sensitivity but high specificity in such cases.[10,11]

The Thoracic Focused Assessment with Sonography for Trauma Examination

In veterinary medicine, a four-point thoracic scan (TFAST) has been introduced for the rapid detection of pneumothorax (PTX) and other thoracic injuries such as lung blast, hemothorax, pericardial effusion, diaphragmatic herniation, and thoracic wall trauma. The original TFAST has evolved into a 5-point scan through addition of the diaphragmatico-hepatic (DH) view (also part of the AFAST examination).[2,3] In Figure 55-3 TFAST is depicted in lateral recumbency for ease of illustration, but is performed in sternal recumbency or standing in respiratorily compromised or distressed animals. *Dorsal recumbency should never be used* because it is dangerous to compromised animals. The chest tube site (CTS) refers to a stationary, horizontally held transducer (parallel to the spine) at the highest lateral point (lateral recumbency) and highest dorsal point ventral to the hypaxial muscles (sternal recumbency) of the thorax that is used to evaluate for PTX. The pericardial site (PCS) and DH views are dynamic, with cardiac transverse-axis (transducer marker toward the elbow) and longitudinal-axis (transducer marker toward the spine) views and broad fanning through the

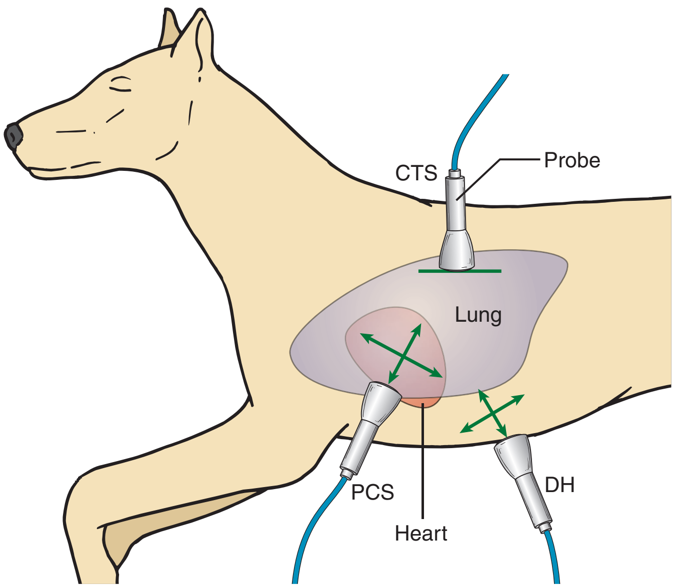

Figure 55-3 Thoracic focused assessment with sonography for trauma examination. *(Used with permission from Lisciandro GR: Abdominal and thoracic focused assessment with sonography for trauma, triage, and monitoring in small animals,* J Vet Emerg Crit Care *12[2]:104-122, 2011.)*

liver into the thorax, respectively. The sage axiom "one view is no view" should be used to help distinguish pleural from pericardial effusions; moreover, by zooming away from the area of interest (increasing depth), misinterpretation of effusions for normal heart chambers is less likely.[2]

The basic ultrasound findings on bilaterally applied CTS views include "dry" lungs (A-lines with a glide), PTX (A-lines with no glide and a lung point with partial PTX and absence of a lung point with massive PTX), "wet" lungs (ultrasound lung rockets or B-lines), and the step sign (deviations from the normal expected continuity of the glide sign along the pulmonary-pleural line).[2,3] The Vet BLUE Lung Scan corresponds to a regionally applied lung ultrasound evaluation extending beyond the CTS. The "wet" versus "dry" lung concept is easily appreciated. "Dry" lungs are depicted as an A-line pattern (equidistant parallel lines called A-lines, which represent reverberation artifacts) with a glide sign (without a glide sign, PTX is present). "Wet" lungs are characterized by lung rockets (B-lines), which are defined as hyperechoic lines that do not fade, extend from the pleural line through the far field and obliterate the A-lines, and swing to and fro with inspiration and expiration.[12] "Wet" lungs may reflect several forms of interstitial edema (e.g., cardiogenic pulmonary edema, noncardiogenic pulmonary edema [NCPE]; and pulmonary contusions in trauma).[12,13] B-lines are infrequent in nonrespiratory dogs and cats.[14] Notably, parenchymal abnormalities located in the central lung areas may be missed by sonography.[14] In cases of suspected PTX, operators search for the lung point to determine the degree of PTX (partial vs. massive, Figure 55-4). The lung point refers to the location at which the lung recontacts the thoracic wall as evidenced by either resumption of the glide sign or the finding of B-lines.[2,16]

Ultrasound was suggested to be superior to physical examination and radiography in detecting pleural and pericardial fluid.[11] PCS views are gravity-dependent and used for detecting either type of effusion. The DH view is useful because of the acoustic window that it provides for direct visualization into the pleural and pericardial spaces. The latter is considered a most sensitive view in human protocols.[11] Multiple and repeated views improve the probability of accurate assessment and decrease the probability of pitfalls.

Vet BLUE Lung Scan

The Vet BLUE Lung Scan, referred to as Vet BLUE, is performed with the same technique as previously described for TFAST (CTS views). In addition, the transducer is moved as follows: from the CTS or caudodorsal lung region to the perihilar, middle lung, and finally the cranial lung lobe regions. Operators search for "wet" versus "dry" lungs, for the shred and tissue signs (lung consolidation), and for the nodule sign (neoplastic or granulomatous processes).[12,17,18]

Patient instability or lack of immediate technical support delays radiographic imaging, the historical diagnostic mainstay for veterinarians. Clinical decisions were based on insensitive information.[19] However, the availability of computed tomography, which is considered the "gold standard" for many lung conditions, is gradually changing practices. Ultrasound is a reliable alternative bedside imaging modality. By applying the simple principles of "wet" lung (e.g., cardiogenic pulmonary edema, NCPE, pneumonia, lung contusions) versus "dry" lung (e.g., upper airway disease, pulmonary thromboembolism, asthma, severe acidosis, fever), combined with other findings such as nodules and consolidated lung (e.g., neoplasia, pneumonia), the probability of an accurate

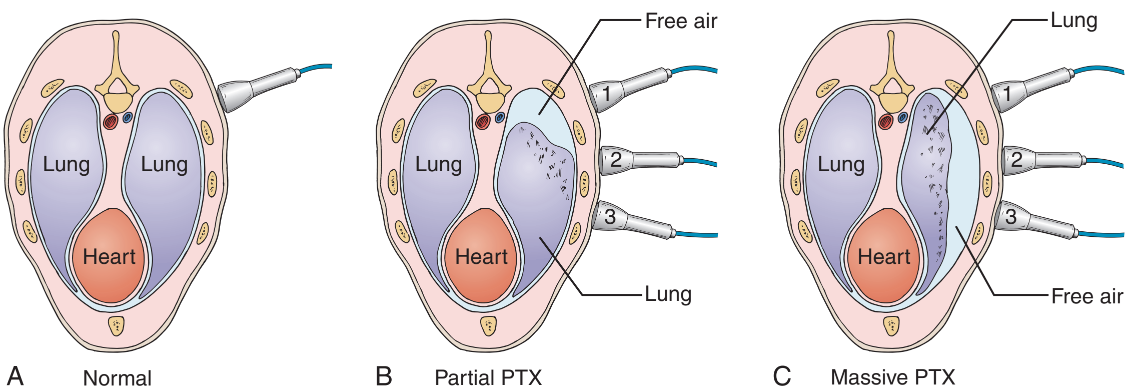

Figure 55-4 Search for the lung point. *(Used with permission from Lisciandro GR: Abdominal and thoracic focused assessment with sonography for trauma, triage, and monitoring in small animals,* J Vet Emerg Crit Care *12[2]:104-122, 2011.)*

diagnosis exceeds traditional means. From a monitoring standpoint, interstitial edema, which precedes alveolar edema, is easily recognized by ultrasound well before physical examination and radiography can detect it. Many acute conditions have classic distribution patterns of "wet" versus "dry" lung. Dogs with left-sided heart failure (other than Doberman pinschers) would have B-lines at the caudodorsal and perihilar lung regions and "dry" lungs ventrally at the middle and cranial lung lobe regions (as would dogs with volume overload). The same pattern may be observed with acute NCPE from neurogenic causes (a dog that has seizures), electrocution (a dog that bites an electric cord), choking, or other causes (e.g., drowning, acute respiratory distress syndrome [ARDS]). Conversely, ventral patterns would be more suggestive of pneumonia (especially in dogs that have acutely aspirated). The Vet BLUE becomes even more valuable in sorting out the cause of respiratory distress in a choking dog, which could be due to NCPE, aspiration pneumonia, a combination of both or neither. If this dog has B-lines only at the right middle lung lobe region, the major cause of its respiratory distress is more likely to be acute aspiration than NCPE. Another major conundrum with respiratory distress in dogs and cats (the latter commonly have asthmatic crises) is determining the cause of their distress. "Dry" lungs in all fields would rapidly rule out left-sided cardiac failure. In veterinary medicine, ultrasound may be used for cardiac assessment during resuscitation and for monitoring fluid therapy (subjectively) by looking at the left ventricular transverse-axis (volume and contractility),[20] whereas the caudodorsal and perihilar lung regions are scanned to detect "wet" versus "dry" lungs (left-sided cardiac status); moreover, scanning may be extended caudally for vena cava analysis and evaluation of hepatic vein distention (right-sided cardiac status).[2,21]

By combining AFAST, TFAST, and the Vet BLUE, veterinarians can arrive at a solid working diagnosis expediently by surveillance of four spaces (peritoneal, retroperitoneal, pleural, and pericardial) and the lung.[2,14] Point-of-care ultrasound aids veterinarians in positively directing therapy with evidence-based information.

Pearls and Highlights

- The AFAST-derived AFS predicts the degree of anemia anticipated in traumatized and nontraumatized bleeding dogs and thus guides clinical management.
- The TFAST examination detects the presence of PXT, hemothorax, and pericardial effusion in traumatized and nontraumatized small animals, whereas the Vet BLUE is used to assess for various lung parenchymal abnormalities.
- By combining AFAST, TFAST, and the Vet BLUE, veterinarians can rapidly and expediently arrive at a solid working diagnosis.

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SECTION X

HOLA Logistics and the Ultrasound Experience/ Training/Credentialing

56

Integrating Picture Archiving and Communication Systems and Computerized Provider Order Entry into the Intensive Care Unit: The Challenge of Delivering Health Information Technology–Enabled Innovation

ANDREW GEORGIOU | ISLA M. HAINS | DAVID MILLISS | LLOYD RIDLEY | JOHANNA I. WESTBROOK

Overview

This chapter presents research evidence on the effective utilization of picture archiving communication systems (PACSs) and computerized provider order entry (CPOE) systems in the intensive care unit (ICU). PACSs provide a centralized communication repository for all imaging data that replaces previous film-based systems by delivering diagnostic images electronically to clinicians. CPOE systems allow clinicians to place orders (e.g., medication, imaging, and pathology) directly into computers with the potential to link to databases containing patient-specific clinical information and decision support software.[1] Both CPOE systems and PACSs can be seen as complementary components of an integrated health information technology (IT) infrastructure. They are key building blocks for the hospital electronic medical record that help improve communication between hospital units (e.g., clinical wards, radiology, pathology, and pharmacy), and they contribute to enhanced evidence-based decision-making and quality of patient care.

