EMERGENCY POINT-OF-CARE ULTRASOUND

SECOND EDITION

Edited by
James A. Connolly
Anthony J. Dean
Beatrice Hoffmann
Robert D. Jarman

WILEY Blackwell

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Contents

List of Contributors

Srikar Adhikari MD
Associate Professor of Emergency Medicine
University of Arizona Department of Emergency Medicine;
Section Chief, Emergency Medicine Ultrasound
Tucson, AZ, USA

Pablo Aguillera MD
Assistant Professor of Emergency Medicine
Chair, Department of Emergency Medicine
Pontificia Universidad Católica de Chile (PUC)
Santiago, Chile

Kenton Anderson MD, FACEP
Clinical Assistant Professor
Director of Emergency Ultrasound Research
Department of Emergency Medicine
Stanford University School of Medicine
Stanford, CA, USA

Robert Arntfield MD, RDMS, FRCPC
Associate Professor
Division of Critical Care & Division of Emergency Medicine Department of Medicine
The University of Western Ontario
London, ON
Canada

Paul Atkinson MB, MA, FRCEM, FRCPC, CFEU
Professor and Research Director
Emergency Medicine
St Johns Regional Hospital
Dalhousie University
Saint John, NB, Canada

Hilary F. H. Beason MD
Emergency Ultrasound Director
Baptist Health System of Alabama
Island Medical Group
Birmingham, AL, USA

Sean Bennett MBBCh, FRCA
Consultant in Cardiac Anaesthesia and Intensive Care
University of Hull
Hull Royal Infirmary;
Consultant in Cardiac and Intensive Care Anaesthesia
Castle Hill Hospital, Cottingham, East Yorkshire
UK

Michael Blaivas MD, FACEP, FAIUM
Professor of Medicine
University of South Carolina School of Medicine
Columbia, SC;
Department of Emergency Medicine
St Francis Hospital
Columbus, GA, USA

Jens Børglum MD
Consultant Anaesthetist
Department of Anaesthesiology & Intensive Care
Bispebjerg University Hospital, Copenhagen
Denmark

Mark W. Bowyer MD, FACS, DMCC
Professor of Surgery
Chief, Division of Combat and Trauma Surgery
Director for Surgical Simulation
The Norman M. Rich Department of Surgery
F. Edward Hébert School of Medicine
Uniformed Services University of the Health Sciences
Bethesda, MD, USA

Raoul Breitkreutz, MD
Associate Professor
FINeST, Simulation Centre
Goethe University Hospital of Frankfurt am Main
Frankfurt am Main, Hessen, Germany

Barton Brown MD
Department of Emergency Medicine
Hancock Regional Hospital
Indianapolis, IN
USA

Adam Bystrzycki MBBS, FACEM, PgDip(Echo)
Consultant
Alfred Emergency and Trauma centre
Senior Lecturer Monash University
Australia

Liberty V. Caroon RDMS
Sonographer
Department of Emergency Medicine
Hennepin County Medical Center
Minneapolis, MI
USA

Luigi Cattarossi MD
Department of Pediatrics
San Antonio Abate Hospital
Tolmezzo, Italy

James A. Connolly MBBS, FRCS(Ed), FRCS (Glas), FRCEM
Consultant and Head of Department
Great North Trauma and Emergency Care Centre
Newcastle upon Tyne
UK

Roberto Copetti MD
Department of Emergency
MedicineCattinara HospitalTrieste
Italy

Elena Costantini MD
Department of Anesthesia and Intensive Care
Luigi Sacco Hospital
University of Milan
Italy

Colleen Cuca MD
Hospital zum Heiligen Geist
Teaching Hospital of Goethe-University
Frankfurt am Main
Germany

Sara Damewood MD
Assistant Professor
Section Chief, Emergency Ultrasound
Department of Emergency Medicine
University of Wisconsin School of Medicine and Public Health
Madison, WI
USA

Lisa Munro Davies
Consultant
Department of Emergency Medicine
University Hospitals Bristol NHS Foundation Trust
Bristol Royal Infirmary
Bristol
UK

Anthony J. Dean MD
Professor of Emergency Medicine and of Emergency Medicine in Radiology
Director, Division of Emergency Ultrasonography
Department of Emergency Medicine
University of Pennsylvania
Philadelphia, PA, USA

