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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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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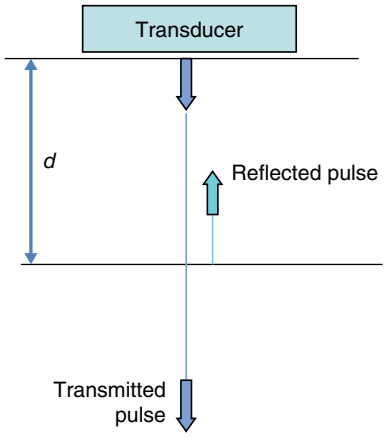

Figure 1.1 The time taken (*t*) for the echo to return to the transducer, and the speed of sound in soft tissue (*v*), can be used to calculate the depth (*d*) of the reflecting interface, where $d = vt/2$.

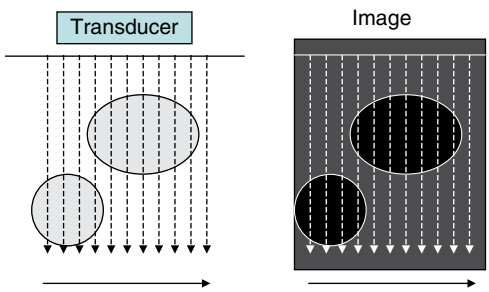

Figure 1.2 Pulses of sound are fired in sequence from multiple adjacent crystals across the face of the transducer. These are used to produce contiguous scan lines from which a single *brightness mode* (B-mode) 'frame' of information can be produced that represents a two-dimensional anatomical cross-section.

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.

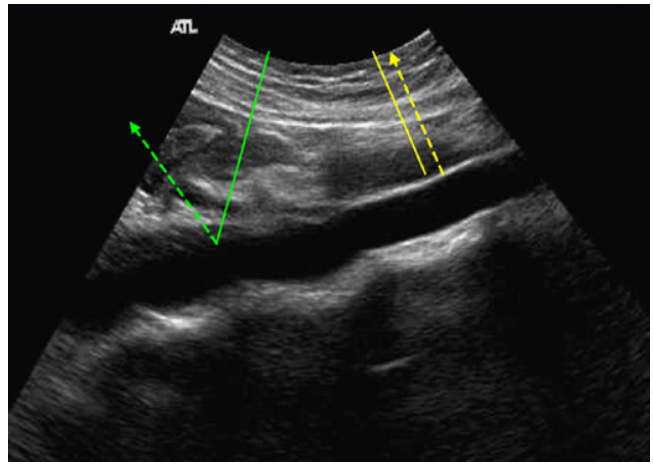

Figure 1.3 The divergent ultrasound beams generated by this curved-array probe demonstrate the effect of angle of insonation on the visualisation of vessel walls. A pulse of sound hitting the wall at 90° (solid yellow arrow) will be reflected back to the transducer (dashed yellow arrow). A pulse hitting 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

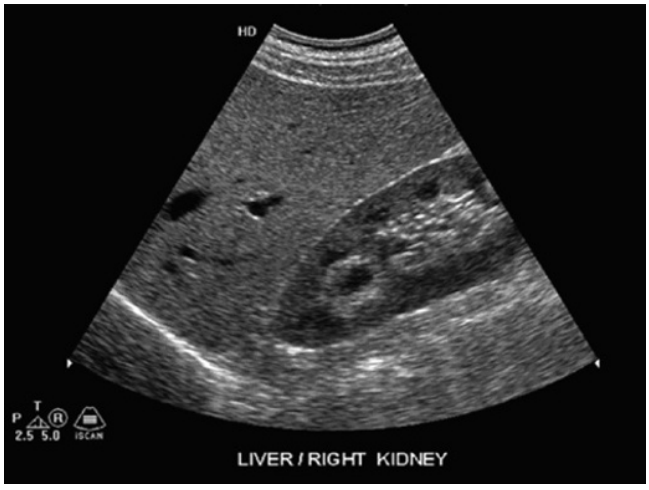

Figure 1.4 Small-scale localised changes in the acoustic properties of many tissues act as tiny reflecting targets that *scatter* the sound in many directions. This produces the characteristic *echo texture* (graininess) associated with solid organs and their relative *echogenicity* (brightness) compared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

for the effective use of any of the Doppler applications described in this book. The references listed below provide useful sources of more detailed information.

Further Reading

Gibbs, V., Cole, D., Sassano, A. (2009) *Ultrasound Physics and Technology – How, Why and When?* Churchill Livingstone.

Guidelines for the Safe Use of Diagnostic Ultrasound Equipment (2009) British Medical Ultrasound Society. Available at: http://www.bmus.org/policies-guides/pg-safetystatements.asp

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Part 2

Ultrasound by Region

Thorax

2

Evaluation of the Chest Wall, Pleura and Lung

Gebhard Mathis and Anthony J. Dean

Introduction

Ultrasound waves are reflected by the bony thorax and scattered by the ventilated lung. For this reason, the utility of sonography in the evaluation of the lung and pleura was until recently overlooked. The ways in which sonography of extra-mediastinal structures can be utilised in the management of the critically ill are outlined in this chapter. Procedural uses of ultrasound in the thorax are discussed elsewhere in this book.

Technique

Equipment

The chest wall and pleura are best imaged with a high-frequency (5–10 MHz) linear array transducer. For evaluation of B-lines and the lung, a curved-array 3.5–5 MHz transducer is preferred. This combination of probes has the advantage of being useful for many other applications, such as abdominal, vascular and small-parts imaging. Skilful manipulation of the transducer, combined with an understanding of respiratory dynamics, will provide views of most parts of the pleura and underlying lung. If only a single transducer is available, a 2–5 MHz microconvex transducer is adequate for the vast majority of situations.

Examination Technique

The examination technique will be determined by a variety of factors, including the diagnostic questions at issue and the patient's clinical condition and habitus. The supine position is used to scan the anterior and lateral chest, while posterior areas are ideally scanned with the patient sitting. If this is not possible, patients are rolled into a decubitus position. Full abduction of the shoulders with the arms crossed behind the head may widen the intercostal spaces, affording better views. The region underlying the shoulder blade can be imaged if the patient puts his/her hand on the contralateral shoulder. If the patient can identify a specific area of pain, this region should be examined first. The scanning depth is usually set at about 4–8 cm for examination of the chest wall and pleura. For the analysis of B-lines and deeper lung structures, the depth is usually set at ≥15 cm.

Scanning of the lung should be systematic and methodical. Each intercostal space should be interrogated from dorsal to ventral with the transducer in both longitudinal and transverse planes with respect to the axis of the body. By using anterior and posterior axillary-lines and a horizontal line superior to the level of the nipple, each hemithorax can be divided into six regions. The presence of pleural sliding should be confirmed in all lung fields. Lung adjacent to the right and left diaphragms can be examined using liver and spleen windows, respectively.

Emergency Point-of-Care Ultrasound, Second Edition. Edited by James A. Connolly, Anthony J. Dean, Beatrice Hoffmann and Robert D. Jarman.

Companion website: www.wiley.com/go/connolly/ultrasound

The axillae should be examined with the patient in the supine position, with the arms fully abducted. The supraclavicular fossa gives views of the brachial plexus, the subclavian vessels and the lung apex. Suprasternal or parasternal windows may afford views of the anterior upper mediastinum.

