Paula Ferrada
Editor

Ultrasonography in the ICU

Practical Applications

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Editor
Paula Ferrada
Department of Surgery
Virginia Commonwealth University
Richmond, VA
USA

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This book is dedicated to residents and fellows who are learning the use of ultrasound to achieve better patient care. I truly believe we can affect patient outcome through education and innovation, and it is up to all of us learners to advance our field.

Preface

In the last decade ultrasound has become an extension of the physical exam. This is especially important when treating patients in extremis since it provides rapid information and does not require patient transport.

The use of this bedside tool has been made easier in order to bring critical care expertise to the location of the patient in need.

This volume illustrates practical applications of this tool, in an easy to understand, user-friendly approach. Because of its simple language and case-based teachings, this book is the ideal complement to clinical experience performing ultrasound in the critically ill patient.

Internet Access to Video Clip

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Paula Ferrada

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Contributors

Michael Blaivas Department of Emergency Medicine, St. Francis Hospital, Roswell, GA, USA

Department of Medicine, University of South Carolina, Columbia, SC, USA

Rosaleen Chun Department of Anesthesia, Foothills Medical Centre, Calgary, Alberta, Canada

Jamie Jones Coleman Associate Professor of Surgery, Department of Surgery, Division of Trauma and Acute Care Surgery, Indiana University School of Medicine, Indianapolis, IN, USA

Bianca Conti Department of Trauma Anesthesiology, R. Adams Cowley Shock Trauma Center, University of Maryland School of Medicine, Baltimore, MD, USA

David Evans Critical Care and Emergency Surgery, Virginia Commonwealth University, Richmond, VA, USA

Paula Ferrada Department of Surgery, Medical College of Virginia Hospitals, Virginia Commonwealth University, Richmond, VA, USA

Heidi L. Frankel Rancho Palos Verdes, CA

Jacob J. Glaser Department of Surgery, R. Adams Cowley Shock Trauma Center, University of Maryland School of Medicine, Baltimore, MD, USA

Kristin L. Gregg Department of Emergency Medicine, Bridgeport Hospital, Bridgeport, CT, USA

Shea C. Gregg Department of Surgery, Bridgeport Hospital, Bridgeport, CT, USA

Arpana Jain Department of Surgery, University of Arizona, Tucson, AZ, USA

Andrew W. Kirkpatrick Department of Surgery and Critical Care Medicine, Foothills Medical Centre, Calgary, Alberta, Canada

Irene W. Y. Ma Department of Medicine, Foothills Medical Centre, Calgary, Alberta, Canada

Kazuhide Matsushima Department of Surgery, University of Southern California, LAC+USC Medical Center, Los Angeles, CA, USA

Sarah B. Murthi Department of Surgery, R. Adams Cowley Shock Trauma Center, University of Maryland School of Medicine, Baltimore, MD, USA

Terence O'Keeffe Department of Surgery, University of Arizona, Tucson, AZ, USA

John M. Watt Department of Surgery, University of Arizona Medical Center, Tucson, AZ, USA

1 Basics of Ultrasound

Irene W. Y. Ma, Rosaleen Chun and Andrew W. Kirkpatrick

Basics of Ultrasound

Ultrasound is increasingly used as a point-of-care device in the clinical arena, with applications in multiple clinical domains [1–6]. To be able to use ultrasound devices appropriately for its various applications, appropriate training, practice, and a requisite understanding of the basic physics of sound transmission are of paramount importance [7–14].

Generation of an ultrasound image relies on interpreting the effects of sound waves propagating in the form of a mechanical energy through a medium such as tissue, air, blood or bone. These waves are transmitted by the ultrasound transducer as a series of pulses, alternating between high and low pressures, transmitted over time (Fig. 1.1a, b). As they are transmitted, these sound waves mechanically displace molecules locally from their equilibrium. Compression occurs during pulses of high pressure waves, causing molecules to be pushed closer together, resulting in a region of higher density (see Fig. 1.1a), while rarefaction occurs during pulses of low pressure waves, causing molecules to be farther apart and less dense. Once transmitted, these sound waves interact within tissue. Based on the select properties of the sound waves transmitted as well as properties of the tissue interfaces, some of these sound waves are then reflected back to the transducer, which also acts as a receiver. The signals are then processed and displayed on the monitor as a two-dimensional (2-D) image. This type of image is the typical image used in point-of-care imaging and is known as B-mode (or brightness mode) for historical reasons.

Frequency, Period, Wavelength, Amplitude, and Power

A number of parameters are used to describe sound waves, and some of these have direct clinical relevance to the user. These parameters include frequency, period, wavelength, amplitude, and power.

Frequency is the number of waves passing per second, measured in hertz (Hz). Two closely related concepts are the *period* (p), which is the time required for one complete wave to pass, measured in microseconds (µs) and *wavelength* (λ), which is the distance travelled by one complete wave, measured in millimeters (mm) (see Fig. 1.1a). Frequency is inversely related to period and wavelength. That is, the shorter the

I. W. Y. Ma (✉)
Department of Medicine, Foothills Medical Centre, 3330 Hospital DR NW, T2N 4N1 Calgary, Alberta, Canada
e-mail: ima@ucalgary.ca

R. Chun
Department of Anesthesia, Foothills Medical Centre, 1403-29th Street NW, T2N 2T9 Calgary, Alberta, Canada
e-mail: Rosaleen.Chun@albertahealthservices.ca

A. W. Kirkpatrick
Department of Surgery and Critical Care Medicine, Foothills Medical Centre, 1403 29 ST NW, T2N 2T9 Calgary, Alberta, Canada
e-mail: Andrew.kirkpatrick@albertahealthservices.ca

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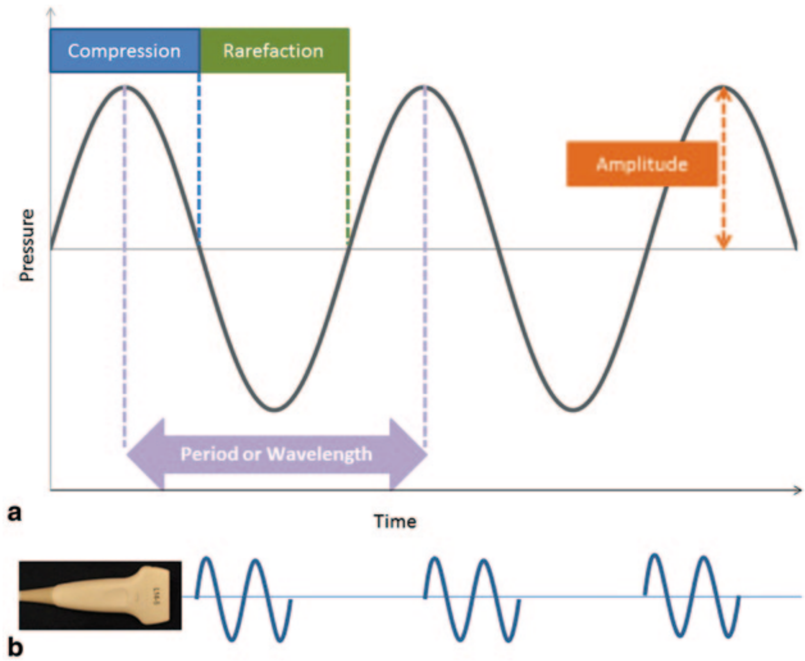

Fig. 1.1 **a** Sound waves transmitted propagating through a medium, alternating between high and low pressures, transmitted over time. Compression occurs during high pressure waves, pushing molecules mechanically closer together. Rarefaction occurs during low pressure waves, causing molecules to be farther part. Period refers to the time required for one sound wave to pass. Wavelength refers to the distance travelled by one complete sound wave. Amplitude refers to the height of the wave. **b** Transmission of a series of pulses of sound waves by a transducer

period, the higher the frequency; the shorter the wavelength, the higher the frequency. Ultrasound equipment typically operates within the range of 1 megahertz (MHz) to 20 MHz, which is well above the range of human hearing, generally considered to be between 20 to 20,000 Hz (0.00002 to 0.02 MHz). An understanding of frequency is clinically relevant to the operator and users of ultrasound. Specifically, choosing an appropriate frequency range will affect both the resolution of the image as well as the ability to penetrate tissues and image structures at the desired depth.

Frequency is one of the factors determining spatial resolution. Spatial resolution refers to the ability of ultrasound to distinguish between two objects in close proximity to one another as being distinct objects. Higher frequency sound waves yield better resolution than lower frequency waves. However, this improved resolution for higher frequency sound waves is at the expense of lower penetration [15]. That is, higher frequency sound waves are less able to image structures that lie further away from the transducer than lower frequency sound waves. Therefore, for typical applications in the intensive care unit, higher frequencies are more useful for imaging superficial structures while lower frequencies are more useful for imaging deeper structures. Thus, transducers with frequency ranges of 5 to 15 MHz are used for imaging superficial structures such as superficial vascular anatomy while ranges of 2 to 5 MHz are used for imaging deeper structures such as intra-abdominal organs.

Amplitude refers to the strength of the sound wave, as represented by the height of the wave (see Fig. 1.1a). Amplitude is measured in units of pressure, Mega Pascals (MPa). *Power* of the sound wave, refers to the total amount of energy in the ultrasound beam, and is measured in watts [16]. Power and amplitude are closely related, with power being proportional to the square of the amplitude [17]. In using ultrasound, one must keep in mind that for instance, by only doubling the amplitude, four times the energy is being delivered to the patient.

Understanding concepts regarding amplitude and power is critical to appreciate in facilitating the safe use of ultrasound. In general, the performance of ultrasound scans should comply with the ALARA (as low as reasonably achievable) principle by keeping total ultrasound exposure as low as reasonably achievable [18]. All ultrasound machines capable of exceeding a pre-specified output are required to display two output indices on the output display: Mechanical Index (MI), which provides an indication of risk of harm from mechanical mechanisms, and Thermal Index (TI), which provides an indication of risk of harm from thermal effects [18, 19]. The higher the indices, the greater the potential for harm. The Food and Drug Administration (FDA) regulations allow a global maximum MI of ≤1.9, except for ophthalmic applications, where the maximum allowed TI should be ≤1.0 and MI ≤0.23 [20]. For obstetrical applications, the current recommendations are for MI and TI to be ≤1.0 and the exposure time to be as short as possible: generally 5 to 10 min and not exceeding 60 min [21, 22].

Generation of Sound Waves

The generation of sound waves was made possible by the discovery of the piezoelectric effect in 1880: certain crystals vibrate when a voltage is applied to it, and conversely, subjecting the crystal to mechanical stress will result in an electrical charge [23]. Utilizing this principle, the transducer of an ultrasound machine houses crystal elements (Fig. 1.2), such that by applying electrical energy through the cable to these piezoelectric crystals, they change shape, vibrate, and in so doing, convert electrical energy into mechanical energy. Conversely, the piezoelectric crystals can also convert mechanical energy back into electrical energy, thereby allowing it to act as both a transmitter and a receiver. Within the transducer, the piezoelectric crystal is supported by the backing material (see Fig. 1.2), which serves to dampen any backward-directed vibrations, while the lens in front of the crystal serves to assist with focus. Finally, the impedance matching layer in front of both the piezoelectric elements and the lens assists with the transmission of sound waves into the patient [24]. Together, these components allow the transmission and receiving of sound waves. Irrespective of the characteristics of the transmitted sound waves, all ultrasound imaging relies on users interpreting the display of sounds waves reflected back to the receiver. Thus, an understanding of how sound waves travel and reflect from tissue is critical knowledge for any sonographer.

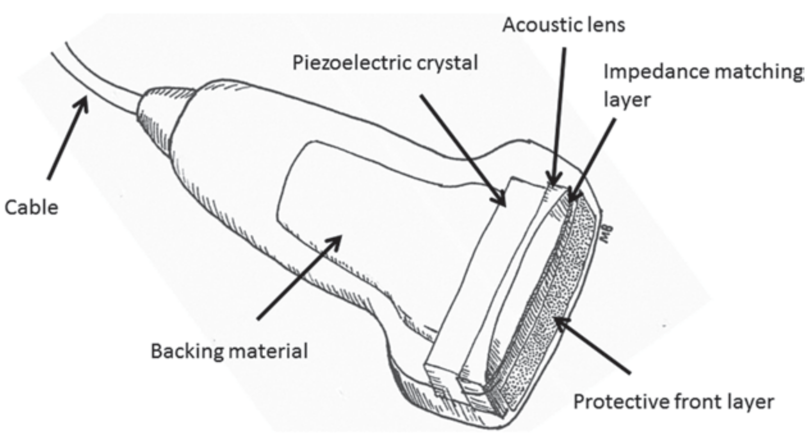

Fig. 1.2 A schematic representation of components of an ultrasound transducer. Illustration Courtesy of Mary E. Brindle, MD, MPH

Interactions of Sound Waves with Tissue

In order to understand how an ultrasound image is generated, it is important to understand the many ways in which sound waves propagate through and interact with tissue. Tissue characteristics such as density, stiffness, and smoothness, and surface size of the object being interrogated, all play critical roles in determining the amount of signal reflected back to the transducer. As only sound waves reflected back can assist in generating an image, it is critically important for the users to recognize how sound waves return to the transducer as well as how they fail to do so.

Propagation Velocity

The speed at which sound waves propagate within tissue is measured in meters per second (m/s). This velocity is determined by the density and stiffness of the tissue, rather than by characteristics of the sound waves themselves. Propagation velocity is inversely proportional to tissue density and directly proportional to stiffness of the tissue [17]. In other words, the denser the tissue, the slower the propagation velocity through that tissue, while the stiffer the tissue, the higher the velocity. In general, propagation speed is slowest through air (330 m/s) and fat (1450 m/s) and fastest through muscle (1580 m/s) and bone (4080 m/s) (Table 1.1) [25]. The average velocity through soft tissue is 1540 m/s, and it is this velocity that the ultrasound machine assumes its sound waves are travelling, irrespective of whether or not that is the case.

Understanding propagation velocities of different tissues is important for three reasons. First, propagation velocities through different tissue interfaces determine the amount of sound wave reflections, which in turn, determines the brightness of the signal display. Second, differences in propagation velocities are an important source of artifacts (see the section “Speed Propagation Error”). If the sound waves travel through tissue at a slower velocity than is assumed by the machine (e.g., through air or fat), any wave reflections from the object of interest will be placed at a farther distance on the display from the transducer than the true distance. Finally, as all diagnostic ultrasound uses the above mentioned approximation of ideal tissue characteristics, ultrasound will never yield the same fidelity of imaging as computer tomography (CT) or magnetic resonance imaging (MRI).

When sound waves interact with tissue, any or all the following processes may occur: reflection, scattering, refraction, absorption, and attenuation [15].

Reflection

When ultrasound waves propagate through tissue and encounter interfaces between two types of tissue, some of the sound waves will be reflected back. This reflected sound wave is called an *echo*. As previously mentioned, ultrasound imaging hinges upon the production and detection of these reflected echoes. Production of an echo is critically dependent upon the presence of an *acoustic*

Table 1.1 Propagation velocity in various media, measured in meters per second [25]. Acoustic impedance, measured in kilogram per meter squared per second [62, 63]. Attenuation coefficient, measured in dB/cm/MHz [25]

Medium	Propagation velocity (meters/second)	Acoustic impedance (kg/(m^2s))	Attenuation coefficient (dB/cm/MHz)
Air	330	430	10.00
Fat	1450	1.33×10^6	0.63
Water	1480	1.48×10^6	0.00
Average soft tissue	1540		0.70
Liver	1550	1.66×10^6	0.94
Kidney	1560	1.64×10^6	1.00
Blood	1570	1.67×10^6	0.18
Muscle	1580	1.71×10^6	1.30 (parallel)—3.30 (transverse)
Bone	4080	6.47×10^6	5.00

impedance difference between the two tissue types. Acoustic impedance is a property of the tissue, and is defined as the product of its tissue density and the propagation velocity of sound waves through that tissue. If two tissue types have identical acoustic impedance, then no echo will be produced, as no sound waves will be reflected back.

The brightness of the signal is directly related to the amount of reflection, and that the amount of reflection is proportional to the absolute difference in acoustic impedance between the two media. It therefore follows that a large acoustic impedance mismatch between two tissue types will result in a bright echogenic signal, while a small acoustic impedance mismatch between another two tissue types will result in an echo-poor signal. For example, at the interface between the liver and kidney, because of a minimal acoustic impedance difference between the two tissues, only about 1 % of the sound is reflected (see Table 1.1). Thus the interface between the kidney and the liver is somewhat harder to distinguish from one another (Fig. 1.3a) and less echogenic than the interface between muscle and bone, which has a large

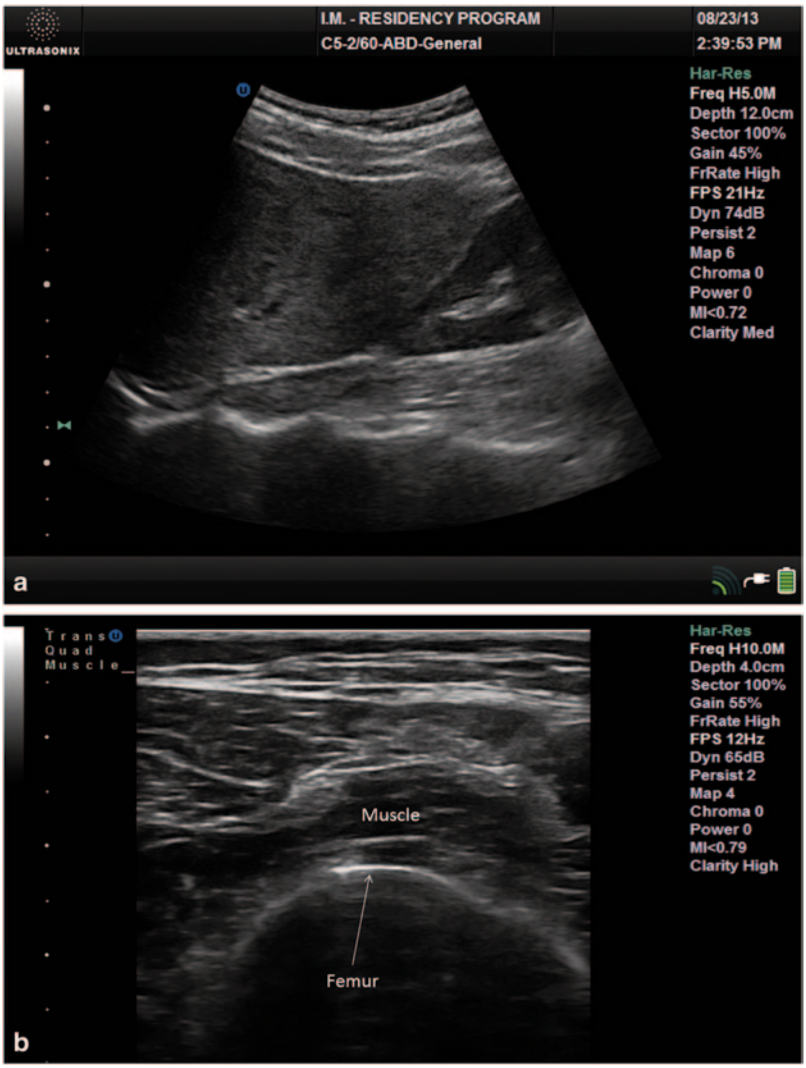

Fig. 1.3 **a** A longitudinal, oblique ultrasound view of liver and right kidney. Small acoustic impedance difference between liver and kidney results in a minimally echogenic interface between the two organs. **b** A transverse ultrasound view of the quadriceps muscle. Large acoustic impedance difference muscle and femur results in a bright echogenic interface between the two structures

acoustic impedance mismatch, resulting a bright echogenic line (see Fig. 1.3b). Finally, because of the very large acoustic impedance difference between tissue and air, upon encountering air, >99.9% of the sound waves are reflected. This results in minimal further propagation of sound waves. Therefore, beyond that interface, there is limited to no ability to further directly image structures [24]. This large acoustic impedance difference between air and skin is also the reason why coupling gel must be used for imaging purposes. Application of gel eliminates any air present between the transducer and the skin, assisting in the transmission of sound waves, rather than having most of them reflected back.

A second factor that determines the amount of reflection is the smoothness of the surface. For smooth surfaces that are large, compared with the size of the ultrasound's wavelength, *specular reflection* occurs (Fig. 1.4), resulting in a robust amount of reflection. However, for surfaces that are rough, where the undulations of the surfaces are of a similar size to the size of the ultrasound's wavelength, sound waves are reflected in multiple directions. This results in *diffuse reflection* (Fig. 1.5) [26]. Because the returning echoes are in multiple directions, only a few of them are received back on the transducer. As a result, diffuse reflection results in a less echogenic signal.

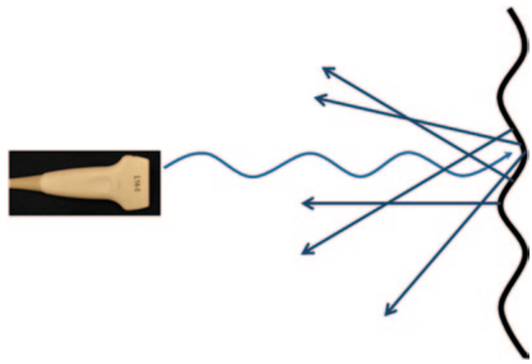

Fig. 1.5 Diffuse reflection occurs when sound waves are reflected off a rough surface of a similar size to the size of the wavelength

Scattering and Refraction

Additional ways in which emitted ultrasound waves do not reflect fully back to the transducer, resulting in attenuation of sound waves include scattering and refraction. Scattering occurs when ultrasound waves encounter objects that are small compared to the size of the ultrasound's wavelength, [15] which serves to diminish the intensity of the returned signal (Fig. 1.6).

Refraction occurs when sound waves pass from one medium to another with differing propagation velocities. These differing velocities

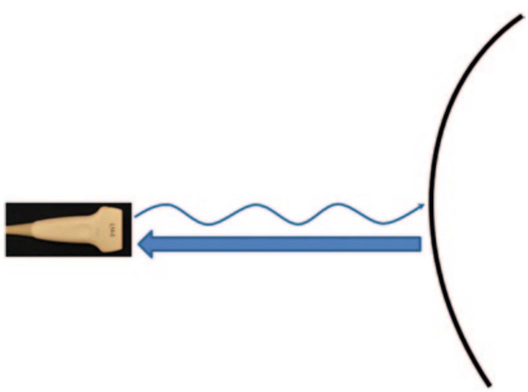

Fig. 1.4 Specular reflection occurs when sound waves are reflected off a smooth surface that is large compared with the size of the wavelength

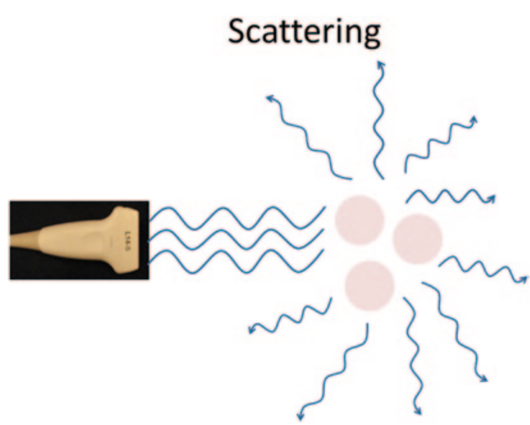

Fig. 1.6 Scattering occurs when sound waves are reflected off objects that are small compared with the size of the wavelength

result in refraction, or change in the direction of the original (or incident) sound wave [25]. The refracted angle, or magnitude of the change in direction of the ultrasound wave, is determined by Snell's law using the following equation:

$$\sin \theta_1 / V_1 = \sin \theta_2 / V_2$$

where θ_1 is the angle of incidence in the first medium, V_1 is the propagation velocity of sound in the first medium, θ_2 is the angle of refraction, and V_2 is the propagation velocity of sound in the second medium (Fig. 1.7). As can be seen from the equation, the higher the difference between the propagation velocities in the two media, the larger the magnitude of angle change of the refracted beam. Because the ultrasound machine assumes that the sound wave travels in a straight line and does not know that the sound path has been altered by refraction, [24] this results in artifacts such as the double-image artifact (see the section "Refraction Artifacts"). Thus, to minimize refraction, except for Doppler applications (see the section "The Doppler Effect"), an ultrasound image should be obtained at an angle as perpendicular as possible to structure of interest, in order to minimize the angle of incidence (Fig. 1.8a, b).

Absorption and Attenuation

As sound waves propagate through tissue, part of the acoustic energy is absorbed and converted into heat. The amount of absorption that occurs is a function of the (1) sound wave frequency, (2) scanning depth, and (3) the nature of the tissue itself.

Higher frequency sound waves are absorbed more than lower frequency sound waves. As stated earlier in this chapter, although higher frequency sound waves yield better resolution than lower frequency sound waves, this improved resolution is gained at the expense of lower penetration [15]. The inability of high frequency sound waves to penetrate deeply into tissue is a direct result of high absorption and conversion of acoustic energy into heat. Thus, a shallower depth, provided it captures sufficiently the structure of interest in the field of view, will result in

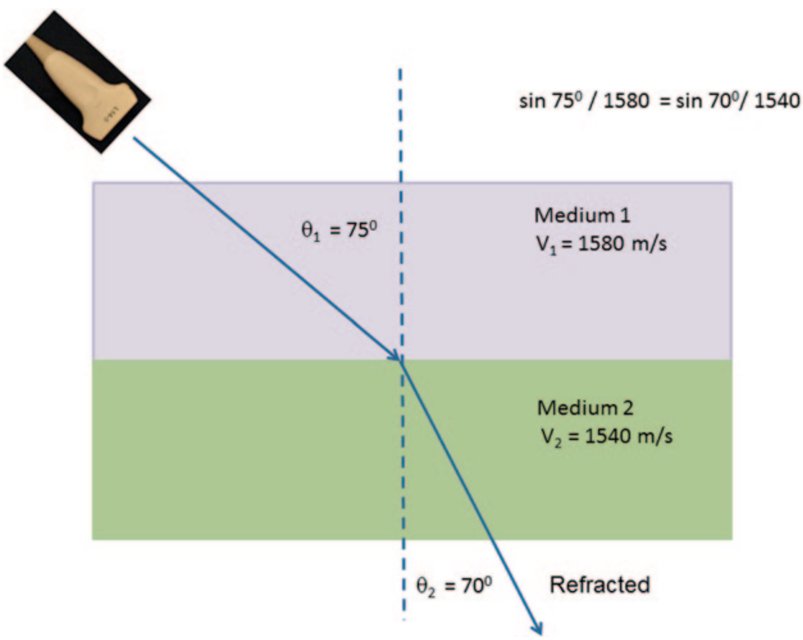

Fig. 1.7 Refraction occurs when sound waves pass from one medium with a propagation velocity to another medium with a differing propagation velocity

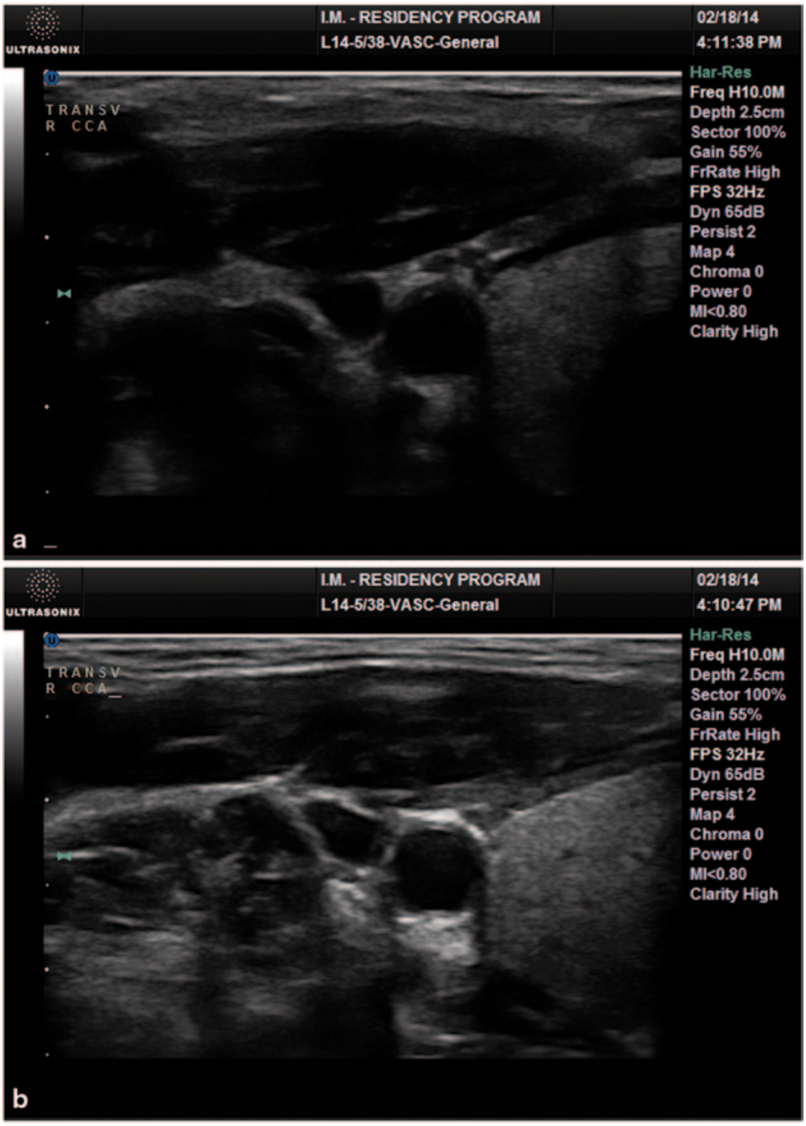

Fig. 1.8 **a** A transverse ultrasound view of the right carotid and internal jugular vein with the transducer angulated. **b** The same transverse ultrasound view of the right carotid and internal jugular vein with the transducer held at 90° to the structures. Without the need to modify any controls, the image resolution of the vascular structures is improved

a better image than one at a deeper depth, as it results in less absorption.

The amount of absorption that occurs is also a function of the medium itself, with certain media resulting in higher attenuation than others. Overall attenuation through a particular medium is described by the attenuation coefficient, which is measured in decibel per cm per MHz (see Table 1.1). As can be seen in Table 1.1, very little absorption occurs in water while high attenuation occurs in bone and air.

All these described processes, such as diffuse reflection, scattering, refraction, and absorption, all serve to *attenuate* the strength of the returned echo signal, because they all ultimately in one way or another divert energy away from the main ultrasound beam [24].

Summary

- **Increasing frequency results in less penetration and more detail:** Use high-frequency probe for vascular access, soft tissue, and pleura. Use low-frequency probes for the chest and abdomen.
- **Body habitus matters:** Sound waves get absorbed and attenuated. With increasing soft tissue from skin to target organ, the quality of the image obtained decreases.
- **Watch out for air and bone:** Bone will result in almost complete reflecton, making it impossible to image structures under it. Air is a poor conductor of sound, and it will result in artifacts and failure to obtain a quality image.

The Machine

An ever increasing number and variety of commercially available ultrasound machines are available from multiple manufacturers, [27] and which unit to purchase depends on a variety of factors such as price, durability, ease of use, image quality, ergonomic design, boot-up time, lifespan of the battery, and portability [27, 28]. The size of point-of-care devices is becoming smaller and with this trend, portability has correspondingly becoming better, with some of these point-of-care devices being no bigger or even smaller than the size of a laptop machine (Fig. 1.9a, b, c, d). While each machine has its unique instrumentation, some of the basic components are universal, and many devices offer similar functionalities.

The critical components of all ultrasound machines include a transducer, a pulser, a beam former, a processor, a display, and a user interface [26, 28].

Transducer, Pulser, and Beam Former

The function of the transducer, which is to emit and receive sound waves, has already been described (see the section “Generation of Sound

Fig. 1.9 **a** Portable ultrasound machine The Edge®. Image Courtesy of FUJIFILM SonoSite, Inc., with permission. **b** Portable ultrasound machine SonixTablet. Image Courtesy of Analogic Ultrasound/Ultrasonix, with permission. **c** Portable ultrasound machine MobiUS SP1 smartphone system. Image Courtesy of Mobisante, with permission. **d** Portable ultrasound machine Vscan. Courtesy of GE Healthcare

Waves"). The piezoelectric elements which generate the ultrasound waves are typically arranged within the transducer either sequentially in a linear fashion offering a rectangular field of view (linear array), in an arch which offers a wider trapezoid field of view (convex or curved array), or steered electronically from a transducer with a small footprint (phased array) (Fig. 1.10), or less commonly, arranged in concentric circles (*annular array*).

Sound waves are transmitted in pulses (see Fig. 1.1b), by the *pulser*, also known as the transmitter. The pulser has two functions. First, it transmits sound waves as its electrical pulses are converted by the transducer's piezoelectric elements into sound waves. Applying higher voltages will increase the overall brightness of the image. Practically however, the maximum resultant brightness is limited because the maximum voltage that can be applied and maximum acoustic output of ultrasound devices are restricted based on regulations by The FDA [29]. Second, the pulser controls the frequency of pulses emitted (number of pulses per second), known as the *pulse repetition frequency* (PRF). It is necessary that pulses of sound waves are delivered, instead of continuous emission of sound waves, so that in between the pulses, there is time for the reflected sound waves to travel back to the transducer [30, 31]. Thus, the time between pulses is essential to allow the transducer to *listen*, or receive echoes. The higher the PRF, the shorter is the "listening" time. Thus, to interrogate deeper structures, a lower PRF should be used, compared with imaging more superficial structures. Medical ultrasonography imaging typically uses PRFs between 1 to 10 kHz.

Once sounds waves are generated by the pulser, the *beam former* then controls both the shape and the direction of the ultrasound beam. The ultrasound beam has two regions: a near field (or Fresnel zone), and a far field (or

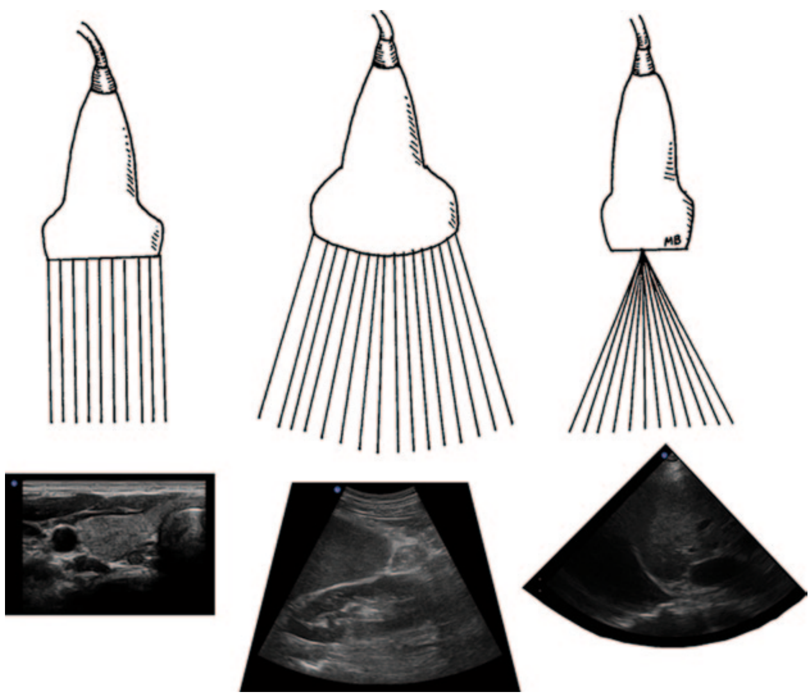

Fig. 1.10 A linear array transducer (*left*) where piezoelectric elements are arranged in a linear fashion resulting in a rectangular field of view. A curved array transducer (*middle*) where transducer elements are arranged in an arch, resulting in a trapezoid field of view. A phased array transducer (*right*) where transducer elements are electronically steered, resulting in a sector or pie-shaped field of view. Illustration Courtesy of Mary E. Brindle, MD, MPH and Irene W. Y. Ma, MD, MSc

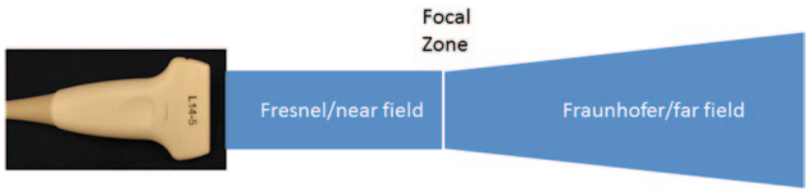

Fig. 1.11 Ultrasound beam shape

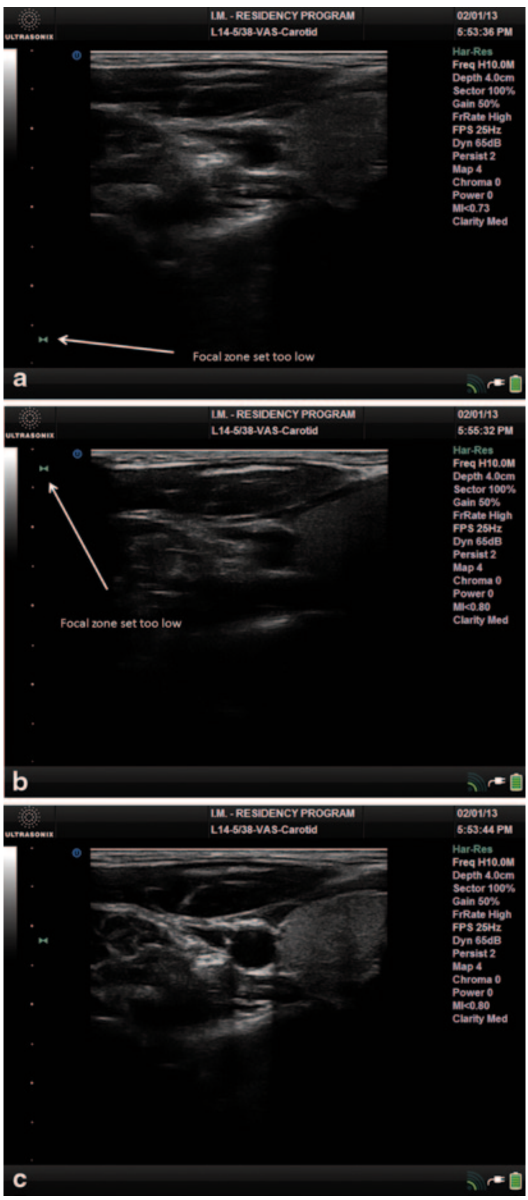

Fig. 1.12 **a** Transverse view of right carotid artery with focal zone set too low. **b** Transverse view of right carotid artery with focal zone set too high. **c** Transverse view of right carotid artery with focal zone set at the correct level

Fraunhofer zone), where the beam begins to diverge (Fig. 1.11). Because sound waves are emitted from an array of elements along the transducer, these waves are subject to constructive and destructive interferences, especially in close proximity to the transducer, resulting in variable wave amplitudes in the near field. Resolution is optimal at the near field/far field interface, known as the focal zone [31, 32]. The beam former allows the ultrasound user to manipulate the focal zone at the desired spatial location either mechanically by the use of physical lenses or electronically by beam forming. In general, the focus level is represented by an arrow or arrowheads, displayed at either the left or right side of the image. To optimize resolution, the focus should be set at or just below the level of the area of interest (Fig. 1.12a, b, and c).