Mahmoud A. Elbarbary MD, MSc, EDIC, PhD (Deceased)
Consultant and Assistant Professor, Critical Care Medicine
King Saud Bin Abdulaziz University for Health Sciences
Riyadh
Saudi Arabia

J. Matthew Fields MD
Associate Professor of Emergency Medicine
Emergency Ultrasound Fellowship Director
Thomas Jefferson University Hospital
Philadelphia, PA
USA

Jonathan Fischer MD
Attending Physician
Department of Emergency Medicine
Lankenau Medical Center
Wynnewood, PA, USA

Christian Alcaraz Frederiksen MD
Research Associate
Department of Anesthesiology and Intensive Care
Aarhus University Hospital
Aarhus
Denmark

Rajat Gangahar FRCEM
Consultant
Department of Emergency Medicine
Royal Oldham Hospital
Oldham, Lancashire, UK

Lara Goldstein MBBCh, FCEM(SA)
Specialist Emergency Physician
Registrar Programme Director
Division of Emergency Medicine
University of the Witwatersrand;
Gauteng Emergency Medical Services;
Head, Department of Emergency Medicine,
Helen Joseph Hospital
Johannesburg, South Africa

John Gullett MD
Associate Professor
Co-Director Emergency Ultrasound
Department of Emergency Medicine
University of Alabama Birmingham
Birmingham, AL, USA

Tim Harris FACEM, FCEM, DipImmCare, Dip O&G, BM, BS, BMedSci
Consultant and Professor
Department of Emergency Medicine
Pre-Hospital Care and Intensive Care Medicine
Royal London Hospital and London HEMS
Newham University Hospital
Barts Health NHS Trust and QMUL
London, UK

Frank Heringer MD
Frankfurt Institute of Emergency Medicine and Simulation Training
Goethe-University
Frankfurt am Main
Germany

Beatrice Hoffmann MD
Associate Professor of Emergency Medicine
Harvard Medical School
Division Chief, Emergency Medicine Ultrasound
Beth Israel Deaconess Medical Center
Boston, MA
USA

Erskine J. Holmes MBBCh Bio, MRCS, FCEM
Consultant, Emergency Medicine
Wexham Park Hospital
Slough, UK

Richard A. Hoppmann MD
Professor of Medicine
Director, Ultrasound Institute
University of South Carolina School of Medicine
Columbia, SC
USA

Robert D. Jarman MBBS, MSc(Medical Ultrasound), FRCS(Ed), FRCEM(UK), FRCP(Ed), CFEU
Consultant in Emergency Medicine
Royal Victoria Infirmary
Newcastle upon Tyne;
Visiting Professor and MSc Point-of-Care Ultrasound Lead
University of Teesside
Middlesbrough
UK

Dietrich von Kuenssberg Jehle MD, RDMS
Professor of Emergency Medicine
SUNY at Buffalo
Director of Emergency Ultrasonography and Associate Medical Director
Department of Emergency Medicine
Erie County Medical Center
Buffalo, NY
USA

Kenneth Jensen MD
Associate Professor
Department of Anaesthesia and Intensive Care,
Copenhagen University Hospital, Bispebjerg,
Denmark

Tyler Johnston MD, MPA, MPH, FRCPC
Emergency Physician
Muskoka Algonquin Healthcare
Huntsville, ON
Canada

Phil Johnstone MBBS, FCEM
Consultant, Accident and Emergency
Newcastle upon Tyne Hospitals
NHS Foundation Trust
Newcastle upon Tyne, UK

Peter Juhl-Olsen MD
Research associate
Department of Anesthesiology and
Intensive Care
Aarhus University Hospital
Aarhus, Denmark

John L. Kendall MD
Associate Professor
Director of Emergency Ultrasound
Denver Health Medical Center;
Department of Emergency Medicine
University of Colorado School
of Medicine
Denver, CO, USA

Andrew M. Kestler MD, MBA, DTMH, FACEP, FRCPC
Clinical Associate Professor
St. Paul's Hospital & University of
British Columbia
Vancouver, BC, Canada

Andrew W. Kirkpatrick MD, MHSc
Regional Trauma Services, Departments of
Surgery and Critical Care Medicine,
Foothills Medical Centre,
Calgary, Alberta
Canada

Michael Lambert MD, RDMS, FAAEM
Department of Emergency Medicine
Advocate Christ Medical Center
Oak Lawn, IL, USA