Normal Sonographic Findings

The superficial surface of the adult ribs gives rise to an intense echo with dense underlying acoustic shadow. Costochondral regions have a hypoechoic oval morphology with adequate through-transmission of ultrasound to underlying structures (Figure 2.1). The normal pleura is 0.2–0.4 mm thick, and hence is at the resolution limits of ultrasound, although the parietal and visceral layers are sometimes distinguishable. The visceral pleura may appear thicker due to complete reflection of the incident beam by the underlying air spaces. Between the two pleural layers, physiological amounts of pleural fluid may appear as an echo-free line. In some patients a hypoechoic layer of extrapleural fat may also be seen (Figure 2.2).

Many horizontal lines appear in the ultrasound image of the lung. The first and most important to be identified is the pleural line, which is seen immediately beneath the ribs. With respiration, the visceral pleura moves with respect to the parietal pleura (*pleural sliding*). In patients with decreased respiratory effort (e.g., due to pain after trauma), subtle motion of the pleura can often be more clearly seen by decreasing the gain, and ensuring that the angle of insonation is perpendicular to the pleura. In the healthy state, occasional B-lines (laser-like vertical reverberation artefacts that reach the bottom of the screen set to a depth of 15 cm; see Video 2.5) and z-lines (laser-like vertical reverberation artefacts that only reach a few centimetres of depth; see Figure 2.7a and Video 2.1) may be seen arising from the visceral pleural line. Widely spaced reverberation artefacts caused by the skin surface and the pleural line ('A'-lines) appear as widely spaced lines

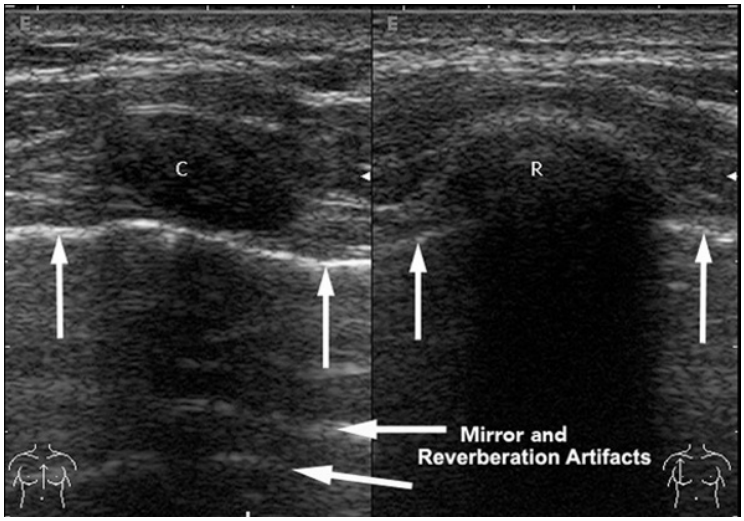

Figure 2.1 Chest wall. Left: The costochondral cartilage (C) allows through-transmission of ultrasound waves so that the underlying pleural line (vertical arrows, both images) can be seen. Right: Ossified rib causes almost complete reflection of sound waves with an underlying sonographic shadow. In cases where it is difficult to identify the pleural line with certainty, its location should be identified immediately underlying the rib and/or cartilage. Horizontal mirror and reverberation artefacts caused by the skin surface and underlying tissue planes are also seen.

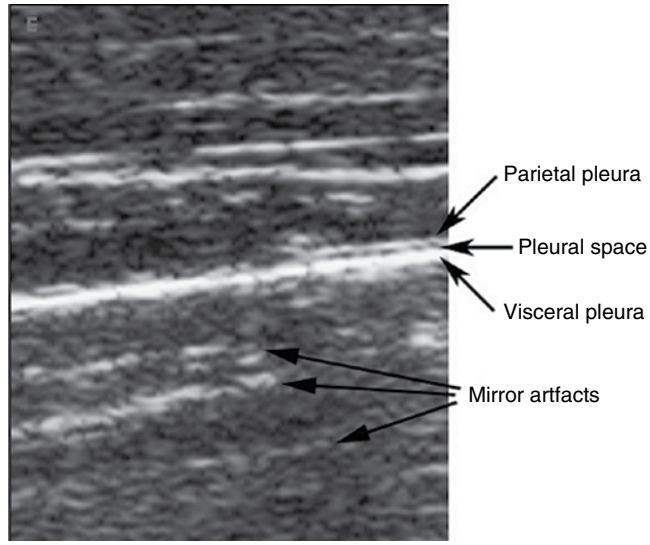

Figure 2.2 Both layers of pleura are echogenic. Usually, the two layers cannot be differentiated by ultrasound unless (as in this case) there is a small layer of fluid between them. This amount of fluid may be physiological (see also Figure 2.19). Horizontal mirror artefacts caused by the fascial layers of the intercostal muscles are seen.

projected into the lung (Figures 2.7b and 2.8; see Videos 2.3 and 2.4). Pleural sliding and 'lung pulse' (cardiac motion transmitted to the lung) can also be demonstrated and recorded with (Video 2.2) or without (Video 2.4) colour Doppler, as well as by M-mode (Figure 2.7c and d). Both of these findings exclude the presence of pneumothorax (at the location of the ultrasound probe; see below).

Chest Wall Lesions

Soft-Tissue Lesions

Suspicious or unclear findings during a physical examination of the chest wall should be examined using ultrasound. In trauma patients, haematomas may be identified as variably hypoechoic structures with blurred internal echoes. The echogenicity of haematomata depends on the erythrocyte content and the stage of organisation. Lymph nodes (usually seen as well-corticated hypoechoic structures with a hyperechoic medulla) and lipomata (usually seen as capsulated structures with fine linear echodensities running parallel with the skin surface) are also visualised using ultrasound.

Rib and Sternum Fractures

Sonographic signs of rib fractures include osseous discontinuity, step-off, adjacent haematomata, pulmonary contusions (discussed below) and pleural effusions (Figure 2.3). Small dislocations and fractures may be identified by a reverberation artefact.

Pleural Diseases

Pleural Effusion

Whilst physiological amounts of pleural fluid (3–5 ml) are detectable with ultrasound, at least 150 ml of effusion is needed for detection by upright chest radiography. Pleural effusions without cellular or proteinaceous aggregates are echo-free. Non-loculated pleural effusions are best detected in both supine and sitting patients in the posterior axillary line above the diaphragm. The morphology of the effusion shows respiratory variation, allowing differentiation from pleural scarring or thickening. Colour Doppler (scale set to detect very low velocity flow) may also be used to distinguish these by demonstrating motion of the liquid. Sonography