Processor, Display and User Interface

Once the returning echoes return, the transducer acts as a receiver for these signals that are then processed by the processor. Two primary characteristics of the echoes determine the image ultimately placed on the display: (1) strength of the echo, and (2) the time taken for the echo to return. First, the strength of the echo is displayed by its brightness, such that a stronger returning signal is more echogenic than a weaker returning signal. This is readily evident in structures where spectral reflection occurs, such as the diaphragm. However, ultrasound waves are not directed at perpendicular angles throughout the diaphragm. Thus, the portion of the diaphragm that is not at perpendicular angles with the transducer results in refraction of the sound waves. This refraction causes a weaker returning echo and a hypoechoic signal (Fig. 1.13). Second, the time taken for the echo to return is used by the processor

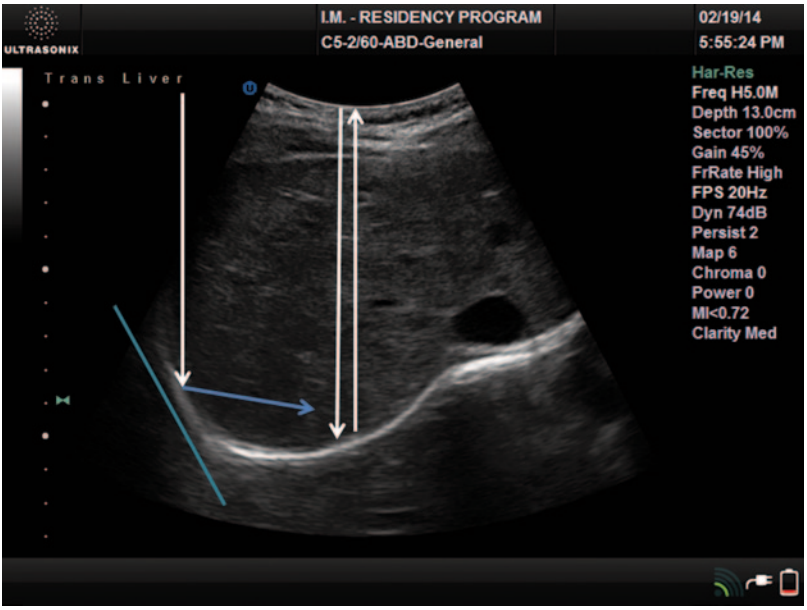

Fig. 1.13 Transverse image of the liver. Portions of the diaphragm at perpendicular angles with the transducer results in specular reflection and echogenic signals. Portion of the diaphragm at an oblique angle to the transducer (*turquoise line*) results in refraction (*blue arrow*) and hypoechoic signals

to determine the distance of the object from the transducer, using the range equation (distance = velocity × time/2). As ultrasound assumes that all signals travel at a propagation velocity of 1540 m/s, the time taken for the echo to return will determine the location of the reflector. Information regarding brightness and distance is then collected from each scan line by an array of piezoelectric elements within the transducer and collated to form a 2-D B mode image (Fig. 1.14).

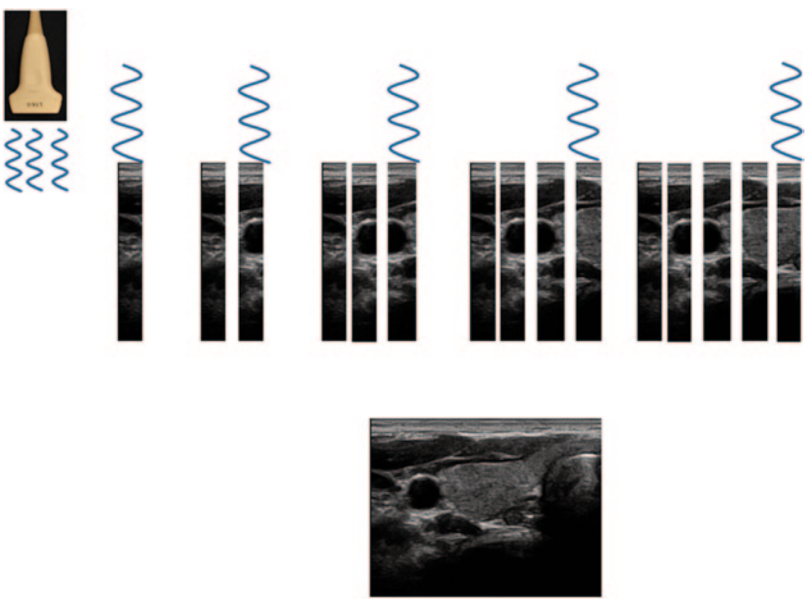

Fig. 1.14 Information on brightness and distance is collected from each scan line by the array of piezoelectric elements within the transducer and collated to form a two-dimensional image

This image is then shown on the display. As the user sweeps through a section of tissue with the transducer, real-time imaging is made possible by the rapid processing of multiple scan line data.

In order for the user to adjust various controls, a user interface allows these manipulations to occur, either in the form of a keyboard, knobs, buttons, tracker ball, track pad or touch screen [28]. In addition to providing the user access to various controls, in many machines, the user interface also assists the user in making measurements, storing images and videos, freezing the image and playback frame by frame using the cineloop control function.

Instrumentation and Controls

Irrespective of the type of user interface available, certain functions and controls are universal, while many others are commonly available in most units. Familiarity with these available controls will allow users to use most available ultrasound devices. After turning on the device, choosing the appropriate transducer, and applying coupling gel to the face of the transducer, the image obtained will need to be adjusted.

Depth and Zoom

The overall depth range is, to some degree, predetermined by the frequency of the transducer. For example, high frequency (10–15 MHz) transducers are typically unable to image deep structures beyond 10 to 15 cm. Conversely, lower frequency transducers (2–5 MHz) are not able to appropriately image superficial structures within the first several centimeters. Thus, an appropriate choice of transducer needs to be made. However, once the appropriate transducer is chosen, depth can be further adjusted in order to ensure that the region of interest is appropriately interrogated. During the initial scanning, initial depth setting should be set high in order to survey the region appropriately, so as to not miss far field findings as well as to assist with orientation of surrounding structures. Once the region is surveyed, the user can then decrease the depth using either the depth button or knob on the device. Most devices display the depth, either by displaying the total depth shown, with hash marks along the side of the ultrasound screen display (Fig. 1.15a) or by displaying the actual depth next to the hash marks (see Fig. 1.15b).

Alternatively, the zoom feature may be used to magnify an area of interest (Fig. 1.16a, b). This is often activated by first placing an on-screen box over the area of interest using either a track ball or a track pad. Zoom may or may not improve image resolution, depending on the ultrasound device available, as some devices are able to increase scan line density while others are not [26]. It is important to keep in mind that once a zoom feature is employed, the structure displayed at the top of the zoomed image may no longer be the most superficial structure directly under the transducer.

Gain, Time Gain Compensation, Automatic Gain Control, and Focus

The various attenuation processes of sound waves within tissue, such as absorption, scatter, and refraction, all contribute to weaken the strength of the returning echoes. The receiver, through the gain function, can amplify these returning echoes in order to compensate for tissue attenuation. By increasing gain, the overall brightness of the image is increased. However, excessive gain can result in increased "noise" to the image, as all returning signals are amplified (Fig. 1.17a, b, c).

The degree of attenuation is directly related to scanning depths. Thus, sound waves returning from increased depths in general suffer from a higher degree of attenuation. Most modern machines allow for users to selectively amplify gain in signals returning from deeper depths, through the function known as *time gain compensation* (TGC), also known as *depth gain control*. Control of TGC is typically controlled using a series of slider controls, with the buttons near the top corresponding to the echoes reflected from the near field, while the buttons at the bottom correspond to the echoes reflected from the far

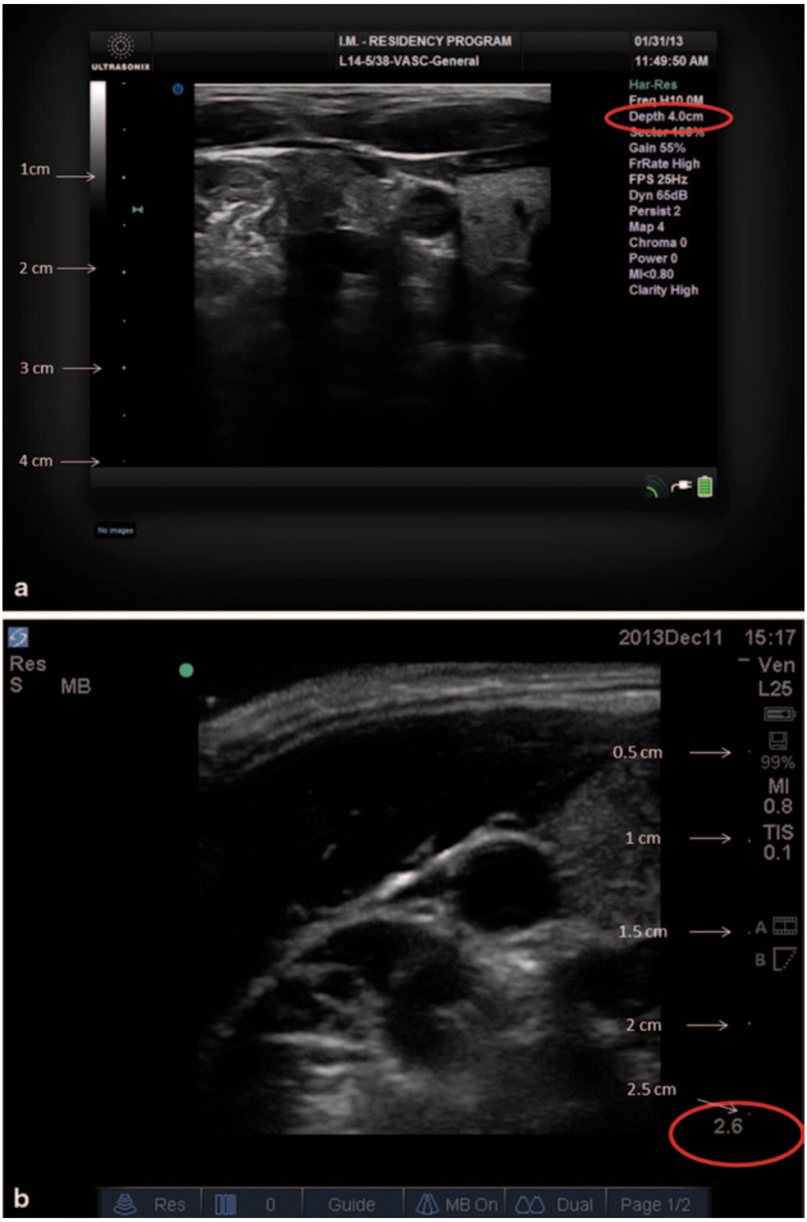

Fig. 1.15 **a** Distance information of ultrasound image illustrated by total depth displayed, with hash marks along the side of the screen display. In this image, total depth is 4.0 cm (*red circle*). Each large hash mark is thus 1 cm (*white arrows*). **b** Distance information of ultrasound image illustrated by depth displayed next to the hash mark. In this image, total depth is 2.6 cm. Each hash mark is thus 0.5 cm (*white arrows*)

field (Fig. 1.18). Sliding the button to the right will typically increase the gain, while sliding the buttons to the left will supress gain. Some ultrasound devices control near field and far field gain using knobs instead of slider buttons, but the principle behind the use of TGC is the same. It allows users to selectively amplify the strength of signals returning from deeper tissues without increasing overall noise to the near field (Fig. 1.19a, b, c).

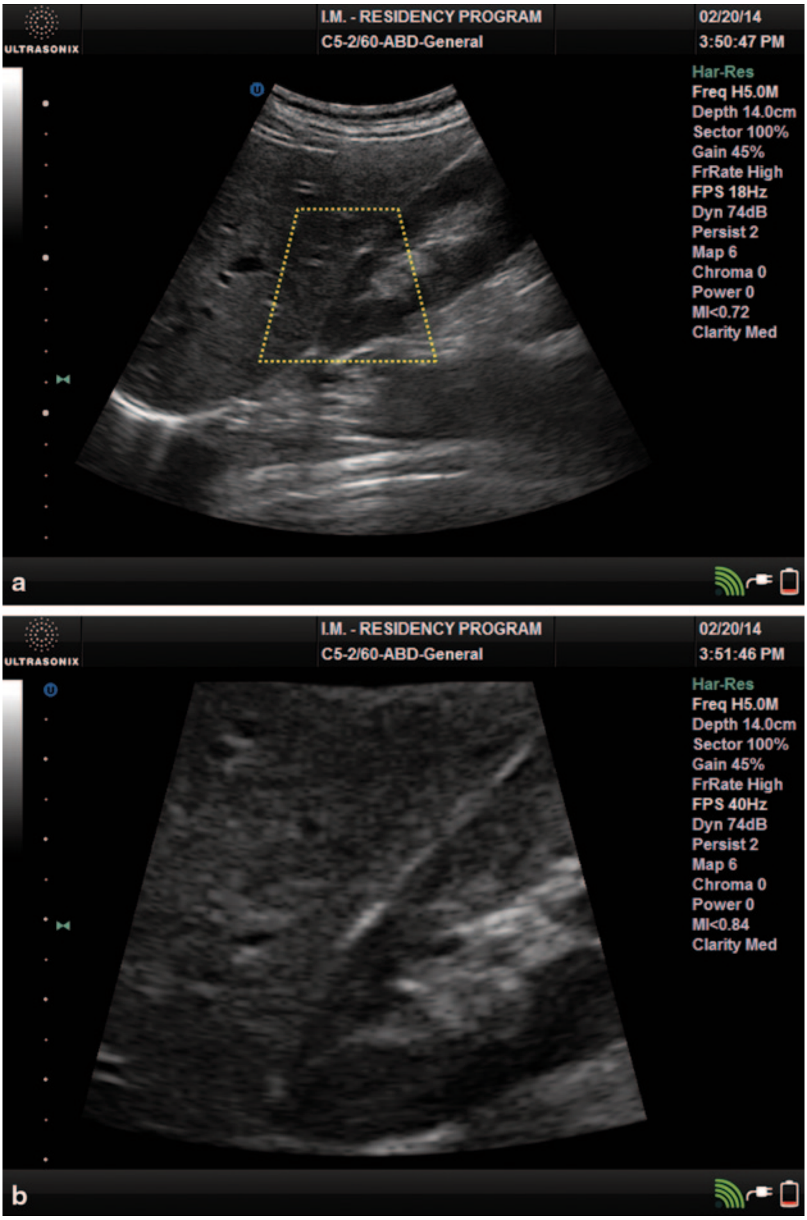

Fig. 1.16 **a** A longitudinal, oblique ultrasound view of liver and right kidney. Area of interest is marked by the yellow zoom box. **b** Zoom function activated. Top of the image corresponds to the area within the yellow zoom box and no longer refers to anatomy that is immediately beneath the transducer

Lastly, some machines are equipped with the automatic gain control function, which detects the decrease in echo amplitude with depth and applies the compensatory amplification to those echoes [33]. Use of this function requires less time and user control. However, artifacts around anechoic regions may be introduced by this function [34]. The use of focus has already been discussed in the section "Transducer, Pulser, and Beam Former." The focus should be set at or

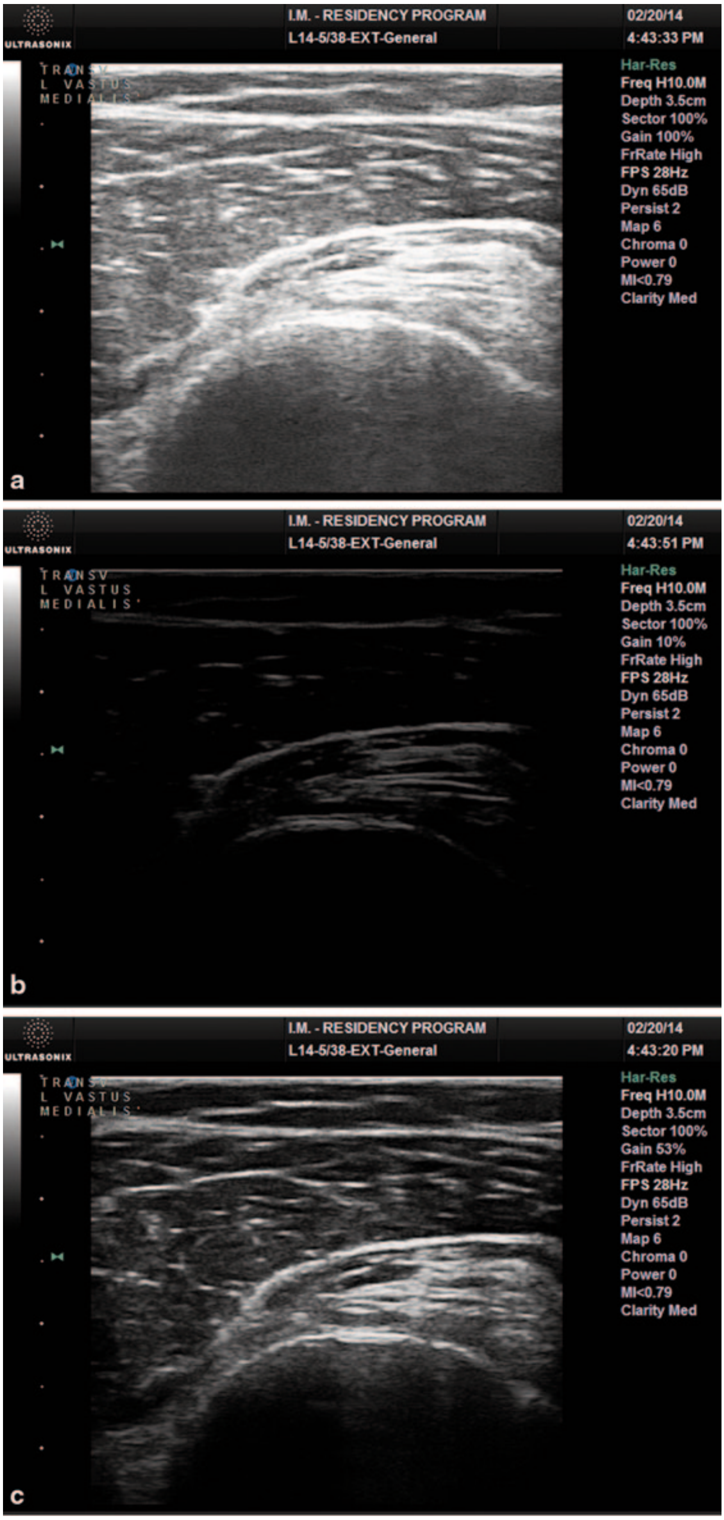

Fig. 1.17 **a** Transverse image of the left vastus medialis. Too much gain is applied. **b** Same image. Too little gain is applied. **c** Same image. Correct amount of gain is applied

Fig. 1.18 Typical slider controls for adjusting time gain compensation

just below the level of the area of interest (see Fig. 1.12a, b, c).

Dynamic Range

When echoes are reflected back to the transducer, a wide range of amplitudes of waves are present. However, the machine is not able to display this entire range of amplitudes in varying degrees of brightness, as it is limited by its dynamic range. Dynamic range refers to the ratio of the largest to the smallest wave amplitude that can be displayed for the machine, expressed in decibels [35]. As a result of this limitation, for display purposes, gray scale information is *compressed* into a usable range, by selectively amplifying the weaker signals, compared with the stronger echoes. By decreasing the dynamic range, fewer shades of gray are available. Conversely, by increasing the dynamic range, more shades of gray are available. The effects of dynamic range changes can be readily discerned in Fig. 1.20a, b.

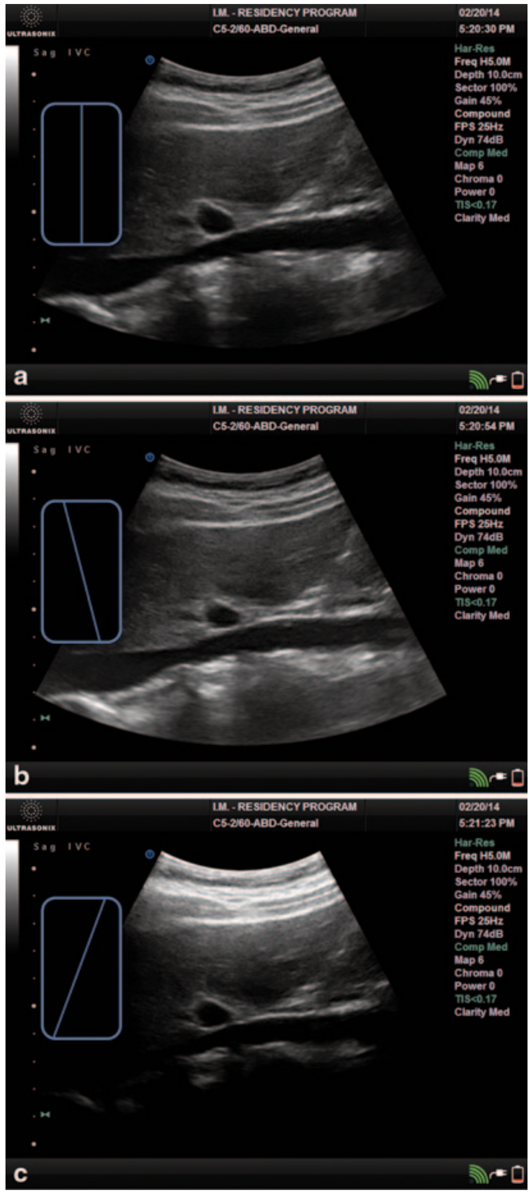

Fig. 1.19 **a** Longitudinal image of the inferior vena cava with even application of time gain compensation. **b** Same image with higher gain selectively applied to the far field. **c** Same image with higher gain selectively applied to the near field

Harmonic Imaging

Transmission of ultrasound signals in the patient is often distorted because human tissue is not perfectly elastic [36]. That is, in response to the compression and rarefaction phases of

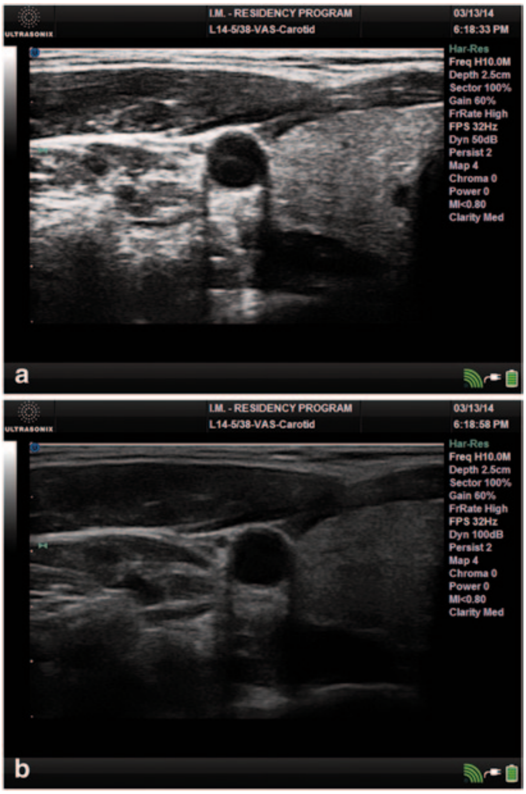

Fig. 1.20 **a** Transverse image of the carotid artery with a low dynamic range (50 dB). **b** A higher dynamic range is used (100 dB)

sound waves, tissue does not compress and relax at exactly the same rate (see Fig. 1.1a). For instance, during the compression phase of a sound wave (see Fig. 1.1a), sound travels in fact faster through this denser tissue than during the relaxed phase [37]. This differential speed results in a distorted sound wave, with higher frequencies present during the compression phase than the original transmitted frequency (also known as the fundamental frequency) (Fig. 1.21). These higher frequencies generated by tissue occur at multiples of the fundamental frequencies and are known as *harmonics*. As a result of these distortions and other attenuating factors within tissue, in traditional fundamental mode imaging, by the time the echoes arrive back at the transducer, significant noise may be present, resulting in a suboptimal image.

Harmonic imaging aims to detect specifically these distorted harmonic frequencies that are generated from the tissue and create images based on these harmonic sound waves rather than the fundamental frequencies, and in so doing improves the image quality by improving both image resolution and also in accentuating the appearance of artifacts such as enhancement,

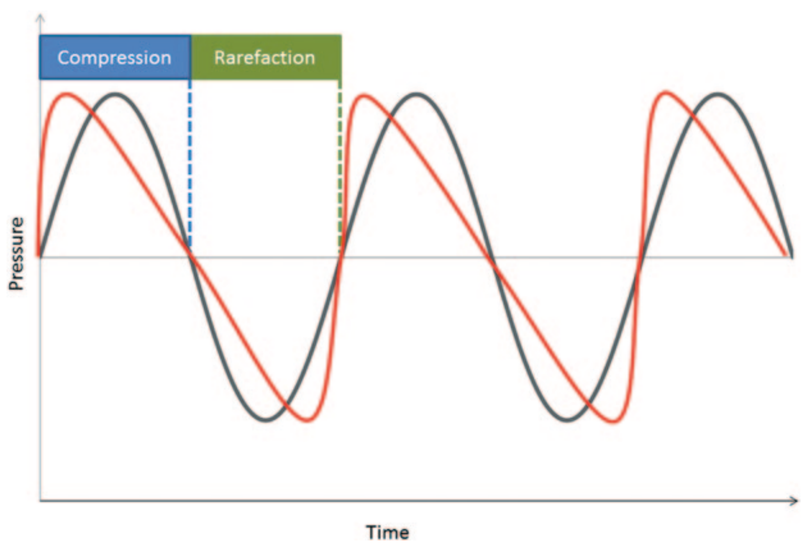

Fig. 1.21 Propagation of sound waves. Fundamental sound wave is generated (*dark grey*). Differential propagation velocity as a result of compression and rarefaction results in a distorted sound wave (*red*)

shadowing, and comet-tail artifacts (see the section "Common Artifacts") [26, 35, 36]. This modality is particularly helpful for imaging patients within whom the distortion of sound waves is likely to be significant (i.e., scanning deep structures within obese patients). The benefits of harmonic imaging in patients whose distortions are unlikely to be significant (i.e., thin patients; superficial scans) are questionable as the intensity of harmonic frequencies is lower than that of the fundamental frequencies [37].

Use of Presets

Many machines are equipped with presets for select applications such as thoracics, vascular access, or abdominal. Presets typically preconfigure gain, depth, and focus such that with the push of a button, the most applicable settings are in place for the scan. Presets offer a good starting place for scanning. However, the user should still be familiar with the relevant controls as presets cannot account for individual patient characteristics and body habitus.

Display Modes

While thus far the discussion has concentrated primarily on 2D B-Mode imaging, M-Mode, or Motion Mode, is an another useful ultrasound mode. M-mode is used to depict the ultrasound signal along a single scan line. To do so, a 2-D image is first acquired. The user can then adjust a single scan line along the area of interest and in so doing, reflected sound waves along that single scan line is displayed over time. Because information outside of the scan line is no longer displayed in real time, the machine is able to process and update the display quickly and efficiently, resulting in excellent temporal resolution. Clinically, M-mode is commonly used in cardiac and pulmonary applications. For example, use of M-mode assists in the diagnosis of pneumothorax as the absence of movement below the pleural over time becomes readily apparent (Fig. 1.22a, b, c).

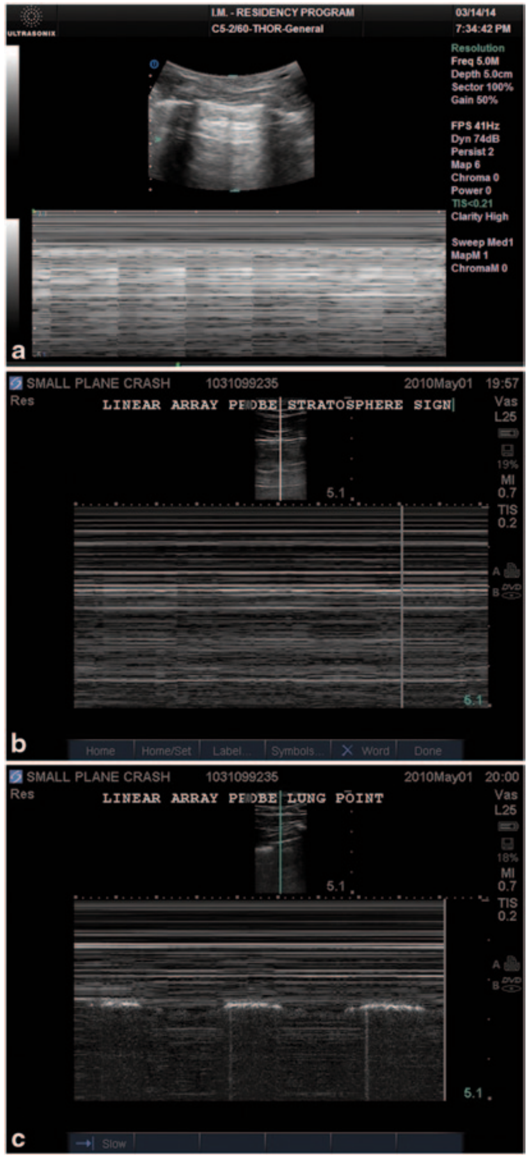

Fig. 1.22 **a** M-mode image of normal lung and pleura. Beneath the pleura is the sandy (shore) appearance, while above the pleural line is a linear pattern (sea), known as the "seashore sign." **b** M-mode image of pneumothorax. Above and below the pleural line is a linear pattern, known as the "stratosphere sign" or "barcode" sign. **c** M-mode image at the boundary of the pneumothorax. This demonstrates an alternating pattern of "seashore sign" and "stratosphere sign"

Other modes commonly used clinically include Doppler modes, which are discussed in the section "The Doppler Effect."

Summary

- **Know your machine and the pre-sets:** In most modern machines, required adjustments are minimal.
- **Not too much, not too little:** Adjust gain so you can see an appropriate amount of brightness. Too much gain will result in an image impossible to interpret, as it would look too white. Not enough gain will result in a dark image. Find a sweet spot and educate your eye.

Common Artifacts

Artifacts are ultrasound wave reflections that do not display or accurately represent the anatomic structure of interest. Typically artifacts can be an obstacle to accurate image acquisition and can lead to diagnostic error. On the other hand, understanding the mechanism of some artifacts can be utilized effectively to understand physiology and improve critical pathologic diagnoses and bedside care.

There are many types of artifacts that are a result of factors including incorrect assumptions of the speed and direction of sound waves in biological tissue (i.e., that sound waves travel at 1540 m/s and in a straight line), instrumentation errors, the physics of ultrasound in general and physical limitations of image acquisition [38, 39]. Artifacts that are related to improper imaging techniques, such as inappropriate use of gain are preventable and will not be described further in this chapter (Fig. 1.23). In describing artifacts, specific ultrasound terminology is utilized. A summary of these terms is presented in Table 1.2. Some of the more commonly encountered artifacts potentially impacting clinical care, as well as some useful artifacts are described.

Reverberation Artifacts

Reverberation artifacts are the result of a sound wave that bounces back and forth between two strong reflectors that are positioned along the path of the ultrasound beam, before eventually

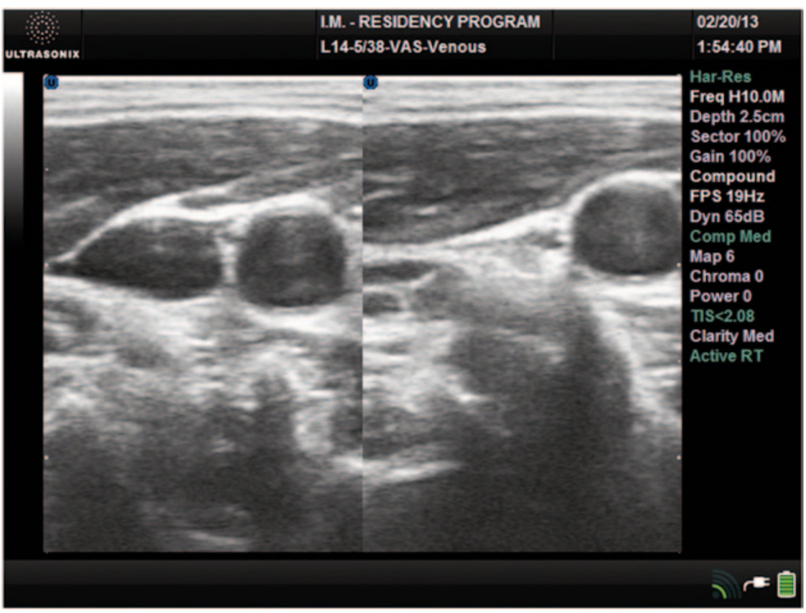

Fig. 1.23 *Left panel*: Transverse image of carotid on right and internal jugular vein on left. Excessive gain applied resulted in "noise" within the vessels, which may be mistaken for the presence of a thrombus. *Right panel*: Gentle compression reveals compressibility of internal jugular vein

Table 1.2 Common ultrasound descriptive terms[a]

Anechoic	Part of an image that produce no echoes (echo-free)
Hypoechoic	Parts of an image that are less bright than surrounding tissues
Isoechoic	Structures that have equal brightness
Homogeneous	Structures wherein there are similar echo characteristics throughout
Heterogeneous	Structures wherein there are differing echo characteristics throughout
Reflector	A structure off of which all or a portion of a propagated sound wave bounce, and may be reflected directly back to the sound wave source depending upon the angle of incidence against the reflector

[a] Adapted from [38] and [39]

returning back to the transducer. This delay in return to the transducer is interpreted by the machine as being farther away from the transducer, and thus is displayed at a greater depth on the image (Fig. 1.24) [40]. Typically, these artifacts appear in multiples, are equidistantly placed, perpendicular to, but extends in a parallel direction to the sound beam's main axis. They extend further than the structure of interest (Fig. 1.25) [39]. The repeating hyper echoic A-line, an artifact seen in both normal lungs and in pneumothorax, represents reverberations between the skin-air interface and the chest wall-pleural interface is another example (Fig. 1.26) [41].

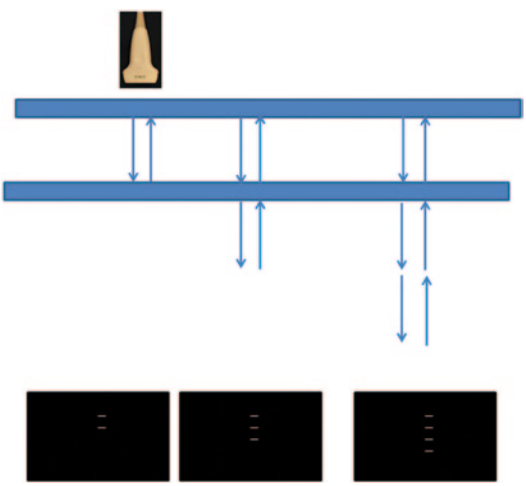

Fig. 1.24 Reverberation artifact. As sound waves encounter two strong reflectors, waves bounce back and forth between the two reflectors. The delay in return of echoes to the transducer is interpreted as sound waves that have travelled farther away and is displayed correspondingly at a greater depth

Comet Tails or Ring Down Artifacts

Comet tails or ring down artifacts are a type of reverberation artifact that occurs between two very closely spaced reflectors (comet tails) or from vibration of very small structures such as air bubbles being bombarded with sound pulses (ring down artifacts) [39, 40, 42]. These typically appear as a series of multiple closely spaced, and short bands that extend longitudinally, appearing as a single long hyperechoic echo, parallel to the ultrasound beam (Fig. 1.27) [43]. The comet tail artifact has been well described and studied in point-of-care lung ultrasound. This artifact is based on the visceral lung pleura appositioned to the parietal pleura where it may present water density of interstitial lymphatics [2, 41, 44, 45]. Also called 'B-lines', this specifically defined artifact, in conjunction with other signs such as 'lung sliding', can be utilized effectively to discern normal lung physiology, pneumothorax and interstitial lung syndromes [2, 46].

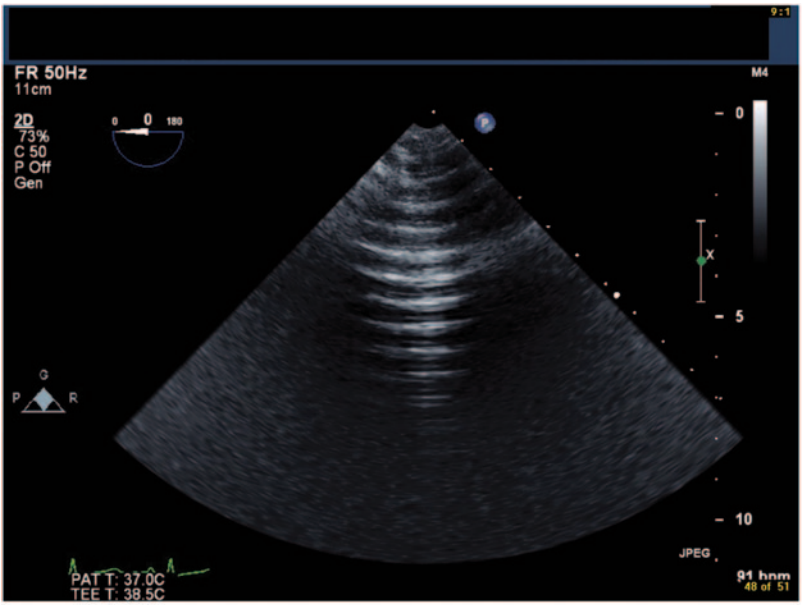

Fig. 1.25 Reverberation artifact. Multiple parallel lines resulting from reverberation artifacts from the trachea seen in a high esophageal view on transesophageal echocardiography at the level of distal ascending aorta

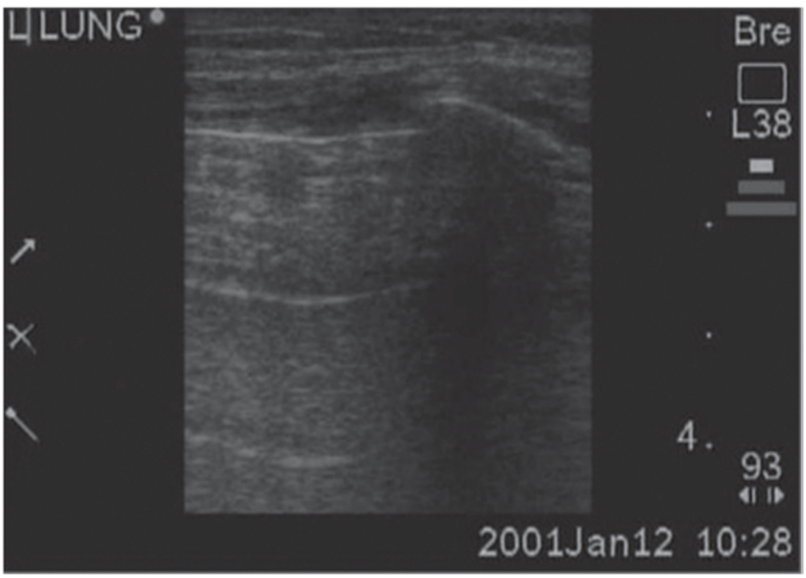

Fig. 1.26 Multiple parallel hyper echoic A-lines, resulting from reverberation artifacts between the skin-air interface and the chest wall-pleural interface

Mirror Image Artifacts

Mirror image artifacts is another form of reverberation artifacts whereby sound waves reflect off of a strong reflector (see *specular reflection*, Fig. 1.4), which acts as a 'mirror' and is then redirected towards another structure, causing another copy of this structure to appear deeper than the real structure [39]. Typically the bright reflector, or mirror, is located in a straight line between

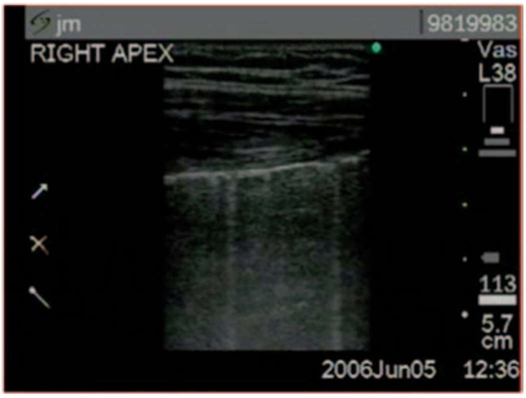

Fig. 1.27 Two comet tails (or B- lines), resulting from reverberation artifacts arising from the pleural line and extending to the edge of the display

the artifact and the transducer and the true image and mirror image are at equal distances from the mirror plane (Figs. 1.28 and 1.29) [39].