Hein Lamprecht MBChB, FCEM(SA), FRCEM, DA(UK), CFEU(UK)
Programme Director, Clinical Ultrasound
Stellenbosch University
Cape Town
South Africa

David Lewis MB, BS, FRCS, FCEM, CFEU, PGDipSEM
Associate Professor
Department of Emergency Medicine
Saint John Regional Hospital
Dalhousie University
Saint John, NB
Canada

Resa Lewiss MD
Associate Professor of Emergency
Medicine
University of Colorado;
Director of Point-of-Care Ultrasound
University of Colorado Hospital
Aurora, CO
USA

Veronica M. Madigan MD
School of Biomedical Science
Charles Stuart University
Bathurst, New South Wales
Australia

Jennifer R. Marin MD
Director of Emergency Ultrasound
Division of Emergency Medicine
Children's Hospital of Pittsburgh
of UPMC;
Assistant Professor of Pediatrics
University of Pittsburgh School
of Medicine
Pittsburgh, PA, USA

Gebhard Mathis MD
Professor of Internal Medicine
Innsbruck University
Austria

Stefan M. Mazur BPhEd, MBChB, PGCertAME, DipIMC, DRTM (RCSEd), CCPU
PreHospital and Retrieval Physician
SAAS MedSTAR;
Consultant in Emergency Medicine
Royal Adelaide Hospital, North Terrace, Adelaide;
Associate Professor
Public Health Tropical Medicine
James Cook University
Townsville, Australia

Lawrence A. Melniker MD, MS
Vice Chair, Continuous Quality Management
Department of Emergency Medicine
New York Methodist Hospital, Brooklyn;
Assistant Clinical Professor
Department of Medicine
Weill Medical College
Cornell University
Ithaca, NY, USA

James D. Milne BScKin, MD, CCFP
Family Physician
Fraser Health Authority
Agassiz, BC, Canada

Christopher L. Moore MD, RDMS, RDCS, FACEP
Associate Professor
Division Director Emergency Ultrasound
Department of Emergency Medicine
Yale University School of Medicine
New Haven, CT
USA

Craig Morris
ITU Consultant
Derby
UK

Vicki E. Noble MD RDMS
Professor and Vice Chair
Department of Emergency Medicine
University Hospital
Case Western Reserve University School of Medicine
Cleveland, OH, USA

Nova L. Panebianco MD, MPH
Assistant Professor of Emergency Medicine;
Associate Director of Emergency Ultrasound
Department of Emergency Medicine
Hospital of the University of Pennsylvania
Philadelphia, PA, USA

David C. Pigott MD, RDMS, FACEP
Professor and Vice Chair for Academic Development
Co-Director, Division of Emergency Ultrasound
Department of Emergency Medicine
University of Alabama at Birmingham
Birmingham, AL, USA

Robert F. Reardon MD
Associate Professor of Emergency Medicine
University of Minnesota Medical School;
Ultrasound Director
Department of Emergency Medicine
Hennepin County Medical Center
Minneapolis, MN
USA

Joshua S. Rempell MD, MPH
Assistant Professor
Cooper Medical School of Rowan University
Cooper University Hospital
Camden, NJ
USA

Simon Richards MHSc, PgC(L&THE), DCR(R)
Senior Lecturer and Programme Lead Medical Ultrasound
Teesside University
Middlesbrough, UK

David B. Richards MD, FACEP
Assistant Professor
Department of Emergency Medicine
Denver Health Medical Center
University of Colorado School of Medicine
Aurora, CO
USA

Joe Rigley MD, FRCPC
Assistant Professor
Department of General Internal Medicine
Dalhousie University, Halifax, NS;
Department Chief of Internal Medicine
Miramichi Regional Hospital
Miramichi, NB
Canada

Daniel Runde MD, MME, FACEP
Assistant Clinical Professor
Department of Emergency Medicine
University of Iowa Hospitals and Clinics
Carver College of Medicine
Iowa City, IA, USA

Conn Russell MD
Consultant in Anaesthesia and Intensive
Care Medicine
Department of Anaesthetics and Intensive
Care Medicine
Ulster Hospital
Belfast, UK

Fernando Silva MD, MSc
Department of Emergency Medicine
Kaiser Permanente
North California
Napa/Solano Region, USA