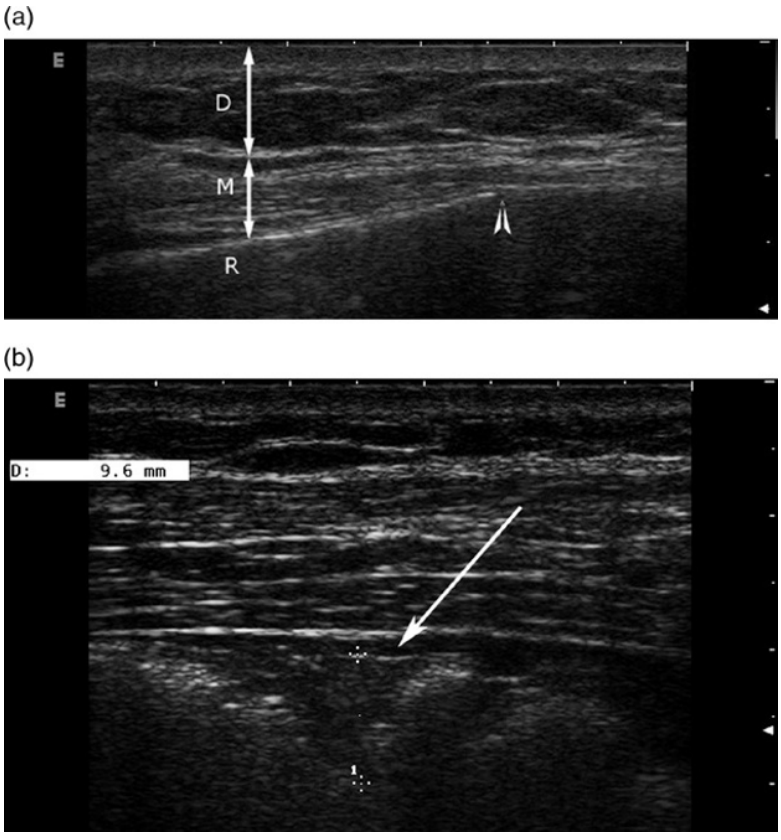

Figure 2.3 (a) A longitudinal image (with respect to the rib) of a subtle rib fracture is seen. Note the angulation as well as the cortical disruption (D = dermal layer, mostly comprised of subcutaneous adipose; M = skeletal muscle (note the striations); R = rib). Due to rib shadowing, the underlying pleural line cannot be seen. (b) An image obtained in the adjacent rib space, parallel to the image in panel (a), providing information about the underlying lung and pleural. A small triangular lung contusion is seen (between the callipers), and a very small associated pleural effusion between the two pleural layers (arrow).

cannot exclude effusions loculated in the interlobar fissures if they are surrounded by well-aerated lung. Lung ultrasound is more accurate than chest radiography in distinguishing between effusion and consolidation, allowing for its use in elucidating opacities of uncertain aetiology identified by chest radiography.

The shape of pleural effusions is highly variable, and an exact measurement of volume is therefore not possible. However, an estimation of volume may be useful when following patients with chronic effusions, and in determining the risk-benefit ratio in performing a thoracentesis in high-risk patients.

In the supine position, the pleural fluid volume is estimated by the formula:

$$Volume(\text{ml}) = 20 \times (\text{maximal thickness in mm in the posterior axillary line.})$$

In sitting patients:

$$Volume(\text{ml}) = \left[\begin{array}{l} (\text{basal lung} - \text{diaphragm} \\ \text{distance incm}) + \\ (\text{cephalocaudal extent of} \\ \text{the effusion in cm}) \end{array} \right] \times 70.$$

The latter formula is shown in Figure 2.4 (it should be noted that small effusions may be overestimated with this formula).

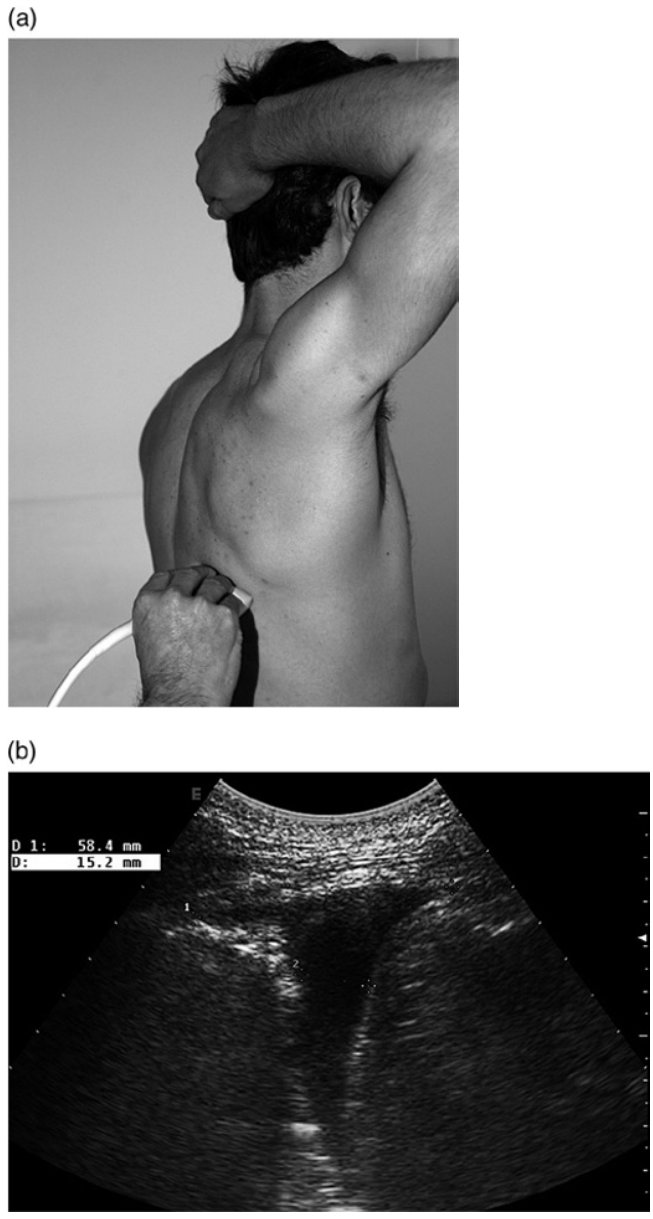

Figure 2.4 (a) Volume estimation of an effusion may be obtained with the patient in the sitting or standing position, by scanning between the scapular and the posterior axillary line. The transducer is usually held in a longitudinal plane (here, the transducer is parallel to the ribs). (b) The volume of the effusion would be estimated as (6 cm + 1.5 cm) × 70 = approximately 500 ml (see text for details).

Ultrasound may also suggest the aetiology of a pleural effusion with important diagnostic and therapeutic implications. Whilst all transudates are echo-free, most exudates are either homogeneously or heterogeneously echogenic, with or without septations, although some may be anechoic (Figure 2.5a and b). Pleural effusion associated with a smoothly thickened pleura may suggest empyema (especially if associated with underlying lung consolidation) (Figure 2.6). Nodules on the diaphragm suggest malignancy.

Ultrasound is an ideal guide for thoracentesis, increasing first-time success rates and reducing complications. (Details of the procedure are provided elsewhere in this book.)