In the last 30 years PACSs have evolved from in-house radiology systems to fully fledged commercial systems that can network across the hospital and beyond. Their integration with radiology information systems and CPOE and incorporation of technologies such as voice recognition and computer-aided diagnosis are part of the move toward paperless systems. The uptake of PACSs has continued to rise. In the United States, 76% of hospitals reported using PACSs in 2008,[2] and at the time of writing, England and Scotland are expected to complete a national rollout of a PACS by the end of 2012.[3] Although CPOE has been in existence since the early 1970s, its uptake is considerably less than PACS. A 2009 report examining CPOE implementation estimated that 15% of U.S. hospitals and only a handful of sites in Australia (predominantly in Sydney) had installed CPOE systems.[4]

There have been optimistic predictions about the potential for health IT to have a positive impact on the quality and effectiveness of patient care. Systematic reviews, however, continue to highlight the complex, variable, and fragmented nature of the evidence for health IT and its effect on patient care outcomes.[5,6] A survey of users' experience undertaken in seven trusts in the United Kingdom by Tan and Lewis[7] found that although the majority of respondents could point to the benefits of PACSs, there were also a number of concerns related to the lack of training, system unreliability, and poor quality of images and monitors. We also note that very little research attention has been paid to the effect of PACSs on ICU clinical work processes.[8]

Impact of Health Information Technology on Work Practices in the Intensive Care Unit

A systematic review by Hains et al[8] investigated the effect of PACSs on clinical work practices in the ICU. The review identified five key performance indicators from 11 studies conducted in either the United States ($N = 9$) or the United Kingdom ($N = 2$). The reported indicators included (1) time until an image is available, (2) time that it was accessed, (3) time that it was reviewed, (4) time that a decision is made, and (5) indicators of the frequency and types of communication that are undertaken between ICU clinicians and the medical imaging department.[8]

Studies of the availability of images generally revealed that PACSs are associated with quicker access to images.[8] Watkins et al[9] examined routine and nonroutine chest examinations in a before and after study and reported an improvement in examination accessibility of up to 30 minutes for routine examinations but no difference for nonroutine images. These results are mirrored in a survey of ICU staff by Cox and Dawe[10] in which it was shown that 90% of users believed that images were available sooner than before the introduction of a PACS and 72% perceived that there were no longer problems related to lost images. The improved availability of images is complemented by decreases in the time taken for an ICU physician to review images. One study by Humphrey et al[11] showed that the mean time from image exposure to image viewing was 39 minutes in a surgical ICU with a PACS versus 78 minutes in a medical ICU without a PACS.[11] Changes in viewing patterns were also highlighted by De Simone et al,[12] who found that physicians incorporated the viewing of electronic images into their morning ward rounds as part of their routine. This replaced the practice before implementation of a PACS in which the majority of films were viewed as part of the daily radiologist conference in the ICU at 3:00 PM. This was associated with reduced time to reach clinical decisions.[12] These findings correspond to surveys reported in separate studies by Cox and Dawe[10] and Humphrey et al[11] in which it was shown that the majority of clinicians perceived that PACSs led to quicker decision-making.

In contrast to the positive findings of the effect of PACSs on efficiency and timeliness, the prevailing evidence about the impact of PACSs on communication patterns within the ICU and across hospitals is variable, with studies showing no difference in the frequency of communication between ICU physicians and the radiology department[13] or significant reductions in the input received (via telephone, direct contact, or reports) from radiologists.[14]

Decision Support Systems

One of the most important potential benefits of health IT relates to the incorporation of decision support systems (DSSs), which can provide on-screen reminders and prompts to enhance adherence to evidence-based guidelines. This can lead to a reduction in the number of low-yield requests, which constitutes an ineffective use of resources and poor risk-benefit return. A systematic review by Georgiou et al[6] published in 2011 identified 14 studies that investigated the impact of CPOE systems on medical imaging services. The studies were either preintervention-postintervention comparisons ($n = 10$) or time-series studies ($n = 4$). Seven of the studies assessed the effect of decision support features that prompted the use of guidelines. These studies generally reported increased adherence to guidelines that led to reductions in unnecessary or low-yield orders. They included a study by Chin and Wallace,[15] which reported an improvement in the percentage of upper gastrointestinal imaging requests conforming to guidelines (from 56% to 86%—significance not stated) after implementation of a CPOE system with guidelines embedded in the ordering process. A time-series study by Carton et al[16] used a CPOE system to provide on-screen reminders displaying recommendations and alerting physicians if a request did not conform to the guidelines. This intervention led to a significant decrease in the percentage of radiology orders that did not conform to the guidelines (from 33.2% to 26.9%; $P = .0001$).[16] Sanders and Miller[17] used a similar decision support feature as Carton et al[16] and reported that the examination recommended by the guidelines was chosen in 60% of cases ($P = .001$). Participants in this study were also required to give a reason for overriding the recommended practice. Reasons for nonconformance included a patient-specific context (79%), influence or verbal order by another person (15%), and the recommended examination already performed (15%).[17]

Evidence on the implementation and utilization of DSSs continues to be inconsistent.[5] This reflects the inherent difficulties involved in the design of effective DSSs. The success or otherwise of DSSs relies on a number of factors, including its usability, perceived relevance, and even just the way that it is presented to clinicians. Implementation of a DSS is a key organizational and communication challenge whose success is contingent on the way that clinical work is carried out across multiple clinical and patient settings.[6]

Cases: Sociotechnical Approaches to Health Information Technology–Enabled Innovation in the Intensive Care Unit

Sociotechnical research perspectives draw attention to the interface between the technical features of health IT and the particular social, human, and ergonomic context in which they operate.[18] To illustrate the contribution that such research approaches can make in understanding the effective utilization of health IT, we highlight three qualitative studies undertaken in ICUs in Sydney, Australia. The studies reported on (1) ward round practices associated with the introduction of PACSs, (2) the impact of PACSs on nursing work practices, and (3) ICU clinicians' perceptions of the impact of health IT on clinical decision-making.

A 2011 study by Hains et al[19] reported on ward round work practice associated with PACSs in the ICU. The study was based on 79 hours of observation of ward rounds and 40 one-on-one semistructured interviews with ICU physicians (staff specialists, registrars, and residents) in three hospitals with different levels of PACS and health IT availability. The results of the study showed that physicians viewed imaging results infrequently during ward rounds in two of the ICU settings—one without a PACS and one with a PACS accessible via bedside computer. In the third ICU, in which a PACS was available only through a central workstation, regular viewing of images throughout the daily ward round was perceived by clinicians to contribute to decisions about patient care.[19] The study concluded that the availability of PACSs on bedside computers did not automatically lead to integration into ward round discussions and decision-making. The authors outlined possible factors that could have influenced this finding, including computer screen resolution and specific contextual factors (ranging from the particular makeup, size, and location of the site to patient intake) that may be unique to each of the settings.[19]

A second study by Creswick et al[20] interviewed 49 nurses and observed nurse practices for 35 hours in the same three ICUs studied by Hains et al.[19] The study found that access to PACSs was associated with nurses having easier and timelier access to images. This was perceived by nurses to have a positive impact on patient safety while also eliminating the need to constantly search for films. In contrast, in the hospital without a PACS, nurses had limited access to images and were able to view them only during the ward round.[20]

A third unpublished study undertaken in four metropolitan ICUs involved 56 semistructured interviews and 133 hours of observations of ward rounds and associated meetings to compare ICUs with varying health IT levels: CPOE systems (sites 1 to 4), beside computers (site 1), and PACSs (sites 1 to 3). Findings from this study showed that overall, physicians believe that health IT improves the availability and accessibility of information. They perceived this to have a positive impact on clinical decision-making. In sites that still used some form of paper records, it was frequently observed that different parts of the record were accessed simultaneously, for instance, one physician writing in the progress notes while another reviewed the medication chart. Senior clinicians at sites without bedside computers reported that it adversely affected their work because they were required to make frequent trips to a central workstation to access images and results. Concern was also expressed about how the location of health IT can have an impact on work practices. Participants noted that workstation computers affected the time that physicians actually spent with patients at the bedside. The study identified the importance of considering work environments and work practices in understanding how health IT systems are used and integrated (or not integrated) into everyday practice.

Taken together, the three studies demonstrated that clinicians perceive clear benefit to be associated with health IT. The evidence also suggests that many factors can have an impact on the implementation and sustainability of health IT in ICUs. Each ICU is different—what works in one setting may not be reproducible in another. Some of these complexities can be attributed to aspects of the culture and team climate of the ICU, its proclivity for change, and the way that the ICU team functions and collaborates; others may be related to aspects of clinical work practices both within the ICU and across the hospital.

Conclusion

The ICU is a data-intensive environment in which clinicians require easy access to information for time-critical clinical care decisions. PACSs and CPOE/DSSs are powerful technologies that fundamentally change the way that data, information, and knowledge are recorded, stored, accessed, and communicated between the ward, the imaging department, and the hospital. They have the potential to facilitate seamless exchange of information across all aspects of the patient care process.[21] This potential should not, however, divert attention from the challenges that come with the introduction of health IT. Technology-enabled innovation in critical care settings needs to be accompanied by agreement between diverse professional groups to ensure that the systems are easy to use, are conducive to team work practices, and contribute positively to the quality and safety of care.[22] Finally, the recent integration of ultrasound technology into many ICUs around the world is gradually changing critical care management logistics. Implementation of ultrasound in routine ICU practice may result in the development of ICUs with their own "imaging" capabilities. This will presumably enhance the utilization of PACSs and CPOE/DSSs by intensivists in the future (see Chapter 57).

Pearls and Highlights

- PACSs and CPOE systems can be seen as complementary components of an integrated health IT infrastructure for enhancing the provision of quality and safe patient care.
- Research evidence has identified the effect of PACSs on ICU clinical work practices, particularly with respect to the efficiency of work practices, clinical decision-making, and communication practices within the ICU and across the hospital.
- One of the most important potential benefits of health IT involves the incorporation of electronic decision support as an aid in the medical decision-making process. Research evidence has shown that when linked to CPOE systems, DSSs can increase adherence to evidence-based guidelines and lead to reductions in unnecessary and low-yield testing.
- Sociotechnical research perspectives highlight the importance of the interface between technical and human and social factors, along with the particular context in which they operate. Technology-enabled innovation in critical care settings needs to be accompanied by rigorous attention to the implementation, usability, and sustainability of health IT systems to ensure that they contribute positively to the quality and safety of care.

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The Holistic Approach Ultrasound Concept and the Role of the Critical Care Ultrasound Laboratory

ASHOT E. SARGSYAN | MICHAEL BLAIVAS | DIMITRIOS KARAKITSOS

Overview

The approaches to examination of patients by clinical providers has evolved with the growth of medical knowledge and expectations of quality care. Though still primarily relying on their senses, physicians have been adding basic equipment (e.g., scale, stethoscope) and more complex devices (e.g., scopes, sphygmomanometer) to patient evaluation standards. In the intensive care unit (ICU), the diagnostic process is rather complex and continuous, and physical examination is deprived of several basic elements, such as pain assessment and general patient cooperation. Therefore, intensivists tend to rely on adjunctive diagnostic tools. The addition of critical care ultrasound (CCU) to the patient examination arsenal has been a major development during the last decade. *The method fits naturally in the logic of the initial assessment process and, because of its repeatability, also in the continuous monitoring of these highly variable patients*. As a generous source of real-time information, CCU shares a pedestal only with the physical examination itself.[1,2]

Notwithstanding the ample supporting evidence vividly exhibited throughout this volume, implementation of CCU is still in its early stages. Further large-scale growth depends on recognition of the evidence, acceptance by leading organizations, further development and miniaturization of equipment and data-handling facilities, training and cross-pollination of expertise, clarification of administrative and financial aspects, and other factors. Physicians are gradually recognizing the benefits of implementation of CCU for themselves and for their patients. Gradual implementation of CCU will eventually lead to stratification of physicians and facilities into those that know and use the advanced CCU support and those that do not.

One overarching and powerful measure capable of tipping the balance toward accelerated maturation and phasing in of CCU is the development and promotion of a high-level, conceptually strong, and realistic approach. This chapter does that by further analyzing the holistic approach (HOLA) concept of CCU imaging that was introduced in Chapter 1. The HOLA concept defines *CCU as part of the patient examination by a clinician to visualize all or any parts of the body, tissues, organs, and systems in their live, anatomically and functionally interconnected state and in the context of the whole patient's clinical circumstances*. The term "holistic" in the HOLA acronym is used in its original meaning in ancient Greek: to emphasize the importance of the whole and the interdependence of its parts. The term and the acronym must not be confused with "holistic medicine," which has a different patient population, scope, and methodology. The authors of this chapter define the following *overarching principles* that should drive implementation of a HOLA-based CCU model in the ICU:

1. CCU is applicable in a "head-to-toe" fashion to follow and augment the process of *physical examination* and has an instantaneous effect on patient management.
2. Although *specific CCU techniques* deal with particular anatomic or pathologic entities, any tissue in any location in the body is subject to *generic scanning*.
3. A *basic battery* (profile) of CCU techniques can be adopted as a standard component of the bedside evaluation of *every ICU patient*.
4. *Specialized batteries* of CCU techniques can be implemented to best address the needs in specific clinical situations or patient categories.
5. Either CCU techniques or generic scanning should be categorized into *basic* and *consultant* levels. Basic techniques are performed by ICU team members. Consultant-level examinations that require radiology, cardiology, or other specialized expertise are supported by other teams external to the ICU but constitute a part of the overall imaging strategy in the ICU.
6. *System- and facility-level acceptance* is necessary for an appropriately planned and executed implementation process to gradually upgrade the conventional ICU to a "HOLA-capable" and, ultimately, an operational "HOLA-certified" status.
7. The *ultimate stage* of HOLA implementation is a *full-fledged CCU laboratory* with advanced equipment; clinical procedure support; archival, training, and broad quality assurance functions; and established interfaces with other hospital services and personnel.