Refraction Artifacts

Refraction artifacts are related to the refraction of a sound wave when it obliquely hits an interface between two media of differing acoustic impedance (see Fig. 1.7). Because ultrasound assumes that the sound waves are travelling in a straight line through the tissue, any refraction of sound waves will result in misregistration of the location of the returning echos [26]. Typically, the artifact is lateral to the true reflector, but located at the same depth [39, 40]. For example, aorta or a single gestational sac may result in a ghost image or double image artifact if sound waves are refracted by the abdominal rectus muscles (Fig. 1.30) [43, 47, 48].

Acoustic Shadowing

Acoustic shadowing is the partial or total loss of images distal or below a structure that has a high acoustic impedance or attenuation, such as calcium in bone or metallic prostheses. This attenuation will result in a hypo echoic or anechoic band or shadows deep to that reflective structure (Figs. 1.31 and 1.32). Depending on the anatomy involved, this shadowed region can be mitigated by imaging the structure in multiple planes thereby avoiding placing the highly attenuating structure directly in the path of the sound waves towards the area of interest.

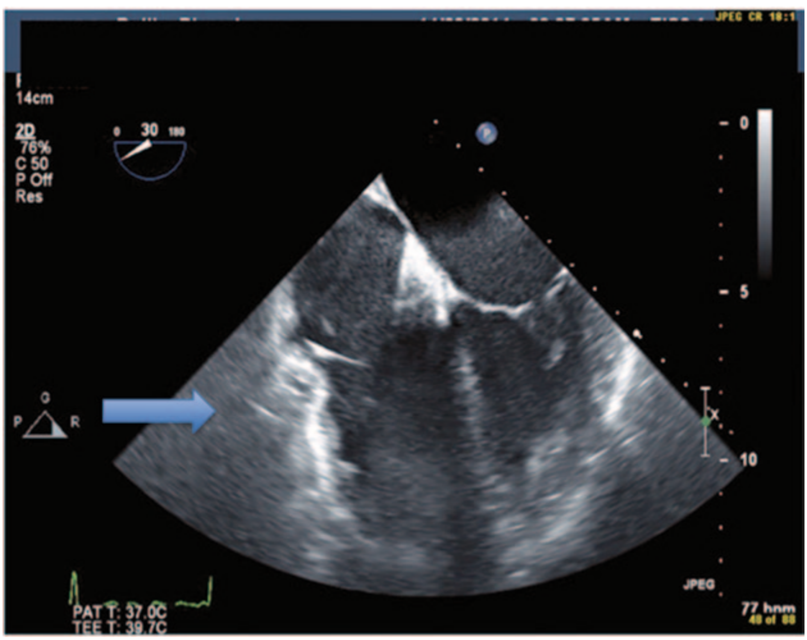

Fig. 1.28 Mirror image artifact. Transesophageal echocardiography four-chamber mid esophageal view with a focus on the right heart, demonstrating a mirror image artifact of a pacemaker wire both in the right atrium above the pericardium and below the pericardium

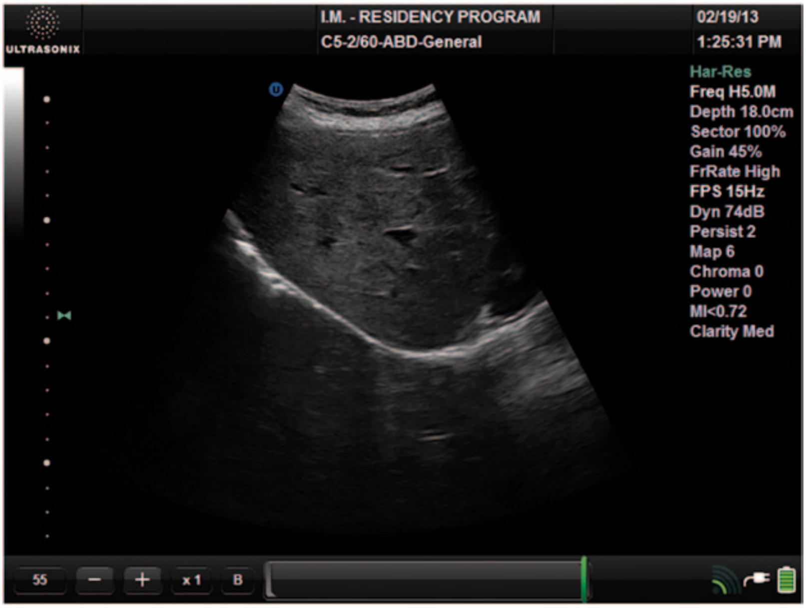

Fig. 1.29 Mirror image artifact. Longitudinal view of the liver. Specular reflection from the diaphragm results in a mirror image of the liver being placed above and below the diaphragm

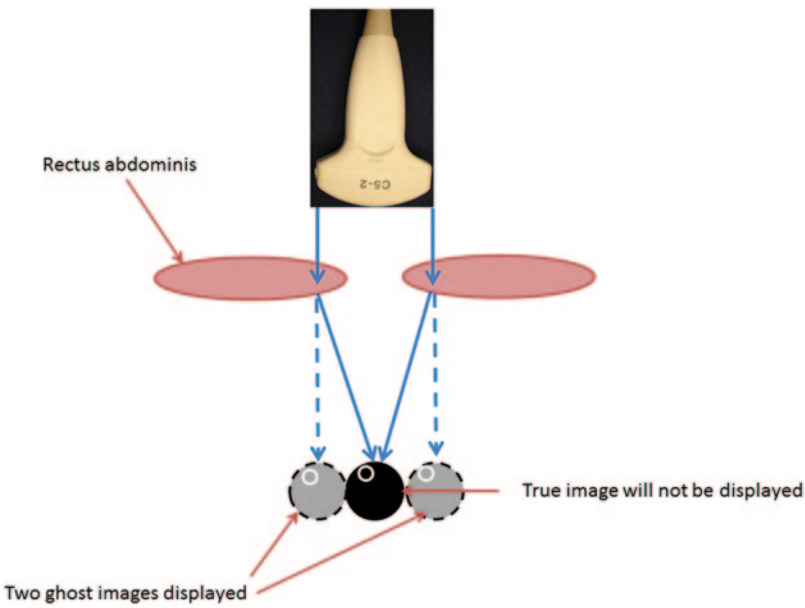

Fig. 1.30 Ghost image artifact. A schematic representation of a transverse scan of the gestational sac through the rectus abdominis muscles. Refraction of the ultrasound beams by the muscles result in the formation of artifacts. Modified with permission from Bull V, Martin K. A theoretical and experimental study of the double aorta artefact in B-mode imaging. Ultrasound 2012 Feb 1; 18: 8–13, with permission from SAGE Publications Ltd.

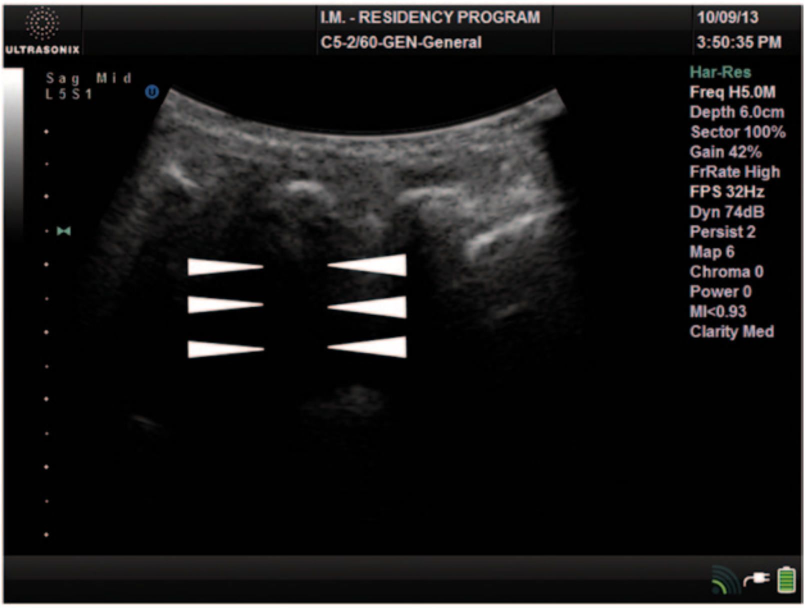

Fig. 1.31 Longitudinal view of lumbar sacral spine. Acoustic shadows are seen posterior to the spinous processes (*white arrowheads*)

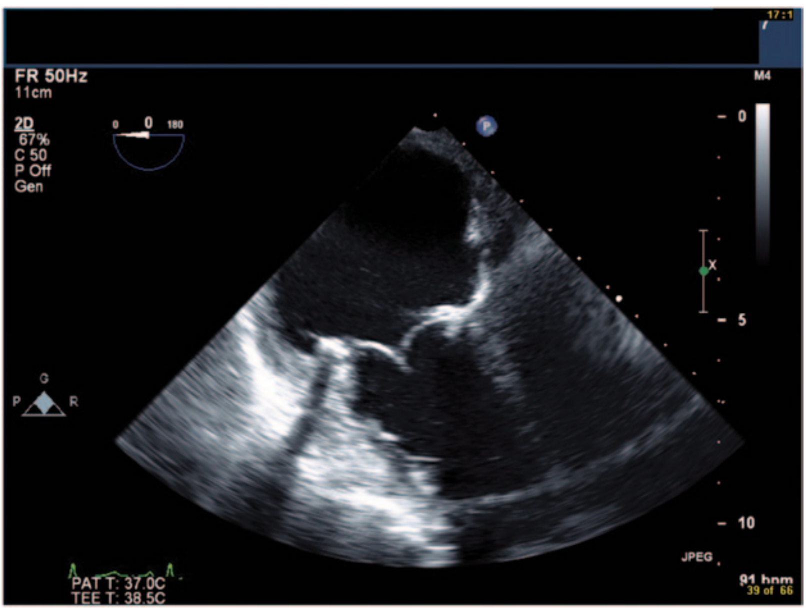

Fig. 1.32 Transesophageal echocardiogram four chamber mid esophageal view demonstrating acoustic shadowing from the a tricuspid valve ring

Enhancement Artifacts

Enhancement artifact is somewhat conceptually the opposite of acoustic shadowing, in that it is a hyper echoic region beneath a structure with abnormally low attenuation. This can occur commonly below blood vessels (Fig. 1.33), cysts, and other fluid-filled structures in which

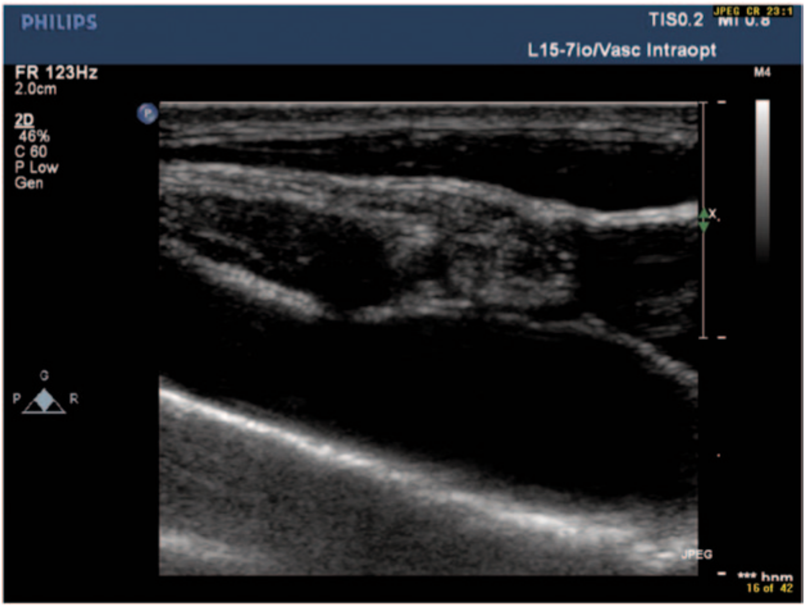

Fig. 1.33 Longitudinal view of the internal jugular vein. Posterior enhancement is seen below the vein

there is very low acoustic impedance relative to the surrounding structures. In another example, acoustic enhancement may occur deep to the low attenuating pleural effusion, causing the positive spine sign (Fig. 1.34).

Speed Propagation Artifacts

Speed propagation artifacts occur when the speed of a sound wave propagating through a medium is not at the assumed speed of propagation of

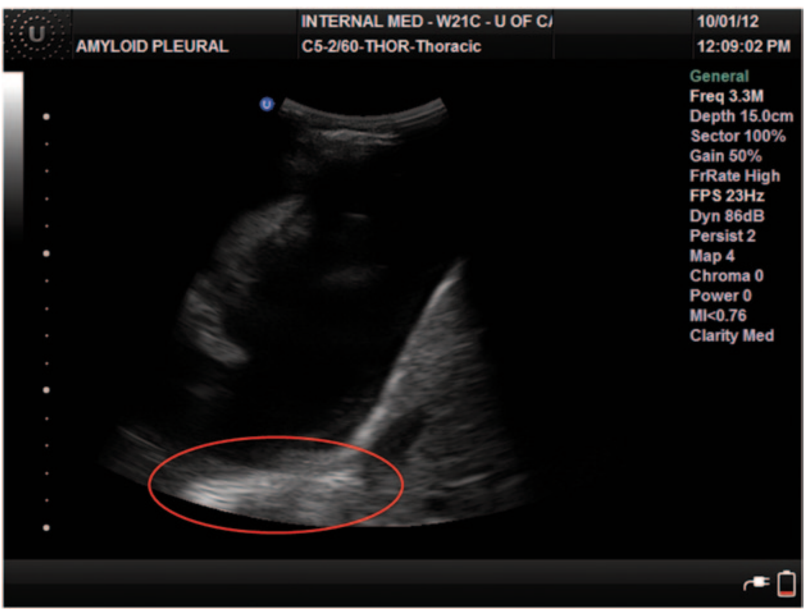

Fig. 1.34 Coronal longitudinal view of the left chest wall. Deep to the pleural effusion is posterior enhancement of the spine (*red oval*)

1540 m/s. Reflectors can then be interpreted by the system as being incorrectly farther away, if the propagation speed is slower than assumed, or incorrectly closer than it actually is, if the propagation speed is faster than assumed [49]. This can appear as a step-off, split or partial disruption of structures (Fig. 1.35).

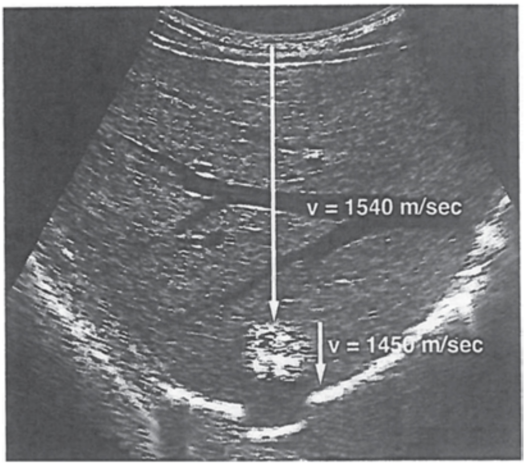

Fig. 1.35 Speed propagation artifact. Sound travels through the focal fatty lesion at a lower velocity (1450 m/sec) than the remaining portion of the liver (1540 m/sec), resulting in a delay in echo return at the interface between diaphragm and liver. The image thus shows a deeper than expected diaphragm. Reproduced from Merritt CRB. Physics of ultrasound. In: Rumack CM, Wilson SR, Charboneau JW, Levine D (Eds.). Diagnostic Ultrasound. Philadelphia, Elsevier Mosby; 2011: 4, with permission from Elsevier

Lobe Artifacts

Lobe artifacts result from parts of the ultrasound beam propagating in a direction different from the beam's main axis [50]. These off-centered beams result in low amplitude echoes and generally are not registered if they are displayed in an otherwise echogenic region of the scan [35]. However, if these off-centered beams encounter a strong reflector and fall within an anechoic region, they can result in an artifact (Fig. 1.36).

Summary

- **Know your artifacts:** Ultrasound is a dynamic exam. Moving the patient and imaging in multiple planes can let you know if an artifact is hiding your diagnosis.
- **Artifacts help you make some diagnoses:** Particularly in lung ultrasound, artifacts are all you will get when evaluating for a pneumothorax.

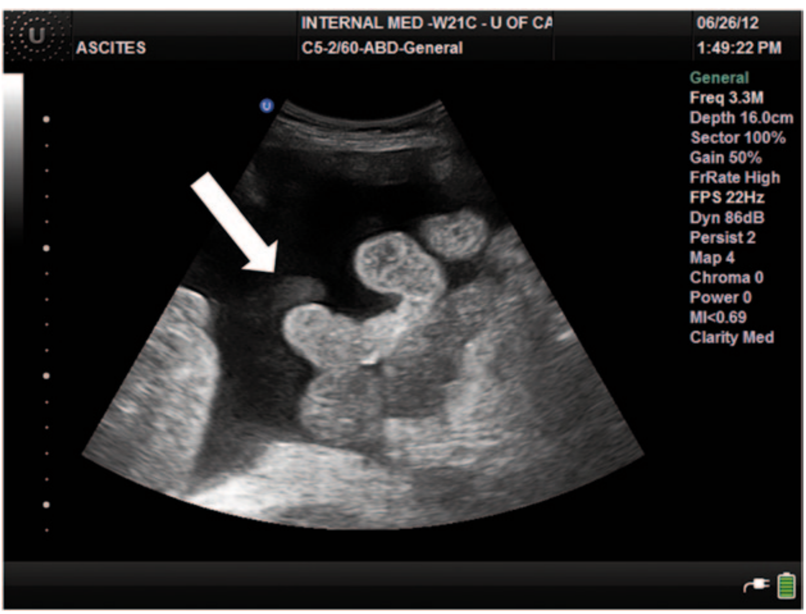

Fig. 1.36 Longitudinal view of abdomen. Ascites is present. White arrow indicates lobe artifact, produced by off-centered beams misregistering bowel from another region into the anechoic ascites

The Doppler Effect

In 1842, Christian Doppler presented his famous paper, "On the Colored Light of Double Start and Some Other Heavenly Bodies" at the Royal Bohemian Society of Learning [51, 52]. In this work, Doppler postulated that in astronomy, light wave frequency increases if it moves towards the source while it decreases as it moves away from the source. This phenomenon was later found to be true of any waves moving within a medium, including sound waves. This phenomenon explains the observation that a siren moving towards the observer has a high pitch, while the pitch drops as the siren moves away from the observer. This frequency change with movement is known as the Doppler effect and is the basis for Doppler imaging in ultrasound for detecting moving objects, most commonly for imaging blood flow (Fig. 1.37). Within the critical care setting and with proper training, Doppler ultrasound can be a useful tool for identifying the presence or absence of overlying vasculature in procedural guidance, clarifying the nature of the vessel (arterial vs venous), identification of other vascular anomalies such as thrombi, stenoses, aneurysms, and flow through cardiac valves.

Under the Doppler effect, the change in frequency is known as the Doppler shift, which can be described mathematically as:

$$\text{Doppler shift} = f_r - f_T$$
$$= 2 \times f_T \times \frac{\text{velocity of object}}{\text{Propagation velocity}}$$

where f_r is the frequency of reflected sound wave and f_T is the transmitted frequency.

However, as we are unable to directly image blood flow or moving objects directly towards or away from the transducer, the Doppler shift needs to account for this imaging angle and includes only the velocity vector that is parallel to the direction of the blood flow (Fig. 1.38). The resultant Doppler shift is directly proportional to the cosine of the imaging angle (θ):

$$\text{Doppler shift} = f_r - f_T$$
$$= 2 \times f_T \times \frac{\text{velocity of object}}{\text{Propagation velocity}} \times \cos\theta$$

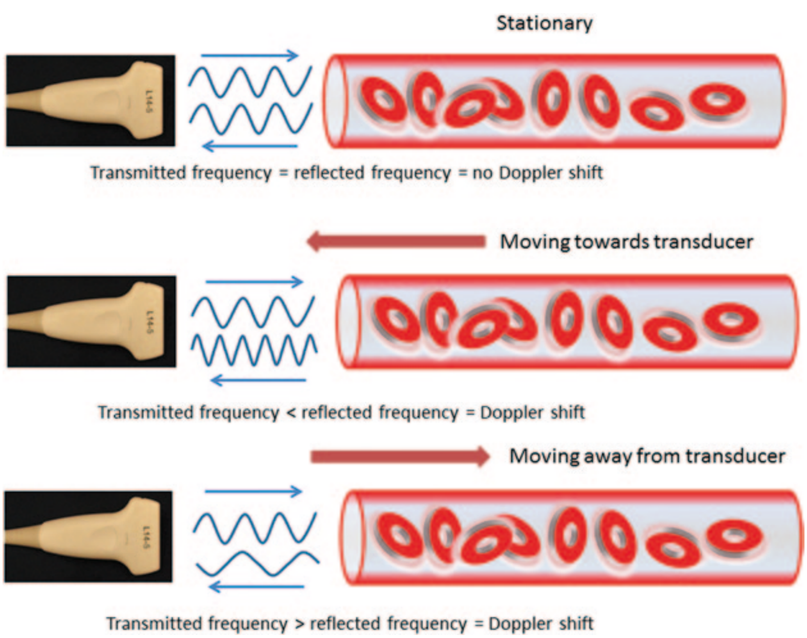

Fig. 1.37 *Top panel*: Stationary blood cells within a vessel. No Doppler shift is noted as transmitted frequency is the same as reflected frequency. *Middle panel:* As red cells are moving towards the transducer, reflected frequency is greater than transmitted frequency, resulting in a positive Doppler shift. *Bottom panel*: As red cell are moving away from the transducer, reflected frequency is now less than the transmitted frequency, resulting in a negative Doppler shift

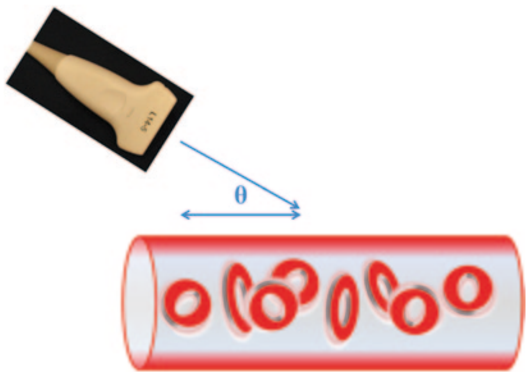

Fig. 1.38 Imaging at an angle (j). Estimation of velocity will require that the user inputs a correct angle for the machine to calculate velocity measurements

Imaging at 90°, or perpendicular to the blood flow will yield a Doppler shift of zero, as cosine of 90° is zero. That is, despite the presence of blood flow, no movement will be detected. In fact, only imaging at an angle of less than 60° will angle-corrected velocity measurements be reliable [25, 35].

The three most commonly used forms of Doppler ultrasound imaging modalities include: color Doppler imaging, spectral Doppler, and power Doppler.

Color Doppler

In color Doppler imaging, Doppler shift information is displayed superimposed upon 2-D imaging from non-moving tissue, also known as duplex scanning. In order to detect primarily blood flow, color Doppler uses wall filters (also known as high-pass filters) to reject stationary or near-stationary echoes as noise or motion artifacts [53]. The sonographer needs to recognize that by setting the wall filters too high, one can eliminate low-velocity signals that may be of interest. In general, filters should be set at low levels (50–100 Hz) [25].

Information displayed in color Doppler imaging includes the direction and velocity of flow. Mean velocities over the entire region of interest are depicted simultaneously, and information on velocity is displayed only qualitatively, based on intensity of color. Information on direction of flow is based on the color map superimposed on the image (Fig. 1.39a). The color at the top of the color map indicates flow towards the transducer, while the color at the bottom of the color map indicates flow away from the transducer. The user should always refer to the color map and not assume that red indicates arterial and blue indicates venous. Further, commonly used mnemonics such as “BART: Blue Away Red Towards” can also be misleading as the color map can be readily reversed with a switch of a button.

In the use of color Doppler, the user needs to be mindful of a number of parameters that need to be adjusted, including angle of insonation, color box size and steering, color scale, pulse repetition frequency (PRF), and Doppler gain [53].

Scanning at an angle of insonation (less than 60°) can occur either by steering the color box, which is available when scanning with a linear array transducer, or by angling the transducer itself (see Fig. 1.39a, b, c, d) [54]. In general, the larger the color box, the slower is the machine’s ability to update its images. The speed at which images are updated is the frame rate. The higher the frame rate, the more real-time the images appear, also referred to as the temporal resolution.

The maximum Doppler shift that can be detected is based on the Sampling Theorem, which states that a wave form can only be represented by its samples if they are obtained at a minimum twice its frequency [55, 56]. This limit, also known as the Nyquist limit, is defined as pulse repetition frequency (PRF) divided by two, since PRF is the sampling frequency [57]. This limit is commonly presented on the display as the maximum velocity range along with the color map. Velocities that exceed this range will be misinterpreted and *aliasing* will occur. Aliasing refers to the artifact that occurs whereby high frequencies that exceed the Nyquist limit are “wrapped around” and produce reverse flow colors that may be mistaken for true flow reversal or turbulence (Fig. 1.40a, b) [57]. This is analogous to forward spinning wheels appearing to rotate in reverse on television or film because frequencies for cameras are slower than the Nyquist limit for wheel rotation frequency. Thus for high flow velocities,

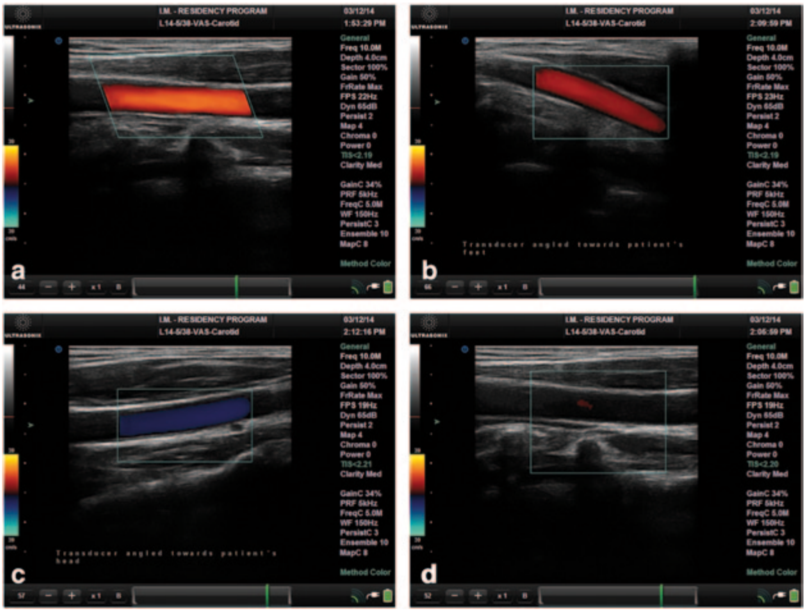

Fig. 1.39 Color Doppler, longitudinal view of the carotid. **a** Angulated or steered color box, demonstrating flow towards the patient's head (*left hand side of screen*). Color bar on the left hand side of the screen indicates that red and yellow colors indicate flow towards the transducer and blue indicates flow away from the transducer. In this image, higher velocity flow is seen in the mid portion of the vessel (*orange*) compared to the portions closer to the vessel walls (*red*). **b** Non-angulated color box. Here the transducer is angulated towards the patient's feet. Flow color indicates flow towards the transducer. **c** Non-angulated color box. Here the transducer is angulated towards the patient's head. The same vessel is now colored blue, indicating flow away from the transducer. **d** Non-angulated color box. As the transducer is held a 90° without angulation, despite the presence of flow within the vessel, little to no Doppler shift is detected

a higher PRF should be set to avoid aliasing. In many machines, wall filter and PRF are linked, such that by setting a high PRF, a high wall filter is automatically adjusted higher, although the user can generally override this link and adjust wall filter independently.

Adjusting the Doppler gain will adjust the sensitivity of the machine to flow [53]. The user should lower the amount of Doppler gain in the setting of excessive random noise and increase in the gain in order to detect low flow states. It is commonly recommended to increase Doppler gain until a "snow storm" appears, then lower the gain until the noise disappears [53, 58].

As with B-Mode imaging, use of presets for color Doppler imaging is recommended as presets are preconfigured with the appropriate velocity scale, PRF, wall filter, and color gain.

Spectral Doppler

Spectral Doppler imaging can be done either using pulsed-wave or continuous wave Doppler. In pulsed-wave Doppler, the transducer both transmits pulses of sound waves and "listens" for the reflected signals (Doppler shifts) in between, whereas continuous wave requires separate transmitters and receivers, both of which are continuously transmitting and "listening" respectively.

In pulsed-wave Doppler, the delay in the return of transmitted pulses determines the depth of the reflector. Specifically for pulsed-wave spectral Doppler imaging, using the same principles, the user can specify the depth of interest by placing the sample volume or range gate directly in the vessel of interest. This allows for the display of velocity information that is site-specific.

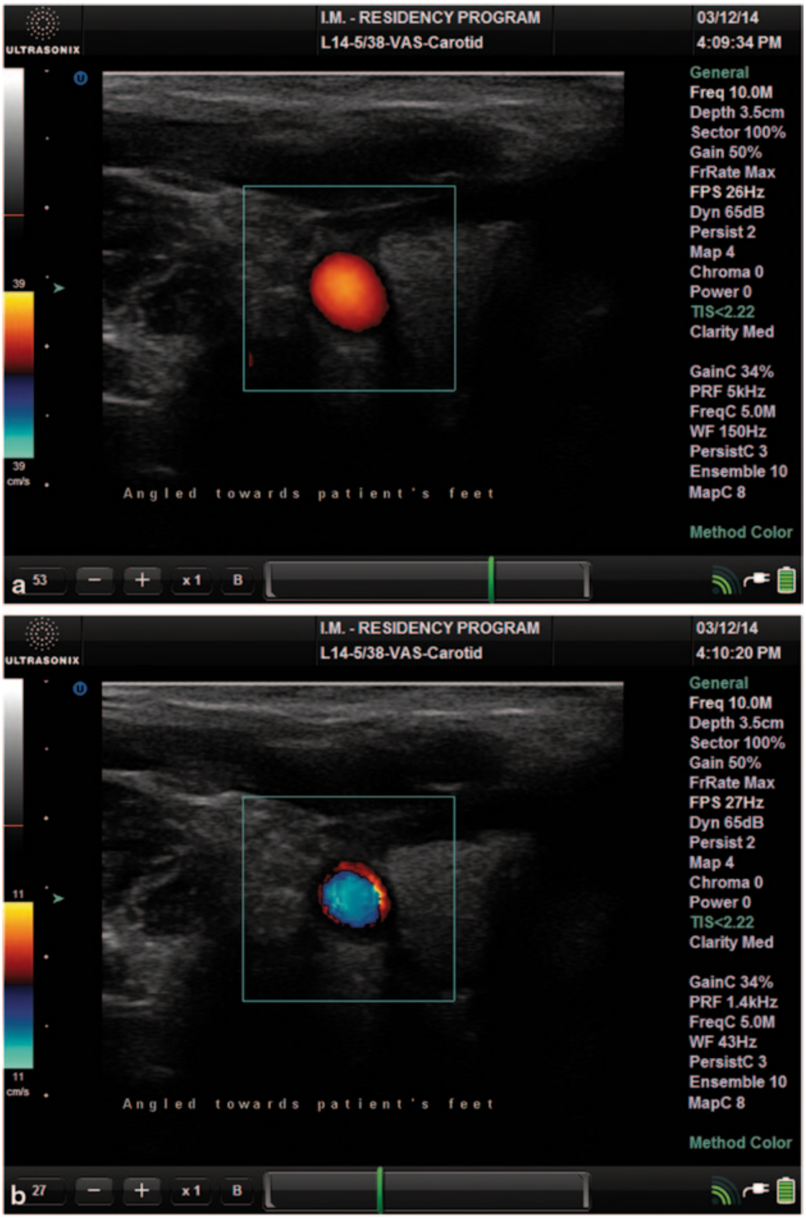

Fig. 1.40 **a** Transverse view of the carotid. No aliasing is detected at a pulse repetition frequency of 5 kHz. **b** Same image of the carotid. At the pulse repetition of 1.4 kHz, aliasing is noted. As flow exceeds 11 cm/s, the color is "wrapped around" from red to blue

Unlike color Doppler where velocity information is displayed qualitatively using color, spectral Doppler imaging presents velocity information quantitatively using a spectrum or spectrogram, which displays Doppler shift (or velocity) on the y-axis, and time on the x-axis (Figs. 1.41 and 1.42) [56]. Direction of flow is indicated in its relation to the baseline, with positive Doppler shifts being displayed above the baseline, and negative Doppler shifts being displayed below the baseline. By convention, positive Doppler shifts refer to flow towards the

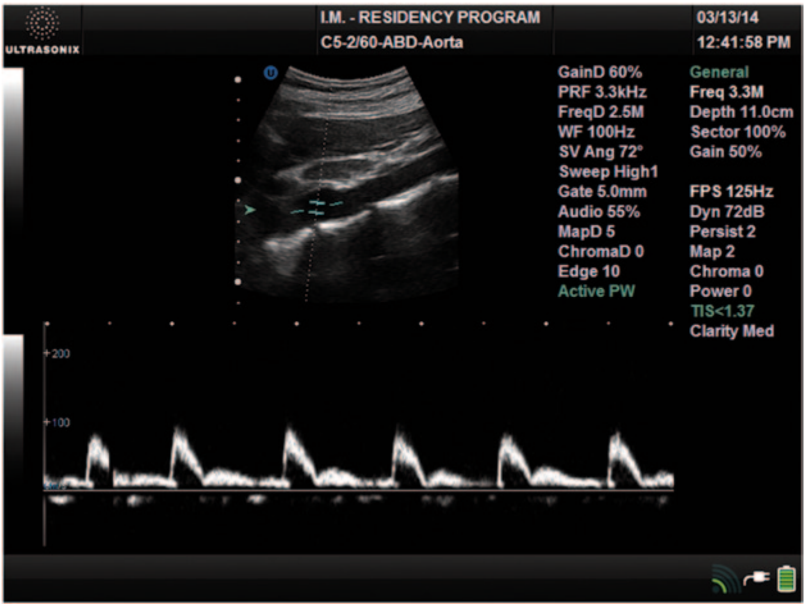

Fig. 1.41 Pulsed-wave spectral Doppler of the aorta

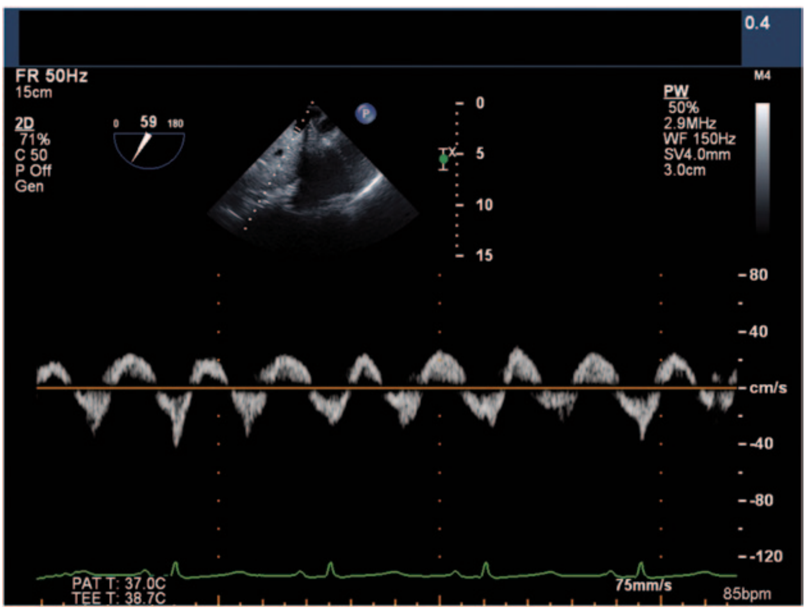

Fig. 1.42 Transesophageal echocardiogram view of pulsed-wave spectral Doppler of the hepatic vein

transducer, while negative Doppler shifts refer to flow away from the transducer. Many ultrasound units can also present this velocity information in an audible format. In addition, because blood flow within vessels is not completely uniform, not all of the red cells are moving at the same speed in the area sampled [59]. This results in a scatter of velocities at any given time point. This back-scatter is illustrated by the brightness of the spectrogram (e.g., the proportion of blood cells moving at that given velocity) [54]. Spectral Doppler is subject to the same potential for aliasing as color Doppler imaging. To avoid aliasing, imaging requires the adjustment of PRF in order

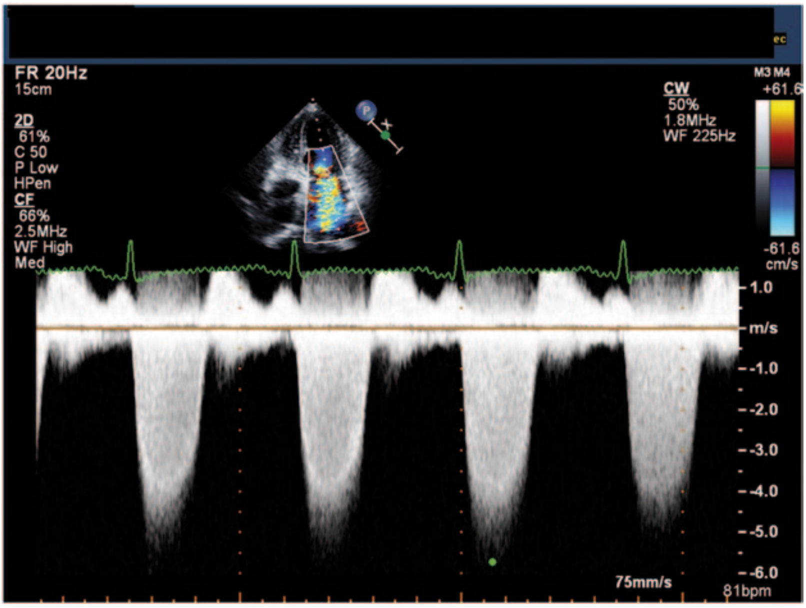

Fig. 1.43 Transthoracic echocardiogram continuous wave spectral Doppler and combined color Doppler. Apical four chamber view demonstrating mitral regurgitation

detect flow at either end of the Nyquist limit. For accurate velocity measurements, the range gate angle correction cursor needs to be set parallel to the direction of flow [54]. In addition, in using spectral pulsed-wave Doppler imaging, the range gate size should be set such that the sample volume includes as little as possible of the unwanted noise information near the vessel walls [25].