Gabriel Simon MD
Department of Emergency Medicine
Nashoba Valley Medical Center
Ayer, MA
USA

Anumeha Singh MD
Faculty
Department of Emergency Medicine
Hartford Hospital
Hartford, CT, USA

Elena Skomorovsky MD
Clinical Instructor
Harvard Medical School
Department of Emergency Medicine
Beth Israel Deaconess Medical Center
Boston, MA, USA

John Sloan
Department of Emergency Medicine
Countess of Chester Hospital
Chester, UK

Erik Sloth MD, PhD, DMSc
Professor
Department of Anesthesiology and Intensive Care
Aarhus University Hospital
Aarhus
Denmark

Brendan E. Smith MBChB, FFA, RCS
Associate Professor
School of Biomedical Science
Charles Stuart University
Bathurst, New South Wales
Australia

Sarah A. Stahmer MD
Clinical Associate Professor of Emergency
Medicine
University of North Carolina School of Medicine
Chapel Hill, NC, USA

Seth R. Strote MD
United Hospitalist Service of AMC
Sait Paul, MN, USA

R. Andrew Taylor MD
Clinical Instructor
Department of Emergency Medicine
Yale University School of Medicine
New Haven, CT
USA

Patricia Van Leer MD
Director of Emergency Department Quality
Assurance
Department of Emergency Medicine
Howard County General Hospital
Columbia, MD, USA

Heather Venables
Senior Lecturer
Professional Lead Medical Ultrasound
University of Derby
Derby, UK

Martha Villalba MD
Department of Emergency Medicine
Jesse Brown
Veterans Affairs Medical Center
Chicago, IL, USA

Felix Walcher MD
Dept. of Trauma and Orthopedic Surgery
Frankfurt Institute of Emergency Medicine
and Simulation Training
Goethe-University, Frankfurt am Main
Germany

Christopher T. Wall MD
Department of Emergency Medicine
Hennepin County Medical Center
Minneapolis, MN, USA

Mike Wells MBBCh, MSc Med (Emergency Medicine), FCEM(SA), DipPEC(SA)
Specialist Emergency Physician
Consultant, Lecturer and Director of
Emergency Ultrasound Training
Division of Emergency Medicine
University of the Witwatersrand;
Netcare Union Hospital Emergency Department
Johannesburg, South Africa

David C. Wherry MD, FACS, FRCS, DMCC
DCW Professor of Surgery
Director, Emerging Technologies
The Norman M. Rich Department of
Surgery
F. Edward Hébert School of Medicine
Uniformed Services University of the Health
Sciences
Bethesda, MD
USA

Joseph Wood MD, RDMS
Vice Chair and Associate Professor
Department of Emergency Medicine
Mayo Clinic Medical School
Phoenix, AZ, USA

Peter M. Zechner
Internist
Graz
Austria

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/connolly/ultrasound

The website includes:

- Videos
- Chapters 44–50
- Appendix

The videos are clearly signposted throughout the book. Look out for .

We note with sadness the untimely death of Dr. Mahmoud Elbarbary during the final stages of publication of this volume. Dr. Elbarbary will be missed as a friend and colleague by many of its contributors, and his activities as a scientist, teacher, leader, and international collaborator reflect the spirit of this book.

Introduction

What is Point-of-Care Ultrasound?

James A. Connolly, Anthony J. Dean, Beatrice Hoffmann and Robert D. Jarman

Barely 60 years have passed since the pioneering days of diagnostic ultrasound in the 1950s. The equipment of that time was complicated and bulky, and dedicated technologists with special training were needed to obtain images, and specially trained physicians to interpret them. As this arrangement was well established in radiography, ultrasonography was naturally and rapidly adopted by radiologists. During the late 1960s ultrasound's ability to generate real-time moving images that provided hemodynamic, physiological and pathological data in addition to structural information without the use of contrast agents led to its adoption by cardiologists. The absence of ionising radiation also gave impetus to its use in obstetrics and gynecology. This traditional workflow was continued throughout many Anglo-American medical systems, but interestingly, many European and Asian countries adopted a physician-performed sonography service as part of their unique medical specialty care.