Scope of Critical Care Ultrasound

One of the prevalent misconceptions regarding physician-performed ultrasound is the concern that it is done in lieu of comprehensive (referred) sonographic studies. Another source of confusion is the lack of a clear distinction between focused emergency ultrasound and CCU.

The scope of CCU is not to replace comprehensive sonography. CCU does not substitute for "radiologic" sonography, very much like Foley catheter placement does not make the urology service irrelevant; CCU replaces only studies that are largely futile in their solely retrospective significance. CCU performed by intensivists or other members of the ICU team augments the physical examination and has an instant effect on patient management. Moreover, it aids in dynamic monitoring of the constantly changing clinical status of ICU patients because of its bedside availability and repeatability. This dynamic monitoring capability is a distinct CCU feature that radiology routines can never adopt (e.g., recognize interstitial pulmonary edema and assess the effect of diuresis every 10 minutes). Most CCU techniques promise better outcomes only if used within the clinically driven time frame. Typically, still image–based, technician-performed studies are associated with delayed radiologist interpretation and serve different purposes.

Thus, CCU satisfies a need that is not currently met and is a highly rational opportunity to improve patient care that has no alternatives at this time. In this sense, CCU is rather similar to physician-performed focused emergency ultrasound—a similarity that at superficial glance makes the two methods appear identical. There are, however, major differences in principle. As part of initial patient assessment, emergency ultrasound usually answers *binary* (yes-no, either-or) questions. CCU answers binary questions too, but does not stop there because ICU patients rarely have a single problem to identify and monitor, and many new questions are often posed in the course of their stay. Following the clinical logic of intensivists, CCU in their hands seeks answers to questions that are not necessarily binary and often proceeds, as time and physician imaging experience permit, onto secondary questions and broader organ or system assessment. Another essential role of CCU is *monitoring* known problems and following the results of treatment measures or recovery from known states. Assessing and monitoring volume status, identifying return of peristaltic activity after major abdominal surgery, and evaluating the effectiveness of respiratory therapy are typical examples of CCU applications. Finally, a very important group of CCU applications are related to *procedure support*, and examples of such are numerous.

In the following section HOLA is explained as a concept that justifies and rationalizes the initial efforts (e.g., equipment procurement, training, planning, credentialing) at implementation of CCU and serves as a basis for planning a phased introduction of ultrasound into the ICU.

The HOLA Concept of Critical Care Ultrasound imaging

The HOLA concept of CCU imaging was introduced in Chapter 1. This textbook in its entirety is, in essence, a detailed description of HOLA. In all fairness, adoption of HOLA is a major, understandably difficult conversion of a physician's mindset and attitude toward changing the established routine of clinical practice. It takes effort to reconsider the notion that scanning is a prerogative of equipment-savvy technicians and image interpretation is a separate "darkroom magic" by radiologists. Such conversion requires realization and acceptance of the *unity and synchrony of scanning and interpretation* when performed by a clinician to see or rule out pathologies in real-time by using somewhat unconventional techniques and implementing complex monitoring protocols.[3]

Applying all possible CCU techniques in imaging a single patient is an obvious exaggeration. However, to explain the HOLA concept, let us consider a fictional scenario in which all CCU techniques are conducted in a single "head-to-toe" examination, like an ultrasound "cocoon" wrapping the entire body surface. For example, encountering a septic patient with acute respiratory distress syndrome and other comorbid conditions is not rare in the ICU. The standard approach is to focus on pulmonary function, acid-base status, and blood gases, but lung ultrasound offers additional means of monitoring trends in lung aeration and edema. These patients may have severely compromised cardiovascular function, and effusions or diffuse cerebral edema may develop by various mechanisms. Foci of possible infection could be located "outside the lung" (e.g., abdominal source). Rapid progression toward multiple organ failure syndrome may be the dominant clinical picture and requires monitoring of renal function as well. Numerous, even more complex clinical scenarios are encountered in routine ICU practice.

From the *facility perspective*, acceptance of HOLA means that all known specialized diagnostic, monitoring, and procedure support CCU techniques are either operationally available or awaiting implementation, and moreover, every part of the human body is a potential target of generic scanning. In a short diversion, let us parse the *generic scanning* principle. Besides the special techniques that are usually based on published evidence, HOLA includes generic scanning based on recognition of tissues and organs by the physician. After specific training and initial practice, the *real-time gray-scale image* on the screen is correctly perceived as a *live cross section* underneath the transducer. Once physicians start recognizing the live anatomy on the screen, their *medical knowledge becomes a strong quality assurance mechanism*. The HOLA concept perceives generic anatomic assessment by CCU as another visual source of structural information from deeper tissues underneath the skin that are hidden from human vision and other senses. Surely, excellent knowledge of normal and pathologic anatomy is an essential prerequisite for successful interpretation of such information. Diagnostic dilemmas occur daily in the ICU, and *expert consultation* is necessary on many occasions. For example, echocardiography requires expert input to correctly assess anomalies that an intensivist cannot adequately clarify. The recent implementation of advanced echocardiographic techniques such as tissue Doppler and three-dimensional imaging into routine practice further underlines the importance of such input. Other techniques (e.g., abdominal or vascular ultrasound) may require additional review or a second opinion when the initial assessment is inconclusive. The introduction of invasive techniques such as *intravascular and endobronchial ultrasound* suggests the creation of on-site suites technically capable of supporting these applications. Moreover, new methods such as *ultrasound molecular imaging* and image-guided interventional procedures will continue their growth. Experimental studies targeting pathologic processes with *contrast-enhanced ultrasound*, such as angiogenesis, inflammation, thrombi, and plaque formation, have shown promising results and require special expertise and conditions.[4-8] Notably, therapeutic agents can be attached to the particles of contrast agents to enhance drug delivery and effect (e.g., continuous transcranial Doppler was suggested to augment tissue plasminogen activator–induced arterial recanalization in stroke).[8,9] Future studies are needed to validate the safety profiles, as well as the diagnostic and therapeutic indications, of the aforementioned and other highly specialized techniques. Assimilation of all established and realistically anticipated ultrasound techniques into the HOLA implementation goals appears to be an essential step-up for ICU services that will remain competitive for a reasonable number of years.

The HOLA concept and the set of overarching principles for its implementation outlined in the beginning of this chapter foresee basic and specific batteries of CCU techniques and generic scanning areas. Even though these batteries will probably differ between facilities and evolve in time, we suggest a number of illustrative examples (Table 57-1). Analyzing all goal-directed HOLA examination profiles is beyond our scope. Mastery of all techniques by the ICU team requires considerable education, training, and experience. Limitations do exist regarding the applicability of several CCU techniques, as analyzed in detail throughout this edition.

Physician Education, Training, and Competence

In 2001 the American College of Emergency Physicians issued guidelines that defined the use of emergency ultrasound. Indications recommended for emergency ultrasound were trauma, pregnancy, emergency echocardiography, abdominal aorta imaging, and biliary, renal, and procedural ultrasound. The guideline was updated in 2008 to include new core applications such as ultrasound for deep venous thrombosis, soft tissue and musculoskeletal imaging, and thoracic and ocular imaging.[10,11] Recently, the American College of Chest Physicians and La Société de Réanimation de Langue Française published their recommendations after a consensus meeting to define the use of ultrasound in the ICU. This consensus suggested that all intensivists should achieve competency in basic CCU techniques such as pleural, lung, abdominal, diagnostic, and procedural vascular ultrasound and basic critical care echocardiography.[12] Notwithstanding the existence of recommendations as a basis for the future training of intensivists in ultrasound techniques, there is still a significant gap in ultrasound education, training, and accreditation. We wish to underline, however, that a tactical approach to CCU implementation based on a solid HOLA concept is a high-level demand that should no longer be overlooked by health authorities at all levels.

With adoption of the HOLA concept of ultrasound imaging by an ICU facility, ultrasound machines are placed in each unit (one machine for every two beds at the bedside) for use by all intensivists and for all patients. In such a setting, implementation of all known CCU techniques is significantly enabled. However, the array of special CCU techniques available depends on the combined CCU knowledge and experience of the intensivists present on a given shift. Moreover, thorough review of ambiguous results may require an expert such as a cardiologist or a radiologist (see Table 57-1). As in other ultrasound settings, CCU remains highly *operator dependent*, and the *level of competency* varies among operators and depends on training programs, background, and experience. In most European countries and in the United States, educational programs are gradually being introduced with specific requirements for various levels of competency in ultrasound applications.[1,2]

TABLE 57-1 Goal-Directed HOLA Critical Care Ultrasound Examination Profiles

Goal: Diagnosis and Monitoring	Technique	Level*	Expert Input†	Score
Central nervous system disorders (brain edema and intracranial hypertension, vasospasm, etc.)	Transcranial Doppler	High	2	4
	Ocular ultrasound	Medium	1	1
Lung disorders (consolidation, atelectasis, interstitial edema, pleural effusion, pneumothorax, etc.)	Lung and pleural ultrasound	Medium	1	1
Mechanical ventilation (assess side effects of mechanical ventilation, recruitment strategies, weaning potential, etc.)	Lung and cardiac ultrasound	High	2	4
Basic cardiac evaluation (pericardial effusion, left ventricular function, etc.)	Basic echocardiography	High	1	2
Cardiovascular disorders (cardiovascular structural and functional abnormalities)	Advanced echocardiography	Advanced	2	6
	Vascular ultrasound	High	2	4
Extended focused assessment with sonography for trauma	Basic abdominal, pleural, and lung ultrasound	Medium	1	1
Exploration of various abdominal targets (solid organs, gastrointestinal and urogenital systems, vessels, etc.)	Abdominal ultrasound	High	2	4
Evaluation of venous circuits (exclude thrombosis, vena cava analysis, etc.)	Vascular ultrasound	Medium	1	1
Soft tissues and musculoskeletal abnormalities (sinusitis, abscesses, hematomas, lymph nodes, fractures, etc.)	Surface and musculoskeletal ultrasound	Medium	2	2
Simple procedures (paracentesis, cannulation of arteries and veins, regional anesthesia, etc.)	Ultrasound-guided procedures	Medium	2	2
Surgical procedures (percutaneous nephrostomy, cholecystostomy, etc.) and other specialized applications (contrast-enhanced and endoluminal imaging, etc.)	Ultrasound guidance and other techniques (intravascular, endobronchial ultrasound, etc.)	Advanced	2	6
Complex evaluations (volume status, cardiac-lung interaction, multiple organ failure syndrome, etc.)	Combination of various ultrasound techniques	Advanced	2	6

*Level of expertise required to perform the examination (on a semiquantitative scale: basic = 0, medium = 1, high = 2, advanced = 3).
†Concomitant evaluation with other imaging, clinical, and laboratory data is necessary with all applied ultrasound techniques. The need for expert input to interpret the results of examinations is designated as 1 for unnecessary and 2 for necessary (or technique performed mainly by experts). The score (score = level of expertise × expert input) reflects the applicability of methods, with scores higher than 4 requiring extensive training and being more technically difficult; the opposite is true for methods with scores lower than 4. Scales were subjectively adjusted to comply with clinical notions and practices in Europe and the United States, as well as with the published literature.[1,2]

However, additional programs are clearly required to meet the growing demand for CCU education and training in most countries around the globe.

The Critical Care Ultrasound Laboratory

Clinicians often favor the use of ultrasound to avoid delays in patient assessment, thus exploiting the fast nature of the method and its immediate effect on patient management. However, the *effect of a specific examination on a particular patient may produce results that are anywhere in the continuum from highly specific and confident to indeterminate or nondiagnostic*. For purposes of integrity of the patient management record, documentation of each examination is essential, and so are trend monitoring across multiple repeated examinations, self- and cross-training of ICU team members, and quality assurance and analysis. Storage of the imaging data is also necessary for secondary review by experts and for reference and development of new techniques.