In using continuous wave, certain transducer elements transmit sound waves continuously while others are continuously receiving. The continuous transmission and receiving of sound waves negate the ability to determine depth from which the signals arise. Therefore, all Doppler shifts within the line of transmission are detected (Fig. 1.43). The advantages of continuous wave spectral Doppler include better frequency resolution and that continuous wave Doppler imaging is not subject to aliasing [56].

Power Doppler

While both color Doppler and spectral Doppler imaging displays velocity and direction information regarding blood flow, power Doppler provides information only on the mean total energy (or power), derived by integrating the Doppler power spectrum [60]. Since its introduction in 1993 [61], power Doppler has since become widely available. Power Doppler displays intensity information using a monochromatic color map: the higher the power, the lighter and brighter the color (Fig. 1.44). Similar to other Doppler imaging modalities, adjustments in PRF, wall filter, and color gain need to be made in its use [60].

The advantages and potential applications for power Doppler include the following: First, power Doppler is relatively angle independent, as it detects primarily the intensity of scatter (see Fig. 1.6) rather than Doppler shift. This allows for the imaging of tortuous vessels and vessels whose direction of flow has not been predetermined, such as collateral circulations. Second, it is highly sensitive to flow and is better able to detect low flow than color Doppler [57]. Third, because it does not display frequency information, it is not subject to aliasing. However, one of power Doppler's main disadvantage includes its motion sensitivity, resulting in flash artifacts (Fig. 1.45). The transducer must be held stationary when imaging with power Doppler.

Familiarity with these varied modalities is important to assist in clinical decision making

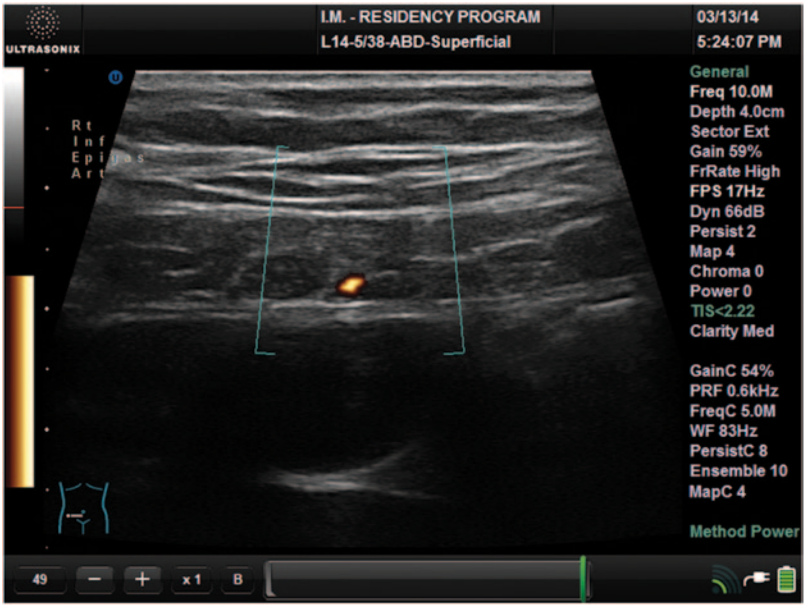

Fig. 1.44 Transverse view of the abdominal wall. Power Doppler indicates the presence of blood flow (inferior epigastric artery)

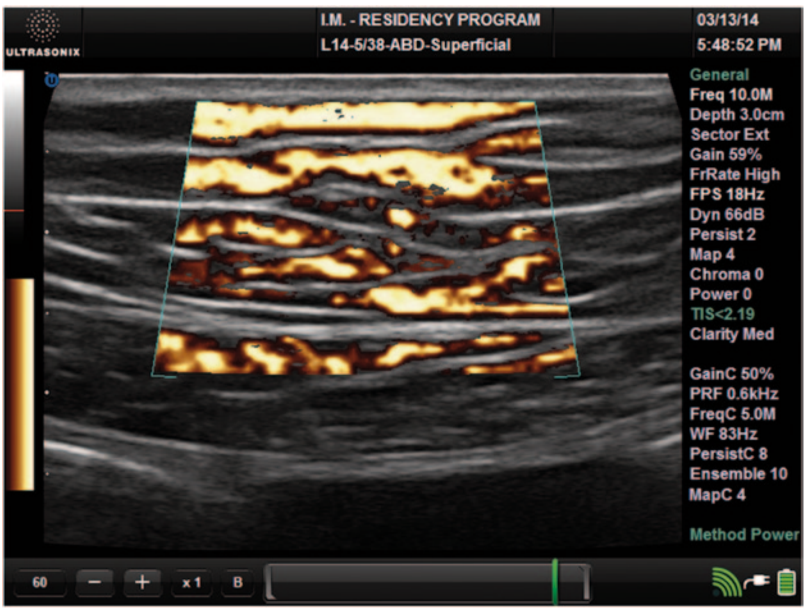

Fig. 1.45 Transverse view of the abdominal wall, power Doppler mode. Transducer movement resulting in flash artifact

in the intensive care unit. Although the understanding the physics may be challenging for clinicians, time invested in truly understanding these principles will provide great dividends in appreciating the anatomy and pathophysiology underlying image generation. Furthermore, once the principles are well understood, interpretations of artifacts can be used to enhance clinical diagnoses rather than to hinder it.

Summary

- **Be careful with the meaning of blue and red:** The Doppler effect is observed whenever the source of waves is moving with respect to an observer. In other words, blue and red reflects movement relative to the probe and does not indicate vein and artery respectively.
- **Doppler is not only for vessels:** Doppler is a surrogate of flow; therefore, it can be used in a myriad of circumstances to evaluate this, such as in the vessels, and even in the heart to calculate cardiac output.

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Thoracic Ultrasonography in the Critically Ill

2

Arpana Jain, John M. Watt and Terence O'Keeffe

Introduction

With the advances in technology and improvements in cost, many ICUs have the capability to rapidly perform bedside thoracic ultrasonography (US), which has been typically performed by an intensivist team that may consist of advance care providers, residents, fellows and/or attending physicians. This allows for the rapid detection of either fluid or air within the pleural cavity with great accuracy. However, while it has become an integral part of management in many ICUs, it remains operator-dependent, and a detailed knowledge of the fundamentals of US and thoracic pathology is necessary to truly appreciate its benefits. Extensive literature has been published on thoracic US that validates both its diagnostic and therapeutic abilities [1, 2].

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A. Jain (✉) · T. O'Keeffe
Department of Surgery, University of Arizona, 1501 N Campbell Ave, PO Box 245063, 85712 Tucson, AZ, USA
e-mail: ARPANAJ@EMAIL.ARIZONA.EDU

T. O'Keeffe
e-mail: tokeeffe@surgery.arizona.edu

J. M. Watt
Department of Surgery, University of Arizona Medical Center, 1501 North Campbell Avenue, 85724 Tucson, AZ, USA
e-mail: Jmw157@email.arizona.edu

Basic Concepts of Thoracic Imaging

Anatomy

Knowledge of normal pleural anatomy is necessary to be able to accurately interpret US images. The pleural cavity is enclosed between parietal pleura, which lines the chest wall, and visceral pleura lining the lung tissue. The layers of chest wall include skin, subcutaneous fat and fascia, muscles of shoulder girdle over anterior—superior aspect, muscles of abdominal wall over anterior—inferior aspect, muscles of back posteriorly, intercostal muscles interspersed with ribs and costal cartilages, parietal pleural, pleural cavity, visceral pleural and lung tissue (Table 2.1 and Fig. 2.1).

The skin, superficial tissue and muscles allow for passage of US waves, however, cast variable degrees of reflection depending on the tissue density. This differential reflection results in a layered appearance. Ribs will completely block

Table 2.1 Layers of chest wall

Skin
Subcutaneous fat
Superficial fascia
Muscles—shoulder girdle, abdominal wall, back
Intercostal muscles interspersed with ribs and costal cartilages
Parietal pleural
Pleural cavity
Visceral pleural
Lung tissue

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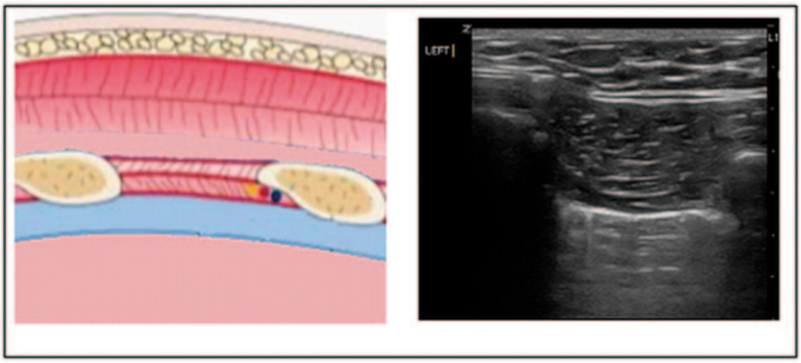

Fig. 2.1 Layers of chest wall

the US waves and create an acoustic shadow. Hence, to image the lung and pleura, it is essential to place the transducer probe between rib spaces and avoid the ribs (Fig. 2.2). This is often one of the more difficult aspects for the inexperienced ultrasonographer to learn, but is critical to obtaining images of the necessary quality.

Air contained in alveoli impedes passage of US waves and creates reverberation at the junction of visceral pleura, resulting in a bright-appearing line that slides along with the lung during breathing cycle directly beneath the layers of chest wall. When air or fluid is present in the pleural cavity, it separates visceral pleura from the chest wall, disrupting this normal sliding. Fluid of whatever type will collect in the dependent areas, which are the posterior costophrenic recess in the upright position, along the lateral chest wall in lateral decubitus position and lateral costophrenic recess in the supine position. Air, on the other hand, will rise to apices with the patient in the upright position and along the anterior chest wall in the supine position. Thoracic US can be done in any position; however, the supine position is most common in the critically ill patient. Abducting the arm above the head can improve access to the lateral thoracic wall, which is particularly useful while performing interventions on thoracic cavity.

Fig. 2.2 Probe position for pneumothorax detection

The probe should be gently placed in the intercostal acoustic window of the located area. The initial plane should be longitudinal, with the long axis of the probe parallel to the long axis of the patient's body. This plane allows visualization of at least two ribs and the corresponding intercostal space. The survey of thoracic cavity is carried in a systematic fashion, from anterior to posterior direction. The anterior zone is lined by sternum, clavicle, anterior axillary line and costal margin. This zone gives maximum yield for detection of pneumothorax. The lateral zone lies between anterior and posterior axillary lines. The posterior zone, lying behind the posterior axillary line, is difficult to assess in a supine patient as the probe is often limited by the bed. If the clinical condition allows, then the patient should be turned to other side with probe facing upside down to achieve comprehensive imaging.

The transducer frequency used in thoracic US varies from 3.5 to 10 MHz. A 2- to 5-MHz curvilinear probe allows visualization of the deeper structures and the sector scan field allows a wider field of view through a small acoustic window.

The chest wall, pleura, and lungs may be quickly surveyed with the curvilinear probe. Once an abnormality has been identified, a high-resolution 7.5- to 10-MHz linear probe can be used to provide detail [3]. Both B and M mode are useful for thoracic US. Doppler imaging has limited application in thoracic imaging, but one possible use is to detect blood vessels within the needle tract while accessing pleural space.

Normal Lung and Pleural Imaging

All lung signs arise at the level of pleura. The signs can be described as either static or dynamic [4]. The usual static artifact is a horizontal, hyperechoic line, parallel to the pleural line, at an interval that is exactly the interval between skin and pleural line. This artifact is called the US A-line. Another static artifact is called the US B-line. These are vertical lines, arising from the pleural line, spreading up to the edge of the screen without fading and are synchronized with lung sliding. The B-line is also called a "comet tail" artifact. Figure 2.3 When several B-line are seen in single lung scan then this pattern is called the "lung rocket." Another kind of vertical artifact, again a comet-tail, is well defined and spreads up to the edge of the screen without fading. However, this artifact does not arise from the pleural line but from superficial layers of the chest wall, NOT the pleura. These line erase pleural lines and are called the E line, E for emphysema, and are seen in subcutaneous emphysema.

Lung sliding is a basic dynamic sign. Lung sliding shows the sliding of the visceral pleura against the parietal pleura. In experienced hands, one second scanning is suffice to detect lung sliding [4]. It is more prominent at lung bases compared to apices. Common pitfalls, which prevent detection of sliding, include a low-frequency probe and application of dynamic noise filters. Lung sliding is best characterized on M-mode scanning and creates a so-called "seashore" sign (Fig. 2.4 and Video 2.1).

Apnea or complete lack of lung ventilation, like main stem intubation, replaces the sliding with "lung pulse," which is the transmittance of cardiac impulse through the lung tissue towards the probe [5]. The lung pulse on M-mode scanning is synchronized with cardiac rhythm.

Pneumothorax

The diagnosis of pneumothorax can be made rapidly and precisely using US. The ultrasonographic identification of pneumothorax involves

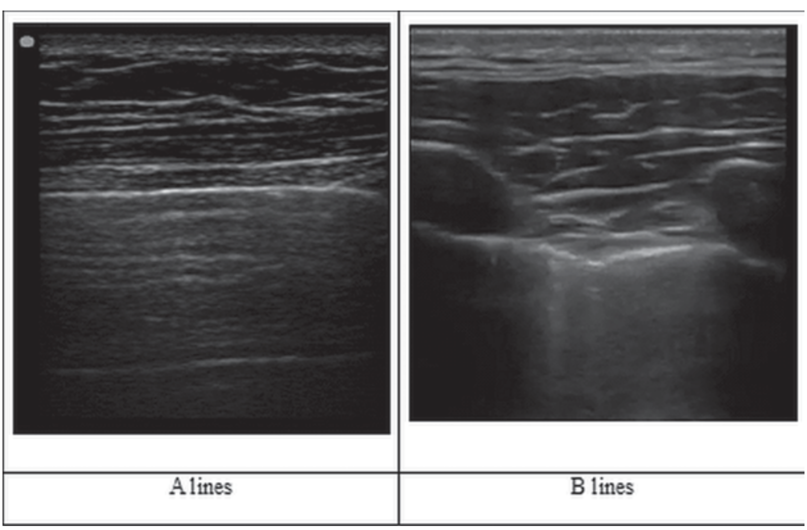

Fig. 2.3 Sonographic A and B-lines

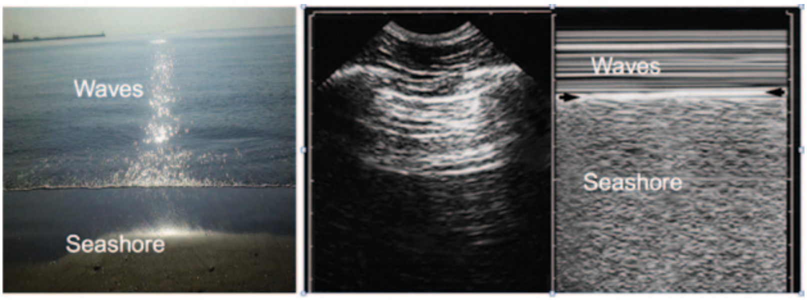

Fig. 2.4 “Seashore” sign

absence of lung sliding, presence of A-lines with or without presence of “lung point.”

The usual finding of lung sliding under the parietal pleura disappears as the lung collapses and air builds up between parietal and visceral pleural. The air between parietal and visceral pleura reflects ultrasonic waves, there by obliterating the B-line. However, the A-line created at the interface of parietal pleura remain intact. On an M-mode imaging, the “seashore” sign created by normal lung parenchyma is replaced by a “bar code” or a “stratosphere” sign (Fig. 2.5).

In patients with mild to moderate pneumothorax, the area of lung that is still in contact with the pleura creates a “lung point”. It is point of transition between absence and reappearance of the lung sliding and the B-line. Lung point is a dynamic sign. Similar observation can be made on an M-mode image as disappearance of “barcode” and appearance of “seashore” sign. The finding of a lung point is highly indicative a pneumothorax. However, lung point is absent if lung is completely collapsed under a massive pneumothorax (Fig. 2.6a, b and Video 2.2).

Absence of the so-called “bat sign” can also be used to look for pneumothorax [6, 7]. This is a normal pattern that can usually be easily seen and represents normal chest anatomy. The reason that it is called the bat sign is due to the likeness of a bat flying with its wings up, towards the viewer (Fig. 2.7). The anatomy that it represents is an upper and lower rib, with a pleural line, with the

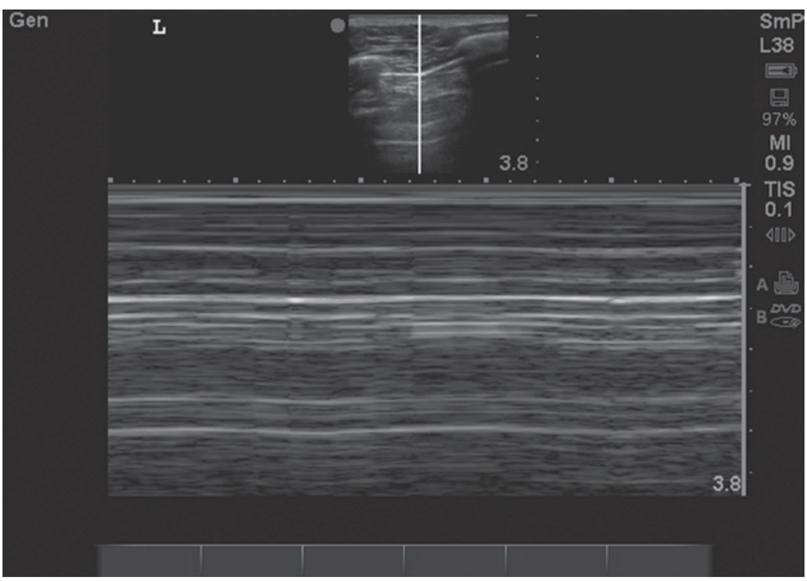

Fig. 2.5 Bar code/stratosphere sign

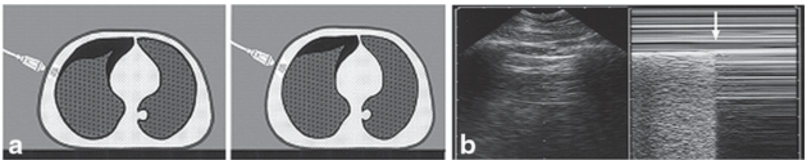

Fig. 2.6 "Lung point" sign

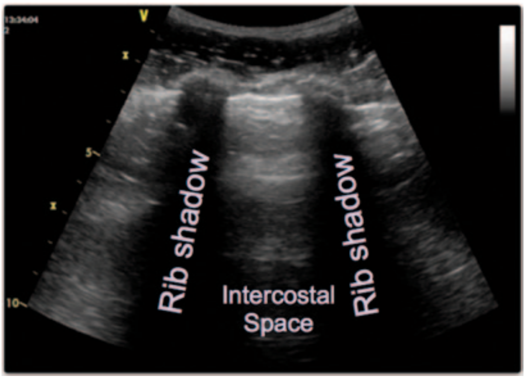

Fig. 2.7 "Bat" sign

echoes thrown off by the ribs forming the bat's wings and the body being made up of the hyperechoic pleural line. In a patient with a pneumothorax, this normal sign is no longer visible.

Thus, it can be seen with these constellations of signs using different scanning modes, it should be possible to accurately determine the presence or absence of a pneumothorax in most patients at the bedside, without waiting for a formal chest radiograph. The question is whether US is accurate enough to make clinical decisions without the use of radiography and we will examine this in the next section.

Evidence Base for Ultrasound for Pneumothorax

Use of US for detection of pneumothorax is extensively validated. Presence of lung sliding in an area spanning over three intercostal spaces has shown to have a negative predictive value of 100 % by Lichtenstein et al. [8]. Another prospective study for presence of pneumothorax by the same group in 73 ICU patients revealed that presence of A-lines (horizontal artifacts) had a sensitivity and a negative predictive value of 100 % and a specificity of 60 % for the diagnosis of pneumothorax [9]. When presence of A-line and absent lung sliding are combined, it had a sensitivity and a negative predictive value of 100 % and a specificity of 96.5 % [9]. Presence of lung point allows for positive diagnosis of pneumothorax. In a prospective study, lung point was present in 44 out of 66 cases of pneumothorax and in no case in control group with an overall sensitivity of 66 % and specificity of 100 % [10]. Absence of lung point, however, does not exclude pneumothorax.

Focusing the scan over high-yield areas can mitigate a common concern over the amount of time taken to achieve an effective scan of chest. A rapid scanning method of obtaining images from the second intercostal space on the mid clavicular line, the fourth intercostal space on anterior axillary line, the sixth intercostal space on the mid axillary line, and the eighth intercostal space on the posterior axillary line has shown a sensitivity of 98.1 % and specificity of 99.2 % in the diagnosis of pneumothorax with US compared to 75 % sensitivity and 100 % specificity of a supine chest x-ray [11].

Advantages of ultrasonographic detection of pneumothorax are numerous including immediate positive or negative diagnosis at the bedside in emergency situations, decrease in irradiation and cost. Ultrasound can be used in a number of non-trauma clinical settings; for example, it can be used to assess for the presence of pneumothorax following an invasive procedure [12, 13]. It is clear, however, that although the sensitivity and specificity of this modality can be high, there will be circumstances where chest radiography is still necessary, e.g., pre-existing lung disease, subcutaneous emphysema, extremes of body habitus, etc.

Table 2.2 Tips for maximizing success when performing ultrasound for pneumothorax

Proper patient positioning if clinically feasible:
a. For pneumothorax: Upright as much as possible and scan apical area
b. Support patient appropriately with pillows and/or blankets
c. Adjust height and position of bed and ultrasound machine to optimize operator ergonomics
Appropriate probe selection:
d. A low-frequency (2–5 MHz) curvilinear probe for rapid scanning and enhancing area seen under the probe
e. High-frequency, high-resolution probe to better define the pathology once identified
f. Adjust depth and focus to maximize area of interest
g. Use both B and M modes to confirm presence of air
h. Color Doppler to identify blood vessels in the needle path before accessing thoracic cavity
Identify surface landmarks:
i. For rapid scanning for pneumothorax- second intercostal space (ICS) in mid-clavicular line, fourth ICS in anterior axillary line and sixth ICS in mid-axillary line, while patient is in upright or semi-upright in position

Another possible advantageous area for the use of US is in the assessment for the presence of pneumothorax following removal of chest tubes. In a study of 50 cardiothoracic surgery patients with chest tubes surgically placed at the time of operation, Saucier and colleagues found that there was 100 % agreement between US and chest radiography following removal of the chest tubes [14]. Similarly, in a study of trauma patients with tube thoracostomy, they noted that use of US in the 4th or 5th intercostal space was highly predictive (100 %) of the presence of post-removal pneumothorax [15]. They also noted that the 4th or 5th intercostal space performed better than the 2nd or 3rd intercostal space, and all of these ultrasounds were surgeon-performed.

Clearly, if we were to more liberally adopt the use of US for the detection of pneumothorax we could make both significant cost savings as well as reduce the radiation exposure to our patients, both central tenets of the “Choosing Wisely” campaign [16].

See Table 2.2 for tips on maximizing success when performing ultrasound for pneumothorax.

Ultrasound for Pleural Effusion/ Hemothorax in the ICU

Intensive care unit patients commonly develop intra-thoracic fluid during the course of their admission. Medical ICU (MICU) patients typically develop transudative or exudative effusions and empyema, while surgical or trauma patients overwhelmingly develop hemothorax [17].

In a prospective study of medical ICU (MICU) patients, over 60 % were found to have radiographic evidence of effusions at some point during their hospitalization. The most common causes included heart failure, atelectasis and parapneumonic processes [18]. Patients who have undergone thoracic or abdominal surgery, as well as those who have sustained thoracic trauma, will frequently accumulate intra-thoracic fluid collections—effusions and, more commonly in trauma patients, hemothorax. Approximately 60 % of poly-trauma patients sustain thoracic trauma and up to 18 % of these patients will require tube thoracostomy for hemothorax during their initial admission [19].

As the availability of small, mobile sonographic units increased during the 1990s, it became much more possible for physicians (non-radiologists) to perform bedside diagnostic procedures and image-guided treatments for effusions and hemothorax. There are of course many advantages of diagnosing and treating intra-thoracic fluid collections via US at the bedside. Compared to CT or x-ray technology, US is inexpensive and avoids ionizing radiation exposure. The performance of bedside US precludes the need to transport critically ill patients. The quality and sensitivity of US imaging is preserved, in contrast to portable x-ray films where up to 30 % of all studies are considered suboptimal [20].

Most of the early studies on diagnosing intra-thoracic fluid collections using portable US originated in the emergency medicine and trauma literature. The first description of the use of US to diagnose effusion was in 1967 [21]. In

1993 Rothlin et al. demonstrated the ease with which US can be used to diagnose CT-confirmed pleural effusion [22]. Shortly thereafter, Ma et al. demonstrated 96 % specificity, 100 % sensitivity and 99 % accuracy for identifying free pleural fluid with portable US as an extension of initial, abdominal examination [23]. Recent studies have demonstrated the superiority of US compared to chest radiograph in detecting lung pathology. In 2011, Xirouchaki et al. demonstrated a higher sensitivity, specificity and diagnostic accuracy for US examination of intrathoracic fluid, compared to chest radiograph in a heterogeneous MICU/SICU patient population [24].

Ultrasound has also been proven effective in determining the etiology of effusions, based on the internal fluid echogenicity and associated changes in pleura and adjacent lung parenchyma [17]. Transudates, most frequently seen in patients with congestive heart failure, cirrhosis, or nephrotic syndrome, are always anechoic. They do not demonstrate any internal septations or echogenic signal. Exudates, on the other hand, can be either echoic or anechoic. Parapneumonic effusions and empyema are two exudative processes that can easily be confused for solid masses because they possess such complex internal septation architecture and echodensity due to fibrin deposition and cellular debris. Blood is usually seen as a heterogeneous hypoechoic collection that may or may not contain internal septations. As a retained hemothorax matures, however, it becomes thick-walled and very echogenic [17].

Studies suggest that the use of US for thoracentesis can be an effective method of delivering care, with an acceptably low rate of complications. Two early initial papers showed good success rates with relatively large volumes removed (mean volumes of 442 and 823 mL, respectively) with low rates of post-procedure pneumothorax—2.8 to 4.2 %, with both studies recommending AGAINST routine chest radiographs post-procedure [25, 26]. Interestingly, although one of these initial reports did not suggest that the volume of fluid removed was a risk for pneumothorax, subsequent work by other authors showed a three-fold increase in the risk of pneumothorax if the volume drained was over 1.8 L, rising to a six-fold increase over 2.8 L [27]. Some authors have recommended the use of pleural manometry to reduce the risks associated with thoracentesis, including pneumothorax and reexpansion pulmonary edema [28].

Further studies looking at purely critically ill patients have corroborated these initial reports. Patients undergoing mechanical ventilation seem to be at no higher risk of developing pneumothoraces following US-guided drainage procedures with a very low rate of 1.3 % [29]. Of note, in this study the gold standard was to perform chest radiography and they noted that morbid obesity and chest wall edema causing a chest wall thickness of more than 15 cm were predictive of failure of the procedure.

In a different approach Tu and colleagues used US-guided thoracentesis for diagnosis in a group of febrile mechanically ventilated patients [30]. They were successful in diagnosing infectious exudates in 62 % of their patients, with a low complication rate of only 2 %, which, however, were two hemothoraces. They had no pneumothorax or reexpansion pulmonary edema in this group.

The position of the patient does not seem to be a limiting factor, either. In a recent study, the authors examined the use of US to gain access to the thoracic cavity with the patients in either the supine or semi-recumbent position [31]. They measured the time required for needle insertion, which was a very respectable 185 s on average, with again a low rate of pneumothorax of 1.4 %.

As we have moved towards more minimally invasive therapies for various diseases, this trend has also spread into the size of chest tubes placed for fluid drainage, which is responsible in some small part for the increasing interest in US guidance as typically the position of the tube is more critical when it is of small caliber as opposed to the traditional 36- or 40-Fr “standard” chest tube placed in the 5th intercostal space in the midclavicular line. In a study examining 10- to 16-Fr chest tubes, the authors quoted a success rate for US-guided tube placement, with a low complication rate of 3 %. With the continuing adoption of small bore catheters, it is likely that US will become increasingly used in pulmonary disease, particularly as it is clear that pre-procedure imaging can be used to predict which patients are most likely to fail with this type of drainage [32].

As the above descriptions show, US can be a highly effective and efficacious tool in the hand of the intensive care physician, and the ease of training makes it a simple and valuable adjunctive skill for the practitioner. In the next section, we will discuss some of the "nuts-and-bolts" of performing bedside procedures.

Performing Thoracic Ultrasound Examination for Hemothorax/Effusion

Positioning

Ideally, US examination for intrathoracic fluid should be conducted with the patient in a seated position. In the ICU, patient mobility is limited as a result of indwelling venous and arterial lines, the need for mechanical ventilation and patient disease, such as spinal injury, preventing the patient from sitting upright. Critically ill patients who cannot be placed in the seated position should therefore be positioned in a head-up or reverse-Trendelenburg fashion because simple fluid collections will settle at the lung bases, improving the sensitivity of US examination; even a small volume of fluid will be more evident sonographically if the patient is in a seated or head-up position. The examining physician should stand facing the patient, with the US unit positioned in such a way that the screen is visible to the examining physician without excessive rotation of the examiner's neck or turning away from the examinee. The patient's arm can be abducted in order to improve access to the lateral chest wall. An assistant is highly suggested to help support and turn the patient, in order to examine the posterior chest wall.

Probe Orientation and Direction

Evaluation for effusion should be performed with a 3 to 5 MHz phased-array probe oriented in the sagittal plane (i.e., parallel to the long axis of the body). The probe indicator should be oriented towards the patient's head. This will orient cephalad structures to the left side of the US display.

Depending on the patient's pathology, it may be necessary to perform a partial or complete examination of the thorax—as mentioned, simple effusions and hemothoraces will settle by gravity in the posterior and inferior costophrenic angles, while loculated pleural effusions can be located anywhere in the chest. To begin a complete sonographic examination of the chest for fluid, the probe is initially placed between ribs in the mid-axillary line (Fig. 2.8) When the structures of the chest wall are visualized, including the subcutaneous soft tissue, intercostal muscle, pleural line and underlying lung tissue, probe depth and gain are optimized. By angling the probe cephalad or caudad, one can visualize the pleura and lung underlying adjacent sonographically opaque ribs. When that first interspace has been satisfactorily visualized, the probe is moved either upward or downward to an adjacent rib-space. In this fashion, moving up and down the long-axis of the chest, a vertical scan-line can be created allowing the examiner to compose a two-dimensional model in her own mind. When this vertical scan line has been completed, the probe can be moved to a second scan line, anteriorly or posteriorly along the patient's chest wall. If, by the patient's history, a hemothorax or simple effusion is suspected, subsequent examination can be directed to the posterior costophrenic

Fig. 2.8 Probe position for hemothorax/effusion detection

angle. Or, by moving methodically across the anterior and posterior chest in regularly spaced vertical scan lines, the entirety of the chest can be examined. In the last several years, protocols have been developed to streamline the need for completing a complete chest examination, expediting diagnosis by examining the chest at a set number of standardized locations [33, 34]. These protocols have not been validated for the diagnosis of effusion or hemothorax—a complete examination guided by knowledge of the patient's pathology and common sense is still recommended.

Landmarks and Characteristic Findings on Examination

The normal anatomy of the chest guides the comprehensive US examination for fluid. At the beginning of the examination, the soft tissues of the chest wall, ribs and pleura should be examined. The ribs themselves pose a barrier to examination due to their sonographic opacity, though this issue is easily dealt with by angling the probe around the rib. Pathology of the chest wall, such as soft tissue edema or costal fractures/hematoma, and anatomic variability, such as excessive adipose or muscle tissue, can also pose as an obstacle to obtaining accurate sonographic images.

Normal anatomy should be examined and used for orientation. The pleura should appear as a bright, echogenic line approximately 5 mm deep to the cortex of the rib (Fig. 2.9). In the presence of pathology, the pleura may be thickened or demonstrate nodules. A thickness greater than 3 mm is considered abnormal and is usually associated with an exudative effusion elsewhere in the thorax. When examining regions of the thorax that do not overly a fluid collection, normal pleural sliding and A-lines should be seen.

Arguably the most important landmarks of the chest, and the site where some authors suggest the effusion exam should start, are the hemidiaphragms with adjacent solid organs, the liver and spleen. The liver and spleen can be used as acoustic windows to the chest—by directing the probe cephalad through these organs, the hemidiaphragms should be visualized. Directing the probe upward through solid organs is also a good way to visualize fluid overlying the diaphragm. Furthermore, as the most inferior structures of the chest, they should be visualized during thoracentesis or the placement of a thoracostomy tube, in order to avoid inadvertently traversing the diaphragm and/or entering the peritoneum.

Fluid appears as a dark, relatively anechoic stripe that displaces the lung from its normal apposition to the chest wall or diaphragm (Fig. 2.10). Fluid depth should be estimated. Most US units will have a distance scale or a caliper function that will allow an estimation

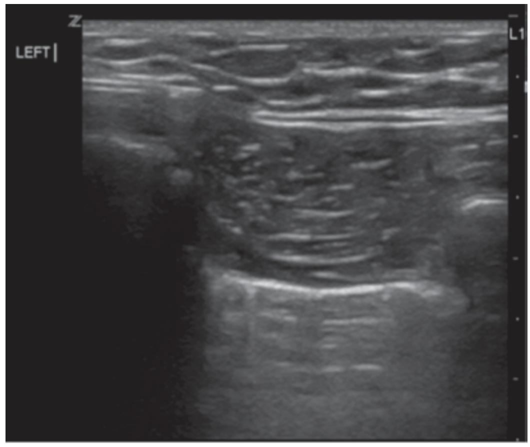

Fig. 2.9 Normal pleural anatomy

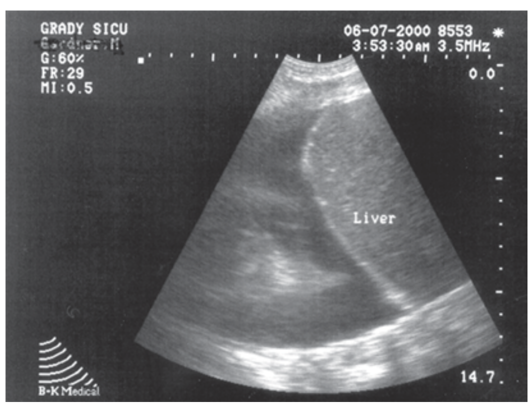

Fig. 2.10 Pleural effusion

of the depth of a fluid collection in two dimensions. If the goal of examining for the presence of intra-thoracic fluid is drainage, a site should be selected where the interpleural distance (i.e., the distance between visceral and parietal pleura) is at least 10 to 15 mm, in order to avoid injuring the lung [35].

The echogenicity of the fluid should be characterized. As mentioned previously, the character of fluid is suggestive of its etiology. Fluid collections can be homogenously anechoic, echogenic (i.e., containing sonographically opaque particulate matter suspended in fluid) or complex (i.e., possessing internal septations). In order to determine the echogenicity of a thoracic fluid collection, it can be compared to the appearance of the gallbladder—in the absence of coexisting pathology, bile is assumed to be a simple, anechoic fluid.

Transudative processes, most frequently seen in patients with congestive heart failure, cirrhosis, or nephrotic syndrome, will always be anechoic and without internal structure or septations. Transudative fluid will appear to be of equal darkness when compared to the contents of the gallbladder.

Exudative processes can be either anechoic or echogenic and can also be complex. Some malignant exudative effusions are thin and appear anechoic. Parapneumonic effusions and empyema, on the other hand, are two exudative processes that are easily confused for solid masses because they possess such complex internal septation architecture and echodensity, due to fibrin deposition and cellular debris. Obviously the success of any thoracic drainage procedure will depend to a certain extent on the type of fluid and the characteristics mentioned above.

Although fresh blood is usually seen as a heterogeneous anechoic or hypoechoic collection, the character of the fluid will change over time as evolving blood clot generates some sonographic shadows. A hemothorax may demonstrate some echogenicity and may or may not contain internal septations. As a retained hemothorax matures, it becomes thick-walled and very echogenic [17].

The most dramatic and obvious ultrasonographic finding indicative of a thoracic fluid collection is the sight of a sliver of lung floating in a dark, relatively anechoic background. The lung can be seen pulsating with patient respirations or with the cardiac cycle (Video 2.3). The lung parenchyma will typically show signs of collapse and alveolar consolidation under these circumstances—B-line artifacts and bronchograms can be seen.

There are three signs that are diagnostic of a pleural effusion or hemothorax. First is the quad sign, which is seen in the 2D mode, in the presence of a small volume of fluid between the chest wall and lung. With the probe positioned over an intercostal space, the displaced surface of the lung forms the base of an anechoic quadrangle; the parietal pleura/chest wall are the top side and the shadows cast by adjacent ribs form the sides of this rough quadrangle (Fig. 2.11).

With the US in M-mode, it is possible to appreciate what is called the sinusoid sign. With the probe again over an intercostal space, the lung's parietal pleura can be seen to be displaced from the parietal pleura. Over the course of several of the patient's respiratory cycles, the hyperechoic visceral pleura can be seen to trace a bright sine-wave pattern as it approaches and then recedes from the chest wall (Fig. 2.12).