It is not surprising then, that during the 1980s, German ambulance-based traumatologists started to use ultrasonography in the field to detect free peritoneal fluid in victims of blunt trauma. This approach was possible as a result of the development of portable machines of similar size and weight to then-available defibrillator-monitoring equipment. Image quality was inferior to that of cart-based systems, but was still far superior to that of state-of-the-art equipment of the previous generation, and was sufficient for the simple clinical question of the traumatologists: does this patient have free intra-abdominal fluid suggesting the need for immediate operative intervention? This application was adopted by trauma surgeons in North America in the early 1990s, and soon thereafter by emergency physicians. With the adoption of ultrasound by *practitioners* who sought to answer *clinical questions* with a *focused and limited examination*, the field of *sonology* was born.

During the 1990s clinicians from countries with the traditional sonographer-performed ultrasound approach started to implement physician-performed sonography in their practice. For instance, urologists and vascular surgeons in Anglo-American countries discovered speciality applications of ultrasound, while generalists in emergency medicine found cardiac, abdominal and pelvic applications and used them to guide invasive procedures. In the past ten years, the scope of clinician-performed ultrasonography has continued to expand both across and within specialities. Its bedside and point-of care applications have also expanded to the European and Asian countries, where ultrasound traditionally was a physician-performed imaging modality. Most recently, practitioners of critical care medicine, family medicine, anaesthesiology and pediatrics have adopted it, and it is increasingly used by non-physician

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healthcare providers such as nurses (for venous access), paramedics (field triage, pneumothorax assessment, vascular access), and midwives (ante-natal testing). The current edition of this book includes several chapters describing new and evolving applications of bedside ultrasound.

The rapid proliferation of ultrasonography in medical practice has been driven by separate, but mutually reinforcing, historical trends. Technological advances have combined with improvements in the design and ergonomics to make ultrasound equipment more user-friendly, mobile, rapidly deployable and accurate. Ultrasound equipment has become increasingly robust and portable, with many machines capable of running for hours using battery power. At the same time, the decreasing costs have made it more widely available. Finally, the financial burden of hospital admissions has created powerful economic pressures to decrease admission times and maximise the outpatient management of many diseases. This has resulted in increasing numbers of critically ill patients both inside and outside the hospital needing emergency care for acute decompensation of their chronic conditions during night-time and weekend hours, when the manpower and technological resources of the hospital are minimal. At such times, an imaging modality that directly evaluates most of the common causes of critical illness and can be deployed by caregivers at the patient's bedside is of great value. Clinician-performed ultrasonography is that imaging modality, and much of this book is devoted to the use of ultrasound in critical and time-sensitive illnesses.

One of the cardinal features of sonology is 'syndromic' use in clinical settings that are no less serious or complex for being common. The first example of syndromic ultrasound was the FAST, with its concurrent evaluation of the heart (traditionally the purview of cardiologists) and abdomen (traditionally the territory of radiologists or internist- or surgeon-performed sonography in many European and Asian countries). Since that time, ultrasound algorithms have been developed and promulgated for the assessment of abdominal pain, unexplained hypotension, shortness of breath and cardiac arrest, to name a few. This book attempts to help clinicians familiarise themselves with this approach, with a number of chapters devoted to syndromic uses of ultrasound.

As a rule, technology-based medical advances in wealthy societies are of limited utility in resource-poor environments. Clinician-performed ultrasonography is a powerful exception to this rule, for the very reason that its use has been driven by the need to provide expedited care in resource-poor settings that exist even in the richest societies. The back of an ambulance at the scene of a motor vehicle crash in Bavaria, hospital wards at night in Paris, and emergency departments on week-ends and holidays in New York City, all have severely limited manpower and equipment resources. The pressures and stresses of practice in these settings are not unlike those in the developing world, as well as those in wilderness settings, space flight and military environments. This book seeks to be a source of information to any clinician anywhere who is attempting to improve patient care by the use of ultrasonography in a resource-limited setting.

Ultrasound has modified the clinical practice of many specialities. To the extent that it does so by means of the clinician's hands, eyes and brain in real time, it is an extension of the clinical evaluation. (This is not to say that ultrasound is an extension of the *physical examiantion*, any more than a plain film, computed tonography scan or blood test are extensions of the physical examination.) In contrast to the stethoscope – with which it is sometimes compared – ultrasound provides extraordinarily detailed anatomical, physiological and pathological information. Perhaps the greatest similarity between the stethoscope and the ultrasound machine is that the information obtained from both tools is *a function of the expertise residing between the operator's ears*. This should strike a particularly cautionary note to practitioners, since the diagnostic power of ultrasound comes with a commensurate potential for diagnostic error.