These considerations have led to a search for mechanisms to integrate CCU data and optimize the application of both diagnostic and procedural ultrasound. Hence, the idea of a *CCU laboratory* (CCUL) was formulated as a rational consequence of the suggested ultrasound model using a HOLA concept (Figure 57-1). A CCUL is, first of all, a data capture and archival capability unit within the ICU that uses in-hospital servers and can therefore be integrated into the well-established *picture archiving and communication system* (PACS). Application of a PACS minimizes consultation responding time and facilitates image interpretation and quality control (Chapter 56). Moreover, the growing availability of telemedicine options further enhances the expert consultation potential. Notably, in facilities with existing electronic medical record systems, the CCU imaging data could be integrated with other clinical, imaging, and laboratory data in the same platform or on the distributed network. Advocates of simple and standalone use of ultrasound may consider this centralized archival concept complicated and redundant. As the HOLA ultrasound concept is adopted and implemented, use of CCU and its effects on patient outcomes grow dramatically, and thus it becomes necessary to keep the imaging data *well organized* and *functional* as part of an overall approach to patient management. Another important feature of a CCUL is an actual *physical suite* within the unit that includes a *central station* with optimal features for specialized procedures such as relatively invasive diagnostics and ultrasound-guided interventions on a cart-based full-featured machine.

In large multivalent units, a CCUL as a physical space must also have a dedicated area for *cleaning* and *maintenance* of the portable machines, storage of transducers and accessories, and minor testing and upgrades. A CCUL must have one or more *image review workstations* with professional-grade monitors for self- and cross-training of ICU staff and consultations. This area, as well as a conference room, can be separate or shared for all similar staff activities. Training plus practice for invasive procedures on phantoms and models justifies a separate multifunctional nonpatient area.

The operational cost of a CCUL should be properly evaluated, but no studies are available at this time to offer reference estimates. In view of the availability of portable ultrasound devices, along with the rapidly spreading integration of PACSs into hospital practice, we speculate that this cost may in fact be reasonable. Intensivists could enrich their knowledge and experience by continuous interaction with experts, and the training

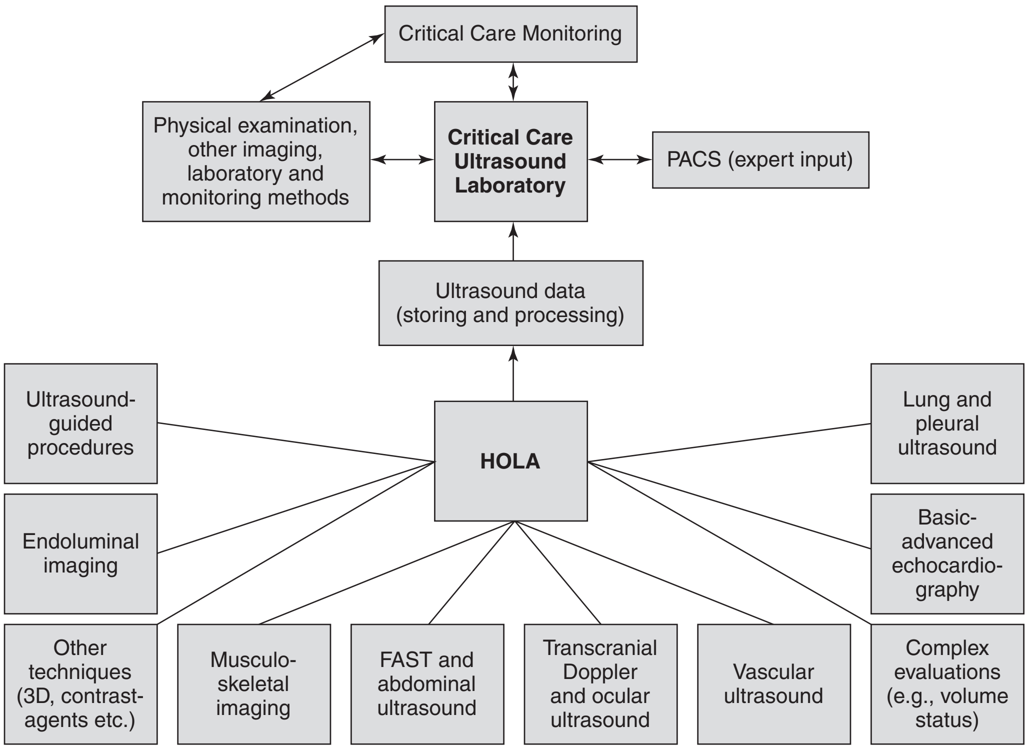

Figure 57-1 Diagram illustrating the capture of ultrasound data and archival capability of a full-fledged critical care ultrasound laboratory (CCUL) being integrated into intensive care unit (ICU) diagnostic and management logistics.

capabilities and benefits for residents, medical students, and operators are endless. Research activities could be strengthened and interactive clinical practice would flourish.

The benefits of adopting a HOLA ultrasound concept for critical care patients cannot be overstated, and the cost of equipment, training, physician credentialing, and other measures appears to be justified. Although current implementation of CCU is *sporadic* and usually initiated by one or two occasional ultrasound enthusiasts on the ICU team, sufficient evidence is already available not only to support such initiatives but also to integrate implementation of CCU into long-term plans of service or facility development.

Further studies are required to validate methodology issues and document the benefits of running a CCUL. The need for specific functions of the CCUL concept, however, will eventually become evident. Future policies and planning by health authorities and institutional boards are essential as well. Key issues such as cost-efficiency, accreditation, requirements, and regulations to ensure safe function of CCULs should equally be addressed.

In the second half of the 20th century there was a general public notion that everything is achievable through technology. This notion remains very strong in modern hospital settings. However, technology should serve and not guide and usurp medical practice, which should be driven by opportunities to improve the standard of care. In that sense, advances in critical care patient management and ICU organization are steps in the right direction, and ultrasound technology has a great potential to support such developments. The primary anticipated benefits of adopting the HOLA concept of CCU imaging are improvement in patient care and outcomes and ICU bed efficiency. Secondary benefits are also numerous and spread beyond the hospital setting since many *CCU solutions* could be applicable to *emergency fields and environments with limited resources*. We highlighted in Chapter 50 the perspective of a very unique medical field, space medicine, as a user of yet another “flavor” of ultrasound diagnostics that combines many features of HOLA ultrasound imaging with telemedicine as it seeks new options to optimize safeguarding of the health of crew members during long-duration space missions.[13]

Pearls and Highlights

- HOLA is a concept that relies on the universality and hands-on nature of ultrasound imaging and expects ultrasound to become a part of the nominal evaluation of every ICU patient, along with other physical examination components; it has an instant effect on patient management.
- A full-fledged CCUL may optimize the implementation and application of HOLA CCU and facilitate regular input by experts, maintain the equipment park, and ensure staff training and quality control.
- Cost-efficiency, credentialing, accreditation, requirements, and regulation issues should be addressed to ensure safe and effective function of a CCUL.

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58

Ultrasonography: A Basic Clinical Competency

RICHARD HOPPMANN

Overview

Ultrasonography has undergone a transformation in the past 2 decades that is fundamentally changing the way that medicine is taught and practiced. Technologic advances have taken ultrasound to the bedside or point of care in the form of laptop and pocket-sized devices that produce high-quality digital images that can be saved in multiple formats or sent anywhere in the world for review.

Because of the portability of ultrasound today, clinicians have real-time information to make diagnoses and management decisions virtually anywhere that they encounter patients, from traditional medical facilities such as the critical care unit to the site of natural disasters and the battlefield. The newer systems are user-friendly and much less expensive than the larger traditional machines, which makes them accessible to many more health care providers.

Ultrasound is a safe imaging modality and should be considered "first" in many clinical scenarios when imaging is indicated, especially those involving children to avoid the risk for cancer from ionizing radiation (i.e., ultrasound versus computed tomography for the diagnosis of appendicitis).[1-3] The cost of ultrasound imaging is also considerably less than that of most other imaging modalities, and it can provide equivalent or better images and thus decrease overall health care cost. When compared with other imaging modalities, ultrasound has the added advantage of providing dynamic examinations, such as evaluation of the shoulder for rotator cuff disease or real-time guidance of procedures such as central line placement and thoracentesis.

If ultrasound has all these advantages, why is it not being used more commonly? A major factor limiting the widespread use of ultrasound is the lack of adequately trained practitioners, for despite the technologic advances and ease of use of the new ultrasound units, there still remains a significant operator-dependent component that requires training and practice. A considerable knowledge base is also needed for accurate interpretation of images and decision-making relative to ultrasound.

In this chapter the argument is made that ultrasound should be considered a basic clinical competency across the spectrum of medical education, including critical care medicine. Ultrasound training should begin in medical school and be continued throughout the professional career of most physicians. The concept of competency-based education for ultrasound will be advanced, as well as recommendations for developing competency-based ultrasound curricula.

Ultrasonography in Medical Student Education

Ultrasound was introduced into medical student education in the 1990s and proved to be a valuable teaching tool in courses such as anatomy, physiology, and physical examination.[4-6] Ultrasound education gradually expanded into the clinical years of medical school, especially in the discipline of emergency medicine.[7] The clinical application of ultrasound being taught is as a focused or point-of-care examination designed to answer a specific clinical question such as "Is there a gallstone in the gallbladder that helps explain this patient's right upper quadrant abdominal pain?" or "Is there overall normal heart function in this patient with shortness of breath?" This point-of-care ultrasound approach has been highly developed in the emergency department setting, and the American College of Emergency Physicians has led the way in defining the necessary training and competencies in point-of-care ultrasound.[8]

In recent years, ultrasound has been successfully integrated across the entire medical student curriculum. Hoppmann et al reported on 4 years of experience with an integrated ultrasound curriculum.[9] As part of the curriculum, all students at the end of the anatomy course in the first year of medical school are observed individually and evaluated for their ability to perform ultrasound on standardized patients and capture and identify anatomic structures in a series of specific ultrasound images. Such structures included the kidney, liver, and Morison pouch in the right upper abdominal quadrant; kidney and spleen in the left upper abdominal quadrant; urinary bladder in the pelvis; carotid artery and internal jugular vein in the neck; and parasternal long-axis view of the heart. The mean percentage of correct responses after 3 years of these examinations was 97.1%. In addition, from student surveys of the same ultrasound curriculum, more than 90% of students thought that the curriculum had enhanced their medical education, allowed increased clinical correlation with basic science instruction, and improved their understanding and skills of the physical examination.

These findings of students learning basic ultrasound well and reporting that the addition of ultrasound had enhanced their education are consistent across the vast majority of reports in the literature on medical student ultrasound education.

Ultrasound across Multiple Specialties

Widely used in radiology, cardiology, and obstetrics and gynecology for several decades, ultrasound is now rapidly expanding across many specialties from pediatrics to critical care medicine and orthopedic surgery.[10] In addition, the list of clinical applications for ultrasound has grown considerably in recent years and will probably continue to grow as more practitioners explore new applications of ultrasound to improve patient care and safety in their particular specialty.

With expanding applications of ultrasound across so many specialties, a persuasive argument can be made that every medical student should learn basic ultrasound similar to learning auscultation, since each student will probably encounter a need to use ultrasound in practice regardless of career choice. One can also make the argument that even if medical graduates do not perform ultrasound themselves, their knowledge of the indications, applications, and limitations of ultrasound will result in more appropriate requests for ultrasound studies and a better understanding of the results of such studies.

Introducing ultrasound into medical student education is an efficient and effective way to train a large number of individuals who will be not only the next generation of practitioners but also the ultrasound educators of the future. Medical education is generally slow to change, and adding something new to an already crowded medical student curriculum requires strong justification.