Finally, the V-sign was recently described as a method for diagnosing the presence of free pleural fluid [36]. This sign is elicited while examining a supine patient, using a low-frequency probe. The probe is placed low on the chest wall, at approximately the level diaphragm and aimed cephalad and towards the spine. Under normal physiologic conditions, the inflated lung would block the transmission of sound waves to the posterior thoracic structures. However, in the presence of fluid, which acts as an acoustic window, it is possible to see the contour of vertebrae at the deep aspect of the US display (Fig. 2.13).

See Table 2.3 for tips on maximizing success when performing ultrasound for hemothorax/effusion.

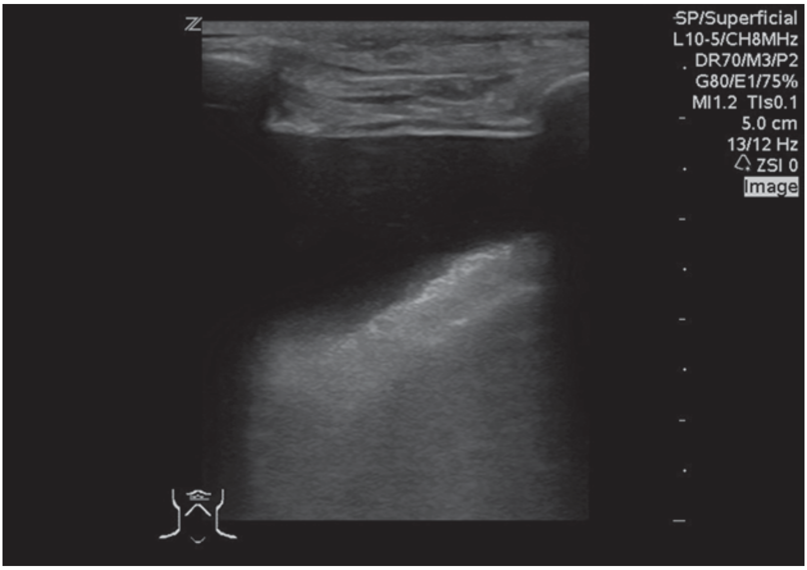

Fig. 2.11 Quad sign

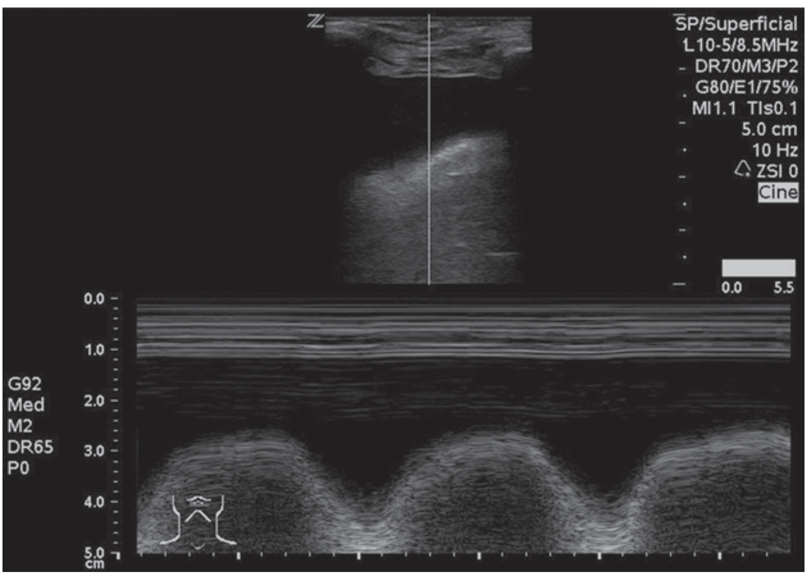

Fig. 2.12 Sinusoid sign

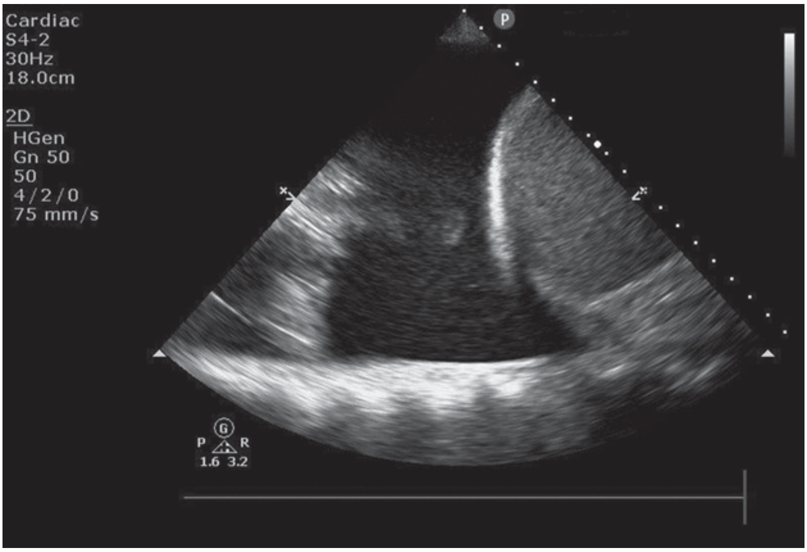

Fig. 2.13 V-sign

Table 2.3 Tips for maximizing success when performing ultrasound for hemothorax/effusion

Proper patient positioning if clinically feasible:
a. For effusion or hemothorax: Upright position and scan posteriorly below scapula
b. While draining fluid from pleural cavity: The affected chest lower than the other side if patient stays in recumbent position
c. Patient can be rotated slightly with a lateralization maneuver to bring the probe into better contact with an dependent effusion
d. Support patient appropriately with pillows and/or blankets
e. Adjust height and position of bed and ultrasound machine to optimize operator ergonomics
Appropriate probe selection:
f. A fairly low frequency (5 MHz) curvilinear probe works best for rapid scanning and evaluation of the intrathoracic pathology
g. Adjust depth and focus to maximize area of interest
h. Use both B and M modes to confirm presence of fluid
i. Color Doppler to identify blood vessels in the needle path before accessing thoracic cavity
Identify surface landmarks:
j. For rapid scanning for fluid: start in the bilateral flanks and then proceed cranially

Evaluating for Lung Consolidations

Consolidations of the lung parenchyma are seen best using a low-frequency probe. The phased array can be preferred rather than a curvilinear probe since it would be easier to fit in between the ribs and also offers a better definition. Water is a good transmitter of US and a consolidated lung is water-rich. Alveolar consolidation usually reaches the lung surface. Collapsed lung segments can resemble consolidation in the US examination, but it will differentiate between consolidation and effusion better than a regular chest x-ray.

Consolidations are visualized as poorly defined hypoechoic lung tissue structure. In contrast, the tissue structure of normal lung cannot be seen. Within the consolidation, hyperechoic images can be seen corresponding to air in the bronchi, these are air bronchograms that will move in the bronchi during respiration.

It is easy to confuse a lower lobe consolidation with the liver or the spleen so care needs to be taken in visualizing the diaphragm to define which structure is intra-abdominal versus intrathoracic

Thoracentesis/Pigtail Catheter Under Ultrasound Guidance at the Bedside

Procedures/Accessing Pleural Cavity

Ultrasound allows for a safe and accurate access to the pleural cavity. The skill used to place venous catheter under US guidance can be easily transferred to the placement of pleural catheter under US guidance. The indications for accessing the pleural cavity can be both diagnostic and therapeutic; including pneumothorax, pleural effusion, hemothorax, empyema, lung or pleural biopsy.

There are various commercial products that are available to access and drain the pleural cavity using percutaneous technique. The practitioner should identify those that are available at their institution and become familiar with their use as well as their advantages and disadvantages. We have demonstrated some different products in the attached pictures, but there are many different types and these are illustrative only. Many of these products use a plastic deformable catheter that can be left in situ to achieve continuous drainage. Most of these catheters employ a modified Seldinger technique for placement.

The first step in the procedure is to identify a suitable target area using US. The patient's position can be adjusted to optimize localization of the pathology, for example sitting up and forward for thoracentesis. For such simple drainage of fluid, once the patient is positioned in upright position the lower part of thoracic cavity can then be scanned with US. The optimal place to access fluid is the dependent portion of cavity, the costodiaphragmatic recesses, however care should be taken not to pierce the diaphragm in the physician's eagerness to access this fluid, and this is where US can be more useful than the landmark technique in identifying the best area for drainage. The scanning process should start from the flank region. The splenorenal recess on the left is identified first and the corresponding hepatorenal recess on the right with scanning then proceeding in a cranial direction. Once the fluid collection is identified above the diaphragm, the area is marked with a skin marker.

The next step involves the access to fluid via a needle placed under guidance. Appropriate analgesia using systemic and local anesthetic infiltration is given. The site is prepared using antiseptic scrub. Complete sterile precaution with gloves, gown and sterile drape are used (Fig. 2.14). The US probe is also draped in a sterile sleeve. The operator should scan the site again to confirm the presence of appropriate target. Under continuous ultrasonographic guidance, a needle is advanced into the fluid while aspirating as the needle moves. Aspiration of pleural fluid as well as direct visualization of needle in the pleural cavity with US confirms the placement. The needle must stay steady after this step to prevent its displacement of needle. For simple thoracentesis, the needle would be withdrawn at this point, and then US can be used to confirm (1) absence of a post-procedure pneumothorax, and (2) resolution of the fluid collection in the case of a therapeutic thoracentesis. There are multiple different kits commercially available, but at our institution we have a preference for the "Wayne" pigtail thoracostomy kit, which comes with a 14-Fr catheter, which can suffice for both pneumothoraces and fluid (Fig. 2.15).

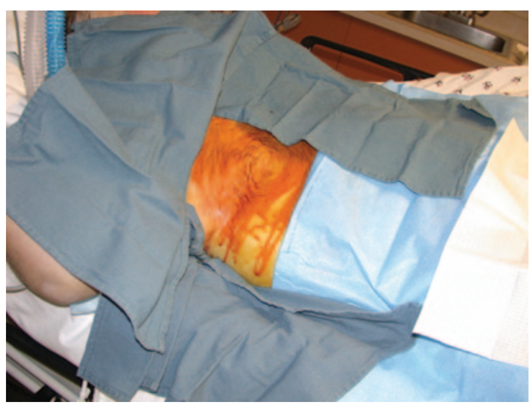

Fig. 2.14 Use of sterile technique for effusion drainage

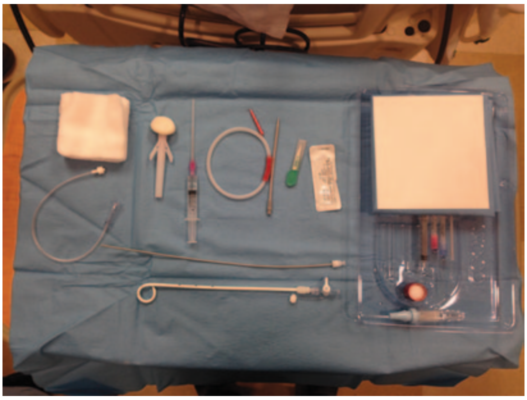

Fig. 2.15 "Wayne" 14-Fr pigtail catheter kit

If a drainage catheter is to be placed, the syringe is then removed from the needle's hub and a flexible guidewire is threaded into pleural cavity via the needle. The needle is then withdrawn once the wire is in the cavity (Fig. 2.16). The position of wire can also often be confirmed as well using US. An appropriate incision is then made over wire to accommodate subsequent placement of the catheter. The next step involves dilatation of the tract over the wire using the dilator provided in the kit. An introducer is often included in the kit as it allows, the curved catheter to be straightened, and both the catheter with the introducer are then placed into the pleural cavity together over the wire. When the introducer and the wire are removed from with the catheter, it allows the catheter to curl up into a "pigtail" (Fig. 2.17). The depth to which the catheter is advanced depends on the soft-tissue thickness over the chest. The position of the "pigtail" should be immediately underneath the parietal pleura and not deeper into the cavity. The fluid is allowed to drain by connecting it to a closed pleural drainage system with or without negative pressure. This fluid may be sampled for diagnostic studies. The catheter must be secured to skin using a combination of both sutures and occlusive dressing.

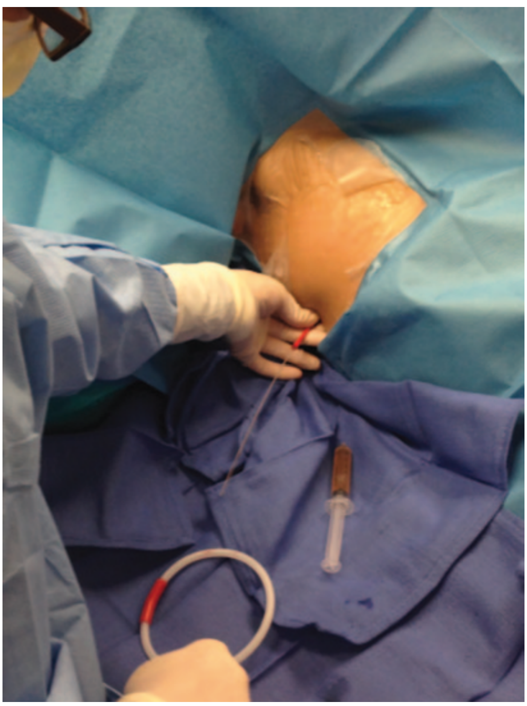

Fig. 2.16 Wire in place for catheter placement

Presence of any post-procedure pneumothorax and resolution of effusion/hemothorax can be immediately detected by US scanning. Once the catheter has served its purpose it should be removed by severing the suture and applying gentle traction, to the catheter. Any post chest tube removal pneumothorax may be detected using US, obviating the need for routine chest radiography.

See Table 2.4 for tips on maximizing success in ultrasound-guided thoracic access.

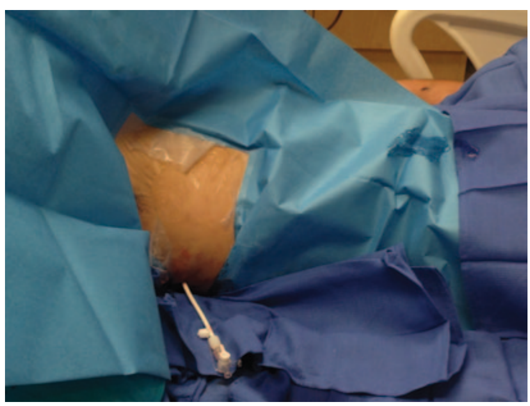

Fig. 2.17 Pigtail catheter in place

Table 2.4 Tips for maximizing success in ultrasound-guided thoracic access

1.	Scan a wide area to identify the best target
2.	Optimize patient position: see Table 2.1
3.	Aim for dependent areas for fluid/blood and apical area for pneumothorax
4.	Use full sterile barrier precautions
5.	Repeat identification of target once the drape is in place
6.	Use a sterile sleeve over ultrasound probe
7.	Ensure location of the tip of the access needle constantly by moving the ultrasound probe in parallel with the advancement of the needle
8.	Following placement of guidewire through puncture needle, confirm its location using ultrasound prior to dilation of the tract
9.	Make a generous incision over skin to accommodate the pleural catheter. If any resistance is felt during dilation then reassess the size of incision
10.	If the wire bends during dilation step, then a new wire should be used. Ensure the diameter and length of new wire are similar to the wire available in the kit. A thinner wire will not be adequate to advance the dilator over and will bend too easily
11.	Ensure all parts of catheter and dilator are flushed with saline for reducing friction while sliding over the wire
12.	Advance just enough length of catheter so that it curls up immediately beneath the parietal pleura
13.	Always secure the catheter once in place with at least two sutures
14.	Watch for “tidaling” of the fluid column in the tubing or the pleurovac with breathing (Video 2.4)
15.	An ultrasound survey is performed after placement to confirm resolution of pathology—pneumothorax or effusion. Post-procedure pneumothorax can be detected in this scan as well
16.	Periodic ultrasound may be performed to assess the ongoing need for the catheter. Remove catheter once it has served its purpose

Summary

- Ultrasound is highly accurate for the diagnostic of pneumothorax, hemothorax and consolidation but it is **operator-dependent.**
- Lung US relies on identification of artifacts:
- A-lines are bright horizontal lines located below the pleural line at regular intervals. A-lines are reverberation artifacts.
- B-lines are vertical hyperechoic artifacts that arise from the pleural line, extend to the bottom of the screen, and move synchronously with lung sliding, abolishing A-lines.
- Lung sliding and B-lines are not present on a patient with pneumothorax. M mode can help differentiate between a seashore sign or stratosphere or bar code signs (seashore = no pneumothorax).
- Remember lung sliding ALONE does not exclude pneumothorax. Scan the entire anterior chest for B-lines.
- Pneumothorax that is not in immediate contact with the chest wall will not be identified on US (e.g., loculated pneumothorax against the mediastinum)
- Pleural effusions will be better visualized on the dependent portions of the thorax.
- Hypoechoic fluid vs. consolidation of the lung can be differentiated while performing an evaluation of the chest cavity with US.
- Preponderance of B-lines can be present when a pulmonary process is present. If the pattern is localized, this could be a pneumonia; if the pattern is diffuse, pulmonary edema.

Acknowledgements With grateful thanks to Dr. Srikar Adikhari who generously aided in the supply of high-quality images and videos for this chapter.

Appendix

Video 2.1 Lung sliding.
Video 2.2 Lung point sign.
Video 2.3 Hemothorax moving with respirations.
Video 2.4 “Tidaling” in pigtail catheter.

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3 Cardiac Ultrasound in the Intensive Care Unit: Point-of-Care Transthoracic and Transesophageal Echocardiography

Jacob J. Glaser, Bianca Conti and Sarah B. Murthi

Introduction

Constant change makes learning ultrasound both exciting and challenging. It is likely that by the time you are reading this chapter, there will be innovative applications that we have only touched on here. Thankfully, human anatomy remains unchanged, as do the basics of ultrasound imaging, and once they are mastered understanding new ways of using ultrasound becomes much easier. Transesphogeal echocardiography (TEE) is the original form of point-of-care echocardiography [1]. It has been used by the treating physician in the operating room and intensive care unit (ICU) for over 30 years to manage complex patients. As technology has advanced, transthoracic echo (TTE) has become the primary mode of assessment in the emergency department and ICU [2]. Recently it has been demonstrated that adding a basic cardiac evaluation to the Focused Assessment Sonogram for Trauma (FAST), is feasible and may improve outcome [3], while more quantitative hemodynamic exams have been shown to change care in the ICU [4, 5]. Whatever the format, TEE, basic TTE or hemodynamic TTE, familiarity with echo is an essential part of modern critical care.

In this chapter we will briefly review ultrasound physics and machine basics specific to cardiac imaging. Spending a few minutes understanding the underlying principals of ultrasound will make obtaining and interpreting images easier in the long run. Intermittently returning to physics as experience with ultrasound is gained is oddly rewarding, and will result a fundamental understanding modality. The discussion of physics will be followed by descriptions of basic TTE, hemodynamic TTE, and a standard TEE. Safety concerns and future innovations will also be briefly discussed. By the end of this chapter you will be familiar with all forms of bedside echocardiography.

J. J. Glaser (✉) · S. B. Murthi
Department of Surgery, R. Adams Cowley Shock Trauma Center, University of Maryland School of Medicine, 22 South Greene Street, 21201-1595 Baltimore, MD, USA
e-mail: jglaser@umm.edu

S. B. Murthi
e-mail: smurthi@umm.edu

B. Conti
Department of Trauma Anesthesiology, R. Adams Cowley Shock Trauma Center, University of Maryland School of Medicine, 22 South Greene Street, 21201-1595 Baltimore, MD, USA
e-mail: bconti@umm.edu

Cardiac Ultrasound Physics

The Transducers TTE and TEE

The primary instrument used for TTE is a low-frequency 3.5-MHz phased array transducer. The small rectangular footprint makes it ideal for getting in between rib spaces, while its lower frequency allows deeper penetration needed for

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transthoracic imaging. The crystals in the transducer can both pulse at set frequency to send a signal and bend to receive the returning echo after impact with a structure. The crystals can be sequentially fired to create an adjustable focal point. The number of crystals in the transducer head determines the image resolution. A cardiac quality probe with more crystals provides a better quality image, but costs more to manufacture. A curvilinear transducer can be used if a phased array transducer is not available for more basic imaging. Indeed many centers use a curvilinear probe for shock assessment, as it is better for imaging the abdominal aorta, and then fan-up into the thorax from below the xiphoid to get a global assessment of cardiac function. Similarly, the FAST is performed with a curvilinear probe in some centers, and rather than switching transducers using the probe at hand is reasonable. However, for more dedicated cardiac exams the phased array probe is preferred [6].

The TEE transducer is higher frequency, usually 7 MHz [1]. The only tissue between the probe and the heart is the esophagus, so the signal does not need to penetrate deeply. The higher frequency of the TEE transducer allows for much better, more resolved images. The tip of the probe can be flexed and retroflexed, but not really rotated and tilted like a TTE probe on the thorax because it is in the esophagus and not hand-held. Instead the ultrasound crystal within the esophageal transducer head can be rotated 180 in two planes, horizontal and vertical, using controls on the handle of the transducer. By rotating the transducer, flexing and retro-flexing the tip, and rotating the crystal TEE, an experienced operator can see the heart from almost any angle. TEE provides excellent visualization of the right ventricle, valvular structure and the thoracic aorta. While it provides excellent images, TEE is confusing to learn at first, as it takes time to understand the planes and angles.

US Systems Cardiac and Point of Care

An ultrasound system consists of a transducer, a display screen, and a computer that can process the sound signal into a digital image. Software loaded into the computer allows optimization of the image, storage of exams, and hemodynamic calculations. Computers are becoming increasingly small, fast, and inexpensive, and so is ultrasound. However, the most important, and expensive, item in the system is not the computer; it is the transducer. To reliably perform hemodynamic measurements, a high-quality cardiac probe is needed, while a more basic exam can be performed with any transducer [6]. As an added benefit high-quality transducers produce beautiful 2D images and increase the yield of results in critically ill patients who are often very difficult to image. Many of the point-of-care systems marketed to the emergency departments and ICUs are advertised as able to do measurements, but the probe is not cardiac quality. This is partially because most of the systems are modified from an abdominal ultrasound base, and partially because cardiac transducers cost more to manufacture. Keep in mind that if the transducer is unable to obtain a quality Doppler signal the measurement will be inaccurate, and even if the device has a software package able to calculate a value it will also be inaccurate. For manufactures adding on new software is easy and inexpensive. To perform cardiac assessments we use either the Philips XC 50, or the GE Vivid i which are both cardiac-based systems. As a result we have demonstrated excellent correlation and agreement with pulmonary artery catheter (PAC) derived CI with echo, while other groups using a point-of-care system and automated calculations, have shown poor correlation [4, 7]. For more basic imaging any probe will do the trick in the vast majority of patients.

Exam Type and Presets

All new machines come with modifiable features, which can be set to optimize different types of imaging. These preset packages of settings are called “presets” or “exam types.” Common exam types include cardiac, abdominal, lung and vascular exams. Each manufacturer installs different software packages. As a result, how to set and change the presets/exam type vary, but are easily mastered with minimal experience on a specific ultrasound system. Furthermore, once ultrasound is mastered (on any machine), learning a new system is relatively easy. Regardless of the manufacturer, there are several important differences between cardiac and abdominal presets. Unlike the liver or the kidney, the heart is beating rapidly, so higher sweep speeds are needed to see movement clearly. There are also differences in transducer orientation and compression of the brightness scale between cardiac and abdominal imaging.

- *Transducer Orientation:* One of the assets of TTE imaging is that the probe can be turned 360° to allow any angle to be seen. There is a groove, or light on the transducer head that is displayed on the screen. Where that groove is displayed on the screen is a modifiable feature in presets. Abdominal imaging makes intuitive sense, because the groove is always displayed to the left of the screen, so that in a FAST for example, the caudal part of the image (i.e., the thorax) will be displayed on the left of the screen. However cardiac ultrasound and abdominal ultrasound developed independently. By convention in cardiac imaging (and in cardiac presets for point-of-care) the groove is displayed on the *right* of the screen. The cardiac convention allows correlation orientation of TTE images with cardiac catheterization. In addition, for all of the windows except the parasternal long, the probe is turned to the right so the displayed images match patient orientation. Transesophageal imaging is, of course, from behind the heart, and the crystal can be rotated in two planes, so the orientation is completely different from either abdominal or TTE convention. Understanding the orientation of the heart in the patient relative to the image on the screen takes time. At first simply learning the manual aspects of obtaining the images and memorizing the anatomy displayed on the screen is acceptable. The ability to mentally rotate the heart will come eventually.
- *Compression:* Compression is the difference between highest and lowest pixel value assigned to the returning signal. More compressed abdominal imaging has less difference and thus a more grey soft image. Conversely, cardiac imaging is less compressed and will appear more black and white; this allows for better definition of the endocardium and pericardium.
- *Sweep Speed:* The crystals in the transducer head are sequentially fired as they "sweep" across the object. Imaging a rapidly moving object requires a high sweep speed, so that it does not appear blurry. Unfortunately, higher sweep speeds allow less scan lines to be fired, and the number of scan lines determines the resolution of the still or frozen image. As a result when a moving image obtained at a high sweep speed is frozen it can appear grainy and unresolved. Cardiac imaging, which must be able to evaluate rapid valvular function, has very high sweep speeds. Conversely, abdominal organs are more static and a slower sweep speed can be used.

As a result of these differences in probe orientation, compression and sweep speed, a cardiac exam performed in abdominal presets will appear more grey, fuzzy, and backwords, while the same exam in cardiac presets would appear more resolved, more contrasted (i.e., be more black and white then grey), and be oriented correctly. Conversely an abdominal exam performed in cardiac presets, will look grainier, and appear upside down, or backwards (Fig. 3.1). As with probe selection, a basic cardiac evaluation can be performed in abdominal presets, while a comprehensive exam should be performed with cardiac settings.

At our center, and most centers that do dedicated cardiac point-of-care US, the orientation is cardiac (probe grove displayed on the right of the screen) to maintain consistency with a standard echocardiogram. When performing a cardiac ultrasound in abdominal presets, standard TTE orientation can obtained by simply rotating the probe 180°. For the remainder of this chapter the images will be displayed and discussed in standard cardiac orientation. Keep in mind that some centers that do primarily abdominal imaging use

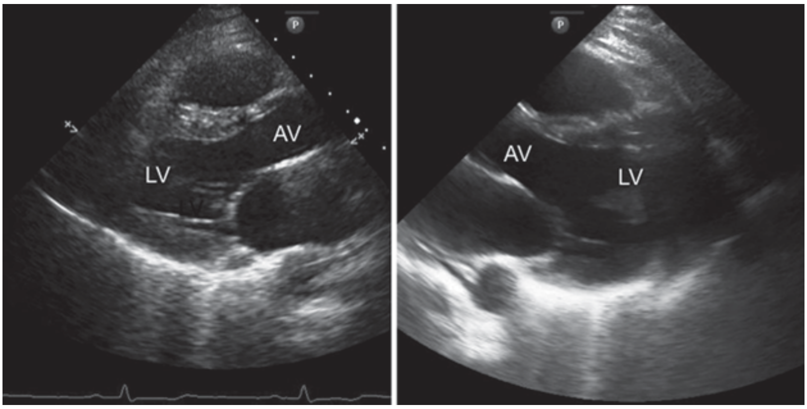


Fig. 3.1 Parasternal long axis (PLA) in cardiac and abdominal imaging. The image on the *left* is the PLA in cardiac presets, and the image on the *right* is in abdominal presets. *AV*, aortic valve; *LV*, left ventricle. The *P* icon at the top of the image corresponds to probe orientation. Note the orientation of the heart is opposite with the *AV* on the *right* in cardiac imaging and on the *left* with abdominal imaging

the abdominal convention with the grove displayed on the left.

Modalities in Cardiac Imaging

- *2D/B-mode:* The terms 2D and B-mode are interchangeable. They describe standard 2D imaging that assigns a pixel value, or brightness value hence B-mode, to the amplitude of the return signal. In general systems and individuals primarily trained in abdominal imaging use the term B-mode, whereas those from a cardiac background use the term 2D. The 2D image is created by intermittently firing the crystals that send and receive the US signal across the field, thus sweeping it across the object. The difficulty is in measuring rapid movement, because high sweep speeds involve sending less scan lines and the still image will appear blurry (as discussed above).
- *M-mode:* In distinction motion-mode or M-mode uses one crystal to continually send and receive the signal, so there is no sweep speed. It can be thought of as an ice-pick view through a 2D image. M-mode is ideal for precisely measuring motion of an object (Fig. 3.2).

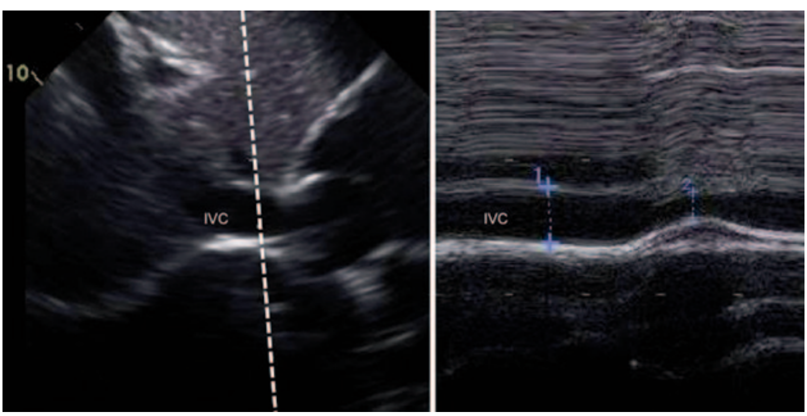


Fig. 3.2 M-mode of the inferior vena cava (*IVC*). The image on the *left* is a 2D depiction of the liver at the *IVC*, and the image on the *right* is the M-mode or icepick view of the *IVC*. The dotted line is the cursor showing the plane through which the M-mode image is taken. The variation in the IVC seen in the M-mode is respiratory variation

- *Doppler Ultrasound:* Whereas both 2D and M-mode measure amplitude of the return signal; Doppler ultrasound measures the frequency-shift (also called Doppler shift) of the return signal created by impact with a moving object. Objects moving towards the transducer will increase the frequency of the return signal, whereas those moving away will decrease it. The velocity of the movement determines the magnitude of the shift.

There are two different ways of sending/receiving the signal; pulsed-wave (PW) and continuous-wave (CW) as described below. Color flow Doppler (CF) is a form of PW Doppler. In both PW and CW the Doppler shift is assigned a pixel value and displayed around a baseline, with flow towards the transducer above, and away from the transducer below the baseline. This allows for detailed assessment of flow including identification of stenotic areas. Conversely in CF the Doppler shift is assigned a color value and displayed over a 2D image, which allows for localization of flow.

- *Pulsed-wave Doppler (PW):* As the name implies in PW the ultrasound signal is pulsed. One crystal is used to send and receive the signal, thus the time the signal returns is known. In ultrasound time of signal return is how depth of an object is determined, so PW Doppler allows flow to be assessed at a specific depth, or anatomic location. PW is ideal for quantifying flow in a specific area (Fig. 3.3). The frequency of the pulse is called the pulse-repetition frequency (PRF) which is important because there is an upper limit of flow that be accurately displayed with PW determined by the Nyquist limit. If the frequency shift is greater than on-half the PRF, then the signal will alias (Fig. 3.4). As a result high flow jets will alias with PW, and flow cannot be accurately displayed.
- *Continuous-wave Doppler (CW):* CW Doppler uses two crystals, one to continually send, and one to continually receive the signal. Because the signal is continuous and not pulsed there is no PRF. As a result, the signal does not alias, which makes it ideal for assessing areas of high flow. However, because the signal is continuously received, the time it takes the signal to be sent and return cannot be determined, so flow cannot be measured at a precise depth. PW and CW can be used together to precisely locate and quantify stenosis (Fig. 3.5).
- *Duplex or Color Flow (CF) Doppler:* Color flow is a type of PW Doppler, as a result it will alias with high velocity flow. Color flow applies a color value to the frequency shift. By convention flow towards the transducer is red and away blue. The brightness of the pixel corresponds to flow velocity of flow. Duplex refers to displaying CF over a 2D image. This makes duplex CF Doppler ideal for localizing both normal and pathologic blood flow (Fig. 3.6).

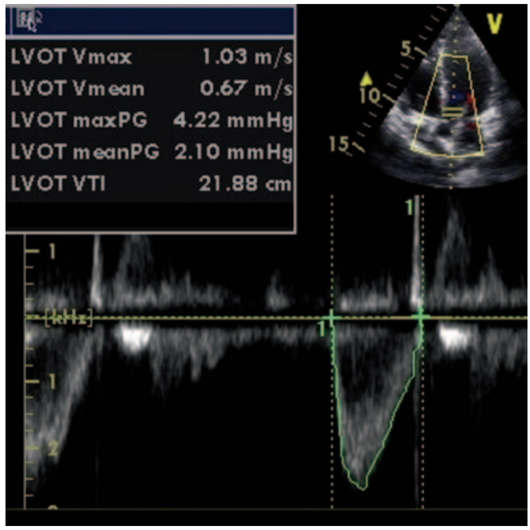


Fig. 3.3 Pulsed-wave Doppler (*PWD*). This image shows pulsed wave through the aortic valve. *LVOT*, left ventricular outflow tract; *VTI*, velocity time integral. The *LVOT VTI* is used to calculate the stroke volume and cardiac index. *PWD* allow assessment at a specific location, in this care at the *LVOT*, shown by the *double hash marks* on the cursor in the *top right* of the image

Focused Cardiac Ultrasound

Focused cardiac imaging has become a standard of care for diagnostic imaging in the emergency room, the intensive care unit, and any clinical

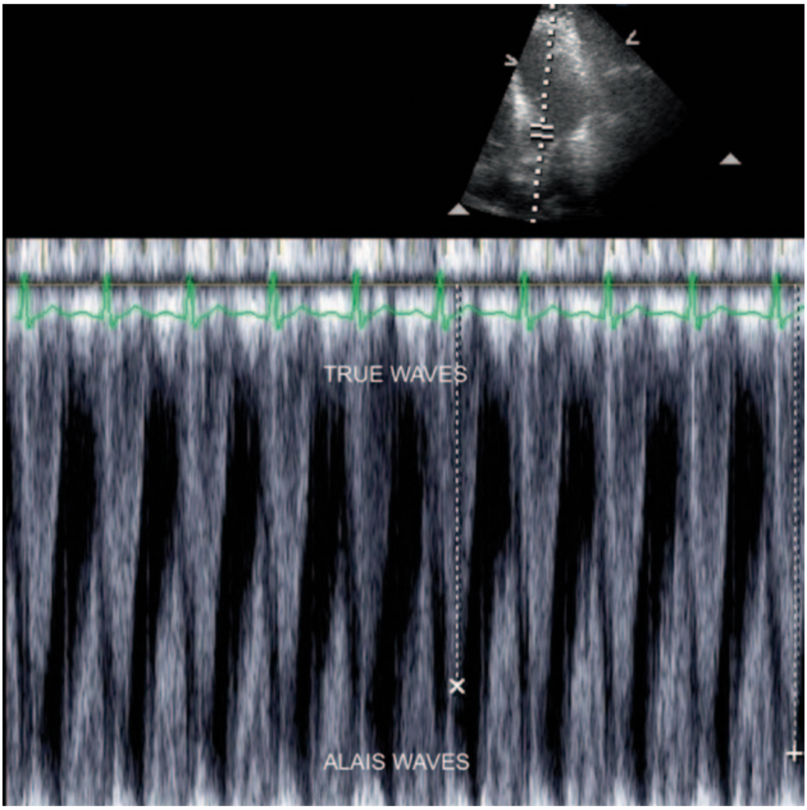


Fig. 3.4 Aliasing in pulsed-wave (*PW*) Doppler. Aliasing is a common artifact in *PW* imaging, observed with high flow jets. Aliasing can make it very difficult to perform accurate measurements

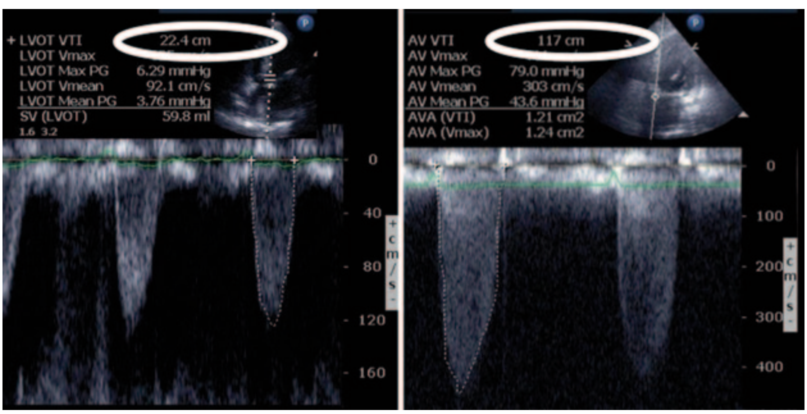


Fig. 3.5 Pulsed-wave Doppler (*PWD*) and continuous-wave Doppler (*CWD*) in aortic stenosis. *PWD* on the right measures at a specific point, whereas *CWD* measures along the entire cursor. Used in conjunction they can detect areas of stenosis. Note the much higher velocity time integral (*white circle* at the *top* of each image), with *CWD*. This finding indicates an area of stenosis at the aortic valve

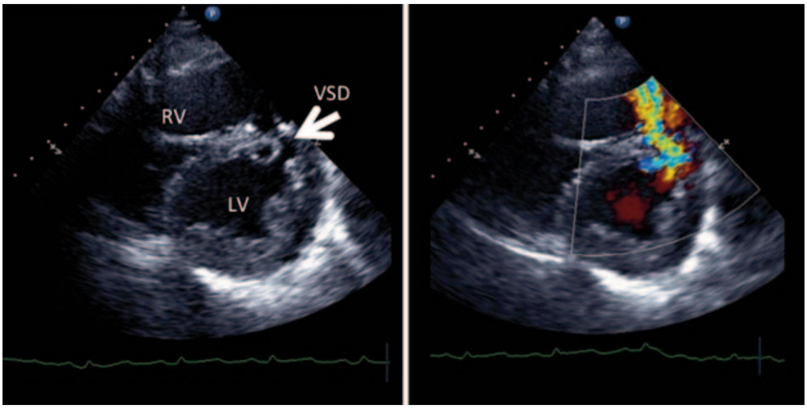


Fig. 3.6 Ventricular septal defect (*VSD*) with color flow Doppler (*CFD*). This is a short-axis view of the heart. On the *left* is a 2D image, and on the *right* is the same image with *CFD* applied, showing pathologic blood flow from the left ventricle to the right. *RV*, right ventricle; *LV*, left ventricle

scenario requiring assessment of the heart and great vessels [2, 6]. There is currently a concept of the ultrasound stethoscope and sonography replacing the physical exam. The intention of the ultrasound should not be used to replace clinical decision making or physical exam of the patient, but should instead be seen as a useful adjunct to evaluation of the critically ill patient. It also has the added benefits of avoiding ionizing radiation, providing real time diagnostic information, allows findings to be directly correlated with the patients signs and symptoms, and is repeatable, allowing the clinician to follow a clinical course or track an intervention.