The skills of a sonologist can be roughly broken into three distinct types of knowledge. First, there are *cognitive* skills relating to the patient's disease and the known (or unknown) limitations of ultrasound as a diagnostic test. Second, there are *visual pattern recognition* skills developed through repetitive exposure to ultrasound images of healthy and diseased conditions. Third, there is the *psychomotor* skillset needed to operate the machine, manipulate the transducer, and optimise images. These three distinct – but mutually reinforcing – skills constitute the abilities of the *sonologist*: a healthcare provider who has mastered the '*logos' of ultrasound*.

With this small book we hope to help not only those clinicians who have set themselves the goal of incorporating ultrasound into their clinical practice, but also those who have already embarked on that process and who wish to extend their knowledge. Using copious images and clear succinct text, this book strives to provide the basic cognitive and visual pattern recognition skills needed for basic sonology. The format is designed to fit into a lab-coat pocket, and it is hoped that it will find use as a reference in the clinical environment. Due to its widening utilisation in almost every field of medicine, ultrasonography is increasingly recognised as having a place in undergraduate medical training. We hope that this book will also be a useful introduction to clinical ultrasound for medical students. Clearly, the psychomotor skills of sonology cannot be obtained from a book. In the time-honored traditions of many hands-on fields of medicine, these can only be mastered by *practice*, *practice*, *practice*!

We are deeply indebted to the enormous efforts of the authors of the chapters in this volume, all of whom are acknowledged world leaders in this field. Editing their work has been a source of enlightenment and inspiration. We would also like to thank the pioneer sonologists who beat the path that we now follow when the destination was less clear, and the way less certain. Finally, thanks to our long-suffering families and friends whom we hope have understood our passion and motivation.

Part 1

Physics

1

How Does Ultrasound Work?

Heather Venables

Introduction

The aim of this chapter is to outline the basics of how ultrasound works. The construction of an image and some of the physical principles that govern the behaviour of sound in tissue will be introduced.

What is Ultrasound?

Sound is simply the transfer of mechanical energy from a vibrating source through a medium. *Ultra*sound is defined as sound of a frequency above the human audible range, that is, above 20 kHz.

Piezoelectric crystals within the face of the transducer have the property of contracting or expanding when a voltage is applied across them. A thin layer of a synthetic piezoelectric material can be constructed to vibrate at a resonant frequency within the required range. This acts as a source of ultrasound. A very short (approximately 1 μs) pulse is generated by the transducer and transmitted into the soft tissues. After generation of the 'pulse', the transducer receives no further electricity for a period of time (typically about 100–300 μs) and acts as a 'listening device' to detect returning echoes generated within the medium of the soft tissues.

As the ultrasound wave of a returning 'echo' hits the transducer surface, the piezoelectric crystals vibrate, causing them to generate an alternating electric current. This is transmitted back to the ultrasound machine through the wires attached to the transducer. The magnitude of the voltage of this current is related directly to the amount of energy carried by the returning echo, and will determine the brightness level displayed for this location on the monitor. The machine measures the time that elapses between the *pulse* and the *echo*, and by using the known velocity of sound in soft tissues (1540 m s^{-1}) the distance to the echoing object can be calculated. Many animals (e.g., bats and marine mammals) use the same principle for echo-location of objects in their environment. (It is worth noting that the construction of the transducer with its sensitive crystal elements does not respond favourably if it is dropped or if the wheels of the machine run over its wires.) Diagnostic ultrasound utilises the pulse-echo principle to construct a two-dimensional sectional image of anatomical structures (Figure 1.1).

Constructing the Image

Each pulse of sound transmitted into the patient generates a stream of echoes from multiple reflectors at various depths. As noted, the energy carried by each echo is converted into electrical energy by the piezoelectric crystals. In simple terms, these values are then stored

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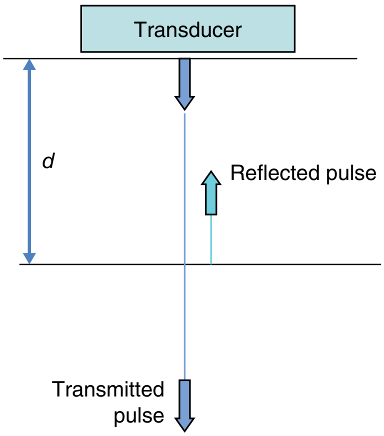

Figure 1.1 The time taken (*t*) for the echo to return to the transducer, and the speed of sound in soft tissue (*v*), can be used to calculate the depth (*d*) of the reflecting interface, where $d = vt/2$.