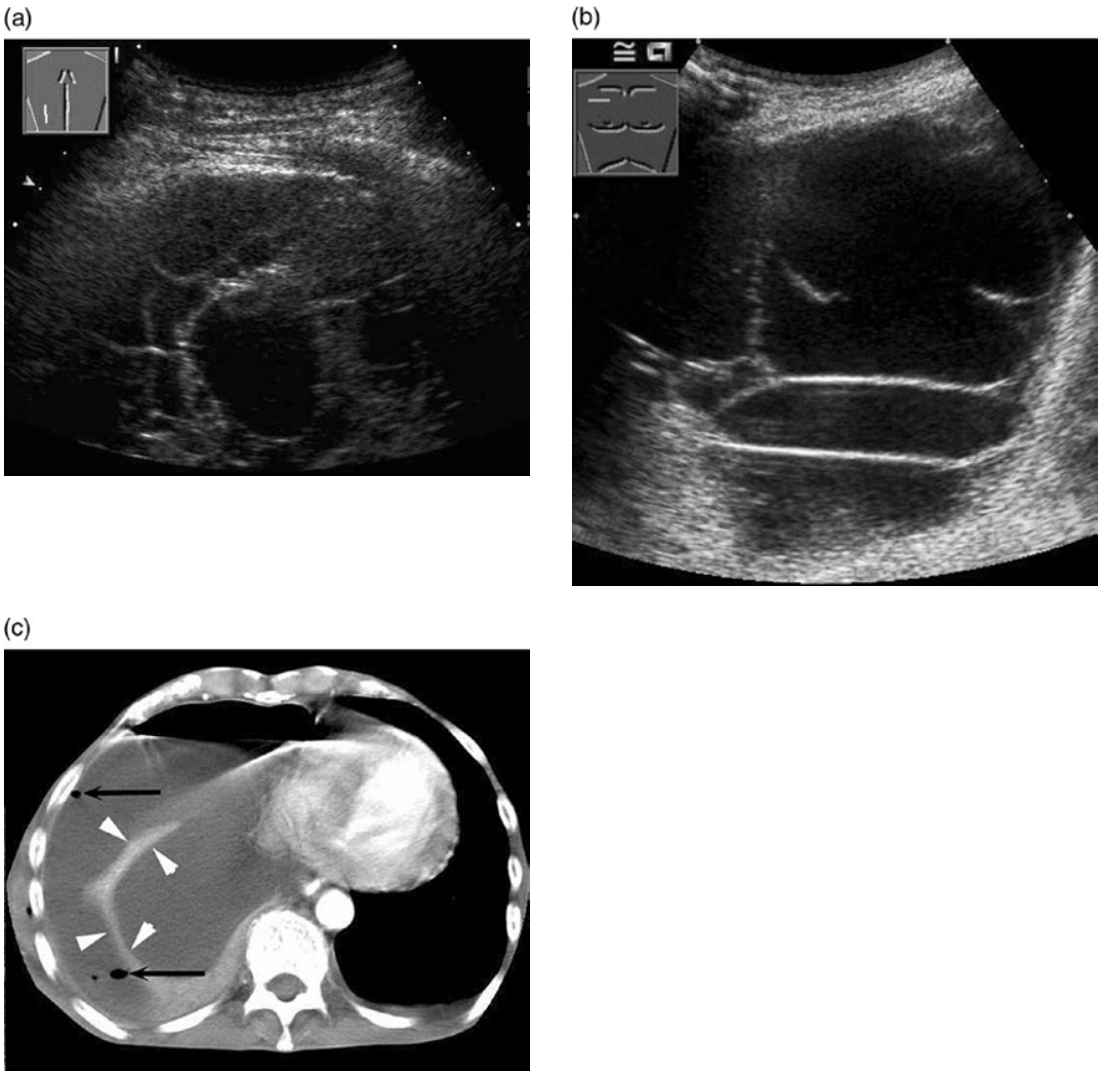

Figure 2.5 (a,b) Two complex septated effusions. The CT from panel (b) is shown in panel (c) with atelectatic lung (white arrowheads) and pockets of gas (black arrows) that suggest the presence of septations because they are not floating. As can be seen, ultrasound identifies septations with greater clarity than CT, and real-time ultrasound allows for drainage with directed access to multiple cavities.

Pneumothorax

With pneumothorax, air between the parietal pleura and lung prevents the ultrasound waves from reaching the visceral pleura, with a resultant loss of pleural sliding (as discussed above). There are several sonographic signs of pneumothorax, most of which require real-time analysis of the ultrasound, although there are subtle findings on still images that suggest pneumothorax (see Figure 2.7). The real-time findings include:

1) Absence of lung sliding (Video 2.3). It should be noted that B-lines and z-lines *by definition* arise from the visceral pleura, so that their presence excludes pneumothorax in that location.

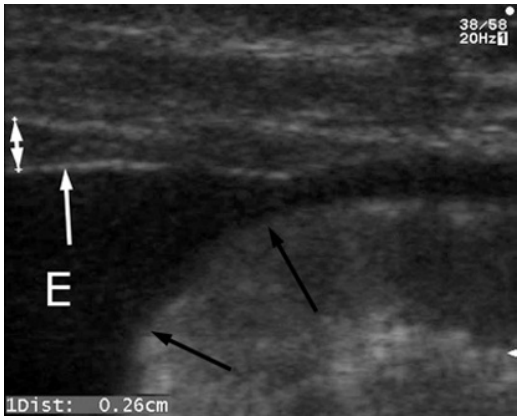

Figure 2.6 Empyema (E), overlying the diaphragm (black arrows). When associated with an effusion, the thickened parietal pleura (white double-headed arrow) suggests empyema. The inner serosal surface of the parietal pleura is indicated by the single white arrow.

2) Absence of lung pulse (Video 2.3, compare with normal in Video 2.1). An absence of lung sliding *and* lung pulse occurs whenever there is pneumothorax beneath the transducer. Occasionally, with normal lung sliding the lung pulse cannot be seen, so the latter in isolation should not be used to rule in pneumothorax.
3) In incomplete pneumothoraces, the transition point between collapsed lung (no lung sliding seen) and expanded lung (lung sliding can be seen) can be identified moving back and forth under the transducer with respiration (Figure 2.8; Video 2.4). This is referred to as the *lung point*, the location of which allows an estimation of the size of the pneumothorax.

In supine patients, the least gravitationally dependent areas are evaluated first (i.e., the anterior chest). The transducer is usually placed inferior to the clavicles in a longitudinal plane, and each rib space is systematically interrogated to the diaphragm in the midclavicular line. On the left side of the chest, if the heart is encountered before the diaphragm, the transducer should be moved laterally to complete the evaluation. If a pneumothorax is found, the lung point may be sought more laterally. If no pneumothorax is identified anteriorly and a pneumothorax is still strongly suspected, lateral scanning may identify a loculated pneumothorax. Pneumothorax can be documented by recording a video clip demonstrating the absence of lung sliding, or by an M-mode image (as described in Figure 2.7).

Any process that causes a loss of pleural sliding and/or pleural adhesions can lead to ultrasound findings of pneumothorax. Examples include inflammatory lung conditions such as pneumonia or pulmonary contusion, and pleural scarring from prior pleural injury or inflammation. Thus, if an absence of lung sliding is identified it is important to confirm that this is due to pneumothorax by ensuring that there are also no B-lines, no lung pulse, and no hepatisation of the underlying lung parenchyma. Bullous emphysema may also give a false appearance of pneumothorax due to effacement of the visceral pleura and underlying lung, often combined with pleural adhesions. Particular caution should be taken in patients with chronic obstructive pulmonary disease (COPD), since they are at high risk of spontaneous pneumothorax but also have a low tolerance of iatrogenic pneumothorax from an unnecessary tube thoracostomy. Despite these potential pitfalls, ultrasound is superior to supine chest radiography in the diagnosis of pneumothorax.