History

Traditionally, ultrasound of the heart was the sole domain of the cardiologist. As a community, cardiologists have been resistant to accept a non–cardiologist-performed echo for fear of false information being obtained, and patients subsequently suffering from misdiagnosis or misguided interventions. This is reflected in the early American Society of Echocardiography guidelines from 1999 [8]. In this policy statement there is a clear concern that even simple conditions, like cardiac tamponade, may be misdiagnosed or misinterpreted by non-cardiologist sonographers. In their summary statements, it is recommended that all emergency departments collaborate with more experienced echo providers and that systems be established to limit gaps in coverage by a trained sonographer. In the situation of a life-threatening condition like tamponade, if the sonographer was not immediately available, they hesitantly supported the concept of a lesser trained physician acquiring and interpreting initial images with subsequent review by a sonographer as soon as possible.

In 2010 a combined statement between the American Society of Echo and the American College of Emergency Physicians describe a much more collaborative approach. In this statement it is suggested that the term focused cardiac ultrasound (FOCUS) be used to describe point-of-care evaluations, allowing differentiation between a comprehensive TTE, performed by a cardiologist, a limited echo (performed by a cardiologist but without all images obtained) and FOCUS performed by a non-cardiologist [9]. They state that the goal of focused sonography in symptomatic emergency patient is limited. Specifically, the focused exam, per their guidelines, should be used in assessing for cardiac tamponade or effusion, global left and right heart function, and an intravascular volume. In the cases of effusion or tamponade, ultrasound can be also used for guidance of pericardiocentesis.

Flash forward to 2013 and the most recent policy statements of the American Society of Echo, where clearly a softer attitude towards FOCUS exists [10]. With the proper definitions of comprehensive echo, limited echo, and focused ultrasound having been delineated, the American Society of Echo seems to have accepted the role of FOCUS as an adjunct to the physical exam in the emergency setting, off hours, or when formal echo is not available. These guidelines state that focused cardiac ultrasound should be used only for specific situations and answering specific questions, with the intent that follow up formal echo will be performed to confirm findings as well as identify associated findings that would likely go unrecognized by the focused exam.

There are a variety of important applications of FOCUS, and there is substantial emergency medicine literature supporting its use in bedside decision making, even without confirmatory imaging by a cardiologist [2, 11]. For example, independent assessment of the heart in the setting of blunt and penetrating trauma has been the standard of care since the introduction of the FAST exam in the 1990s [12]. The subxyphoid view of the heart for pericardial fluid is an integral part of the initial assessment in trauma patients. Furthermore, the presence or absence of cardiac findings on this exam decreases time to diagnosis, treatment, and has been shown to improve mortality [13, 14].

In addition cardiac ultrasound commonly used during ACLS as it can be used to differentiate between PEA, asystole, and profound hypotension [15, 16]. Furthermore, FOCUS in conjunction with other ultrasound imaging can be used in identifying a pulmonary embolus, pneumothorax, or tamponade as treatable causes of the arrest. Also, the presence or absence of cardiac activity on this exam decreases time to diagnosis, treatment, and has been shown to improve mortality [13, 14].

Follow-up formal echocardiography is indicated at the treating physician's discretion. The underlying points of the American Society of Echo's recommendations are well taken, but more often than not action is required before confirmatory testing can be obtained. In addition cardiologists are trained in echo for a specific application; to evaluate the heart. But many of the applications of echocardiography in the ICU and emergency department employ it as a tool to guide resuscitation. It is more about optimizing end organ perfusion, or determining the cause of shock, than it is about managing heart failure or diagnosing valvular dysfunction. Often it involves imaging other organs, and a knowledge base in resuscitation in addition to an understanding of cardiac physiology. A new form of echo has evolved, and it is possible that cardiologists are not the best trained at interpreting it simply because they initially developed the field. Ideally cardiologists, emergency medicine physicians, intensivists, and surgeons would share resources and work for the common good of the patients, but when that is not the case, patients' needs and advancing medicine trump territoriality.

Standard Views

There is a spectrum in the complexity of focused cardiac ultrasound, from answering simple binary questions, to some objective flow and volume measurements, to exams that rival formal echo [4, 11, 17]. Regardless, the technical approach to the cardiac exam is essentially unchanged (Fig. 3.7). It is often necessary to look 'through'

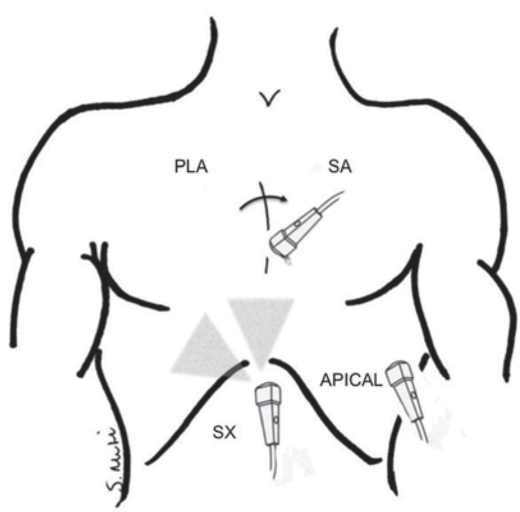


Fig. 3.7 Four views of a *TTE*. Depicted are the four standard views of a *TTE*: the posterior long-axis (*PLA*), posterior short-axis (*SA*), apical and sub-xiphoid (*SX*) windows

the ribs, and for this reason a phased array or small footprint probe is best. In addition, the best fidelity imaging will be obtained on a cardiac quality machine, with a full service cardiac software package. If this is not available, it is still possible to obtain images and evaluate basic cardiac function, with any low frequency transducer.

1. Parasternal long axis (PLA)
2. Parasternal short axis (PSA)
3. Apical 4- or 5-chamber view (AP 4-chamber, AP 5-chamber)
4. Subxiphoid or subcostal view (SX)

The parasternal long axis (PLA) view is obtained with the patient supine or in a slight left lateral position to improve image acquisition. The transducer is placed on the chest, just left of the sternum at the 3rd or 4th intercostal space. It is oriented towards the right mid-clavicular line, and can be moved up or down with the goal of bisecting the left ventricle on its long axis. The heart is often lower and more medial in intubated patients (Fig. 3.8) With this view, one can see the left ventricle, the mitral and aortic valves in cross section, and some of the right ventricle. It is easy in this view to assess the contractility of the left heart, and to assess for effusions, both pericardial and pleural (Fig. 3.9).

The short-axis window (SA), is obtained after the PLA, by rotating the probe 90° clockwise to bisect the left mid-clavicular line. The SA provides a cross-sectional view across the left ventricle. The probe can be swept along the heart to obtain views through the aortic valve, mitral valve, papillary muscles, and apex of the heart (Fig. 3.10). The SA is excellent for evaluating ejection fraction (EF), as well as right heart function. With right heart failure, one will see a large right heart, and D-shape of the left heart with diastole (Fig. 3.11). Ejection fraction (EF) can by quantified in both the PLA and SA, but is best assessed after viewing all four windows. Both the PLA and SA can be obtained in greater than 90 % of patients [18], and the EF can be assessed in > 90 % as well [4].

The apical (AP) view is obtained by placing the transducer near the apex of the heart, usually located a few centimeters below the nipple between the left mid-clavicular and anterior axillary lines. The grove is rotating about 45° clockwise from the SA, and aimed towards the bed. Turning

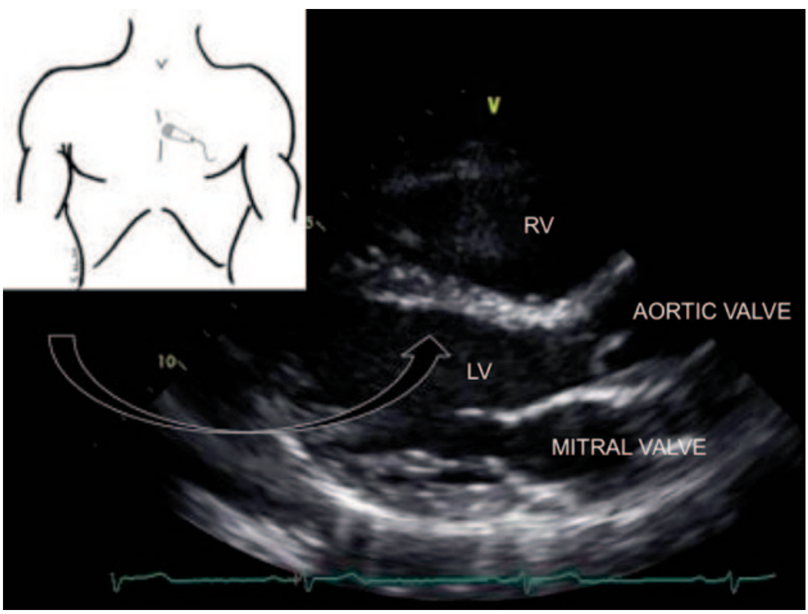


Fig. 3.8 Parasternal long-axis (*PLA*) view. The *PLA* view is obtained by placing the transducer to the *left* of the sternum, with the groove pointed toward the right mid-clavicular line. Because the transducer groove is oriented to the *right* of the screen, the aortic valve appears on the *right*. *LV*, left ventricle; *RV*, right ventricle

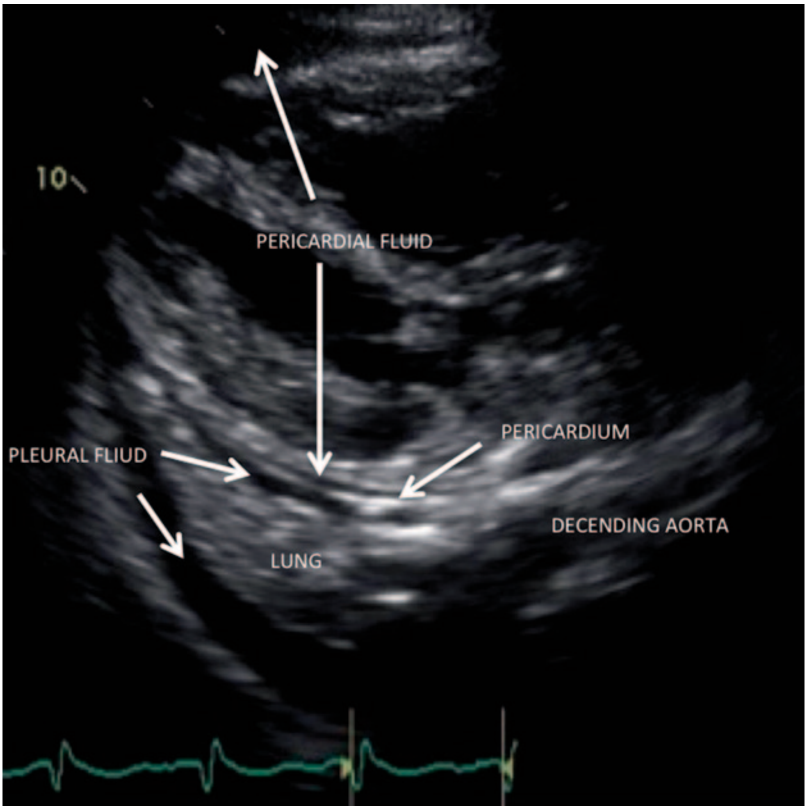


Fig. 3.9 Parasternal long-axis (*PLA*) view showing pleural and pericardial effusions. In this patient both pericardial and pleural effusions can be seen. The pericardial effusions are around the heart, within the pericardium. The pleural effusions surround the lung below the pericardium. Pericardial effusions are anterior to the descending aorta, whereas pleural effusions are posterior

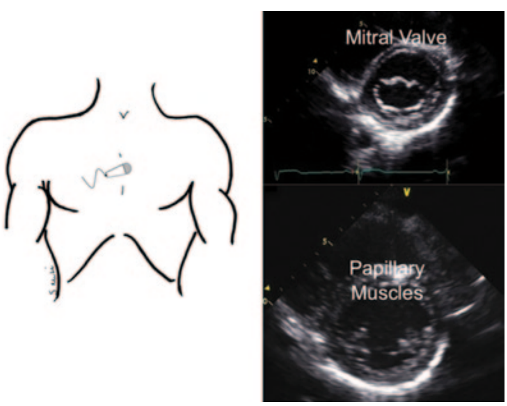


Fig. 3.10 Short-axis (*SA*) view. The *SA* view is obtained by rotating the transducer 90° from the PLA so that the groove is now bisecting the left clavicle. The transducer can then be rocked-up to see the aortic valve (not visualized), the mitral valve (seen on the *top right*) and the papillary muscles

the patient with the right side up can sometimes bring the heart closer to the chest wall making it easier to see. The maneuver is not as effective in mechanically ventilated patients, but it can be helpful in extubated patients The AP window gives a view that bisects the heart in an anterior-posterior orientation. The AP 4-chamber is usually the first view allows excellent visualization of the right atrium (RA), RV, left atrium and LV, then by rocking the transducer head anteriorly the 5-chamber view is obtained. The 5-chamber view allows visualization of the left ventricular outflow tract to the aorta (Fig. 3.12). This view is important for assessing for aortic stenosis, in conjunction with the PLA. It is also essential in calculating the stroke volume (SV) and cardiac index (CI) [4]. The apical windows are ideal views for assessment EF, right heart function, and

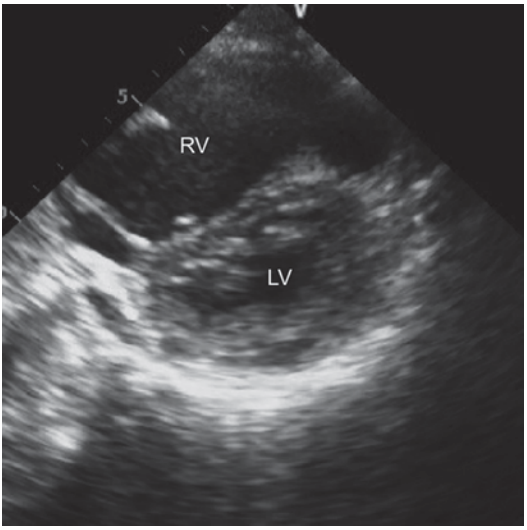


Fig. 3.11 Short-axis (*SA*) view showing *RV* dysfunction. In this patient the right ventricle (*RV*) is pressure volume overloaded, showing classic D-shaped compression of the left ventricle

get a global assessment of right heart size. Normally, the RV is 60 % the volume of the LV [18]. If this ratio is higher, or the right heart is larger than the left, and implies right heart overload or failure, although this may be different in mechanically ventilated patients. We have found in the majority of ventilated the RV appears equal to or slightly larger than the LV although the function appears normal. The apical windows are also essential in obtaining the measurements described in below in the hemodynamic echocardiography section below.

The subxiphoid (SX) view is obtained from the abdomen, looking across the left lobe of the liver up towards the heart. The IVC can be seen across the liver, and then followed up to its confluence with the right heart (Figs. 3.2 and 3.13). This view is excellent for determining presence of pericardial effusion and presence of cardiac activity. At times it is the only view that can be obtained in ventilated patients with high mean airway pressure settings. Often, a qualitative assessment of cardiac function can be obtained, but the heart is often for-shortened and dysfunction should be confirmed by assessment in other widows. This is the classic view obtained in the

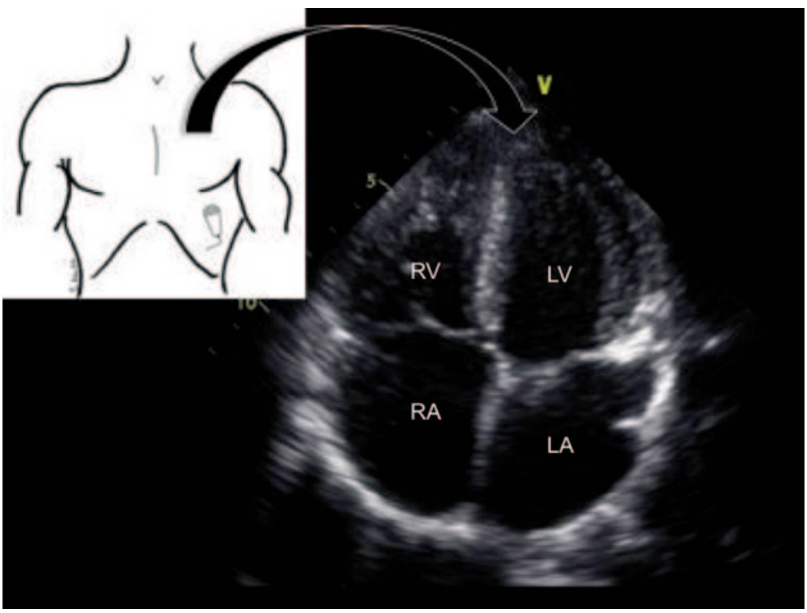
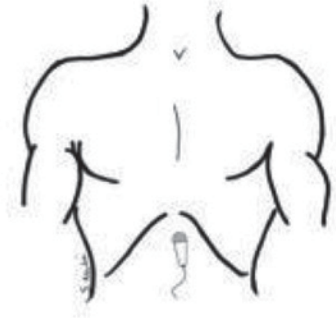


Fig. 3.12 Apical four chamber (*AP*) view. The AP view is obtained by moving the transducer inferio-laterally from the *SA*, and the groove is further turned to the *right* and aimed down to the bed. *RA*, right atrium; *RV*, right ventricle; *LA*, left atrium; *LV*, left ventricle. The ventricles are closest to the transducer head, as it is under the heart, so that the heart appears *upside-down* on the screen



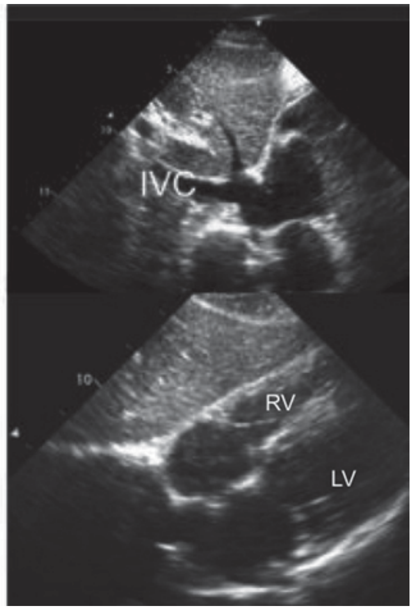


Fig. 3.13 Sub-xiyphoid (*SX*) view. The probe is moved from the *AP* to *below* the *SX*, the groove orientation remains the same to see the right ventricle (*RV*) (image on the *bottom right*). The transducer is then turned to the *right* and the groove rotated to the *left* to obtain the liver and inferior vena cava images

FAST exam, and can be obtained easily with either a curvilinear probe or phased array probe.

FOCUS Exams

Dr. Paula Ferrada et al. described the LTTE and the ABCD Echo, a tool for the initial assessment of the hypotensive patient in the trauma bay. Her work describes a simplified exam, with the goals being an assessment of cardiac function (good vs. poor), volume status (IVC fat vs. flat), and presence of pericardial effusion (present or absent). This is truly the prototype example of binary questions applied to cardiac ultrasound. It has been shown in that therapy is modified in 41 % of patients using LTTE, and 96 % of cases in patients older than 65 years [11]. In follow-up work from the same group, resuscitation guided by LTTE showed statistically shorter time to diagnosis, time to the OR, higher ICU admissions, and lower mortality than those patients resuscitated without the benefit of ultrasound [3].

Prior to Dr. Ferrada, Dr. Heidi Frankel, a pioneer in surgical ultrasound, in 2008 described the BEAT, a point-of-care cardiac exam developed in response to the idea that PA catheter–guided resuscitation may not be of benefit. She described a curriculum, with a didactic and hands-on components, and a formal exam comparable to PA catheter data. It includes B (for Beat/Cardiac index) and uses the consistent 'fractional shortening' technique to obtain a cardiac index. The 'E' portion of the exam evaluates for presence of an effusion, best visualized with the subxiphoid view. The 'A' refers to the 'area' (ventricular size and function). Here the heart is evaluated for global function and right heart overload. 'T' refers to the 'tank,' and is an assessment of the IVC for diameter and collapse. These IVC measurements can be used to estimate CVP [17].

Finally, the RUSH (rapid ultrasound for shock and hypotension) exam is an acronym for the bedside exam that has become popular in the emergency medicine community. It is intended primarily to assess for sources of hypotension in the undifferentiated shock patient. Like the other exams, the authors describe the four classic views of the heart assessing for left heart function, right heart function and size, effusion, and IVC size and collapse. No measurements are required for assessment of stroke volume or cardiac output. In the parasternal short view, however, they estimate that if the size difference between systole and diastole is < 30 % this indicates abnormal function. The RUSH exam also includes assessment of the lungs, Aorta, and leg veins for DVT. This is appropriate in the setting of undifferentiated shock, versus other focused cardiac exams where only the heart is being assessed [19].

There are a variety of other FOCUS exams described in the literature, including the FATE exam [20]. Whatever its format at this point there is significant data to support that non-cardiologists can perform and interpret it, and a growing body of data that it may improve outcome [3, 21]. Further research into the impact of FOCUS on outcome is urgently needed.

Hemodynamic Echocardiography

The FOCUS exams described above are designed to provide a gross assessment of cardiac function and volume status with any machine available. Furthermore for the most part competence can be obtained with minimal training. The question is what can be done with more extensive training and a full service machine? The answer maybe hemodynamic echocardiography. The standard cardiologist based interpretation of TTE is detailed anatomic description rather than a functionally based tool. It is designed to assess valvular dysfunction that may require elective surgery, or detect ventricular dyssynchrony that could benefit from bi-ventricular pacing. A busy university echo lab interprets upwards of 40 TTEs in a day both inpatient and outpatient. As a result the interpretation must be rapid and consistent between totally different patient groups. There is no time to wonder if fluid or inotropic support is better in a given individual. Conversely, hemodynamic echocardiography is a way of interpreting quantitative echo functionally, specifically to guide resuscitative management. Standard echocardiography and hemodynamic echo are used for entirely different purposes, and rather than conflicting they complement one another. Standard TTE will always have an important role in the ICU in assessing regional wall abnormalities and providing detailed valvular assessment. Furthermore it is, and will always be, the gold standard against which all other forms of TTE will be judged, but hemodynamic echo may provide an increasingly important role in directing care in the ICU.

Hemodynamic Exams

The FREE is the best described type of hemodynamic echo [4, 5]. It is very likely that many groups, especially in Europe, Asia and Australia are also performing quantitative function-based assessments to guide complex resuscitation, but in general the published descriptions are of basic qualitative exams [22, 23]. Hemodynamic echocardiography requires a full service cardiovascular machine capable of accurate Doppler measurements. The majority of systems marked to emergency rooms and intensive care units have a good probe adequate for 2D cardiac and abdominal imaging, but not good enough to accurately assess and quantify blood flow. In addition more training and expertise is required to perform hemodynamic evaluations [23]. Unlike the FOCUS exams, which have been shown to be teachable in a one-day course [21, 24, 25], there is a lack of data on how to train non-cardiologists in more advanced quantitative imaging. FOCUS is currently part of the standard of care, and proficiency in it is required in both emergency medicine and critical care training programs, but the ultimate role of hemodynamic echo has yet to be established.

Hemodynamic echo is needed because vascular catheters including the pulmonary artery catheter (PAC) and the Vigileo provide snippets of data, rather than an overall view of what is happening during resuscitation. Arterial pulse contour analysis used by the Vigileo is essentially looking at only one data point, the arterial waveform, which makes it prone to error. Because catheter data is limited, our thinking about resuscitation is a linear and stepwise. We tend to think 2 l of fluid and then start a vasopressor, while we almost guess about adding inotropic support. It does not match a dynamic pulsating cardiovascular system, but is necessary when there is limited data. Unlike vascular catheters, echo allows the physician to see blood flow throughout the whole system, and as a result think more holistically. Perhaps the 21-year-old patient with traumatic shock needs blood *and* a vasopressor, or the 80-year-old with pneumonia needs fluid, inotropic support *and* a vasoconstrictor. Echo interpreted hemodynamically allows for a dynamic thinking process that better matches the true physiology of the patient.

In comparison to a standard TTE, the FREE is functionally rather than anatomically interpreted. It takes into account clinical measurements including the patient's mean arterial blood pressure and body surface area. In addition the primary concern facing the patient is identified as either (1) end organ hypo-perfusion (EOH) or (2) respiratory failure (RF). The primary concern and the hemodynamic profiles (discussed below) are used in conjunction to drive an algorithm, which generate echo-based treatment recommendations. The RF arm tends to fluid conservative while the EOH arm tends to fluid liberal.

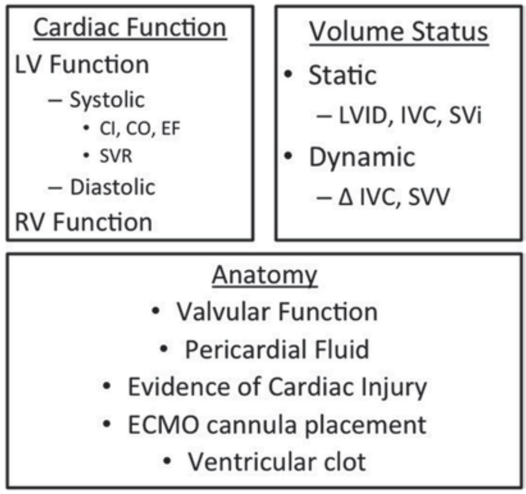


Fig. 3.14 The focused rapid echocardiographic evaluation (*FREE*) measurements. The *FREE* assess hemodynamics in three ways: cardiac function, volume status and anatomy. *CI*, cardiac index; *CO*, cardiac output; *EF*, ejection fraction; *RV*, right ventricle; *LVID*, left ventricular end diastolic dimension; *IVC*, inferior vena cava diameter; *SVi*, stroke volume index; *ΔIVC*, IVC diameter change with respiration; *SVV*, stroke volume variation with respiration

The major sections in the FREE are; Cardiac Function, Volume Status, Vascular Resistance and Anatomy (Fig. 3.14). Using the assessments and measurements patients are categorized into one of four hemodynamic profiles. The profiles are: Normal x 3, Vasodilated/High Output, Hummingbird, and Dysfunctional (Fig. 3.15). If the patient is in shock, the type of shock—hypovolemic, vasodialted, cardiogenic or mixed—can be determined.

The profiles allow for the data to intuitively and holistically interpreted. For example, a Normal × 3 heart is one that has a normal EF and cardiac output, and still appears volume responsive, with a normal peripheral resistance. If the primary issue facing the patient is EOH, then fluid makes sense. If it is respiratory failure then diuresis is reasonable. Conversely, if the patient is placed in the Hummingbird category then by definition the heart is under-filled, the stroke volume is low and the heart rate is high. The combination of low stroke volume and high heart rate place the patient at risk for myocardial stress, so for both EOH and RF the recommendation is fluid. If the physiology is Vasodilated/High Output then vasoconstrictors are a consideration, with or without fluid depending on the volume status of the patient. Finally in the Dysfunctional category inotropic support is major consideration, and fluid is managed more judiciously.

The FREE is just one way of organizing the extensive and potentially important data that can be gleaned from more advanced cardiac imaging. The ultimate form that hemodynamic echo will take has yet to fully be determined, but it has the potential to fundamentally change and improve how we think about resuscitation.

Transesphogeal Echocardiography

Performing an interpreting TEE after learning TTE is a bit like standing on one's head, because the heart is being imaged from behind. Fortunately because the crystal in the transducer can be rotated 180° in two planes almost identical

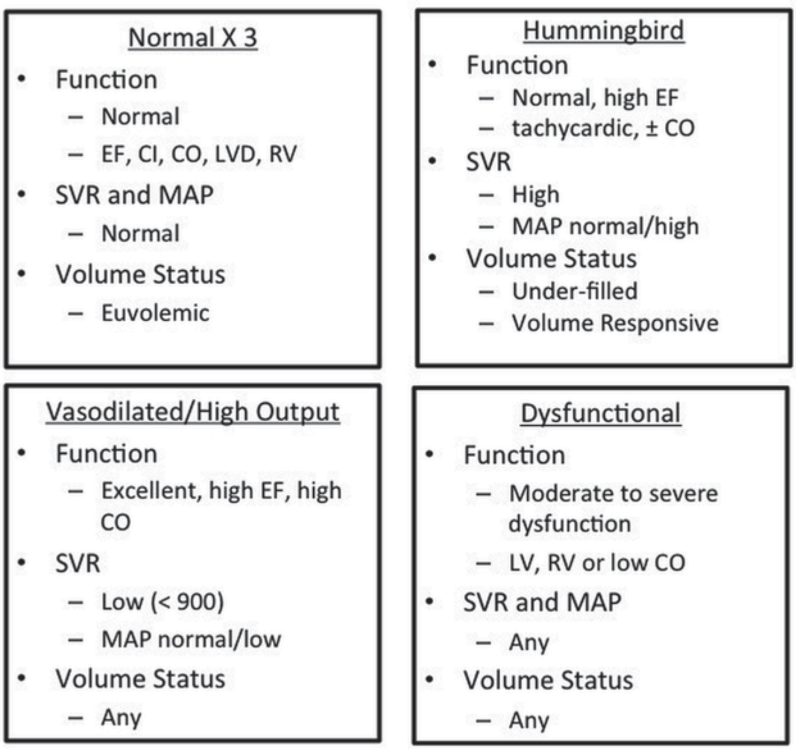


Fig. 3.15 The focused rapid echocardiographic evaluation (*FREE*) profiles. In order to better understand physiology and generate consistent treatment recommendations, the *FREE* combines clinical information including the mean arterial blood pressure (*MAP*) and heart rate to create hemodynamic profiles. *EF*, ejection fraction; *CI*, cardiac index; *CO*, cardiac output; *LVD*, left ventricular diastolic function; *RV*, RV function; *SVR*, systemic vascular resistance

windows can be obtained. Not everything is better imaged by TEE, but more posterior structures like the aorta are much better evaluated from these windows. Furthermore in 5 to 10% of surgical ICU patients cannot be imaged with TTE due to subcutaneous air, surgical incisions or body habitus [4]. Additionally TEE images are beautiful, because the higher frequency probe allows for very resolved images. Expertise with TEE takes time and training. The sections below summarize the basic concepts and images of a standard TEE exam.

TEE the Planes

With TTE the transducer can be rotated, rocked or fanned on the thorax to obtain images on the axis of the heart. These maneuvers cannot be performed form within the esophagus. Instead the crystal in the transducer can be rotated 180° in two planes; longitudinal and vertical. By convention, 0° is transverse orientation, producing a cross sectional image of the heart, and 90° is horizontal orientation, producing a longitudinal image of the heart (Fig. 3.16) [26]. The image obtained at 180° is the mirror opposite of that obtained at 0°. The orientation is the crystal to the transducer, which is in the esophagus. Of course the heart is not completely perpendicular to the esophagus so at 0 and 90° the anatomy will be off the axis to the heart itself. However by rotating the crystal, on axis images can be obtained. The degree of rotation is shown by the icon at the bottom of the display screen (Fig. 3.17).

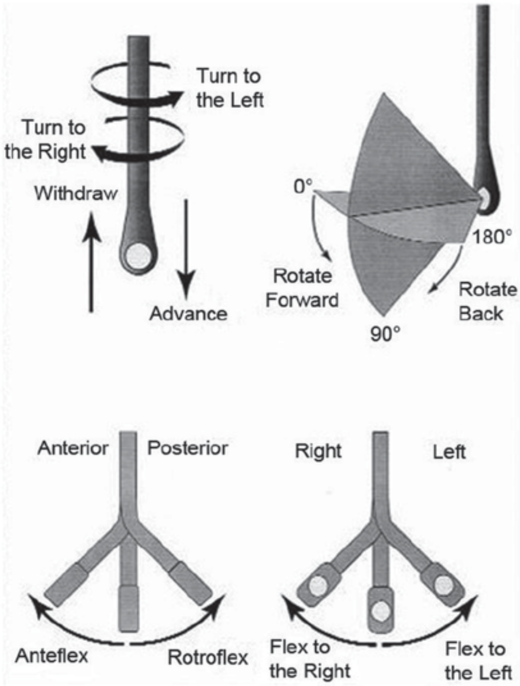


Fig. 3.16 Probe with planes. Reprinted with permission from Shansewise J, Cheung A, Aronson S et al. ASE/SCA Guidelines for Performing a Comprehensive Intraoperative Multiplane Transesophageal Echocardiography Examination: Recommendations of the American Society of Echocardiography Council for Intraoperative Echocardiography and the Society of Cardiovascular Anesthesiologists Task Force for Certification in Perioperative Transesophageal Echocardiography. Anesth Analg 1999; 89 (4)

The American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists have developed a standard basic examination for TEE [27]. This exam incorporates standard views that illicit general etiology and pathology. The 11 views are obtained from either the mid-esophagus or the gastrum. By rotating the mutlitplane crystal from 0 to 180°, and flexing the transducer tip, the heart can be thoroughly interrogated along its transverse and longitudinal axis.

The standard exam is described in detail below, but in summary the transducer is placed into the mid-esophagus, with the tip at neutral and the crystal at 0°. From this window the 4-chamber mid-esophageal view is obtained. By rotating the transducer, retroflexing the tip and angling the crystal, the base of the heart is fully examined, including excellent visualization of the aortic and mitral valves. The transducer is advanced into the stomach and the tip retroflexed to gain short and long axis views of the ventricles from the apex of the heart. The transducer is withdrawn from the esophagus and the descending aorta is fully examined (Fig. 3.18).

TEE Exams

The TEE probe can be performed in either awake or intubated patients. Non-intubated, awake patients should have an empty stomach prior to the exam. Placing the patient in the left lateral decubitus position can make transducer insertion easier. Conscious sedation is administered, and the oropharynx should be anesthetized with a topical anesthetic. A bite block is inserted to protect the patient's teeth and the TEE probe. Ultrasound gel is applied to the transducer to minimize air that would degrade the quality of the pictures. The probe should be unlocked so it can move freely along the pharynx. When the probe is at the glottis opening the patient is instructed to swallow to allow passage through the glottic opening to the esophagus.

In the intubated patient an orogastric tube is inserted into the stomach, suction is applied and the tube is removed prior to probe placement. Neuromuscular blockade often aids with the placement of the probe. The TEE probe is gently inserted midline in the oropharynx and a jaw lift is performed to anteriorly displace the mandible and the tongue. The probe is guided along the pharynx and into the esophagus. If insertion is difficult a laryngoscope can be used to visualize the glottis opening and assist in placing the probe. Excessive force should be avoided and on rare occasions the TEE probe cannot be passed into the esophagus. In this case the TEE exam is aborted.

Once inserted into the esophagus the transducer can be manipulated in many ways. The entire probe can be advanced and withdrawn or turned right and left. The larger knob on the handle of the probe allows the end of the probe to anteflex and retroflex. The smaller knob flexes the end of the probe right and left. Finally, the two buttons on the handle control the multi-plane crystal, which rotates its angle in the transducer from 0 to 180°. Manipulation of the multi-plane crystal allows scanning through the entire heart, provided the heart is kept in center of the transducer [27].

The first view normally obtained after insertion is the mid-esophageal four-chamber view (ME 4-chamber). In this view the atria, ventricles, the mitral and the tricuspid valves are visible. This view is analogous to the AP 4-chamber view in TTE (see Fig. 3.17). The LV septum, which is supplied by the left anterior descending artery (LAD), and the LV free wall, supplied by the circumflex can be interrogated in this view for regional wall dysfunction indicating myocardial ischemia. In addition the LV EF, RV function and volume status can be evaluated.

The second ME view is obtained by keeping the left atrium and ventricle in the middle of the image and rotating the multi-plane 80 to 100°, yielding the ME two-chamber view of the LV (ME 2-chamber). The mitral valve, left atrium, left atrial appendage and left ventricle are visible in this view (see Fig. 3.18). In addition, the LAD and right coronary artery (RCA) distributions can be evaluated for hypo-perfusion and ischemia. The third ME view is obtained by continued rotation of the multi-plane to between 120 and 160°. This maneuver will produce the ME long axis view (ME LAX) of the LV. The mitral valve, left atrium and ventricle, aortic valve, left ventricular outflow tract (LVOT) and proximal ascending aorta are visualized. This view provides excellent visualization of the aortic valve and proximal aorta.

The ME ascending aortic long axis view is found by slowly pulling the probe back from the ME LAX LV view, to image the aorta from above. This view allows the right pulmonary artery and the ascending aorta to be seen (ME AA). Counterclockwise rotation of the probe results in the main pulmonary artery and the pulmonic valve coming into view.