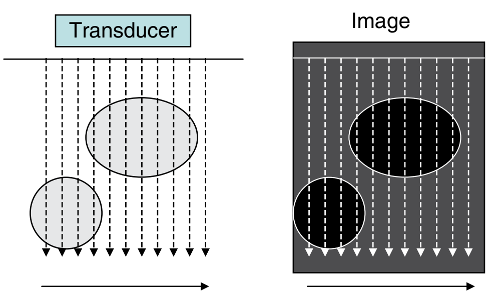

Figure 1.2 Pulses of sound are fired in sequence from multiple adjacent crystals across the face of the transducer. These are used to produce contiguous scan lines from which a single *brightness mode* (B-mode) 'frame' of information can be produced that represents a two-dimensional anatomical cross-section.

within a computer memory as a single 'scan line' of information, and used to determine the brightness levels allocated to points in a vertical line on the image to represent corresponding depths in the patient. By firing pulses of sound in sequence from multiple adjacent crystals across the face of the transducer, numerous contiguous scan lines can be generated and a single 'frame' of information is produced to represent a two-dimensional anatomical cross-section (Figure 1.2). This type of ultrasound imaging is referred to as 'brightness mode' ('B-mode' or 'gray-scale') because the strength of the echoes are represented by the brightness of the ultrasound image at that location.

If performed fast enough, the rapid update of frames can create a 'real-time' dynamic image of the scanning plane. Frame rate is limited by several factors. The ultrasound machine 'waits' for the echoes to return from the maximum depth of interest along each scan line before the next pulse is sent out. Thus, the frame rate depends on the *depth* of interest and the total number of scan lines of the image (*field of view*). Adjusting the depth and field of view allows the operator of the ultrasound machine to optimise the frame rate and the resolution of the image. In general, the image should be adjusted to the minimum depth that will include the entire object of interest.

Making Sense of Ultrasound Images

During an ultrasound examination, most of the diagnostic conclusions about normal and abnormal appearances are based on pattern recognition. This includes a number of key observations:

- the spatial definition of tissue boundaries;
- relative tissue reflectivity;
- echo-texture; and
- the effect of tissue on the transmission of sound.

These appearances are determined by the physical properties of the ultrasound waves and their interactions with tissues. Some of these key interactions are outlined below.

What Happens to a Pulse of Sound as it Travels Through a Patient?

Reflection, scattering and refraction are common to both sound and light waves. An appreciation of this helps us make sense of why structures appear as they do in an ultrasound image.

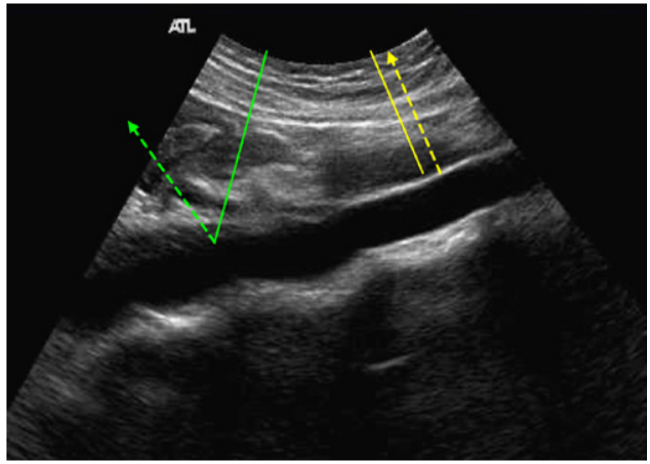

Figure 1.3 The divergent ultrasound beams generated by this curved-array probe demonstrate the effect of angle of insonation on the visualisation of vessel walls. A pulse of sound hitting the wall at 90° (solid yellow arrow) will be reflected back to the transducer (dashed yellow arrow). A pulse hitting the wall at any angle other than 90° will be reflected at an equal and opposite angle (green pathway), with the result that the echo may not be detected by the transducer. This is why in the image, the aortic wall appears well defined in the region of the yellow arrows and cannot be clearly discerned in the region of the green pathway.