Pleuritis

The sharp localised respirophasic chest pain of pleuritis may be caused by any inflammatory process adjacent to the pleura, including lung infarct, contusion, pulmonary embolus and pneumonia. (The sonographic findings of these are discussed later in this chapter.) Non-specific pleuritis, which is often caused by viral infections, is difficult to diagnose by either clinical examination or radiography. However, in most patients (up to 90%), ultrasound of the visceral pleura displays disruption of the usually smooth pleural line and small subpleural lung consolidations, with or without subtle effusions. Absent or diminished pleural sliding and a focal interstitial syndrome with localised B-lines are further evidence of pleuritis (Figure 2.9).

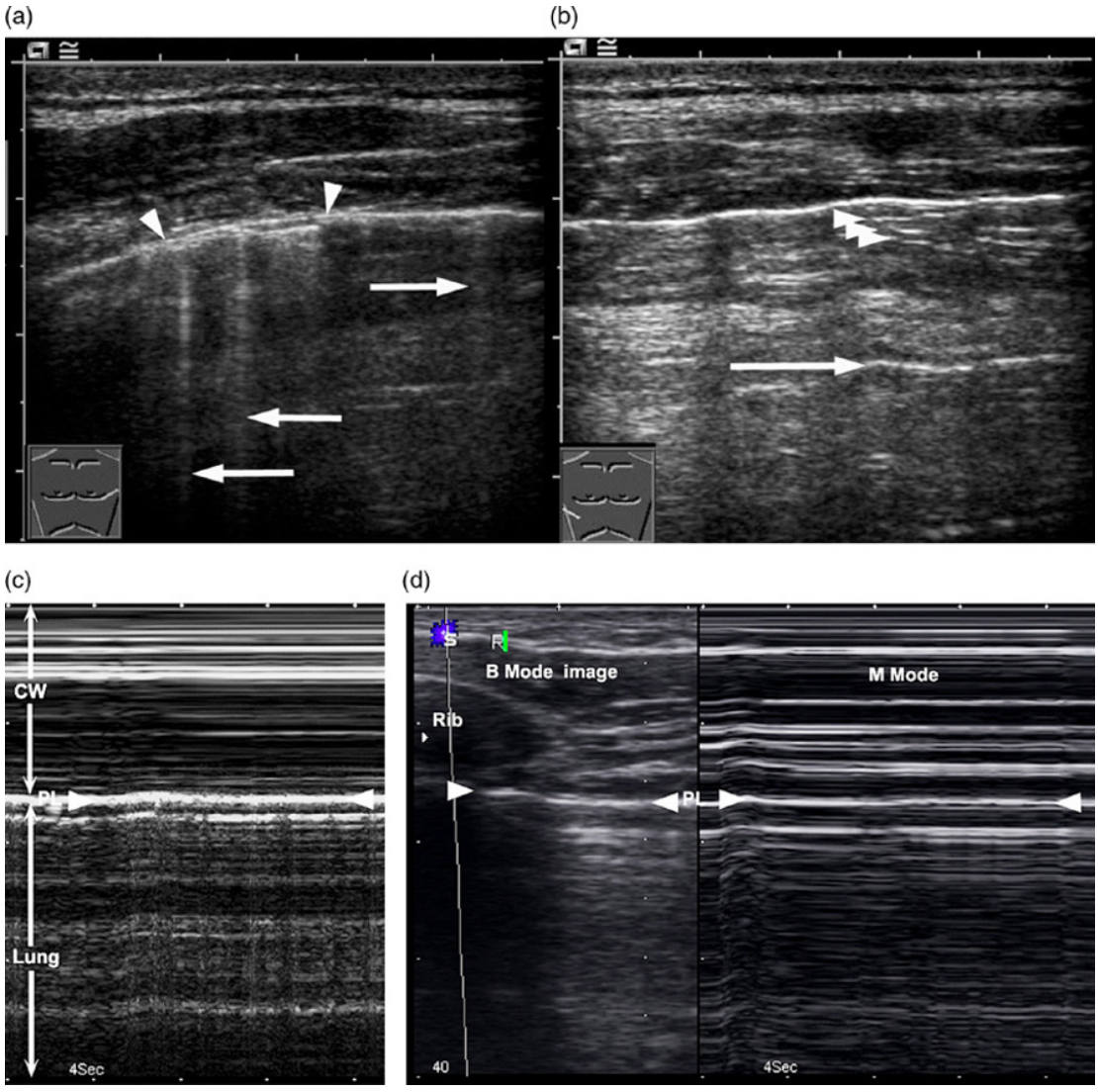

Figure 2.7 (a,b) The images demonstrate the difficulty in distinguishing pneumothorax and expanded lung on still images without using M-mode. (a) Normally expanded lung shows small, subtle pleural-based reverberation artefacts (also called 'z-lines', white arrows) and an area with a loculated pleural effusion that separates the parietal and visceral pleurae (between the arrow-heads). (b) Pneumothorax is suggested by the presence of stronger horizontal reverberation artefact (also known as an 'A-line', white arrow, see also Video 2.4), and by mirror artefacts (arrowheads) as well as absence of the 'Z-lines' seen in panel (a); however, all these findings may occur in normally expanded lung. (c) The M-mode findings of normal expanded lung are shown by a granular appearance of the pleural line itself (PL between arrowheads), and the underlying lung field compared to the straight lines of the chest wall (CW). This appearance is sometimes described as 'waves (straight lines of CW) on the shore (granular appearance of lung)'. (d) Pneumothorax is indicated by the linear horizontal echoes (not granular) below the pleural line, indicating the absence of lung motion. This finding is sometimes called the 'barcode' or 'stratosphere' sign.

Interstitial Syndrome

Increased extravascular (i.e., interstitial) lung water can be caused by a variety of diseases including heart failure, acute respiratory distress syndrome (ARDS), pulmonary fibrosis, inhalation injury and interstitial lung infections, all of which generate a similar sonographic pattern easily identifiable by bedside ultrasonography. In most cases, ultrasound cannot determine the specific aetiology, although it is often suggested by the clinical context. In other situations, ultrasonography can rapidly distinguish among conditions with similar presentations but with mutually exclusive treatment; for example, shortness of breath due to pulmonary oedema versus exacerbation of COPD.

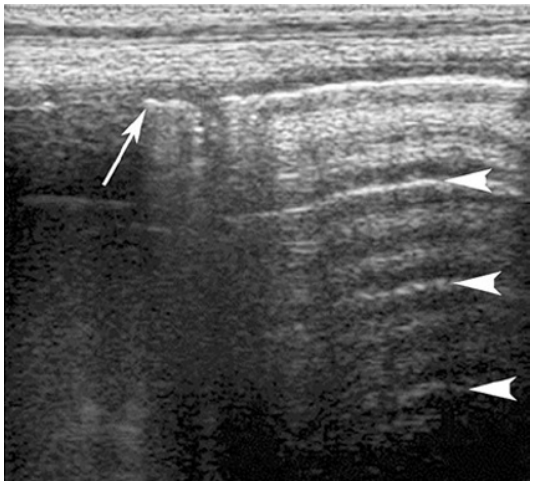

Figure 2.8 Pneumothorax. The lung point (arrow) is the transition point between expanded (to left of arrow) and collapsed (to right of arrow) lung. It is best appreciated in real time. To the left of the arrow lung sliding would be seen, to the right there would be absence of sliding. The lung point moves back and forth across the image with respiration (see Video 2.4). In this case, A-lines are best seen in the area of collapsed lung, although they are also usually seen in normal expanded lung.