Rotating the multi-plane back to between 20 and 40° brings the ME ascending aorta on its short axis (ME ascending aorta SAX) into view. The superior vena cava, pulmonary valve, main pulmonary artery and proximal ascending aorta are visualized. As the probe is advanced the ME aortic valve short axis (ME AV SAX) view is visualized. In this view the leaflets of the aortic valve can be examined and the right ventricular outflow tract (RVOT) can be seen. It is analogous

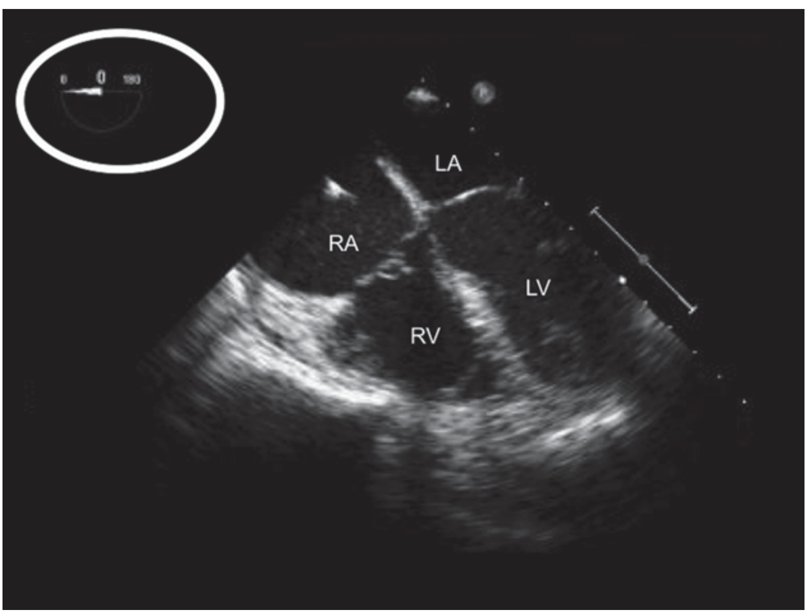


Fig. 3.17 Transesophageal mid-esophageal (*ME*) 4-chamber: The first imaged obtained in most *TEE* is the *ME* 4-chamber. Note that the multiplainer crystal is oriented in the neutral position (depicted in the *white oval*)

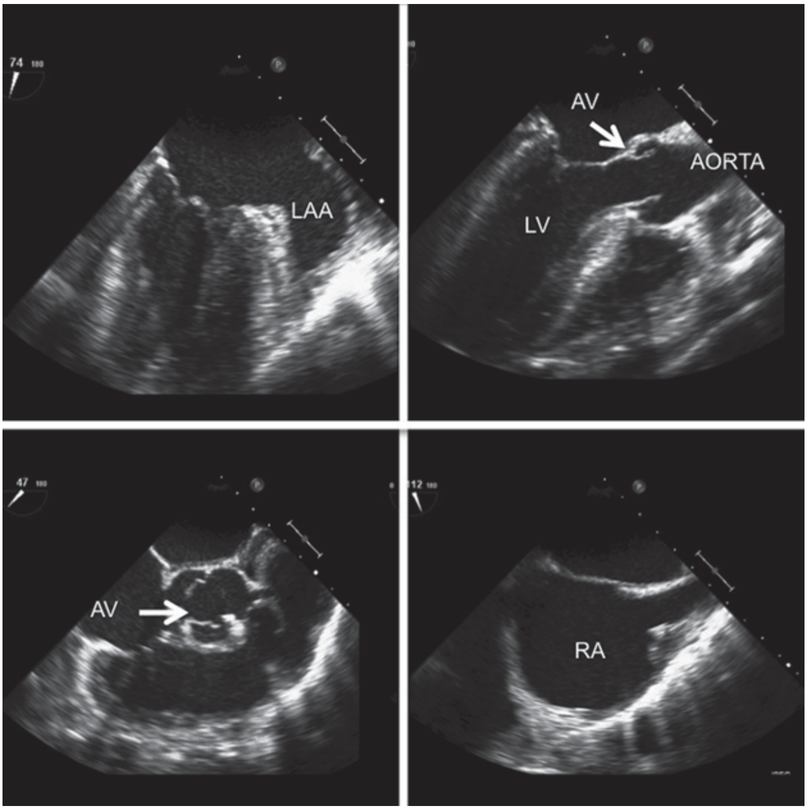


Fig. 3.18 TEE selected windows. Presented are selected views from a TEE. The upper images are from the mid-esophagus, and the lower views are obtained from the gastrum. Note the beautifully imaged left atrial appendage (*LAA*) in the *upper left corner*. The aortic valve (*AV*) and the aorta itself are also much better seen with *TEE*. *LV*, left ventricle; *RA*, right atrium

to the aortic window of the parasternal short axis view on TTE, but provides much better visualization of the RVOT. Clockwise rotation and advancement of the probe brings the tricuspid valve into view. Rotating the multi-plane angle to 60 between 90° will display the ME right ventricle inflow-outflow track (ME RV inflow-outflow). In this image the atria, the tricuspid and pulmonary valves, the RV, and the main pulmonary artery (PA) are seen. The ME RV inflow-outflow view allows through examination of the RV and PA.

As the multi-plane is manipulated to between 90 and 110°, the probe is turned counter-clockwise to obtain the ME bi-caval view (ME bi-caval). The superior vena cava, on the right side of the screen and the inferior vena cava on the left side of the screen can be seen emptying into the right atrium (see Fig. 3.18)

After returning to the ME 4-chamber view, which requires returning the probe tip to neutral and the multi-plane crystal to 0°, the probe can be advanced into the stomach and ante-flexed to look back onto the heart. This will produce the transgastric short axis view, because with the crystal at 0° a horizontal plane is obtained (see Fig. 3.18). In this view all coronary artery supplies are seen, volume can be easily assessed and the presence of a pericardial effusion can be elicited. Withdrawing the probe slightly will bring the ventricular side of the mitral valve into view. Advancing the probe will show the apex of the ventricle. These views are analogous to the parasternal short axis views of the same structures from above with TTE.

To finish the exam everything is returned to neutral and the probe is pulled back to the ME 4-chamber view in order to image the descending aortic short axis and long axis view. The entire probe rotated to the patients left. The short axis of the descending aorta will be seen as the multi-plane crystal is still at 0° as it is rotated to 90° the entire descending aorta can be seen (see Fig. 3.18). Aortic atherosclerosis and the presence of dissection can be evaluated with these views. Withdrawing the probe while maintaining the aorta in the middle of the image shows the descending aorta to the aortic arch. A left pleural effusion may also be seen in these views. The probe is then removed from the patient.

Safety Concerns

There are relative few safety concerns related directly to TTE or TEE. In general all ultrasound imaging should be performed at the lowest power to obtain adequate images. In addition if the transducers and probes are not adequately cleaned they can serve as a vector for disease. TEE carries with it a risk of esophageal perforation, and it is uncomfortable for an awake patient.

Adequate training is essential and quality assurance and a systematic method of storing images and reports is necessary at any high-volume center. The reality is that, regardless of any guidelines, focused ultrasound is practiced in the modern critical care and the emergency setting. With limited exposure and experience, it becomes apparent that images are easily obtainable, and there is no detrimental consequence to the patient. There are, however, no universally standardized procedures for QA, equipment, clinical applications, or training (outside of the cardiology field). Even so, if one accepts that the data obtained are accurate, there is essentially no downside to the FoCUS exam, further data needs to be collected about more advanced imaging.

Future Directions

One of the primary short falls of echocardiography has been that it is intermittent. Now there is miniaturized TEE probe available that be left in place for several hours, providing high-quality continuous images of the 4-Chamber ME or transgastric views [28, 29]. The ability to continually monitor volume status and function during resuscitation may prove to be very important in complex patients. Indeed it has already been shown to help predict who can be successfully weaned from veno-arterial extracorporeal membrane oxygenation [28].

But the most important changes in point-of-care ultrasound are coming from the other end of the technological spectrum. Because it is portable, relatively inexpensive and can provide real-time imaging ultrasound has important applications in under-resourced and remote areas. The World Health Organization has stated that plain x-ray and ultrasound meet approximately two-thirds of the world's imaging needs in the developing countries without access to other imaging [30]. Because ultrasound can rapidly be taught to a variety of providers, it has the potential to fundamentally changing the quality of medical care in the developing world.

Summary and Recommendations

- Performing an echocardiogram is more difficult that imaging an static organ. The heart is in constant movement.
- Obtain practice on healthy individuals before trusting your results in patients.
- A local expert can be of help in providing feedback regarding scanning techniques and image interpretation.
- When performing cardiac ultrasound, critical care physicians should focus on clinical applications. Cardiac ultrasound can provide vital information that can help guide therapy, especially in the hypotensive patient.
- If one is not able to obtain measurements, start with a binary exam to evaluate for global cardiac function, volume status and pericardial effusion. This would at least provide an assessment of causes for hypotension in the declining patient
- When scanning the chest, small movements in your hand result in large movements in the screen. Patience and delicate movements are the keys to a good cardiac image.

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4 Vascular Ultrasound in the Critically Ill

Shea C. Gregg MD and Kristin L. Gregg MD RDMS

Introduction

Over the past two decades, the use of ultrasound has become more ubiquitous in intensive care units (ICUs) around the world. One of its most beneficial contributions to the bedside care of these patients comes from its ability to visualize vascular anatomy. As technology has become more operator-friendly and economical, tissue resolution has also improved, allowing vascular structures of all sizes to be clearly evaluated and interrogated in real-time. Two indications that have been studied extensively in the ultrasound-focused literature include the diagnosis of deep venous thrombosis (DVT) and the placement of vascular access. Once the observation of unilateral lower-extremity swelling is made, confirming the diagnosis of DVT by means of invasive venogram has since been replaced by ultrasound examination. In regards to access-based procedures, reliance on superficial landmarks and direct visualization of vessels remains important to the process of cannulating vessels, however, ultrasound guidance has improved cannulation success rates among all levels of practitioners and trainees. This chapter analyzes the data surrounding these common practices and makes recommendations on how best to incorporate ultrasound into daily practice.

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S. C. Gregg MD (✉)
Department of Surgery, Bridgeport Hospital, 267 Grant Street, Perry 3, Bridgeport, CT 06610, USA
e-mail: striamed1@gmail.com

K. L. Gregg MD
Department of Emergency Medicine, Bridgeport Hospital, 267 Grant Street, Bridgeport, CT 06610, USA
e-mail: kalynch2001@yahoo.com

Anatomy

In order to be successful in vascular ultrasound, one needs a comprehensive understanding of the venous and arterial anatomy of the body. In Fig. 4.1, a schematic drawing highlights the vessels that are typically interrogated by bedside ultrasound for the purposes of either thrombosis determination or vascular access. In Fig. 4.2, sonographic views are shown in short-axis orientation of the particular target vessel(s). It is worthwhile to perform ultrasound on the anatomy of healthy individuals to understand the course and attributes of non-pathologic vasculature prior to performing any invasive procedures or making clinical judgments.

Venous Thromboembolism

Venous thromboembolism (VTE) represents a spectrum of disease, including both deep venous thrombosis (DVT) and pulmonary embolism (PE). DVT may present in the distal calf veins or more proximally involving the popliteal, femoral, or iliac veins. Clinical sequelae of DVT

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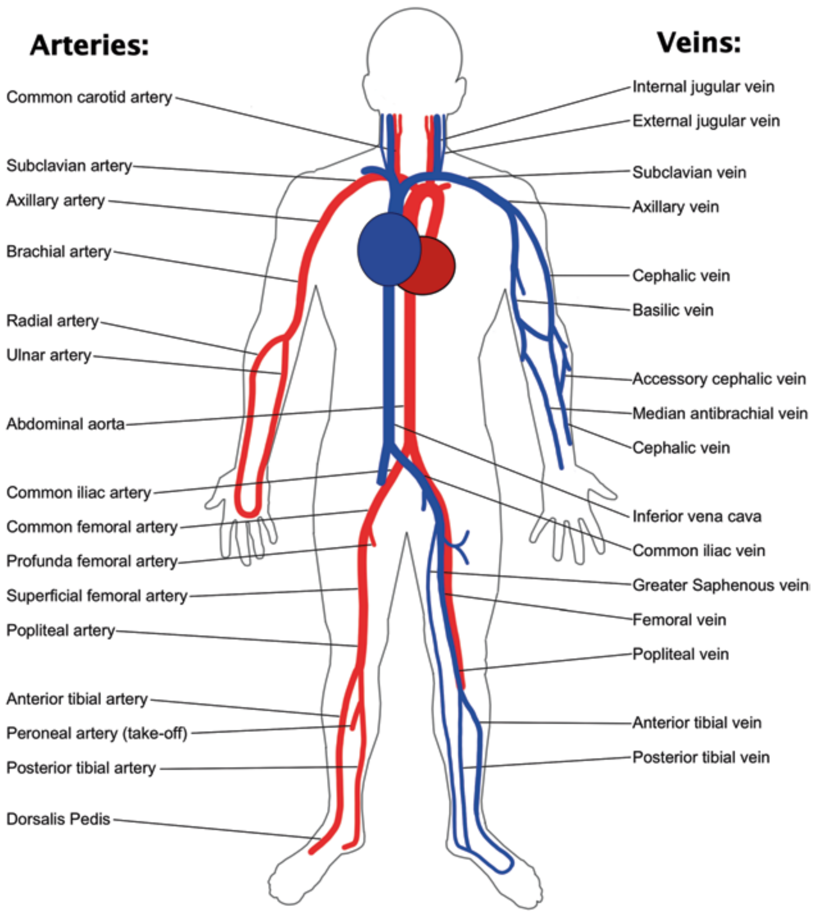

Fig. 4.1 Vascular anatomy that is typically interrogated in bedside vascular ultrasound

include: recurrence, post-thrombophlebitic syndrome, and chronic venous insufficiency. The most serious consequence of DVT is pulmonary embolism. It is estimated that over 90% of cases of pulmonary embolism, emanate from the lower extremity veins [1, 2].

VTE is a common, yet often under recognized problem in the critically ill patient. These patients may have multiple risk factors for VTE that may be inherent, acquired, and/or treatment related. Rates of DVT in different ICU populations range from 10% to up to 80% and PE has been shown to be responsible for up to 15% of in-hospital deaths [2–4]. Despite the increased incidence, DVT remains a challenge to diagnose in the critically ill. Clinical signs and symptoms of DVT may be absent or difficult to obtain in a sedated, mechanically ventilated patient. In the ICU population, studies have shown anywhere from 10 to 100% of cases of DVT were clinically silent [4].

Diagnostic testing for DVT in the critically ill has its own challenges. Traditionally, clinical decision rules have embraced the use of d-dimer to determine the need for further diagnostic workup [5] Unfortunately, the use of highly sensitive d-dimer testing and traditional clinical prediction have been proven to not play a role in the ICU population [6, 7]. Contrast venography has long been considered the gold standard for diagnosis of DVT, however, this modality is technician–dependent, requires transport of potentially unstable patients, and maintains the risk of contrast-induced nephropathy [7]. Radiologist performed Duplex sonography of the lower extremities has been shown to be highly accurate for DVT in the general population with

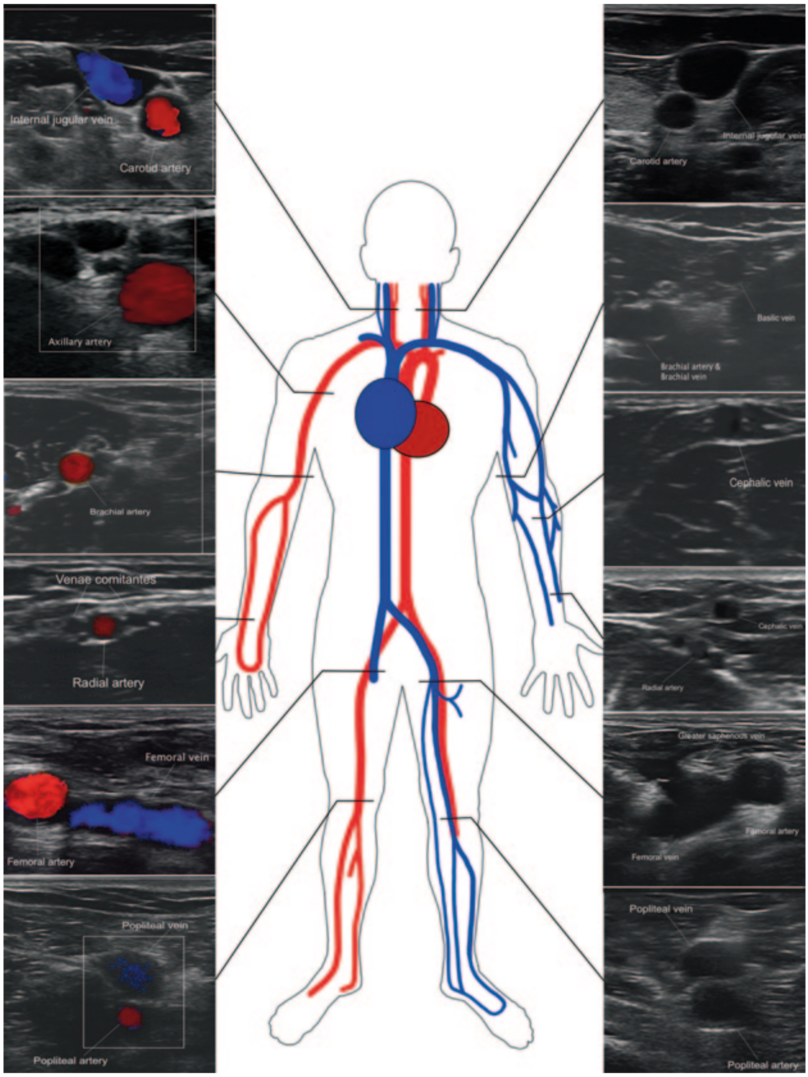

Fig. 4.2 Short-axis views of vascular anatomy typically interrogated in bedside vascular ultrasound

sensitivities ranging from 88 to 100 % and specificities from 92 to 100 % [8]. Similar to contrast venography, these studies are technician and radiologist dependent and may be difficult to obtain in a timely fashion.

There is evidence in the critical care and emergency medicine literature that clinician performed focused vascular ultrasound of the lower extremity is comparably accurate with reported sensitivities of 86 to 95 % and specificities of >95 % [9–11]. The American College of Chest Physicians and the American College of Emergency Physicians recommend focused vascular ultrasound in their training curriculum [12, 13]. Furthermore, clinician-performed lower extremity ultrasound is rapid, reproducible and not technician-dependent which promotes rapid diagnosis and treatment of DVT.

History

The three general conditions for clot formation: stasis, hypercoagulability, and endothelial damage, were first noted in 1856 by a German physician, Rudolph Virchow. Virchow made the observation that clots found in the lungs on autopsy traveled from distant veins in the leg and coined these clots 'embolia' [14]. In his experiments, Virchow injected foreign bodies in the jugular veins of dogs to mimic clot traveling from the leg. Post-mortem, the foreign body was found encased in thrombus formed in-situ in the lung. Virchow theorized that the clot formed as a consequence of the foreign body, which caused: 'irritation of the vessel', 'blood coagulation', and 'interruption of the blood stream' [14].

It was not until late in the last century that these three factors were independently shown to cause thrombosis. Wound studies from World War I provided evidence that endothelial damage lead to thrombosis. Studies in the 1960s linked prolonged bed rest and stasis to the development of thrombosis. In 1965, the first inherited thrombophilia, anti-thrombin deficiency, was discovered [14]. It is controversial whether Virchow truly discovered the theory of thrombogenesis, however, his early observations have been acknowledged by numerous investigators and thus his triad stands today.

DVT in the ICU Population

The risk factors for VTE have expanded significantly from the original triad. ICU patients often present with known risk factors for VTE and may acquire more risk factors during the course of their stay. The most significant inherent patient risk factors are prior history of VTE and malignancy [15]. Mechanical ventilation is considered a risk factor for DVT due to diminished venous return from the heart as a consequence of positive pressure ventilation [15, 16]. Central venous catheters are a known cause of DVT with the relative risk increasing by 1.04 each catheter day [15, 16]. Surgical procedures with the highest rates of DVT include neurosurgical procedures and major orthopedic surgery of hip and knee [16, 17]. Rates of DVT post hip surgery or spinal cord surgery without prophylaxis have been reported to be as high as 50 and 90 %, respectively [16]. Finally, transfusions (especially platelets) and the administration of tranexamic acid are independent risk factors for DVT [3, 18].

Pathophysiology

The majority of lower extremity DVTs initiate in the lower extremity veins of the calf, specifically behind a valve in the soleal sinuses [19, 20]. These sinuses are a storage area for blood and feed the posterior tibial and peroneal veins. In the absence of calf muscle contraction, blood stasis occurs which leads to clot formation. It has been estimated that 40 % of these clots will spontaneously resolve, 40 % will organize into a stable clot, 20 % will propagate to the proximal lower extremity system, and a negligible amount will become pulmonary emboli [21]. About 80 % of calf vein clots are asymptomatic and these tend to occur most frequently in post-operative or immobilized patients [21].

Evidence has shown that compression ultrasound (CUS) without Doppler is sensitive and specific enough to exclude proximal DVT and it has become the first line test for diagnosing DVT [21, 22]. However, there remains controversy over how much of the lower venous system to scan. Crisp et al. advocate a rapid two-point compression US of the common femoral vein/saphenous junction and popliteal vein that has been shown to be 100 % sensitive for DVT above the knee [23]. Of note, these studies were done in symptomatic patients in a predominantly ambulatory setting. This limited approach has been shown not adequate enough for the critically ill, and it is recommended that imaging in the femoral region include a more comprehensive evaluation of the superficial femoral vein [12].

Some vascular labs routinely perform comprehensive evaluation of the lower extremity from the common femoral vein through the calf veins. CUS of the calf veins is more technically challenging, requires more training, and adds to the examination time [20]. In addition, sensitivity of CUS for calf vein thrombus has been reported at 60 to 80 % [7, 8]. Given this low sensitivity in the setting of a high-risk ICU population, a reasonable approach would be to perform serial CUS on days 3, 5, and 7 [24].This would potentially document any calf vein thrombus that subsequently organized and migrated to the upper leg veins.

Compression Ultrasound Technique

A high frequency, 5- to 10-MHz linear array probe is typically used. The obese patient may require use of the 2- to 5-MHz curvilinear probe for greater penetration. The patient should be supine in a reverse Trendelenburg position if clinically permissible to optimize venous return. Externally rotating the hip with the knee in flexion will facilitate compression in the inguinal region (Fig. 4.3).

Gel is applied to half of the transducer to confirm the location of the indicator in relation to the patient's right side (Fig. 4.4). Once confirmed,

Fig. 4.3 Proper patient positioning for a lower extremity DVT ultrasound exam

Fig. 4.4 Gel placed on half probe to confirm sidedness of study with patient and ultrasound machine

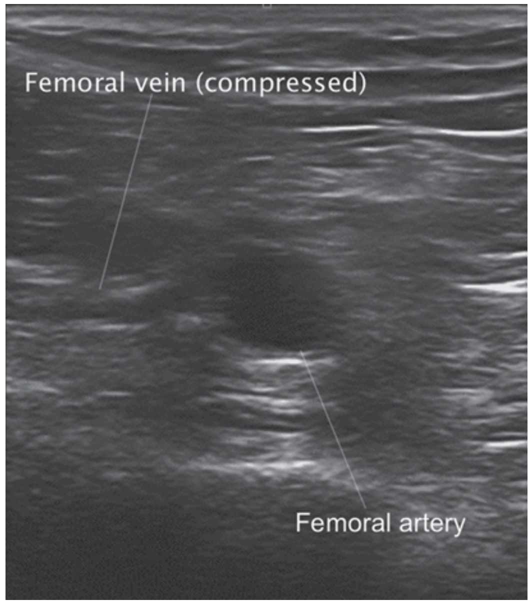

Fig. 4.5 Short-axis view showing compression of femoral vein

the probe is covered with gel and applied in a transverse orientation to the inner aspect of the patient's thigh slightly below the inguinal ligament. The common femoral vein and distally its confluence with the great saphenous vein will be appreciated medial to the femoral artery (see Fig. 4.2). The depth and focus on the ultrasound machine should be adjusted to optimize this view.

The lumen of the vein should be assessed for the presence of any haziness suggesting the presence of clot. If absent, graded compression should be applied externally to the thigh until the walls of the vein coapt and obliterate the lumen (Fig. 4.5). Lack of full compression is indicative of clot. The amount of compression needed to fully compress a patent vein may vary from patient to patient. In general, pressure which causes bending of the femoral artery should be sufficient for full venous compression.

The probe is moved in transverse orientation down the inner thigh, compressing every 1–2 cm until the common femoral vein divides to form the femoral vein and the deep femoral vein. Graded external compression is applied in this area as well in 1- to 2-cm increments until the femoral vein passes into the adductor canal

Table 4.1 Tips for maximizing success when performing ultrasound for DVT

Proper patient positioning:
Hip externally rotated and knee flexed
Support patient appropriately with pillows and/or blankets
Consider reverse Trendelenburg if clinically acceptable
Adjust height of bed or ultrasound machine to optimize operator ergonomics
Appropriate probe selection for patient:
High-frequency linear probe for non-obese patients
Low-frequency curvilinear probe for adequate compression and penetration in obese patients
Adjust depth and focus to maximize area of interest
Compression:
Begin gently and visualize paired vein and artery prior to compression
Consider Doppler:
Color Doppler may help define anatomy
Spectral Doppler to demonstrate respiratory variation or augmentation

(about two-thirds of the way down the thigh) and is lost to further visualization.

The femoral vein resurfaces as the popliteal vein behind the knee in the popliteal fossa. This area is best visualized with the patient's knee flexed about 45°. The popliteal vein will appear to be superior to the popliteal artery, however this is due to the posterior approach of the ultrasound probe (see Fig. 4.2). Graded compression in this area may be more difficult due to the smaller surface area and the potential instability of the flexed knee (Video 4.1). Supporting the patient with pillows may help stabilize the knee and facilitate scanning (see Table 4.1 for DVT ultrasound performance tips).

Adjunctive Techniques

Technically difficult studies may benefit from the use of Doppler. Color Doppler is useful to confirm anatomy and/or the presence of clot. Pulsatile flow will distinguish the artery from the vein (Video 4.2) and lack of flow may be further evidence of venous clot or a confounding structure such as an abscess, hematoma, or lymph node.

Color Doppler may also used to demonstrate augmentation of the popliteal vein. External compression of the calf muscles will produce an increase in flow in the popliteal vein in the absence of DVT (Video 4.3) or a filling defect representing a DVT. Pulsed-wave Doppler may also be used to demonstrate respiratory variation seen predominantly in the common femoral vein in the absence of DVT (Fig. 4.6). Loss of respiratory variation in the common femoral vein may be suggestive of proximal thrombosis in the iliac vein.

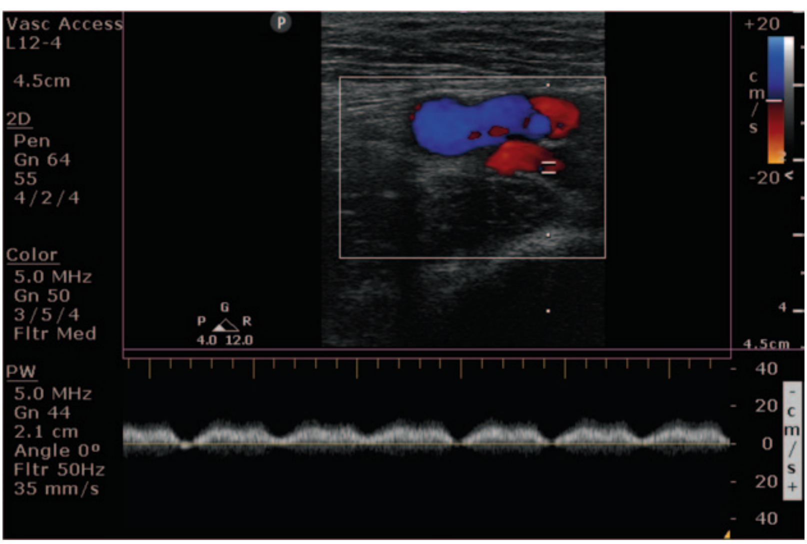

Fig. 4.6 Short-axis view with color-flow Doppler: Respiratory variation of the femoral vein

Upper Extremity DVT

Approximately 10% of all DVTs occur in the upper extremity veins (subclavian, axillary and brachial veins) causing an estimated 7 to 17% of Pes [25, 26]. Upper extremity DVTs are categorized as primary or secondary. Primary DVT may be caused by compression of the vein due anatomic abnormalities of the costoclavicular junction or injury to the vein in the setting of repetitive trauma or strenuous activity [25]. Secondary causes predominate in the ICU and include central venous catheters, malignancy, recent surgery, trauma, or cardiac procedure. Patients presenting with upper extremity DVT are more likely to have had a recent central venous catheter, cardiac procedure, infection, malignancy, or ICU stay [27]. The incidence of upper extremity DVT has increased concurrently with the increased use of central venous catheters particularly peripherally inserted central venous catheters (PICCs) [25–28]. Catheter characteristics which promote clot formation include luminal diameter, number of ports, incorrect tip positioning, and simultaneous infection [25].

Compression ultrasound of the upper extremity poses more challenges for the clinician operator. The anatomy of the upper extremity is more complex than the lower extremity with paired veins both above and below elbow (see Fig. 4.2). In addition, examination of the proximal axillary and mid subclavian vein is complicated by the presence of the clavicle that precludes compression of the vein. In lieu of compression, Color Doppler and spectral waveforms may be needed to demonstrate absence of clot. Flow in the upper extremity will appear biphasic at times due to the proximity of the heart as opposed to the monophasic flow seen in the lower extremities. Loss of biphasic flow in the upper extremity veins seen on spectral Doppler maybe suggestive of clot in the vein. Overall, the negative predictive value of CUS for upper extremity DVT is inferior to CUS for lower extremity DVT andadditional studies such as contrast venography, CT venography, or MR venography should be perused if there is continued clinical suspicion [25].

Pitfalls and Other Findings

Age of the Clot

Clot in the vessel often becomes more echogenic (hyperechoic) with age. However, slow blood flow may be echogenic as well and mimic clot. Use of color Doppler may help to distinguish what may appear to be clot prior to compressing the vessel. If color Doppler is limited due to slow blood flow, augmentation or the use of a tourniquet may enhance color Doppler signal. Acute thrombus is often not visualized at all in the lumen, which is why compression is imperative to make the diagnosis of DVT.

The Eye Does Not See What the Mind Does Not Know

The clinician should be aware of other pathology, which may be visualized during CUS. A Baker's cyst is occasionally visualized in the popliteal fossa. This is a distension of the semimembranosus bursa and will appear as a cystic mass extending into the knee joint. Baker's cysts have well-defined walls and will exhibit posterior acoustic enhancement. Color Doppler will demonstrate absence of flow. Rupture of the cysts will reveal fluid tracking into the subcutaneous tissue of the calf.

Other fluid collections such as abscesses and hematomas will appear to have an irregular shape and varying internal echogenicity with absence of flow with color Doppler. Soft tissue edema is characterized by the classic cobblestoning of the subcutaneous tissue, which may also be seen in the setting of cellulitis.

Point-of-Care Ultrasound as a Screening Tool

More ominous pathologies may be discovered including popliteal aneurysms, tumors, and arterial thrombus. The clinician should have a low threshold to refer any questionable or incidental findings for a formal radiology study.

Limitations of CUS in the ICU

Compression ultrasound of the proximal veins is most sensitive in patients who are symptomatic for DVT. In addition, CUS of the proximal veins precludes diagnosis of calf vein thrombus unless it extends into the popliteal region. Critically ill patients tend to be asymptomatic for DVT and have an elevated incidence of calf vein thrombus. Serial CUS at days 3, 5, and 7 is recommended if the initial study is negative. Finally, CUS may be technically challenging due to patient dressings, casts, limited mobility and patient size. If clinical suspicion is strong enough, alternate imaging such as venography, CT venography, or MR venography should be pursued.

Conclusions

The use of bedside ultrasound to diagnose DVT in critically ill patients is supported by the literature. Because of the body habitus challenges that may be encountered in some of the sickest patients, it is important for clinicians to scan a wide variety of patients regularly in order to understand vessel responsiveness to CUS, Doppler flow, and augmentation maneuver response in both pathologic and non-pathologic situations.

Ultrasound-guided Vascular Access

Adequate vascular access is a cornerstone to the management of a wide range of critical illness states. Given the importance of early resuscitation and restoration of adequate perfusion, the insertion of indwelling vascular catheters must be performed as efficiently as possible. Strategies for approaching this issue have historically relied on either superficial structures and their relation to underlying vascular anatomy or the direct visualization of vessels millimeters below the skin. Although these approaches to access are time-tested, practitioners of ultrasound have since questioned how well the classical methods are in achieving any given access. Overall, the widespread deployment of ultrasound has led an overall improvement in the successful establishment of access in diverse care settings. The following is a review of the modern usage of ultrasound for vascular access in critically ill patients.

Central Venous Catheters

Central venous catheters remain a popular means of vascular access in the intensive care unit. It is estimated that over 5 million central venous catheters are placed yearly in the United States [29]. With ultrasound becoming more widely available, several studies have demonstrated its efficacy, efficiency, and safety which has lead some organizations to advocate for ultrasound-guided technique as the standard of care when placing central venous catheters [30, 31]. Although placement related complications may have been significantly reduced through the use of ultrasound, cannulation of the central veins remain a source for significant infectious morbidity in the intensive care setting [32]. It is estimated that 80,000 bloodstream infections occur yearly which have been shown to not only increase hospital length of stay, but also increased health care costs, and possibly increased risks of death [33, 34]. Given that several indications for central venous access remain absolute (i.e., parenteral nutrition, hemodialysis, central medication administration, and hemodynamic monitoring), the use of central lines continue to be considered an "imperative" in the treatment of critically ill patients.

Two of the most common types of catheters used in the intensive care setting have received a significant amount of focus in the literature: Centrally inserted, non-tunneled central venous catheters, and peripherally inserted central catheters (PICCs). Each have their own particular risk/benefit profiles and may be more or less beneficial to different patient populations.

Centrally Inserted, Non-Tunneled Central Venous Catheters

Although the concept of intravenous access as a means of administering blood and other “medicinal substances” has been known for centuries, the idea of obtaining access into the central venous circulation has only existed since the early 1950s [35]. Aubaniac has been described as the first person who published the method of accessing the subclavian vein for the purposes of resuscitating war victims in 1952 [36]. Shortly after this, descriptions of primary and adjuvant methods of access techniques entered the literature: Seldinger described wire-guided placement of catheters in 1952 [37]. Yoffa described the supraclavicular approach to subclavian access in 1965 [38], and Dudrick et al. described the successful delivery of parenteral nutrition via the central veins of puppies (1966) then humans (1967) [39, 40]. It wasn’t until 1978 when the use of ultrasound, then in the form of Doppler, was used to locate the internal jugular vein for the purpose of guiding central venous catheter placement [41]. In 1986, Yonei et al. reported their experience of using real-time, ultrasound guidance to place internal jugular central venous catheters [42]. In their letter to the editor, these authors reported no complications encountered with internal jugular central line placement over the span of 2 years [42]. Since this report, the use of ultrasound has been explored as a means of improving the safety of central line placement.

When accessing the central veins, several complications have been described when using traditional landmarks as a means of guiding access placement. In the 1970s and 1980s, the incidence of pneumothorax, arterial puncture, and hematomas have been described in 5 to 21 % of patients and unsuccessful cannulation was reported in as many as 35 % of patients [43–46].Since these early reports, practitioners began to ask whether ultrasound would be able to mitigate against the incidence of these complications. By 2003, as reported in a meta-analysis by Hind et al., several studies comparing ultrasound vs. landmark techniques showed fewer failed catheter placements, fewer complications, fewer attempts to successful access and quicker access rates using ultrasound depending on the site of cannulation [47]. Specifically, the internal jugular (IJ) had the most supportive evidence in favor of the superiority of ultrasound-guidance over landmark. As the technology become more available in a variety of care settings, ultrasound continued to repeatedly show its merits in the realm of safety and efficiency of access [48]. As a result, ultrasound-guided central venous access has not only been advocated as the standard of care in ICU settings, but ultrasound education has become an important component of resident training [31].

When placing a non-tunneled, central venous catheter using ultrasound, several techniques have been described to maximize success rates (see Table 4.2 for a summary). First, ideal patient positioning has been extensively studied using ultrasound to measure the diameter of the target vessel. For right subclavian approaches, maximal cross sectional area of the vein has been achieved in healthy subjects in the Trendelenburg position, shoulders neutral, with the head turned away from the proposed area of puncture [49]. For the left subclavian, maximal diameter can be achieved in Trendelenburg position with the head and shoulders neutral [50]. For internal jug-

Table 4.2 Tips for maximizing success in ultrasound-guided central venous access

Use a higher frequency (12 MHz) linear probe with the depth set to 3–6 cm
Position patient appropriately (see text)
Prepare skin with chlorhexadine
Ensure differentiation of venous versus arterial structures through their response to compression; veins should easily compress completely and arteries should remain patent and pulsatile with moderate compression
Ensure location of the tip of the access needle constantly by moving the ultrasound probe in parallel with the advancement of the needle
Following placement of guidewire through puncture catheter, confirm intravenous course of guidewire using ultrasound prior to dilation and catheter placement
Following securement of catheter and lumen flushing, line course and location can be confirmed through ultrasound interrogation of the adjacent veins and through saline flush ± air bubble enhanced echocardiography
Consider pneumothorax or hemothorax evaluation using ultrasound

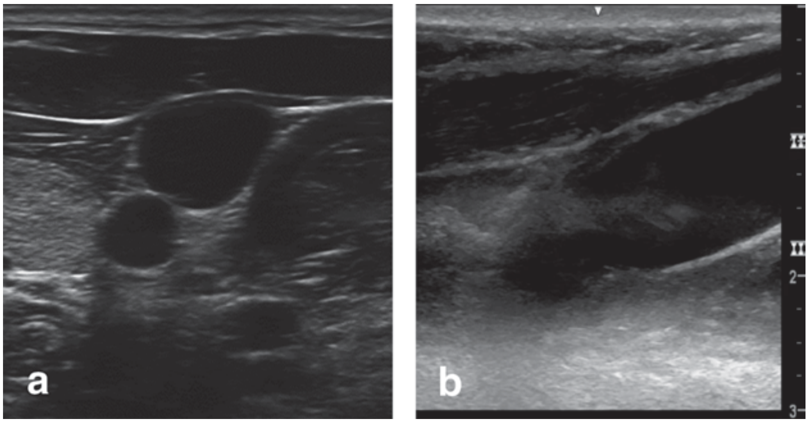

Fig. 4.7 Short-axis view (**a**) and long-axis (**b**) ultrasound views of the internal jugular vein. Images Video by Paul Possenti, PA

ular access, 15° of Trendelenburg, a small head support, and the rotation of the head close or at midline can maximize the diameter of the IJ [51], however, no head rotation has been shown to be as safe as head rotation 45° away from the side of puncture [52]. For femoral access, reverse Trendelenburg can be beneficial to maximizing the vein's diameter [53]. Given that many of these studies were conducted on either healthy subjects and/or patients that were able to give informed consent, these ideals may not be achievable in all clinical settings, however, they can serve as a useful foundation that can be tailored to fit the situation.

How to position the ultrasound probe during central line placement has also been studied. When accessing the vessel, proceduralists can either ultrasound the vessel, remove the probe, and mark the skin at the proposed site of access (the "quick view" approach) or use the ultrasound images to guide the needle directly into the vessel. Airapetian et al. has shown that real-time guidance of internal jugular puncture can have a lower incidence of access related complications and increased success rates as opposed to the "quick view" approach [54]. Additionally, the incidence of catheter bacterial colonization is the same in the two techniques if performed using sterile technique [54]. When imaging a central vein, an operator can guide cannulation by means of a short-axis view (also known as the cross-sectional or transverse view; Fig. 4.7a) or a long-axis view (also known as the longitudinal view; Fig. 4.7b). Tammam et al. has shown that by using either view to guide access, there are fewer complications than standard landmark approaches to the IJ, however, there were no significant differences in access time, success rate, number of attempts, or mechanical complications between the two different ultrasound-guidance views [55]. Taking all this data into account, the authors of this chapter have been successful using the short-axis view and moving the probe to follow the progress of the needle. This allows for real-time imaging of the progression through structures/hazards superficial to the vessel. Regardless of approach, the use of ultrasound provides an added ability to visualize what happens below the surface of the skin that allows for an overall safer experience than relying on superficial features.

The modality to confirm the course and final position of central lines placed above the waist has traditionally been the post-procedural chest radiograph. Complications such as pneumothorax, hemothorax, and aberrant line courses can be readily visualized by this simple bedside study, however, there may be time delays depending on the responsiveness of the radiographer. Since bedside ultrasound has shown efficiency in the placement of central lines, questions have surfaced regarding its use in detecting placement related complications in comparison to chest x-ray (CXR). In one example, inadvertent arterial access and cannulation is a complication that may not be picked up until the abnormal course of the central line is observed on CXR. Gillman et al. have reported that by confirming that the guidewire is not inside the artery, one can ultimately avoid accidental tract dilation and arterial cannulation [56]. As a means of confirming the final course of a line, several studies have described different approaches. Direct visualization of intravenous catheter course can be combined with echo to evaluate whether the tip sits above or within the right atrium [57, 58]. As an adjunct that can enhance either direct or nearby tip visualization, saline injected with or without a small volume of bubbles through the catheter can be visualized on an echocardiographic view of the right atrium [59, 60]. To assess for pneumothorax, ultrasound has been described as a useful tool for diagnosis, however, given the relatively low incidence of pneumothorax following line placement, only a limited experience of its use has been reported [57, 58]. Overall, the bedside diagnosis of a variety of line related complications can be made through the use of ultrasound and taking the time to learn such methods may allow for earlier interventions.