Reflection

Reflection of the ultrasound pulse occurs at interfaces between two media that have differences in acoustic *impedance,* which is a medium's physical properties as a transmitter of sound. Impedance is determined primarily by the medium's density and elasticity). At such boundaries, a proportion of the sound energy will be reflected, while the remaining sound energy is transmitted beyond the boundary. If the impedance difference at a boundary is high enough, for example at a soft tissue/air interface or at a soft tissue/solid interface, total reflection occurs and no sound energy is transmitted to deeper structures. Gas-filled structures and bone are therefore a significant challenge in ultrasound imaging.

Specular Reflection

If a reflective boundary is smooth and large, specular reflection occurs. This is similar to when light is reflected from a smooth surface. Typical specular reflectors include the diaphragm, renal capsule and vessel walls.

Where the sound pulse hits a boundary (especially if it is specular) at an angle other than 90°, then by the basic 'law of reflection' it will not be reflected back towards the transducer, which means that the structure will not be detected by the ultrasound machine. Conversely, boundaries will be detected most clearly if they are at 90° to the direction of travel of the ultrasound wave. This phenomenon is demonstrated in Figure 1.3.

Diffuse Reflection

Diffuse reflection occurs where irregularities in the tissue boundary exist that are small compared to the wavelength of the sound. (At 5 MHz this is approximately 0.3 mm or less.) These irregularities cause the sound energy to be reflected in multiple directions – an optical analogy would be to consider the difference between gloss and matt paint. In practice, most soft-tissue boundaries are irregular and produce diffuse reflection to some degree.

Scattering and Echo Texture

Acoustic impedance changes occur at large-scale boundaries, but are also present throughout soft-tissue structures. Small-scale localised changes in acoustic properties act as tiny reflecting targets that *scatter* the sound in many directions. This is what produces the characteristic *echo texture* (graininess) that is associated with solid structures on ultrasound, and the relative *echogenicity* (brightness) of adjacent organs (Figure 1.4).

Attenuation

As sound travels through tissues, it loses energy. A number of interactions contribute to this

Figure 1.4 Small-scale localised changes in the acoustic properties of many tissues act as tiny reflecting targets that *scatter* the sound in many directions. This produces the characteristic *echo texture* (graininess) associated with solid organs and their relative *echogenicity* (brightness) compared to adjacent organs, as seen in this view of the right lobe of the liver and right kidney.

process of *attenuation*, including reflection, scattering and absorption. This results in the pulse becoming progressively lower in intensity (and therefore producing weaker echoes) the deeper it travels into the patient.

In practice, Time Gain Compensation (TGC: increasing amplification or 'gain' of the electric signals generated by returning echoes from increasingly deep structures) is used to compensate for this reduction in signal strength with depth. Scattering contributes to beam attenuation and increases significantly with increasing frequency of the ultrasound wave. This results in increased attenuation, and thus a reduced *penetration* of the sound beam to deeper structures, when higher transmit frequencies are used.

Absorption

Absorption is the process by which the mechanical energy carried by the pulse is converted into heat within the tissues. Absorption is the most significant form of attenuation in soft tissue. As sound travels though the patient, there is the potential for tissue damage, either through heating or mechanical effects (such as shearing or cavitation). In practice, ultrasound machines are designed to continually minimise the power of the ultrasound waves according to the principle of ALARA ('as low as reasonably attainable'). While deleterious bio-effects caused by diagnostic B-mode ultrasound have never been conclusively demonstrated, in case such bio-effects actually exist (albeit at levels below current powers of detection), ultrasound should be used clinically in situations where the information it provides is of potential net benefit, especially when used in the evaluation of pregnancy.

Why is Frequency Important?

Both, absorption and scattering result in reduced penetration to deeper tissues with higher frequencies. Unfortunately, higher frequencies result in a higher image resolution, and therefore there must be a trade-off between image quality and penetration. In practice, the highest frequency should be used that allows adequate penetration to the depth of interest.

Summary

The power of ultrasound in a clinician's hands will be significantly affected by his or her ability to operate the machine in such a way that it can obtain the highest-quality images. This, in turn, entails an understanding of the physics of ultrasound. This brief overview should serve as an introduction, but further study is called for if the reader wishes to use ultrasound in anything more than a rudimentary fashion, and especially