B-lines are discrete reverberation artefacts arising from the pleural line that spread to the bottom of the screen without fading, and move synchronously with lung sliding (Figure 2.10; see Videos 2.5 and 2.6). They are the hallmark sonographic sign of the interstitial syndrome. Ideally, eight zones of the thorax are interrogated (Figure 2.11), but a quick anterior scan of one region on each side of the chest may often be sufficient. A positive region is defined by the presence of a rib space with three or more B-lines. With increasing severity, the extravascular lung water gives rise to confluent B-lines. Under such circumstances, some authorities recommend estimating the percentage of the rib space filled by the confluent B-lines and multiplying that by 10 to estimate the 'number' of B-lines at that location. Lung ultrasound is superior to chest radiography in the identification and exclusion of significant interstitial syndrome. Focal regions of

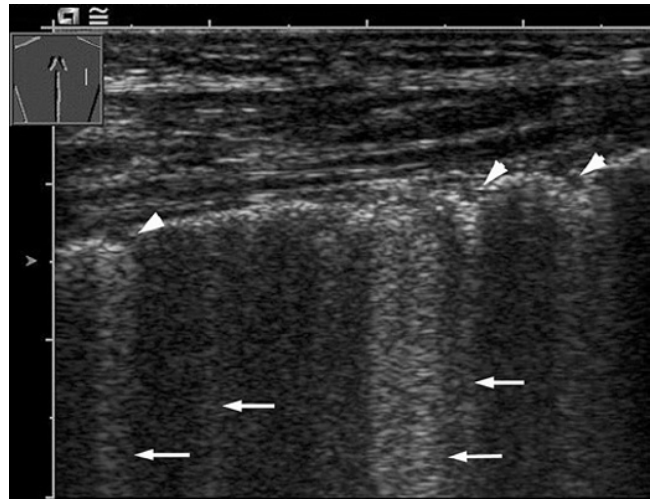

Figure 2.9 Pleuritis may be due to any inflammatory process adjacent to the pleura (see text). In the case of non-specific pleurisy, the normally smooth visceral pleura is irregular with small subpleural consolidations (arrowheads) or nodules and a focal B-line pattern (arrows). Ultrasound examination should be done at the location of the patient's symptoms.

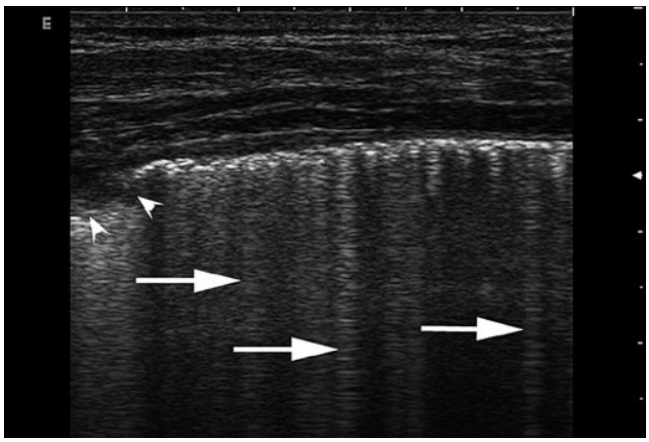

Figure 2.10 Multiple B-lines in diffuse interstitial syndrome demonstrated by a linear array transducer (some indicated by arrows). B-lines are vertical reverberation artefacts that arise from the pleural line and extend to the bottom of the screen without fading, moving synchronously with lung sliding. Many authorities prefer to use a curved-array probe set to a depth of about 15 cm to be certain that the reverberation artefacts extend to an adequate depth. On the left there is a small subpleural consolidation (arrowheads).

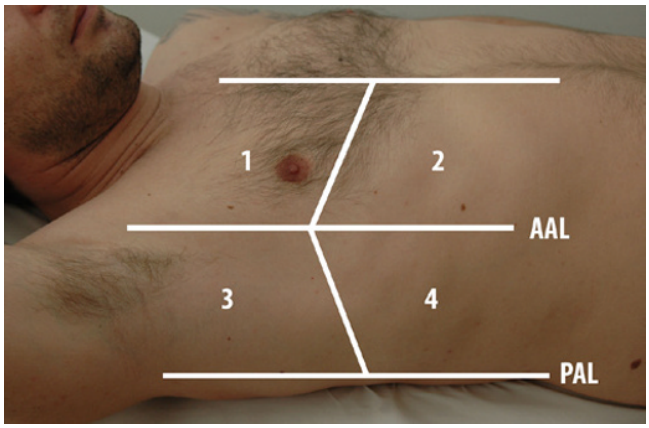

Figure 2.11 One widely used system for evaluating the chest for interstitial syndrome in which a rib space is sampled from each of eight regions on the anterior and lateral thorax. This image shows the four regions on the right side.

interstitial syndrome may be seen in the presence of pleuritis, pneumonia, pulmonary infarction and lung contusion.

In addition to the differentiation of cardiac and pulmonary causes of acute respiratory failure, B-lines have been shown to be useful in the risk stratification of patients with chest pain and dyspnoea once pulmonary fibrosis has been excluded, and to monitor response to treatment of volume overload in both cardiac and renal failure.

Lung Consolidations

In healthy persons, ultrasound imaging of the lung parenchyma is not possible because the ultrasound waves are completely reflected, scattered, and absorbed by the air-filled lung underlying the visceral pleura. Pulmonary processes that cause consolidation allow the transmission of ultrasound waves, but they can only be visualised sonographically when they abut the pleura, have an overlying sonographic window, and have no overlying subcutaneous emphysema or pneumothorax. Consolidations that are completely surrounded by normal air-filled lung are therefore sonographically occult.

Pneumonia

In the early stages of pneumonia, the consolidated lung has a sonographic appearance similar to that of liver (*hepatisation*) except that it contains arborising air bronchograms and numerous echogenic foci that measure a few

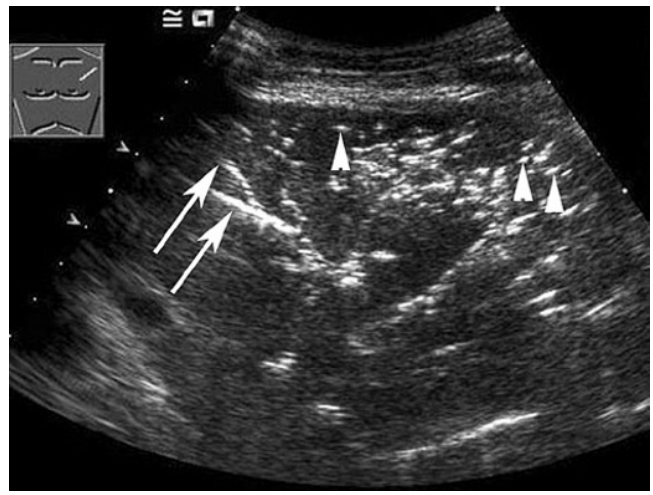

Figure 2.12 A large pneumonia seen as consolidated lung with liver-like echotexture and multiple highly echoic air bronchograms (arrows) and pockets of trapped air (vertical arrowheads) is seen. Unless seen in longitudinal section, air bronchograms (tubular structures) and air pockets (discrete) can only be distinguished with real-time scanning (see Video 2.7).