Competency-Based Medical Education

If ultrasonography is to be a basic clinical competency, it is essential that educational programs be developed that result in competent users of this technology. In its most basic definition, competency would be the ability of an individual to do a job properly.[11] There has been increasing pressure in recent years in medical education globally to move from a time- and process-based system of training to a competency-based training framework.[12]

Frank et al outlined six stages in planning competency-based medical education.[13] Step 1 calls for identification of the abilities needed by graduates to provide a high standard of patient care based on evidence and expert consensus. Starting with the abilities needed by the practitioner and then working backward to develop the appropriate educational program constitute the essence of competency-based education. Step 2 calls for well-defined competency components that fit together to define a competent practitioner. In step 3, milestones are determined along the developmental path to competency. These milestones are sequenced in a logical fashion to form a foundation of skills and knowledge on which to build to the desired level of competency. In step 4, the educational activities, experiences, and instructional methods are determined to reach these milestones. Step 5 calls for assessment tools to measure student progress, and finally, step 6 requires that a method be in place to evaluate the educational program as a whole.

Ultrasound competency is well suited for this educational approach because it has objective and measureable components and much has been defined with respect to the knowledge and skills that are needed in the clinical arena. Emergency medicine has defined many of these necessary skills with respect to point-of-care ultrasound. Various specialties and subspecialties throughout medicine are defining the core ultrasound knowledge and skills needed within their fields. Since the various specialties better define the abilities needed in their respective fields, medical student educators can use these competencies to develop curricula that will form a foundation to prepare students for further ultrasound training in residency regardless of the career specialty chosen. Having students enter residency with a solid foundation of knowledge and skills in ultrasound will allow them to more easily and quickly develop more sophisticated ultrasound abilities for their particular specialty.

Critical Care Ultrasound

Dozens of applications of ultrasound have been identified in critical care medicine.[14] It has also been shown that ultrasound examination reveals significant unsuspected clinical abnormalities in patients admitted to the intensive care unit.[15,16]

A review of intensive care medicine in 2011 highlighted a number of applications and trends of ultrasound use in critical care medicine, among which were the rapidly evolving use of ultrasound to detect pneumothorax, intracranial hypertension by measuring the diameter of the optic nerve sheath, and gastric fluid with the potential to reduce the risk for aspiration during endotracheal intubation.[17]

There is little doubt that ultrasound should be a competency of critical care practitioners; in fact, there was 100% agreement among a panel of international experts in critical care ultrasonography that "general critical ultrasound and basic critical care echocardiography should be mandatory in the curriculum of intensive care unit physicians."[18] The expert panel defined clinical competencies in the field, and these are serving as a practical guide for physicians seeking training and those who train physicians in critical care ultrasonography.[19]

Electronic Portfolio

Determining a student's competency formatively during medical school and then at the end of a course or medical school could be done and documented by way of a student ultrasound electronic portfolio. There are numerous advantages of an electronic portfolio for undergraduate medical education.[20] Students can document their activities and provide evidence to demonstrate their development of competencies. Portfolios also provide reflective practice and are an excellent platform for dialogue and mentoring with faculty.

To address the spectrum of knowledge, skills, and behavior that pertain to ultrasound competency, one might consider a four-component learner portfolio. The four components would include web-based interactive ultrasound learning and assessment modules, an archive of images saved over a web portal and evaluated for quality and interpretation, ultrasound simulation results, and video-recorded, objectively structured clinical ultrasound examinations. This last component would have the added advantage of allowing evaluation of the interactive and professional behavior between the learner and patient. Such a four-component portfolio would enable identification of milestones and progress along the path to competency.

Conclusion

Ultrasound has the potential to transform medical education and the practice of medicine for the benefit of patient and learner alike. Ultrasound is a safe and valuable teaching and clinical practice tool. Its expanding role in clinical applications, multiple medical specialties, and clinical settings speaks to its value for a wide variety of practitioners. Ultrasonography should be given serious consideration as a basic clinical competency for all physicians and many other health care providers. Ultrasound instruction should begin in medical school with a competency-based curriculum and continue throughout the professional career of the practitioner. There is strong support for ultrasound as an essential critical care medicine competency. An electronic ultrasound portfolio could prove to be an effective way to manage ultrasound curricula and postgraduate training and document ultrasound competency in practitioners over time.

Pearls and Highlights

- Ultrasound is a safe imaging modality for users and patients.
- Ultrasound is a valuable teaching tool for basic science and clinical medicine.
- Medical students can learn ultrasound basics very well.
- Ultrasonography can improve patient care and safety and decrease health care cost.
- Ultrasonography has applications across many specialties in medicine and can be applied in virtually every clinical setting.
- Ultrasound provides dynamic imaging.
- The size and cost of ultrasound systems have made them more accessible to practitioners.

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Integrating Ultrasound into Critical Care Teaching Rounds

SASSIA DONALDSON-MORGAN | MICHAEL YEE | LEWIS A. EISEN

Overview

Significant advancements have been made in the use of ultrasound technology since its inception in the early 1950s.[1] These advances have revolutionized the practice of critical care medicine. Currently, clinicians in the intensive care unit (ICU) have at their disposal a tool at the bedside that augments the physical examination and is safe, portable, noninvasive, and readily available.

Safety

Ultrasound technology uses sound waves, and through reflection, refraction, and attenuation of these ultrasound beams, image acquisition occurs, thus limiting the patient's exposure to radiation, unlike chest radiography and computed tomography.[2,3] The lack of radiation exposure also allows multiple sites to be evaluated repeatedly with minimal risk to the patient (Chapter 1).

Immediate assessment of hemodynamically unstable patients is possible with the use of ultrasound, and the need for transportation with possible complications is reduced.

Availability

Ultrasound is available to intensivists 24 hours per day, 7 days per week. It is also under control of the primary provider of care, so it is readily accessible when needed to avoid delay in diagnosis and therapeutic intervention. Also, bedside ultrasound enables immediate reassessment of patients after therapeutic interventions to confirm appropriateness of the care instituted.

Time Efficiency

Bedside ultrasound enables immediate integration between the clinical scenario that requires investigation and the operator. This allows a more focused, goal-directed evaluation of hemodynamically unstable patients with immediate interpretation of data and implementation of personalized therapy.[4]

On review of the literature, the time needed to obtain information during bedside ultrasound evaluation is very brief given the magnitude of information obtained during each evaluation (Table 59-1). Appropriate, focused examinations can be performed as part of routine practice on teaching rounds.

TABLE 59-1 Time Needed to Obtain Information during Bedside Ultrasound

Investigation	Average Time
Lung ultrasound	2-3 min[5,6]
Internal jugular vein cannulation (mean start until vessel located)	9.5-13.8 sec[7-10]
Subclavian vein cannulation (mean start until vessel located)	26.8 sec[11]
Doppler ultrasound	11.7-15 min[12-14]
Transthoracic echocardiography	6-10.5 min[15-17]
Inferior vena cava measurements	5-5.8 min[18,19]

Critical Care Ultrasound is Clinically Useful

Goal-directed echocardiography enables qualitative assessment of left and right ventricular size and function, identification of pericardial effusion and evaluation for tamponade physiology, measurement of internal vena cava (IVC) diameter, and assessment of respiratory variation to determine preload responsiveness.[17,20,21] Critical care ultrasound (CCU) facilitates bedside detection of pleural fluid and pneumothorax and can be used to guide thoracocentesis for diagnostic-therapeutic purposes, as well as other invasive procedures (e.g., placement of thoracostomy tubes, paracentesis, abscess drainage). CCU guides arterial and central venous cannulation and facilitates the placement of peripherally inserted central catheters and hemodialysis catheters.[22] CCU detects venous thrombosis[14] and free intraperitoneal and pericardial fluid (focused assessment with sonography for trauma) and facilitates the evaluation of patients for acute renal dysfunction[23-25] and volume status.

Teaching Tool

CCU can be used in conjunction with the physical examination to improve accuracy and clinical utility and enhance the teaching of various physiologic principles.[26] It can provide immediate feedback to confirm or refute the physical findings. For example, within a few minutes of using CCU the cause of life-threatening conditions triggering hypotension can be elucidated or excluded from the differential diagnosis. If a resident hears a typical murmur of mitral regurgitation on physical examination, this can be confirmed within minutes with bedside echocardiography. Immediate feedback enhances learning.

A Typical Day on Intensive Care Rounds at Montefiore Hospital

The value of CCU can best be appreciated during routine patient care rounds. It would be ideal to perform focused ultrasound examinations during this time, when information is gathered and used to formulate management plans. A characteristic day in our 14-bed medical ICU is described next.

Bed 2. A morbidly obese 23-year-old woman with drug-induced liver failure and subsequent aplastic anemia was admitted to the ICU with neutropenic fever and septic shock secondary to gram-negative bacteremia. The patient is receiving appropriate broad-coverage antibiotics. She is febrile and hypotensive and requires increasing dosages of vasopressor support. Focused echocardiography is performed to evaluate left ventricular function (ruling out cardiogenic shock), the presence of pericardial effusion (ruling out cardiac tamponade), and evidence of right ventricular dilatation and strain (acute pulmonary embolism). The IVC is visualized to determine the diameter and presence of respiratory variation while on mechanical ventilation (intravascular hypovolemia). The examinations show that the heart is hyperdynamic and that significant respiratory variation suggestive of distributive shock is present. The patient is given a fluid bolus. In light of the new fever, all preexisting invasive catheters will be removed and replaced. Since this patient has underlying thrombocytopenia, the use of real-time ultrasonography to guide central venous catheter and arterial catheter placement will help achieve higher first-pass success and reduce complications.

Bed 3. A 47-year-old man with hepatitis C cirrhosis was admitted because of upper gastrointestinal hemorrhage secondary to esophageal varices. The patient is now undergoing evaluation for possible liver transplantation. The transplant surgeon believes that he is volume-overloaded, but the hepatologist believes that he is volume-depleted. Central venous pressure measured via his right internal jugular catheter is 6 mm Hg. Focused echocardiography and IVC analysis reveal normal cardiac function with an IVC diameter of 2.5 cm. The patient is not intravascularly depleted and will not benefit from further fluid administration.

Bed 5. A 63-year-old man with chronic obstructive lung disease was admitted for hypoxic respiratory failure secondary to multilobar pneumonia. The patient still requires support from the mechanical ventilator. A portable chest radiograph is obtained but interpretation is limited because of excessive soft tissue and poor technique. It is difficult to distinguish on a chest radiograph whether a pleural effusion, worsening infiltrates, or atelectasis is present. Lung ultrasound shows the presence of a moderate right pleural effusion, probably parapneumonic. A pigtail drainage catheter is placed at the bedside by the ICU team under direct ultrasound guidance, and 1 L of fluid was drained.

Bed 7. A 29-year-old man with mixed connective tissue disease (MCTD) was admitted for severe myositis and respiratory distress. The patient is taking corticosteroids, and generalized weakness developed during his ICU course. Arterial blood gas analysis now shows mild respiratory acidosis. Ultrasound is used to assess the patient's diaphragm. No change in diaphragmatic thickness is noted during inspiration, which suggests diaphragmatic weakness or paralysis, in part attributable to the patient's MCTD. In concert with the rheumatology service, a course of high-dose corticosteroids was started.

Bed 8. A 70-year-old man was admitted for chronic pancreatitis and lower gastrointestinal bleeding. The patient has a urinary Foley catheter in place and just 35 mL of urine drained over the past 2 hours. The nurse mentions that there was difficulty inserting the catheter. Ultrasound is used to visualize the bladder and confirm proper catheter placement. Assessment of the IVC showed significant respiratory variation. The patient is probably hypovolemic and is given a fluid bolus based on the ultrasound findings. Finally, his urinary output improves.

Bed 12. A 57-year-old woman with acute promyelocytic leukemia was admitted for hypoxemic respiratory failure that developed within hours after receiving a transfusion of red blood cells and plasma. A chest radiograph showed bilateral infiltrates consistent with cardiogenic pulmonary edema or acute respiratory distress syndrome (ARDS). Diuretics were ordered for the patient before coming to the ICU. CCU shows that the patient's left ventricular function is normal and the IVC has significant respiratory variation. These findings suggest that ARDS has developed secondary to transfusion-related acute lung injury and that she does not have cardiogenic pulmonary edema. The order for diuretics was canceled.

Bed 13. An 83-year-old woman with monoclonal gammopathy of unknown significance was admitted to the ICU because of an acute change in mental status and hypoxia. She was initially hospitalized for cholecystitis, but her hospital course has been complicated by left tibial and fibular fractures after a fall. She is currently receiving a heparin infusion empirically. A bedside examination with compression ultrasonography is performed immediately on rounds, and a left common femoral venous thrombus is found. This finding supports the suspicion of pulmonary embolism. The patient will continue full anticoagulation.

Bed 14. A 77-year-old obese woman with chronic obstructive pulmonary disease was admitted because of hypercapnic respiratory failure. Her course is complicated by the development of new atrial fibrillation, for which she is now receiving a heparin infusion. Overnight, swelling developed in her left shoulder and the upper part of her chest, and a recent decrease in her hemoglobin level was documented. Bedside ultrasound examination of the swollen area shows a new fluid collection in the subcutaneous tissue over the left shoulder and chest. The findings suggest a probably expanding hematoma. The heparin infusion is stopped and surgery is consulted.

CCU-derived information augments the history and physical examination and can lead to significant changes in management plans. The use of CCU for diagnostic and therapeutic purposes should become an integral part of every critical care unit's rounds.

Pearls and Highlights

- Focused CCU can answer clinically relevant questions quickly.
- Focused CCU has great value as a teaching tool for confirming or refuting the findings on physical examination and for reviewing basic physiology and anatomy.
- Focused CCU can aid in bedside teaching of the differential diagnosis of common reasons for admission to the ICU, such as hypoxemia, shock, or renal failure.

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Training and Competence in Ultrasound-Guided Vascular Access

MASSIMO LAMPERTI

Overview

Despite well-established evidence on the use of ultrasound for placement of any vascular access,[1] a formal training program on how to perform ultrasound-guided vascular access (UGVA) and how to certify adequate competence has not been clearly defined.[2,3] According to recommendations by the National Institute for Clinical Excellence, those involved in UGVA should undertake appropriate training to achieve competence.[4] Defining a competent practitioner in objective terms is a difficult task. Recently, the American Society of Echocardiography declared that training in UGVA should include a minimum of 10 proctored procedures, but the learning curve needed to perform these procedures was not defined, nor was it specified who should be considered expert and supervise new users.[5]

Evidence-based guidelines for defining a common educational process and establishing credentialing for any type of UGVA that can be considered as a model for any kind of training course in UGVA were recently published by the World Conference on Vascular Access.[6] The guidelines emphasized that the use of ultrasound reduces insertion-related complications, increases the success rate at first attempt, assists in selection of the correct vascular device according to safety, and enables preservation of veins.

Didactic Education

Educational programs facilitate a reduction in delayed complications such as infection and thrombosis.[7,8] The didactic contents of UGVA courses should be specifically directed at how to perform UGVA. Clinicians' knowledge of certain subject areas and competence in device insertion affect the rate of UGVA-related complications. The following topics should be discussed in formal educational training programs:

- Ultrasound physics: characteristics of sound waves, effects of interactions with ultrasound waves, and creation of image from ultrasound beams
- Sonographic anatomy of relevant structures such as vessels, nerves, bony structures, soft tissues, muscles, lung, pleura, and basic cardiac anatomy
- Knobology and interpretation of vascular images (transverse and longitudinal views) and needle visualization (out of plane and in plane)
- Techniques for insertion and assessment ("4 P's" technique: preprocedure scanning of relevant ultrasound anatomic structures, preparation of a sterile field and sterile ultrasound probe for vascular access, puncture of the vein or artery, placement of catheters)
- Sonographic detection of the tip of the catheter (contrast-enhanced echocardiography[9])
- Evaluation and management of complications: accidental carotid or posterior venous wall puncture, hematoma, pneumothorax, and abnormal position of the tip of the catheter
- UGVA in neonates and pediatric patients and ultrasound-guided cannulation of peripheral veins and arteries

All didactic content should be included in a training manual so that trainees can read it before beginning the didactic portion of the training. A minimum of 6 to 8 hours of didactics has been suggested. Theoretic competence should then be evaluated with a multiple-choice test that has at least 100 questions. The trainee must pass the test with at least 70% correct answers before proceeding to hands-on training.[6]

Simulation Training

Training laboratories should offer a variety of ultrasound machines to facilitate understanding of their basic functions such as depth, gain, and freeze (knobology). Training should start with examination of normal vascular anatomy in healthy volunteers and with hands-on simulation (models). Several inanimate models of vascular access are available. The best simulation model should not only include vessels but also mimic the normal body anatomy in terms of muscles, soft tissues, and bones. Inanimate animal models such as turkey breasts may be useful to demonstrate these anatomic findings. In the future, virtual simulators could be useful for measuring the correct hand-eye coordination of the trainee. Although it is not possible to include visualization of abnormal vascular anatomy in inanimate models, a collection of videos should be incorporated into the didactic material to show all significant abnormal findings during preliminary evaluation of the vessels before cannulation (e.g., intraluminal thrombosis, significant collapse of the internal jugular vein during inspiration). Trainees should complete 6 hours of hands-on training on normal human volunteers for detection of normal ultrasound anatomy and 4 hours of hands-on training on inanimate models.[2,6]

Learning Curves and Training Time

Application of the learning-curve concept to UGVA placement results in a 50% reduction in major complications during the learning process. There is still no evidence to establish the ideal number of supervised procedures for trainees to reach the learning curve.[2,3,5] The main goal of supervision is to guide the trainee in avoiding major complications while performing the procedure so that the required minimal skill competence with the lowest rate of major and minor complications can be achieved. The suggested number of tutored procedures to achieve minimal learning curves ranges from 10 to 25 UGVA placements, but this number could be different in trainees already experienced in placement of a central venous line, as well as if minor complications are to be considered.[10] Research should be conducted to establish a suggested number of procedures for reaching the learning curve benchmark or for calculating a personal learning curve according to the time needed to successfully perform UGVA.

Accreditation and Level of Performance of Ultrasound-Guided Vascular Access

After appropriate tutored training, the trainee should be examined according to an objective step-forward checklist called the *Global Rating Score* (Figure 60-1).[11] This final audit evaluates levels of a trainee's performance. In case of failure, the trainee

ULTRASOUND GUIDED VASCULAR ACCESS TRAINING EVALUATION CHECKLIST: Global Rating Scale

Operator: ……………………….... Date …… /….. /…… Supervisor…………………………....................

Scale: Level 0: Not completed

Level 1: Novice: Uses 'rules' to perform a ridged text book procedure. Requires lots of practice.

Level 2: Advanced beginner: Requires direction with many questions. Requires further practice.

Level 3: Competent but lacks self direction and is inflexible with performance.

Level 4: Proficient: Sees the situation as a whole. Performance guided by knowledge and expertise.

Performance Criteria	Level	Comments and Case Difficulty
1. Demonstrates effective ultrasound use for sizing of vessels and depth determination for establishing needle angle with gel, aseptic management of probe and ergonomic positioning of clinician and patient		
2. Identify relevant veins and arteries: internal and external jugular veins/carotid artery, Subclavian vein/artery, brachial vein, basilic vein, cephalic vein		
3. Differentiate veins from arteries based on anatomic position, compressibility, respirophasic changes, views via in-plane and out-of-plane orientation, can identify vascular thrombosis by visualisation or by compression		
4. Prepares patient's skin effectively and establishes and manages a sterile field during the procedure including maximum sterile barriers and ultrasound sterile cover		
5. Demonstrates knowledge of the effects of patient positioning on anatomical topography depending on type of placement: Trendelenburg, head rotation		
6. Demonstrates a skilful and accurate ultrasound guided venous puncture, management of supplies and sterile catheter preparation consistent with manufacturer instructions		
7. Demonstrates a good understanding of the steps leading to a successful CVC placement including: Guidewire manipulation, tunnelling (if necessary), dilator and peel away sheath use		
8. Appropriately secures the CVC post insertion, completes confirmation of tip, cleans probe and unit after use		

Case Difficulty

Extremely easy	Fairly easy	Average	Fairly difficult	Very challenging
1	2	3	4	5

Figure 60-1 Global Rating Scale. *(Adapted from Gentile DL: Applying the novice-to-expert model to infusion nursing,* J Infus Nurs *35:101-107, 2012; and Benner P:* Novice to expert: promoting excellence and power in clinical practice, *Menlo Park, CA, 1984, Addison-Wesley.)*

Declaration

Box 2: Satisfactory Standard
Grade 3 or 4 across all domains with the following provisos: No Level 1's or 2's. Please initial relevant box below Standard Achieved ☐ Standard **not** achieved ☐ *Failure to achieve the Standard by the participant requires a repeat of the supervised insertion until the Standard/Competency is achieved*

Please also complete the expert global evaluation below – this will be used to validate the process, and will not be used in assessing the candidates.

Confidential: Expert Global Evaluation - Overall Judgement
In order to help with setting standards and validating the process, please give your expert global assessment ***independent*** of the above grading – in other words, do you personally judge that the operator is a competent independent operator? Please check one of the two boxes below. The candidate: Is competent in inserting CVC's independently ☐ Is **not** competent to independently insert CVC's ☐

I CERTIFY THAT THE OPERATOR/PERFORMER ____

Medical Registration/License Number ____ _

Meets the criteria outlined in box 2 YES ☐ NO ☐

NAME OF SUPERVISOR ____

By signing this document you have supervised the entire insertion and confirm the participant's performance of each individual performance criteria and rated the level of performance

SIGNATURE OF SUPERVISOR ____

Medical Registration /License _________________________ DATE_____________________ _

EMAIL ______________________________ EMPLOYER ______________________

SIGNATURE OF OPERATOR/PERFORMER ____ _

EMAIL ______________________________ EMPLOYER _____________________________ _

Figure 60-1, cont'd

should have to continue practicing until all practical goals have been achieved. Once an ultrasound technique for access at a specific site is achieved, it may be applied to other sites accordingly. A quality control registry includes the recording of all complications (including minor ones such as multiple needle punctures) in a personal logbook.

Skill Learning, Maintenance of Skills, and Self-Training

It remains crucial that operators still undergo training and become proficient in the standard landmark method of insertion of a central venous catheter.[12] Maintenance of skills is also crucial. It is suggested that an operator could perform at least 10 UGVA placements per year to maintain minimal proficiency in this technique. Self-training is integral to proficiency in all operator-dependent techniques. Self-training should be used in conjunction with and not instead of didactics and instruction from supervisors.[13] Notably, whenever UGVA was performed by two operators, the experience of the physician controlling the needle did not influence procedural success or the complication rate, whereas both were significantly reduced if the physician manipulating the transducer was experienced.[14] This explains the fact that there is a learning curve associated with sonography and that guidance based on misinformation can harm patients.

Specific Requirements of Training for Ultrasound-Guided Vascular Access in Neonates and Children

UGVA in neonates and pediatric patients is a challenging practice, mainly because of reduced diameters of vessels and a thinner layer of subcutaneous fat, as well as the need for sedation to achieve a stable position and allow a safe puncture. However, UGVA in children and neonates reduces the frequency of failures during insertion of central venous lines and time to cannulation as a result of increased first-time success.[15,16] Specific technical requirements for safe performance of UGVA in neonates and children are small (2 cm), high-frequency (10 to 15 MHz), broadband transducers; short, steel microneedles (21 or 22 gauge); soft, floppy, straight-tipped nitinol guidewires; soft peel-away introducers; and short polyurethane catheters (8 and up to 12 cm in length). The operator should place the head of the child in a stabilized position by putting pillows under the head if it is turned to the opposite side of the cannulation. Operators should sit down while performing preliminary scans of all vessels. Once the vein to cannulate is determined, operators should have their hands stabilized by placing their elbows down on the bed of the patient. In the case of very small vessels (2 to 3 mm) it could be useful to perform the maneuver with two operators. The first operator punctures the vein and the second simultaneously places the guidewire to perform real-time, ultrasound-guided venous cannulation. UGVA in children requires excellent hand-eye coordination. It was suggested that previous UGVA experience in adults with at least 15 tutored procedures is necessary to become proficient in performing the procedure in pediatric patients.[17]

Training Costs of Ultrasound-Guided Vascular Access

UGVA educational programs should be mandatory in every setting in which venous and arterial cannulation is routinely performed and should be included in the responsibilities and job descriptions of doctors and nurses. UGVA training expenses include the cost of ultrasound machines (including maintenance), didactic courses, hands-on training, final audit, and revalidation. These costs were calculated to be higher than £8 per cannulation. However, this calculation should be upgraded because cost is estimated to be around 1000 Euros per operator, with a break-even point of totally successful procedures being reached after the completion of 200 ultrasound-guided cannulations.[18] After this point a real increase in benefits and zeroing of costs related to complications are achieved.