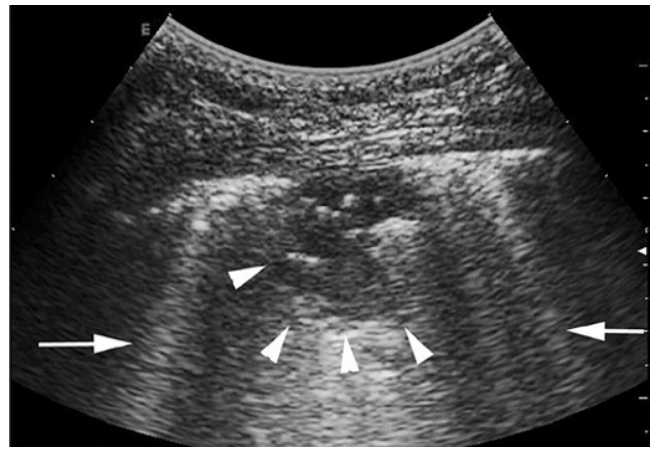

Figure 2.13 In this small pneumonia caused by the H_1-N_1 virus, the consolidation has a typically irregular 'shredded' contour (arrowheads). The adjacent pleura shows focal areas of B-lines (arrows). Other viral pneumonias may show less aeration.

millimetres in diameter and result from pockets of trapped air within the consolidation. Viral or fungal pneumonias are often more poorly ventilated and therefore contain fewer air bronchograms. In contrast to those seen in obstructive atelectasis, the air bronchograms associated with pneumonia are dynamic (Figure 2.12; Video 2.7). The transition zone between pneumonic consolidations and unaffected lung has an irregular 'shredded' appearance unless the consolidation abuts a major fissure. (Figure 2.13). Fluid bronchograms may also be present, seen as anechoic/hypoechoic branched tubular structures (Video 2.7). A persistent fluid bronchogram prompts suspicion of an obstructive cause for the pneumonia and may call for bronchoscopy. The characteristic colour-flow Doppler findings of pneumonia include a profuse vascular flow with normally arborising vessels (Figure 2.14 and video 2.8).

With progression, bacterial pneumonias may coalesce and form abscesses that appear as round or oval hypoechoic foci without inner vascular flow on colour Doppler. The smooth echo-dense margin of a capsule may be seen. If a patient does not respond to antibiotics, a microbiologic specimen may be obtained by ultrasound-guided needle aspiration.

As the pneumonia resolves, improving aeration of lung is sonographically evidenced by diminishing hepatisation, which is replaced by areas of reflection and reverberation artefacts

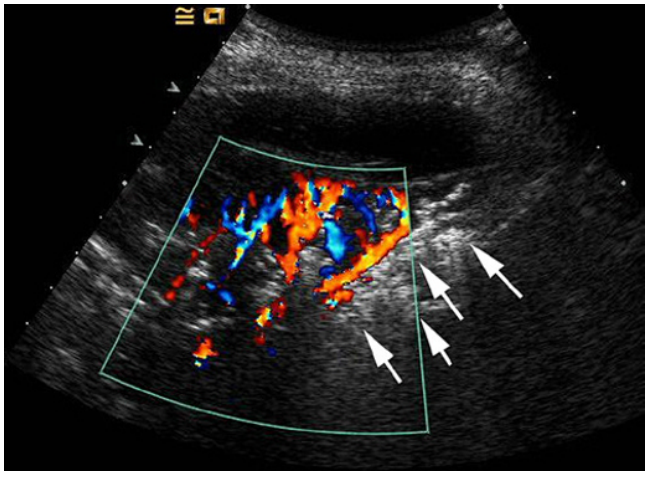

Figure 2.14 The pneumonia seen in Figure 2.12 shows a profuse pattern of vascularisation on colour Doppler sonography. On gray-scale the 'shredded' transition zone between consolidated and aerated lung (arrows) is seen.

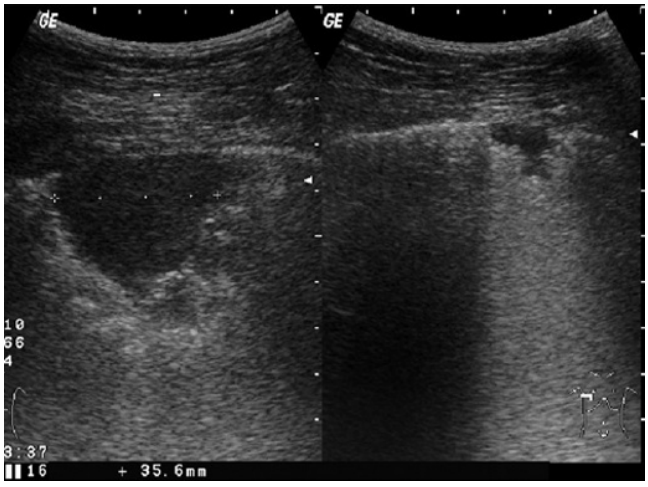

Figure 2.15 Two typical lung consolidations due to pulmonary embolism. They are pleural-based, mostly triangular, sometimes polygonal or round, with relatively well-demarcated margins.

('shred' zones) that are ultimately replaced by normal (non-transmissive) lung. The sonographic resolution of pneumonia is a more accurate reflection of the patient's clinical course than that of chest radiography.

Pulmonary Embolism

Following the occlusion of a pulmonary artery, surfactant loss within its vascular distribution leads to alveolar collapse. Interstitial fluid and erythrocytes flow into the alveolar space causing haemorrhagic infarcts that tend to abut the visceral pleura, creating good conditions for chest sonography. The frequency of reperfusion of these pulmonary infarcts has been shown to be much higher than previously reported as demonstrated by computed tomography (CT) and ultrasound. The sonographic signs of pulmonary embolism are multiple (usually) small (typically 1–3 cm, sometimes larger or smaller) pleural-based, echo-poor consolidations with sharp margins and with minimal or absent central colour-flow by colour-Doppler (Figure 2.15; Video 2.9).

With suspected pulmonary embolism, the examination should start at the site of localised pain, if the patient has one. If the patient has

dyspnoea without pain, the examination is started at the dorsobasal lung regions, where two-thirds of emboli are localised. Patients unable to sit up may be examined in an oblique or decubitus position.

There are some impediments to the use of lung sonography for the diagnosis of pulmonary embolism. For a complete examination, every rib space from spine to sternum should be systematically evaluated, but this requires a relatively mobile and cooperative patient. The patient is asked to 'hug' his or her chest, placing both hands on the contralateral shoulder. The examination should be performed slowly so as to allow the lung in each rib space to be evaluated throughout the respiratory cycle and to minimise the likelihood that a small infarct escapes detection beneath a rib. Time constraints may therefore limit the ability of sonologists caring for critically ill patients to perform a complete and thorough examination. Even with adequate time, a proportion of pulmonary emboli will lodge in arteries that supply lung abutting the mediastinum or major fissures, rendering them sonographically inaccessible.