Pearls and Highlights

- UGVA training includes a didactic manual plus tutoring by certified supervisors. Didactics should include knobology, sonographic anatomy and its variations, ultrasound techniques, detection and treatment of complications, and care and maintenance of vascular devices.
- Hands-on training on inanimate phantoms should be used to evaluate the visual-manual competence of trainees before any practice on patients.
- Initially, practice on patients needs to be supervised. A final audit after 25 procedures should be done to evaluate a trainee's proficiency and competence. Training for performing UGVA in neonates and children is more prolonged.

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Training in Critical Care Echocardiography: Both Sides of the Atlantic

PAUL H. MAYO | SUSANNA PRICE

Overview

Echocardiography provides intensivists with a means of rapidly assessing the anatomy and function of the heart in intensive care unit (ICU) patients with hemodynamic failure, thus guiding management. Since echocardiography is a key skill for frontline intensivists, developing effective training programs is essential to ensure that clinicians have competence in the field. This chapter discusses some issues related to training in critical care echocardiography (CCE) while considering the challenges from both the European and North American perspectives. Information in this chapter is relevant for two groups: for intensivists who seek to develop competence in CCE, it provides a guide for the process of training, and for intensivists who have the responsibility to train others to become proficient in CCE, it provides guidance for process development.

The North American Challenge

Roughly 6000 intensivists (at the attending level) in the United States need training in CCE. These frontline clinicians work on a full-time basis in the ICU and have the potential to use CCE as a primary bedside imaging modality. Some of these intensivists are faculty at fellowship programs and have the responsibility of training fellows in CCE. In the United States in 2011, 170 fellowship training programs under the specialty of internal medicine offered training in critical care medicine. These programs graduated 545 fellows with an additional 89 from anesthesiology-based critical care programs. CCE is an essential part of their training. For the individual fellow or attending intensivist, the question is how to become competent in CCE. At the system level, the challenge is how to provide training in CCE to many thousands of intensivists at both the fellow and attending levels.[1-3]

The European Challenge

Europe has 49 self-governing countries, 27 of which are member states of the European Union. The health care systems in each of these countries are different, as is the status of critical care itself, thus providing considerable challenges when considering the development of unified training programs. Accreditation in echocardiography at a European level is run by the *European Association of Cardiovascular Imaging* (formerly known as the European Association of Echocardiography) under the auspices of the European Society of Cardiology. Certification in intensive care medicine is provided at a national level. The *European Society of Intensive Care Medicine*, which aims to promote and coordinate activities, foster research and education, and provide recommendations for optimizing facilities in intensive care medicine, runs a diploma service in intensive care medicine but is not responsible for certification or accreditation. As in North America, for the individual intensivist in training the challenge is how to become competent in CCE. With the different systems that exist in Europe, the challenge of providing training has devolved to the individual nations. The role of regulatory bodies and relevant international societies is rather to provide guidance regarding the key skills and level of competence required in CCE for nations to be able to devise the most appropriate training program given the way that intensive care is structured in their own country.

International Statements: Competence and Training

The goal of training both for the individual and for the training system is competence; hence the latter must be explicitly defined. At an international level this was undertaken as a cooperative venture when a working group consisting of representatives from France and the United States coauthored a statement that defined competence in critical care ultrasonography.[4] The document "American College of Chest Physicians/La Société de Réanimation de Langue Française Statement on Competence in Critical Care Ultrasonography" reviews the elements that define competence in CCE. At this point the statement on competence is commonly accepted as a guide that defines the goals of training for CCE.

The statement on competence defines *basic-level* and *advanced-level* CCE. Basic CCE comprises a number of standard views for assessment of cardiac function (parasternal long- and short-axis, apical four-chamber, long-axis subcostal, and longitudinal inferior vena cava views) to categorize and guide management of hemodynamic failure. Basic CCE includes the use of basic color Doppler techniques, but no additional type of Doppler measurement is included. Advanced CCE requires competence in standard cardiology-type echocardiography and includes additional elements that are applicable to critical care medicine, such as measurement of stroke volume and preload sensitivity, as well as estimation of left-sided filling pressure and lung ultrasonography. Training in advanced CCE requires a level of study identical to that for cardiology echocardiographers. It includes training in transesophageal echocardiography (TEE) when the equipment is available. Currently, most intensivists in the United States and many in Europe do not have access to TEE, although this is rapidly changing. Although competence in basic CCE is desirable for all intensivists, competence in advanced CCE is not needed by all. Some proportion of intensivists may desire training in advanced CCE, but what number is unknown.

The statement on competence clearly defines competence in CCE and is designed to be a "road map" for training. Following its writing, representatives from major critical care organizations from around the world met in Vienna in 2009 to develop guidelines for training in critical care ultrasonography. The resulting document titled "International Expert Statement on Training Standards for Critical Care Ultrasonography" represents the consensus of the working group. It addresses the question of how to become competent in both basic and advanced CCE.[5]

Regarding basic CCE, the *Vienna group* adopted the statement on competence as the foundation document that summarized the goals of training. *For basic CCE, it was agreed that 10 hours of course work that combines lecture, didactic cases, and image interpretation constituted the minimum requirement for cognitive training in CCE. A minimum of 30 fully supervised studies was suggested as a goal for image acquisition training.* Initial training could take place on normal subjects, but training should include scanning of patients in the ICU under supervision of a local expert. A logbook should be maintained to document scanning activity. Review of a comprehensive collection of images with abnormal findings should be required for training in image interpretation. Training in TEE remained an optional part of training in basic CCE. *Regarding advanced CCE, it was suggested that 40 hours of course work, 150 transthoracic echocardiographic (TTE) studies, and 50 supervised TEE studies constituted the minimum requirement for training.* Review of a comprehensive image collection, initial training on normal subjects, and bedside scanning under direct supervision of a local expert were also considered necessary to complete advanced CCE training. The Vienna group decided that a formal certification process was not required for basic CCE. Regarding advanced CCE, the group suggested that a formal certification process was required to ensure competence given the complexity of training and the need for recognition of a high skill level by colleagues and administrative entities.

The statement on competence was detailed, whereas the statement on training was synoptic. As an example, the number of studies required for training was only a suggested target because the evidence was insufficient to make more definitive recommendations. Hence the goal was to establish a broad standard to permit flexibility in the design of training programs for a variety of medical cultures. The training statement did establish that basic-level CCE and general critical care ultrasound should be a required part of the training of every intensivist. Since publication of the training statement, Vignon et al reported on a program to train house staff in basic CCE.[6] The results supported the recommendations of the statement on training. Regarding advanced CCE, Charron et al reported that competence in TEE requires approximately 30 studies under supervision, a number that is less than the 50 suggested in the training statement.[7] Furthermore, these numbers are significantly lower than recommended by European certifying bodies in echocardiography (Table 61-1). In the United Kingdom, the British Society of Echocardiography has developed an accreditation process for CCE that requires the same standards (and number of studies) as for standard TTE accreditation.

Represented at the Vienna meeting were four professional societies from North America: the American College of Chest Physicians (ACCP), American Thoracic Society (ATS), Canadian Critical Care Society (CCCS), and Society of Critical Care Medicine (SCCM). The SCCM did not formally endorse the final document, but its representatives were involved in the roundtable discussions. The international accrediting bodies in echocardiography were not represented; however, it is reasonable to assume that the statement on competence and the training statement are widely recognized by intensivists as the present standard in North America and Europe.

Training Programs, Certification, and Accreditation

Even though the two statements are useful in planning a training program, competence in CCE is not ensured. Poorly designed didactic programs, lack of skilled bedside trainers, and a focus on number rather quality of studies performed may all work against achievement of competence. A well-defined process of training does not guarantee competence. An alternative approach is to emphasize competency-based testing at the completion of training. Although this may exist at the local level in fellowship programs, no competency-based testing has yet been widely accepted in either North America or Europe at a national level.

To avoid conflict of interest, a meaningful certification program should be designed by an agency that is completely independent of the training system. In the United States, the authorities responsible for developing the highest standard of certification are not likely to be interested in developing a high-level certification program for basic CCE given that it applies to a relatively small number of physicians. In the United Kingdom, a national program does exist for basic echocardiography as an entry level for all acute practitioners. This was a joint venture between the Resuscitation Council and the British Society of Echocardiography; it was not limited to CCE but linked to advanced life support. Basic CCE is only one skill of a larger skill set intrinsic to critical care medicine. Although it is perceived that certification in basic CCE is necessary, this implies a need for certification in other aspects of critical care medicine

TABLE 61-1 Recommended Numbers for Logbook Submission to Demonstrate Competence in Critical Care Echocardiography in Europe

European Association of Cardiovascular Imaging (EACVI)*	250 (150 if holding TEE accreditation)	125 (or 75 if holding TTE accreditation)
British Society of Echocardiography (BSE)†	250 (150 if holding TEE accreditation)	125 (or 75 if holding TTE accreditation)

*Jointly with the European Association of Cardiothoracic Anesthesiology.
†Jointly with the Association of Cardiothoracic Anesthesiology.
TEE, Transesophageal echocardiography; *TTE*, transthoracic echocardiography.

that are of higher risk and complexity, such as airway management and vascular access. It could be argued that basic CCE should be bundled into other important aspects of critical care practice that do not require individual certification. However, these discussions are possibly irrelevant since in the future, the inevitable adoption of basic universal ultrasound training as part of undergraduate medicine will make requirements for this basic level of echocardiography training for intensivists irrelevant (see Chapters 57, 60, and 62).

Across Europe and North America, accreditation (which has legal, financial, and interdisciplinary and intradisciplinary implications) is reserved for full echocardiography training—that is, the level at which one is able to practice independently and perform a fully comprehensive study. It is not competency based per se; however, each trainee completing the accreditation process has a mentor who supervised the training and certified that the trainee is of a sufficient standard (and has undertaken the logbook studies). In the United States, there is no means for intensivists to achieve high-level certification in advanced CCE because the National Board of Echocardiography (NBE) does not issue certification in echocardiography to noncardiologists. However, it allows any licensed physician to take the echocardiography boards, including intensivists. Many cardiologists have decided not to take the echocardiography boards, so they cannot receive certification in echocardiography by the NBE. Cardiologists who decide to not take the echocardiography boards may still demonstrate competence in echocardiography. This pathway is described in a statement by the major cardiology societies.[8] Intensivists may also satisfy the competence requirements, and if they do, they are competent in echocardiography to an equal extent as cardiologists. One approach is for the intensivist to satisfy the requirements for competence and to pass the echocardiography boards. Passing this challenging examination demonstrates to cardiology colleagues that the intensivist has mastery of the subject. In Europe, clinicians who wish to practice echocardiography (irrespective of their underlying specialty) and cardiac physiologists are encouraged to achieve accreditation in echocardiography. Indeed, the initial British Society of Echocardiography TTE accreditation process was devised for echocardiographic physiologists and has only recently been adopted by cardiologists as a demonstration of the minimal level of competence needed to be an independent echocardiography practitioner. Moreover, accreditation is available for primary care practitioners, and in the United Kingdom a critical care accreditation process exists; however, it currently includes only TTE. TEE accreditation was largely developed in response to the recognition that the majority of TEE studies are currently undertaken by cardiovascular anesthesiologists. Thus, accreditation processes were developed in the United Kingdom and Europe in conjunction with the relevant cardiothoracic anesthesia societies.

Final Thoughts

THE AMERICAN PERSPECTIVE

Currently, the American College of Graduate Medical Education (ACGME) has established national requirements for fellowship training in critical care medicine. *Even though the ACGME has mandated training in some aspects of critical care ultrasonography, CCE is not one of them.* Fellowship program directors may choose to offer training in CCE during fellowship training. This is becoming increasingly common for basic CCE, but it is not universal. It is not known what proportion of programs train their fellows in basic CCE, but it is still a minority. This will change if the ACGME mandates training in CCE. Until this happens, each program will need to make the choice of whether to train fellows in this important skill. In the *New York City area*, training in CCE during critical care fellowship training is common. Ten of the area fellowship training programs send all of their first-year fellows to a standard 3-day course in critical care ultrasonography that includes basic CCE. Volunteer faculty from the programs give the course and continue the training back at their hospitals.