The overall sensitivity and specificity of chest sonography in pulmonary embolism are 80% and 94%, respectively. Depending on the clinical context, the lung evaluation should be performed in conjunction with echocardiography (which is sensitive and specific in the detection of haemodynamically significant emboli; see Chapters 5 and 6) and leg vein sonography if pulmonary embolism is not identified. With this approach, bedside sonography can potentially 'kill three birds with one stone' by evaluating the source, transit point and destination of thromboemboli, in some reports raising the sensitivity of sonography to 92%. Thoracic ultrasound in combination with laboratory tests is a particularly attractive alternative to CT in cases of renal failure, pregnancy, contrast allergy, or when CT is unavailable. Given its widespread availability, relative cheapness and the avoidance of ionising radiation, sonography may also be preferable in settings where the approximately 8% false-negative rate is deemed acceptable in the evaluation of this disease.

Pulmonary Carcinomas and Metastases

Malignant invasion of the chest wall frequently causes local pain. Targeted ultrasound-based investigation of the region may allow for the immediate identification of this condition. Lung carcinomas and metastases are sonographically visualised as hypoechoic or heterogeneously echogenic structures that are usually rounded or polygonal, sometimes with echo-poor necrotic areas. The margins are often sharp, but the lesions may be speculated with finger-like extensions into the ventilated lung. In colour-flow evaluation, the tumour-vessels appear irregular and corkscrew-like (Figure 2.16). Dynamic ultrasound examination may identify malignant invasion of the chest wall or subclavian vessels more clearly than CT (sensitivity 89–100% for ultrasound versus 42–68% for CT).

Atelectasis

The partial or complete absence of ventilation of lung has several causes, and leads to atelectasis.

Compression atelectasis is usually due to massive pleural effusion. Sonographically, it appears as an area of hepatised lung containing minimal air (in contrast to pneumonias; see above). The consolidations may appear wedge-shaped or resemble a pointed hat. Similar to pneumonia, the transition to ventilated lung may be irregular and shaggy (Figure 2.17). The compressed lung may be seen to float in the effusion, like a waving hand (Video 2.10). Partial re-expansion may occur during inspiration and after drainage of the effusion. On colour-flow Doppler the vessels within the atelectatic lung will show a normal branching pattern.

Obstructive atelectasis appears sonographically as mostly hypoechoic regions of hepatisation, with little or no effusion. In the acute phase of obstruction, air bronchograms may be seen. With the passage of time, secretory congestion within the bronchi may lead to fluid bronchograms which appear like vessels on B-mode but lack a colour-flow Doppler signal. The appearance is similar to that of pneumonia, but with significantly less air bronchograms (Figure 2.18).

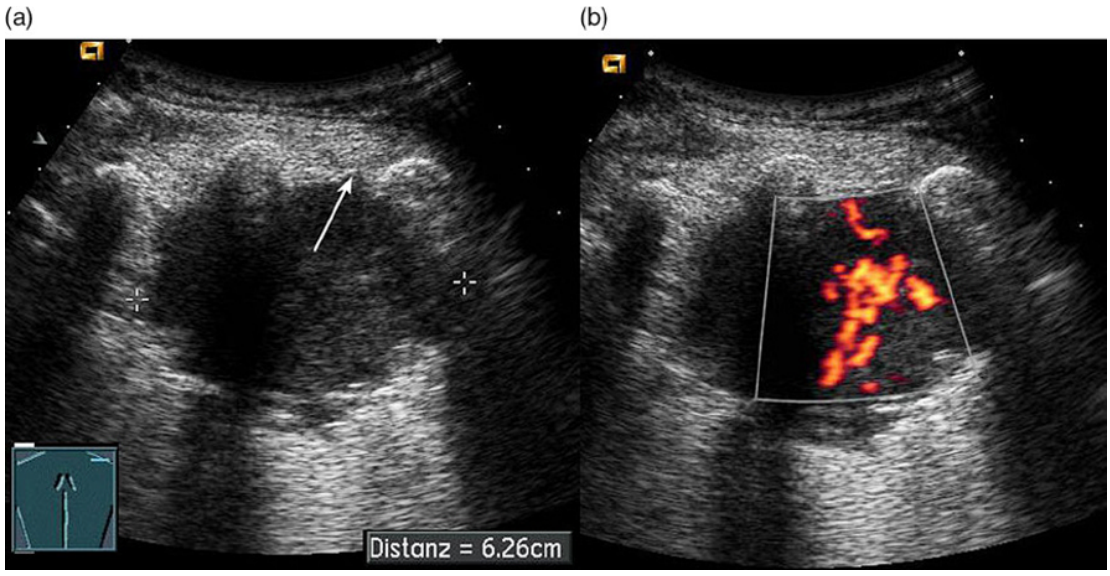

Figure 2.16 Lung cancer appears as a rounded consolidation at the site of the patient's pain. (a) The disrupted pleural line (arrow) indicates that the tumour has infiltrated the chest wall, resulting in a loss of pleural sliding. (b) The characteristically exaggerated blood flow on colour Doppler due to neovascularisation is often described as a 'vascular inferno'. An ultrasound-guided biopsy confirmed the diagnosis.

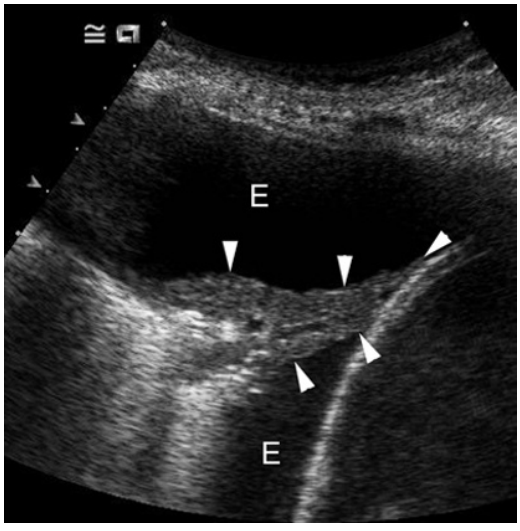

Figure 2.17 Compression atelectasis. A triangular-shaped lung consolidation (arrowheads) is seen floating in a simple effusion (E) with a shred sign at the transition between collapsed and normally expanded lung.

Obstructive atelectasis may have a variable shape, with clear margins if it abuts a fissure. Sometimes an underlying central tumour can be identified.

Plate-like atelectasis, frequently seen on plain film, is due to regional areas of hypoventilation and collapse. It is usually surrounded by normally expanded lung, making it difficult to identify sonographically.

Lung Contusion

In cases of blunt chest trauma – especially multiple rib fractures – pulmonary contusions are seen better on sonography than by plain-film radiography. Alveolar oedema and haemorrhage are visualised as shallow hypoechoic sub-pleural consolidations with irregular borders with respect to adjacent ventilated lung. These are more pronounced in the presence of concomitant pleural effusion (Figure 2.19). A focal