Training in CCE may be challenging for attending-level intensivists in the United States. Beyond the time constraints and job responsibilities that do not exist in fellowships, attending physicians may come from an adverse training environment where they cannot turn to colleagues for help with their training. When attending intensivists cannot access local training, both the SCCM and the ACCP have developed multiday courses on critical care ultrasonography (including basic CCE) that are designed to meet their needs. The ACCP has a program for attending intensivists who want definitive training in critical care ultrasonography (thoracic, cardiac, abdominal, and vascular). The training sequence requires a total of 7 days of course work, 20 hours of Internet-based training, compilation of an image portfolio that is reviewed by the ACCP faculty, and a high-stakes board-type examination. The examination includes hands-on testing in which the trainee is required to demonstrate skill in image acquisition. The course design includes 28 hours of basic CCE (4 hours of didactic lectures, 12 hours of image interpretation training, and 12 hours of hands-on training). The Internet-based training consists of 12 hours covering basic CCE. If trainees pass the examination, they receive a certificate of completion. The ACCP has declined to label this as certification because they believe that the American Board of Internal Medicine must be involved in the process as an external agency.

THE EUROPEAN PERSPECTIVE

In Europe, because of the diverse health care systems (including both training and practice), development of standardized recommendations for training in CCE that suit all nations is probably not achievable nor indeed appropriate, and at the basic level, several different programs exist. In Denmark, a training program consisting of precourse e-learning, together with a 1-day hands-on training program, has been developed (FATE) through the Scandinavian USabcd group. Students are then encouraged to undertake a period of mentored study locally[9]; however, no certification or examination process exists to determine competence. In France, a 12-hour learning program (including lectures, clinical cases, and tutored hands-on sessions) has been developed and validated.[6] In Germany and the United Kingdom, an 8-hour training program (including lectures and tutored hands-on sessions) has been developed and validated to additionally incorporate advanced life support compliance where required.[10] Thus a range of programs exist, each individualized to the country in which they were developed, but all consisting of blended learning and tutored hands-on sessions and most requiring postcourse mentorship (all achievable within existing training programs). National recognition of these courses by regulatory and certifying bodies varies, with only the United Kingdom having programs approved by both the national echocardiography and intensive care societies. *However, training in advanced CCE (including TTE and TEE) to achieve full accreditation status is realistically achievable only during a dedicated fellowship.*

Conclusion

The statements on competence and training standards serve as useful guides in CCE training. In the United States it will become a uniform standard only when the ACGME requires CCE training as part of fellowship training. In Europe, as with cardiology (for which accreditation by the European Association of Cardiovascular Imaging is required only by those subspecializing in echocardiography), it is likely that intensivists who wish to practice advanced echocardiography will obtain appropriate national or international accreditation. Whether a specific accreditation process for CCE will be developed at the European level remains uncertain.

By contrast, basic CCE should be achievable by all intensivists, and although attending-level intensivists may find it difficult to obtain training in CCE in their own hospital, the professional societies offer courses to remedy this situation. It is hoped that in the future, basic ultrasound will be incorporated into the medical student curriculum. Thus current challenges in basic CCE training will not exist (see Chapter 60).

Pearls and Highlights

- The nomenclature on basic and advanced echocardiography can be confusing; in general, advanced echocardiography is regarded as being equivalent to accreditation, and it must not be forgotten that accreditation is the level required to be an independent practitioner, not an international expert.
- There is consensus regarding the requirement for intensivists to be able to perform basic CCE, which can be achieved by blended learning during existing training programs.
- Advanced CCE requires a period in a dedicated fellowship/training program.

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Ultrasound Training in Critical Care Medicine Fellowships

JENNIFER HOWES | ARIEL SHILOH | ADAM KEENE | LEWIS EISEN

Overview

Critical care ultrasound (CCU) is a noninvasive tool used for diagnostic evaluation and for guiding procedures in critical care patients. Ultrasound improves success and lowers complication rates when used to guide procedures such as vascular access and fluid drainage.[1] Despite these advantages, formal training in CCU has not been incorporated into many fellowship programs, and training in this skill remains heterogeneous. The American Board of Internal Medicine (ABIM) has recommended that fellowship training in critical care medicine include training in the use of ultrasound to guide thoracentesis and central venous access.[2] The definition of competence in CCU, suggested training guidelines, the prevalence of fellowship training in this skill, and current barriers to ultrasound training are considered in this chapter.

Definition of Competence in Critical Care Ultrasound

A consensus statement sponsored jointly by the American College of Chest Physicians (ACCP) and La Société de Réanimation de Langue Française (SRLF) outlined specific competency guidelines for achieving proficiency in CCU.[3] The statement divides CCU into general ultrasound (pleural, lung, abdominal, vascular access, and vascular diagnostic) and echocardiography (basic and advanced). For each, the panel defines a reasonable minimum standard of specific skills required to achieve proficiency in CCU. Importantly, competence is distinguished from certification, which refers to the recognition of competence by an external agency. In the United States, no formal certification process for CCU is currently available. The specific competency skills outlined in the ACCP/SRLF document will be briefly summarized here.

SKILLS FOR ACHIEVING COMPETENCY IN THE BASIC PRINCIPLES OF CRITICAL CARE ULTRASOUND

Knowledge of *basic ultrasound physics* is required to acquire images and recognize artifacts. Also important is knowledge of the *machine controls* and how to manipulate the transducer to obtain images. Intensivists should be aware of when the examination required exceeds the scope of their capabilities and seek appropriate assistance when necessary (see Chapters 1 and 57).

SKILLS FOR ACHIEVING COMPETENCY IN PLEURAL ULTRASOUND

Skills for competency in pleural ultrasound revolve largely around correctly identifying a pleural effusion and locating a safe site for needle insertion. Competency requirements include being able to identify the pleural space and surrounding anatomic boundaries, the presence or absence of fluid, and the characteristics of the fluid. A semiquantitative assessment of fluid volume should also be performed.

SKILLS FOR ACHIEVING COMPETENCY IN LUNG ULTRASOUND

Competence in lung ultrasound requires being able to distinguish normal aeration from an alveolar interstitial pattern by using signs such as A-lines, B-lines, and lung sliding. Additional requirements include using the presence of lung sliding and B-lines to rule out pneumothorax (while understanding the limitations of not visualizing these signs) and using the lung point to rule in pneumothorax.

SKILLS FOR ACHIEVING COMPETENCY IN ABDOMINAL ULTRASOUND

Requirements for competence in abdominal ultrasound include being able to identify the presence or absence of intraabdominal fluid, the characteristics of the fluid, and surrounding anatomic structures. A semiquantitative assessment of fluid volume should also be performed. Additionally, one must be proficient in evaluating the bladder, kidneys, urinary tract, and abdominal aorta.

SKILLS FOR ACHIEVING COMPETENCY IN PROCEDURAL VASCULAR ULTRASOUND

Competence in ultrasound-guided vascular access requires being able to identify the appropriate vessel, differentiate vein from artery, identify normal anatomic variations, recognize the presence of vascular thrombosis, and identify nonvascular structures in the vicinity. Additionally, the clinician must be proficient in proper machine placement and transducer preparation to maintain sterility. This procedure requires visualization of both needle insertion and wire placement into the target vessel throughout the entire procedure.

SKILLS FOR ACHIEVING COMPETENCY IN DIAGNOSTIC VASCULAR ULTRASOUND

Ultrasound can be used by intensivists to diagnose venous thrombosis at the bedside. Clinicians must be able to correctly locate the relevant vein and associated artery and should be able to identify venous thrombosis. They should be familiar with the proper technique of performing a compression study and be aware that a compression study should not be performed in patients with a visible thrombus.

SKILLS FOR ACHIEVING COMPETENCY IN CRITICAL CARE ECHOCARDIOGRAPHY

According to the ACCP/SRLF consensus statement, competence in critical care echocardiography is divided into basic and advanced levels. Because competence in advanced echocardiography requires a high degree of skill and more extensive training than most critical care fellowship training programs would reasonably be able to provide, a discussion of competency in advanced echocardiography is beyond the scope of this chapter (see Chapter 61).

Basic echocardiography involves answering target-oriented clinical questions and assessing the results of therapeutic interventions. Competence in basic echocardiography requires not only the ability to acquire and interpret images but also knowledge of the common clinical syndromes that would prompt echocardiography and the ability to integrate echocardiographic findings into patient management.

Image acquisition requires obtaining images in the parasternal long-axis view, the parasternal short-axis view, the apical four-chamber view, the subcostal four-chamber view, and the inferior vena cava (IVC) view. In interpreting these images, one must be able to evaluate left ventricular (LV) cavity size, systolic function and contraction pattern, and right ventricular (RV) cavity size and systolic function. Additionally important is the ability to identify pericardial fluid and signs of tamponade. IVC diameter and IVC respiratory variation should be assessed. Finally, intensivists should be able to use basic color Doppler to identify severe valvular regurgitation.

The clinical syndromes and associated echocardiographic patterns with which intensivists should be familiar include severe hypovolemia, LV and RV failure, tamponade, acute massive left-sided valvular regurgitation, and circulatory arrest. Competence requires that one be able to formulate a management plan based on these echocardiographic findings. Finally, intensivists must know when it is necessary to obtain consultation from a more advanced echocardiographer.

Suggested Fellowship Training Guidelines

To achieve the aforementioned competencies, a fellow must be trained in both image acquisition and image interpretation. Training in image acquisition requires practice under the supervision of either a physician-sonographer or a trained ultrasound technician. Training in image interpretation is best achieved by reviewing large numbers of normal and abnormal studies with an experienced sonographer. Fellows should also have some means by which to document the studies that they have performed and interpreted to demonstrate competency in CCU.

The European Society of Intensive Care Medicine (ESICM) has recently proposed training guidelines designed around achieving proficiency in the skills outlined by the ACCP/SRLF competence statement.[4] The ESICM document proposes that general CCU and basic echocardiography training should be a mandatory component of intensivists' training and that advanced echocardiography should be an optional component. Furthermore, the authors suggested that to achieve competency in general CCU and basic echocardiography, intensivists should receive at least 10 hours of training in each, divided between lectures and didactics (including image acquisition and interpretation training).

The expert panel could not reach a consensus on the number of examinations required to be performed by the trainee or how many cases of each clinical syndrome the trainee should assess. Rather, the authors suggested that a qualified physician supervisor determine when the trainee has acquired competence in general CCU and basic echocardiography. The guidelines emphasize the necessity of reviewing important abnormal studies as part of their training in image interpretation.

Finally, the authors emphasized the need for documenting training in image acquisition and interpretation. Trainees should maintain a log of the studies that they have performed and interpreted, and these studies should be verified by a qualified supervisor.

Current Prevalence of Training in Critical Care Ultrasound

A recent survey of critical care medicine and pulmonary/critical care medicine fellowship program directors in the United States examined the prevalence of fellowship training in CCU.[1] This survey examined ultrasound training in five specific areas: vascular access, lung/pleural, cardiac, abdominal, and vascular diagnostic. Training in using ultrasound for vascular access was offered by 98% of responding programs. Training in the use of ultrasound in other areas was less prevalent: lung and pleural, 74%; cardiac, 55%; abdominal, 37%; and vascular diagnostic, 33%.[1] This survey demonstrated that even though nearly all programs train fellows in ultrasound-guided vascular access, training in other aspects of ultrasound is not universal.

Barriers to Training

This same survey of program directors examining the prevalence of CCU training also examined barriers to training in this skill. The most commonly cited barriers to ultrasound training included fellow turnover, lack of faculty trained in ultrasonography, financial considerations, and lack of access to an ultrasound machine.[1]

Fellow turnover is an unavoidable difficulty faced by critical care fellowship programs when attempting to train fellows in ultrasound. However, as training programs tailor their curricula to comply with the recent recommendation by the ABIM that ultrasound be considered standard in fellowship training, the number of fellows gaining proficiency in this skill will certainly increase. As these fellows graduate, the number of ultrasound-trained physicians will also increase, thereby eliminating the current shortage of qualified ultrasound faculty available to train others. Finally, the financial concerns associated with ultrasound training will be eliminated as more studies demonstrate the cost-effectiveness of CCU. Such studies would also justify the purchase of dedicated ultrasound machines for training programs that currently lack access to one.

Pearls and Highlights

- CCU is an invaluable tool for the intensivist.
- According to both the ABIM and ESICM, ultrasound should be a component of every intensivist's training.
- Currently, fellowship training in CCU is not uniform.

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