In summary, ever since the 1950s central venous access has become a key component of managing critically ill patients. Placement safety and efficiency can be augmented with ultrasound. Other factors such as ideal patient positioning, probe positioning, and adequate experience can maximize the success of the process while hopefully reducing the incidence of complications.

Peripherally Inserted Central Venous Catheters (PICCs)

PICCs have been used in both the outpatient and inpatient settings. As a device, a PICC maintains the appeal of potentially minimizing patient discomfort while providing a "longer term" access for essential medications. In regards to placement, both nurses and physicians have published reports regarding the successful development of bedside ultrasound guided PICC services throughout the world [61, 62]. Despite their attractiveness, these catheters have been shown to potentially have significant complications when used in critically ill patients. Given that the catheter passes through relatively smaller diameter superficial veins on its way to the larger central venous system, stasis and/or localized damage could occur thus producing thrombosis and/or phlebitis. In one review, the incidence of these two complications among all hospitalized patients may be higher with PICCs as compared to standard central lines [63].Among intensive care patients, similar concerns of thrombotic complications in PICCs are highlighted through several reports [64–66]. Of note, there may be some populations (i.e. burns) that may not have as significant of a problem [67].

When comparing the infectious rates of PICCs to non-cuffed, non-tunneled central venous catheters, the literature is inconsistent. In one study comparing the incidence of PICC infections in ICU to non-ICU patients, there is a statistically significant higher incidence of infections in ICU patients [68]. In contrast, Safdar at al reports an incidence of infection of 2.1 to 3.5 per 1000 catheter days which was comparable to the incidence of infection among standard CVCs reported in the literature [69]. In a different population, Fearonce et al. reported a blood stream infection incidence of 0 per 1000 line days in PICCs versus 6.6 per 1000 line days for central venous catheters in critically burned patients [67]. Finally, Trerotola et al. reported no PICC infections among the 50 patients enrolled in their study of peripherally inserted triple lumen PICCs despite a reported high rate of venous thrombosis [64]. Among such inconsistent results, it becomes clear that a larger prospective trial is needed to truly determine the comparative incidence of blood stream infections among the different devices placed in critically ill patients.

If the determination is made to place a PICC, the patient should be positioned comfortably with the arm outstretched 90-degrees from the torso and appropriate sterile precautions should be followed for skin preparation. A tourniquet is applied and vein identification can be performed using a higher frequency (12 MHz) linear ultrasound probe with the depth set to around 2 cm. Following measurement of the catheter and appropriate anesthesia application, venipuncture is performed and the introducer is inserted into the vein. Following release of the tourniquet, the PICC line is threaded to the correct depth and secured. If resistance is met during the threading process, the PICC line may require removal and a different vein may need to be used. Appropriate sterile dressings are applied and final positioning is confirmed per institutional policy. The lumens are flushed to confirm patency.

Overall, PICCs seem to be a relatively safe means of access in the outpatient setting, however, due to possibly increased thrombotic rates and not clearly defined infection risks, their benefit remains unclear in critically ill patients.

Alternatives to Central Access: Non-Central, Peripheral Intravenous Catheters

Not all patients in the intensive care unit may require central venous access. In the absence of such indications as parenteral nutrition, hemodialysis, central medication administration, and hemodynamic monitoring, care providers should be critical of the need for either ongoing central access or the desire to place a new central venous device. Given their previously described potential morbidity and mortality, every opportunity to remove or avoid a central line should be taken advantage of. One way of achieving this is through the more liberal use of non-central, peripheral intravenous access devices (PIVs). The benefits include infection rates that are potentially lower than central venous lines [70]. Additionally, when infections occur in PIVs, they are typically limited to localized events [71, 72]. The potential problems with PIVs in critically ill patients are twofold. First, Early reports of the incidence of phlebitis among PIVs used in the ICU was as high as 35 % [66]. Given that catheter materials, skin preps, dressings, and insertion techniques (i.e., ultrasound) have evolved since this original report, the phlebitis might not be as common as once encountered [73]. Second, traditional landmark techniques used for PIV placement may not be as successful among critically ill patients with edema, obesity, or thrombosis from previous intravenous access attempts. With ultrasound being used with such high success rates of cannulation in central, arterial, and PICC vessels, questions began to arise regarding how it can improve peripheral venous access when landmark techniques failed.

Several authors have published increased peripheral venous access success rates using ultrasound in different populations outside the ICU. Keyes et al. reported a 91 % success rate in 101 emergency department patients [74]. Constantino et al. showed a 97 % success rate compared to 33 % using landmark techniques among emergency department patients [75]. Additionally, high success rates have been achievable among different types of proceduralists. Blaivas et al. educated emergency department nurses in ultrasound-guided PIV access who then demonstrated an 87 % successful cannulation rate [76]. Aponte et al. reported on increased success rates among nurse anesthetists gaining peripheral access in traditionally difficult patients [77]. Overall, ultrasound has proven to be a superior means of achieving peripheral access in a variety of patients located in diverse hospital settings.

Among ICU patients, data continues to increase on the feasibility and the utility of ultrasound-guided peripheral intravenous lines. In an earlier report, Gregg et al. was able to successfully cannulate 99 % of patients who failed standard landmark techniques by using an ultrasound directed approach [73]. In this study, the majority of requests for an ultrasound-guided attempt was patient edema (95 %), with obesity, intravenous drug history, and emergency access being other reasons. As a result of achieving peripheral access, 34 central lines were avoided and 40 central lines were removed [73]. In a later randomized control trial, Kerforne et al. demonstrated a 73 % ultimate success rate of cannulation using ultrasound as compared to 33 % using landmark techniques [78]. Once again, the majority of their randomized population had edema (77 vs. 80 %) contributing to the challenges of peripheral access [78]. Such reports highlight the fact that when facing the daily challenges produced by

Fig. 4.8 Patient positioning when placing a non-central, ultrasound-guided peripheral intravenous access

complex physiology in critically ill patients, it is possible to entertain peripheral venous access especially when central is not 100 % necessary.

When placing peripheral venous access using ultrasound, it is key to be sitting comfortably with the patient's arm abducted 15 to 3° from their torso (Fig. 4.8). The hand and forearm should be secured in a supinated position by using tape or other means. An elastic tourniquet should be placed high on the proximal bicep and the examination of the venous anatomy should be performed using a higher frequency (12 MHz) linear ultrasound probe with the depth set to around 2 cm. Veins of at least 2-mm diameter are potentially accessible and should be completely compressible to ensure the absence of thrombus within the vein. Given that arterial sticks are described as a complication of US guided PIV access [74, 76]. ensure that the compressed vessel is not pulsatile by partially compressing with the probe and watching for pulsatility on the screen. In terms of access site, the authors have had the most success accessing the veins on the ventral surface of the mid-forearm distal to the antecubital fossa to allow for free arm movement following access placement. Following skin preparation with chlorhexidine, the vein is accessed in the same manor as arteries and central veins: The probe follows the tip of the catheter in a short-axis orientation as the catheter moves through deeper tissues. When the target vein is punctured, a small amount of blood return usually encountered. To enhance success, a wire from a wire-based catheter can be advanced to ensure an intravenous placement. If any resistance is met while the wire is advanced there is a good chance that final advancement of the catheter will either be unsuccessful or the catheter will end up outside of the target vein. If the wire passes smoothly, gently rotate and advance the access catheter over the wire until it seats completely within the vessel. If a guidewire is not used, once a blood return is achieved following venipuncture, guide the tip of the needle into the target vein a couple more millimeters prior to threading the catheter. This will ensure that the edge of the catheter will be intravenous prior to threading and will not get hung up on the edge of the vessel potentially leading to injury or misthreading. Following placement, draw back and flush the IV and finally secure the catheter using standard techniques (see Table 4.3 for a summary of US-guided PIV placement tips).

Table 4.3 Tips for maximizing success in ultrasound-guided vascular access in the arm

Use a higher frequency (12 MHz) linear probe with the depth set to 2–3 cm
Prepare skin with chlorhexadine
Secure hand in a neutral, supinated position using tape or other device
For venous access, veins above the wrist should be ideally used
For arterial access, the radial artery should be accessed slightly proximal to the wrist to reduce "positional" malfunction of the arterial line
Ensure differentiation of venous versus arterial structures through their response to compression. Veins should easily compress completely and arteries should remain patent and pulsatile with moderate compression. If this is not seen, the vessel may be thrombosed
Use an elastic tourniquet to maximize venous diameter
Ensure location of the tip of the access needle constantly by moving the ultrasound probe in parallel with the advancement of the needle
If a guidewire is being used, advance the guidewire once blood return continues to flow into the catheter. If ANY resistance is met, stop and reposition
Successful intraluminal cannulation can be confirmed through the ultrasonographic visualization of turbulent flow following saline flush
Veins of the forearm and upper arm may require longer IV catheters (1.75″ or greater)
Veins 2 mm and greater may accommodate PIV catheters. PICCs may require greater diameter veins

In summary, peripheral intravenous access placed by ultrasound has become a viable option in a variety of populations who could be considered "difficult access candidates." In terms of its safety, placement complications are relatively low, localized infections are more common than systemic, and the potential for phlebitis is at least significant enough to monitor for on a daily basis. Future investigations that focus on the use of ultrasound in placement technique, catheter material, infusates, and site care would be helpful in ultimately determining the true benefits of this access approach.

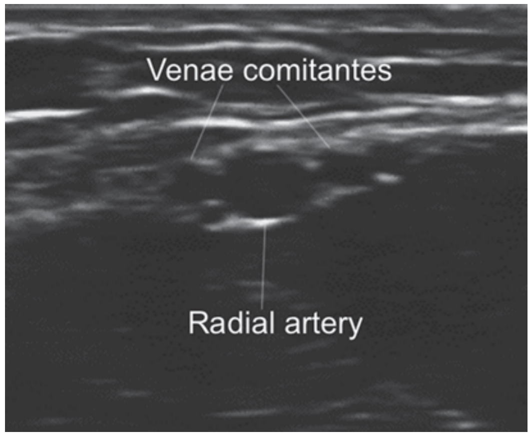

Fig. 4.9 Short-axis view of the radial artery with patent adjacent venae comitantes

Arterial Access

Arterial access catheters are another commonly used access device in critically ill patients. Benefits such as continuous hemodynamic monitoring, blood gas assessment, and the need for frequent blood draws have allowed the "A-line" to become popular as an easily obtainable, safe access device. Unlike central lines, the preferred site used for a-line placement is the radial artery at or near the wrist, however, the femoral, axillary, brachial, and dorsalis pedis arteries can also be used [79]. Despite their widespread use, complications can be associated with up to 13 % of A-lines and multiple attempts of cannulation have been described in 50 to 66 % of patients [79, 80]. Like other access approaches, ultrasound technology has been employed to potentially mitigate placement related complications and improve cannulation success rates.

In 1976, the use of Doppler-based ultrasound was described as a useful adjunct to placing radial a-lines in hypotensive patients [81]. Since then, more mature modes of technology including real-time B-modes have been developed and studied. Levin et al. studied success rates of arterial cannulation by randomizing residents and attendings to ultrasound guided vs. palpation techniques [82]. In their operating room population, the ultrasound approach demonstrated more success, fewer attempts, quicker cannulation times, and fewer numbers of cannulae used [82]. Similar results have been shown by Shiver et al. in emergency department patients with the addition of showing that the use of ultrasound had a lower incidence of localized hematoma [80]. Such results advocate for the regular use of ultrasound in arterial cannulation in hopes of reducing the unnecessary use of devices, maximizing success, and minimizing patient discomfort.

When performing the procedure at the radial artery, a neutral hand position may produce a greater cross-sectional area than dorsiflexion [83]. A variety of techniques including the Allen's test, plethysmography, pulse oximetry, Doppler, and duplex ultrasound have been described to assess collateral flow in the hand and should be considered prior to radial access [84]. Appropriate sterile precautions should be taken and all equipment should be ready to ensure ease of placement. While performing the exam using a higher frequency (12 MHz) linear probe with the depth set to around 2 cm, short-axis visualization of the artery can be obtained with two accompanying venae comitantes as it passes through the wrist (Fig. 4.9). Pre-procedure assessment of the artery should be performed to ensure the artery can be completely compressed yet under partial compression, should remain pulsatile. In addition, this assessment should be performed proximal to the proposed site of cannulation to ensure that the artery is not thrombosed. Following puncture, the tip of the catheter, which appears echogenic on ultrasound, can be directed by moving the probe in sync with passing the catheter to progressively deeper areas. Upon accessing the artery, blood return will typically occur and if a free wire or wire-included catheter is being used, the wire should be advanced without any resistance. The catheter can then be advanced and confirmed to have pulsatile blood return. Following securement of the line, appropriate tubing is connected and dressings are applied. Similar approaches can be used for other sites of arterial access. Ultrasound views of the brachial, axillary, femoral, and dorsalis pedis can be obtained for the purposes of arterial cannulation (see Fig. 4.2).

In summary, arterial access using ultrasound can improve the efficiency and overall success of a procedure that is necessary in managing critically ill patients. Like other vascular access procedures, it should be considered and deployed regularly by proceduralists to maximize these outcomes.

The Future of Ultrasound in Vascular Access: Education and Beyond

In 2010, international experts convened a workgroup that formulated recommendations for the use of ultrasound in vascular access [48]. The final consensus statement was published in 2012 and provided a comprehensive review of the literature with graded recommendations based on the degree of literature support [48]. Through these recommendations, the merits of ultrasound were highlighted in all aspects of pre-placement vessel evaluation, the real-time placement of the access device, and the post-evaluation assessment for complications. With ultrasound having such a promising future and a high likelihood for regular usage in the clinical setting, practitioners must continue to remain critical of the "best way" to use the technology.

The format of modern-day ultrasound-guided vascular access education typically consists of a lecture, a hands-on didactic, and a period of oversight in the clinical setting [3]. The introductory lecture typically includes aspects of the following: an overview of ultrasound physics, how to use an ultrasound machine, a description of target views and how to achieve them, procedural overview, and examples using video and/or models. The hands-on didactic usually will allow students to perform ultrasound examinations and procedures on simulators that range in sophistication from homemade to commercially available [31, 76, 85, 86]. Interestingly, there is not any clear consistency regarding the ideal time duration of the teaching modules or the best hands-on model, with various studies demonstrating increased cannulation success rates regardless of time or type of model [76, 85, 86]. This may partially be attributed to the fact that ultrasound is now used in so many care settings, exposure to it likely occurs earlier in practitioners careers and it is less novel. Going forward, it seems reasonable for educators to offer components of the modern-day educational approach while exposing trainees to ultrasound as part of daily practice. Regardless, consistent assessment of outcomes needs to be a part of the educational process to ensure true learning of skills.

When it comes to technologic components of vascular access, proceduralists should consider the following questions:

1. What are the best catheter designs that can accomplish central, arterial, and peripheral access?
2. Which devices can be maximally visualized sonographically, efficiently placed, cost-effective, and minimize any patient discomfort/complications?
3. What is the best ultrasound technology that is easily usable at the point of care?

Ongoing studies have the ability to guide technology and innovation and it remains our challenge to evaluate and refine the field for the purposes of educating the next group of "international experts."

Conclusions

In every hospital setting, and in diverse patient populations, ultrasound-guidance has enhanced the success of cannulation in central, arterial, and peripheral vascular access. Although its entire impact has yet to be fully defined, ultrasound has already demonstrated a significant contribution to the care we provide our patients in the intensive care setting. Going forward, we must challenge ourselves to innovate and remain

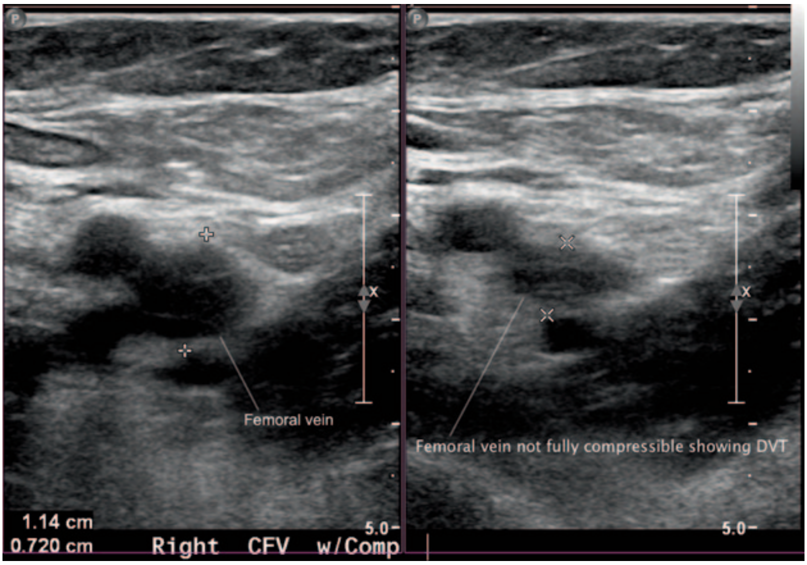

Fig. 4.10 Compression ultrasound exam of the common femoral vein showing DVT

critical of its benefits for our increasingly acute patients.

Cases

Case 1

43-year-old woman with history significant for acute myelogenous leukemia in remission for 5 years presents to the emergency department with dyspnea, and bilateral leg swelling. She has been tachypneic for the past 2 days and has complained of a dry cough. Upon presentation, she is hypoxic to 90% on non-rebreather, and demonstrates bilateral lower extremity edema. A lower extremity ultrasound shows evidence of DVT by CUS (Fig. 4.10). Bedside echo performed shows evidence of right ventricular strain consistent with pulmonary embolism (Video 4.4). The patient was admitted and started on anticoagulation.

Case 2: Ultrasound-guided Vascular Access Through All Aspects of Critical Illness

32-year-old male with distant history of intravenous drug abuse presents in septic shock from complete small bowel obstruction. He recently underwent a right ureteral reconstruction with small intestine interposition for chronic ureteral stenosis. In preparation for the operating room, an ultrasound-guided internal jugular was performed for resuscitation and pressor administration (Fig. 4.11). Upon abdominal exploration, the patient was noted to have an internal hernia that caused ischemia/necrosis of all but approximately 100 cm of small intestine. The patient was resected and managed with an open

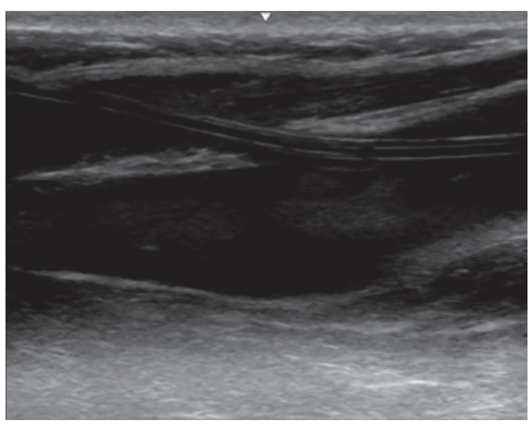

Fig. 4.11 Long-axis view of indwelling right internal jugular triple-lumen catheter. Image Video by Paul Possenti, PA

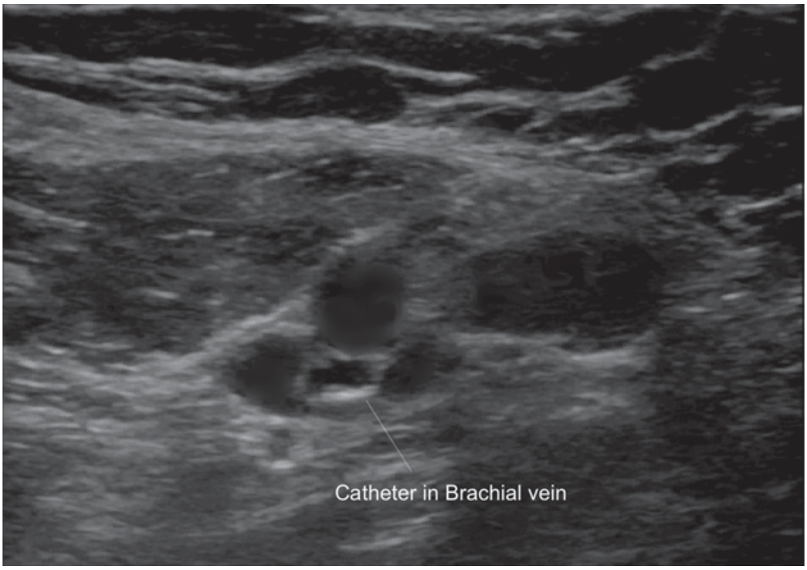

Fig. 4.12 Short-axis view of PICC traveling through brachial vein. Image Video by Paul Possenti, PA

abdomen. He returned for a second look at which time a jejunal-colonic anastomosis was performed. Later on in his course, the patient developed fulminant clostridium difficile colitis with multi-system organ failure. The patient returned to the operating room for a subtotal colectomy and end ileostomy. Post-operatively, the patient recovered but required supplemental parenteral nutrition during his period of intestinal adaptation. He was managed with PICCs throughout this time (Fig. 4.12). Intermittently, the patient would present with evidence of line sepsis, which required PICC line removal and intravenous antibiotics. Given his prolonged hospital course and distant history of intravenous drug use, the patient was a “difficult peripheral access candidate.” Fortunately, PIVs were able to be placed using ultrasound-guidance during these line sepsis periods (Fig. 4.13). After several months, the patient’s ostomy was reversed, he was able to maintain adequate volume status through by mouth intake, and he was weaned off all supplemental parenteral nutrition. He was eventually discharged home with only outpatient nutritional counseling follow-up.

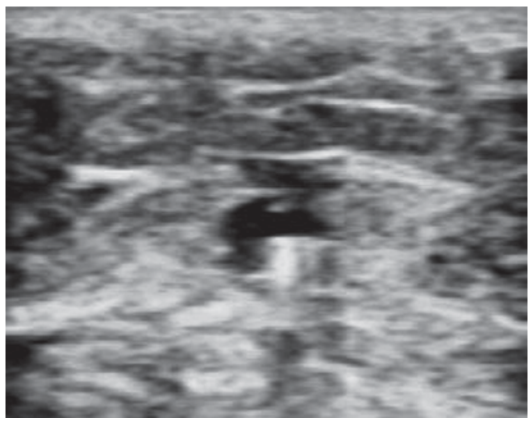

Fig. 4.13 Short-axis view of non-central, peripheral intravenous catheter in cephalic vein of forearm

Video Legends

Video 4.1 Color-flow Doppler showing femoral artery pulsatility.

Video 4.2 Compression of popliteal vein with ultrasound probe.

Video 4.3 Popliteal vein showing augmented flow upon compression of calf muscle.

Video 4.4 Bedside echocardiography showing right ventricular strain in pulmonary embolism.

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Basic Abdominal Ultrasound in the ICU

5

Jamie Jones Coleman, M.D.

Evaluation for Free Fluid

Limited abdominal ultrasound is very useful in the diagnosis of free fluid in critically ill patients. Intra-abdominal fluid in this patient population can represent a variety of etiologies including ascites from parenchymal liver disease, hemoperitoneum, malignancy, tuberculosis, bowel injury, or an intestinal anastomotic leak [1, 2]. Since physical examinations are unreliable due to mechanical ventilation, sedation medications, and prior surgery, ultrasound provides several advantages. Ultrasound is very sensitive in the detection of intra-abdominal fluid, even in amounts as low as 100 mL [3]. In comparison, a physical examination finding of dullness typically isn't produced until the intra-abdominal fluid amount reaches 1500 mL [4]. In addition, because ultrasound is portable, these critically ill patients do not have to be transferred out of the intensive care. Another advantage for the use of ultrasound is the lack of ionizing radiation, which is of particular concern for the critically ill patient who is often subjected to daily chest radiographs and repeated computed tomography scans. The limited exam for free fluid is rapid also and usually able to be completed in under 3 min [5].

The windows utilized to evaluate for free fluid in the abdomen are the same as the abdominal windows used in the focused assessment with sonography for trauma (FAST) exam. The exam is performed using the standard 3.5-MHz curvilinear probe**.** The FAST examination includes visualization of the heart and vena cava in addition to the abdominal windows. The first abdominal view is of Morison's pouch, and obtained by placing the probe in the right mid-axillary line between the 11th and 12th ribs [6]. This view identifies the sagittal section of the liver, kidney and diaphragm. The second window is obtained with the transducer placed in the left posterior axillary line between the ninth and tenth ribs, allowing for visualization of the spleen and kidney [6]. The last view is achieved by positioning the transducer transversely superior to the pubic symphysis, which allows for visualization of the bladder [6] (Fig. 5.1a, b).

How to Perform a FAST

Position

Placing patients in the Trendelenburg position increases the sensitivity of FAST to assess the presence of intra- abdominal fluid.

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J. J. Coleman, M.D. (✉)
Associate Professor of Surgery, Department of Surgery, Division of Trauma and Acute Care Surgery, Indiana University School of Medicine, Indianapolis, IN. USA
e-mail: jcoleman6@iuhealth.org

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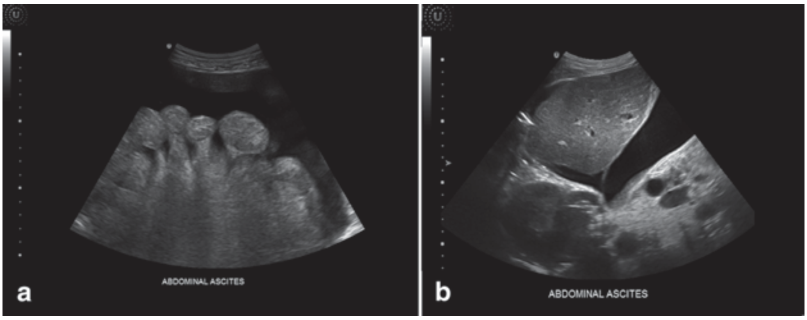

Fig. 5.1 (**a**, **b**) Abdominal ascites

Ultrasound Probe

A probe of a low frequency (1–5 MHz) is used for better penetration of tissues in the abdominal cavity. Either a curvilinear or a phased array probe can be used for this purpose

Evaluation of the Pericardium and the Vena Cava: Subxyphoid Window

- Place the probe in the subxiphoid space probe marker to the right, using the liver as an acoustic window.
- Adjust the depth to allow viewing of the rear of the pericardium.
- This view allows for visualization of the four cardiac chambers and the vena cava (**Video 5.1**).

Evaluation of Hepatorenal Space

- Place the probe in the anterior axillary line at the bottom of the rib cage with the result of the probe head pointing in a coronal plane.
- Move the probe cranially and flow in this or the mid-axillary line until the interface between the liver and kidney is clear.
- Intraperitoneal fluid appears as a hypoechoic or anechoic band (black) in the hepatorenal space (**Video 5.2**).

Evaluation of Splenorenal Space

- Place the probe in the middle or posterior axillary line at the bottom of the rib cage, with the result of the probe facing the head in the coronal plane.
- Note that the left kidney is anatomically positioned higher than the right kidney; therefore, the probe is placed in more cephalic position to see the interface.
- Intraperitoneal fluid appears as a hypoechoic band in black splenorenal interspace, or on top of the spleen in some instances (**Video 5.3**).

Bladder View

- This space should be evaluated in both the longitudinal and transverse plane. Ideally, the bladder is filled to serve as an acoustic window in the space behind the bladder.
- Place the probe above the pubic bone with the probe mark pointing to the right side of the patient and assessing free fluid (it will look like a black line).
- Rotate the probe 90° to the right so that the points of the probe marker toward the head of the assessment in the longitudinal plane (**Video 5.4**).

Abdominal Paracentesis

Abdominal paracentesis in the surgical intensive care unit patient can be both diagnostic and therapeutic. A simple aspiration will often aid in diagnosis as it allows for examination of the quality and character of the fluid. Ultrasound guided paracentesis can be performed in the majority of patients as overall risks are low, and there are no absolute contraindications to this procedure [2]. Risks associated with the procedure are rare but do include: damage to intra-abdominal organs, and rectus sheath hematomas [7]. The placement of nasogastric tubes and Foley catheters aid in

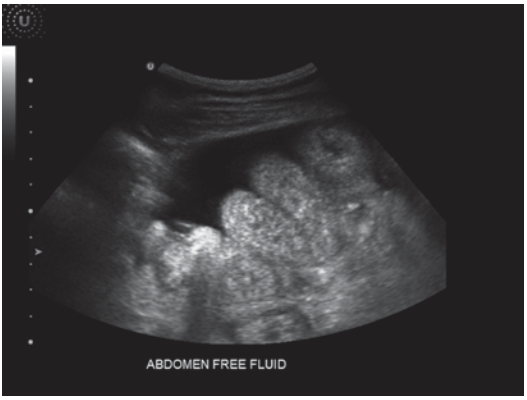

Fig. 5.2 Abdomen free fluid

the prevention of damage to these organs, and blood products should be administered to patients with moderate to severe coagulopathies to reduce rectus sheath hematoma formation [2]. To estimate the amount of fluid present in the abdomen, measure the amount of fluid visible around the intestine. In general, for every 1 cm of fluid visualized approximately 1 L of fluid is present [2] (Fig. 5.2).

To perform an abdominal paracentesis, the patient is first positioned supine and in reverse Trendelenburg to aid in the concentration of the free fluid into the pelvis. A standard abdominal curvilineal 3.5- to 5-MHz transducer is used to then identify the intra-abdominal fluid and visualize any surrounding structures. Typically the bilateral lower quadrants, lateral to the rectus sheath, are the location of choice for this procedure. This avoids the inferior epigastric artery and allows for fluid removal from the more dependent part of the abdomen. In addition, it is important in patients with parenchymal liver disease to be watchful for superficial collateral vessels or varices [7]. The right and left sides are both assessed for the largest amount of fluid present without encroaching bowel. After the site is chosen, the patient is prepped and draped in a sterile fashion, including the ultrasound transducer and local anesthesia obtained. Needle size is often determined by the purpose of the procedure. A smaller needle such as a 22 gauge is adequate when a diagnostic paracentesis is to be performed, as volumes as low as 200 ml are sufficient for laboratory examination [2]. However, if the purpose of the paracentesis is to drain a large quantity of fluid, a larger needle such as an 18 gauge may be more appropriate as it allows faster egress of the ascites. Once the appropriate needle size is chosen, a “Z-tract method” is often recommended for its insertion. This method is described as applying tension to the skin in a caudad fashion during the insertion of the needle, then once the epidermis and dermis are penetrated releasing this pull on the tissue while the needle advances through the muscle and into the peritoneum [2]. The purpose of this method is to prevent leakage of ascites after the paracentesis. Negative pressure is applied to the syringe during the entire advancement of the needle into the peritoneum. In addition, this advancement is visualized with the ultrasound, ensuring that the needle does not get advanced into an intestinal loop. Once the needle is safely in the peritoneal cavity, fluid is either aspirated for diagnosis or drained for therapy. In order to safely drain large amounts of fluid, it is recommended that a catheter be placed into the peritoneum utilizing the Seldinger technique [8].

Patients in the surgical intensive unit can develop intra-abdominal abscesses for a variety of reasons including abdominal trauma and missed injuries as well as surgical complications such as enteric leaks [9]. Although there are limitations, ultrasonography is an important tool in the diagnosis and treatment of intra-abdominal abscesses in critically ill patients. Some of the limitations for this procedure are patients who are obese, have an uncorrectable coagulopathy, extensive abdominal wounds, or an abscess located deep within the abdomen. However, when the abscess is superficial, non loculated and easily accessed without potential damage to a surrounding structure, ultrasound guided abscess drainage is the ideal method (Fig. 5.3).

After pre-procedural localization of the intra-abdominal fluid collection has been performed utilizing the standard abdominal curvilinear 3.5-MHz or 5-MHz probe, the choice of transducer for the procedure is made [7]. A higher frequency probe (7.5–10 MHz) is used for more superficial collections while a lower frequency probe

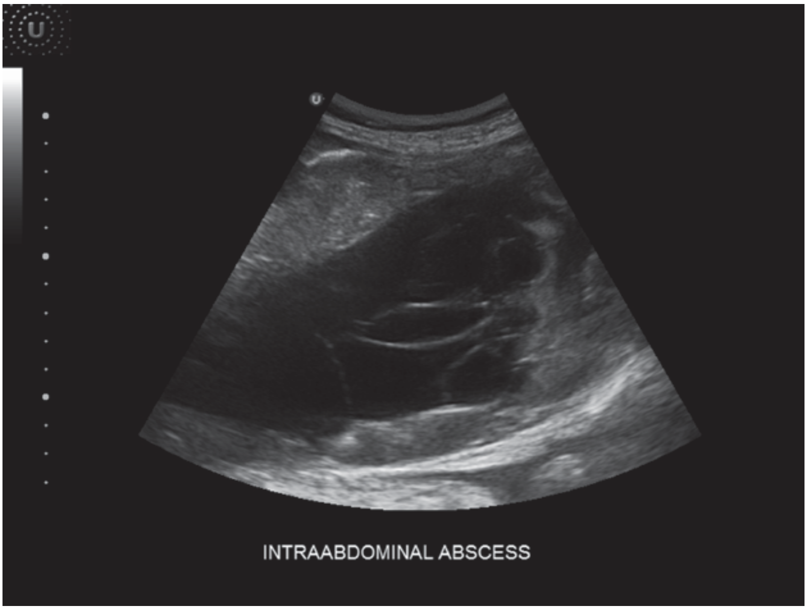

Fig. 5.3 Intraabdominal abscess

(3.5–5 MHz) is used for deeper collections [9]. The skin is then prepped and draped in sterile fashion, again including the ultrasound transducer. Due to the viscous nature of the fluid likely encountered, a larger needle such as an 18 gauge, is used for this procedure after local anesthesia has been obtained. The needle is advanced into the peritoneal cavity avoiding the epigastric arteries within the abdominal wall and under real time visualization with the ultrasound. Negative pressure to the attached syringe is applied once the needle enters the dermis, and once fluid is encountered, a guidewire placed through the needle. The needle is then removed leaving the guidewire in place inside the abscess, and a size 6- to 12-Fr catheter is then placed over the guidewire into the collection [9]. The catheter is then secured to the skin typically using suture, and a collection bag attached. The fluid can then be sent for culture and laboratory examination.

Evaluation of the Gallbladder

Acute right upper quadrant pain is a common complaint bringing patients to the emergency department. However, gallbladder pathology can also develop in patients hospitalized for completely unrelated conditions, and can result in significant morbidity and mortality in already critically ill patients in intensive care units.

Cholelithiasis is a common disease that affects from 10 to 20 % of the population during their lifetime [10]. Obesity, female gender, increasing age and genetics all play a role in the development of cholelithiasis. Although only 1 to 4 % of patients with cholelithiasis become symptomatic annually, complications include pancreatitis, biliary obstruction, acute cholecystitis and cholangitis [10, 11].

On ultrasound, gallstones can have a varied appearance dependent upon the composition of the stones. Regardless of composition however, all stones on ultrasound must move with a change in patient position and produce a shadow [12] (Fig. 5.4).

Choledocholithiasis occurs in approximately 8 to 10 % of patients with cholelithasis and is a significant complication [13]. This occurs when a stone migrates from within the gallbladder into the common bile duct. Although ultrasound may not always be able to detect actual stones in the common bile duct, it is useful in detecting biliary obstruction. When the common bile duct is

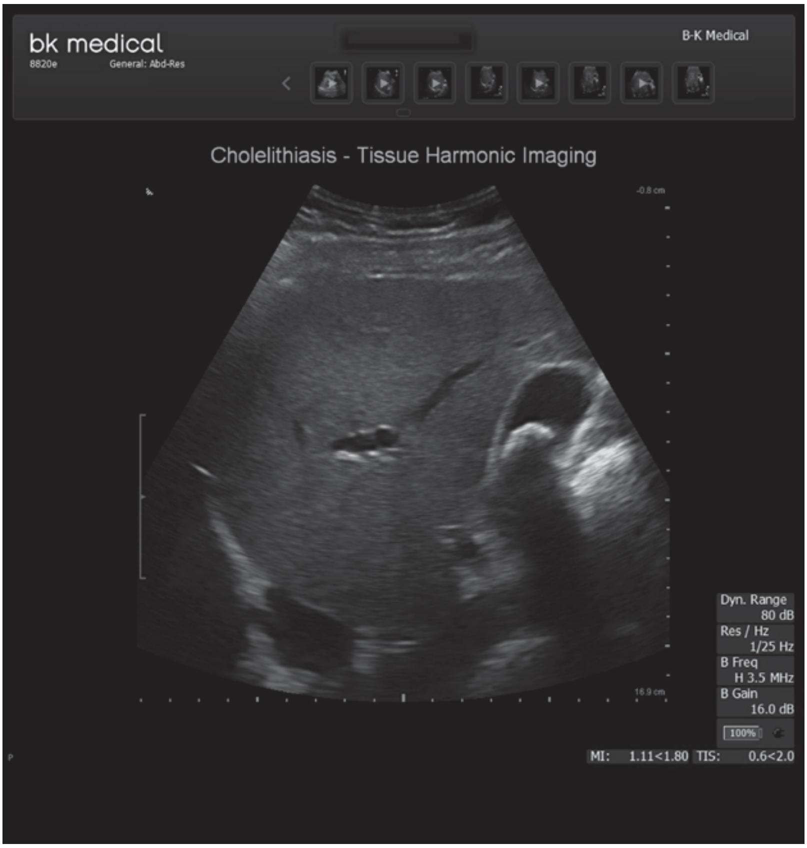

Fig. 5.4 Cholelithiasis

dilated, or greater than 1 cm in diameter, choledocholithiasis should be suspected. In fact, as the common bile duct dilates and it is visualized next to the portal vein, a double channel or parallel channel sign often results [12]. In order to ensure that it is indeed a dilated common bile duct and not the hepatic artery, color Doppler can be used. As biliary obstruction progresses, the biliary tree within the liver parenchyma also dilates, and can be appreciated on ultrasound. At times the shape of the obstructed end can signify the etiology. A tapered end is more consistent with a stone as a source of the obstruction in comparison to a blunt, abrupt end which is more consistent with a tumor, likely in the head of the pancreas [12] (Figs. 5.5 and 5.6).

Acute cholecystitis is known to be fairly common, and has a prevalence of 5% in patients presenting to the emergency department with abdominal pain [14]. However, acute cholecystitis is also a well-recognized entity in critically ill patients in the intensive care unit. Although the pathology may be similar, the presentation, physical examination, diagnosis and treatment may alter significantly in the intensive care unit setting. The majority of cases in the outpatient setting are caused by stones as compared to only about 10% of cases in the intensive care unit [15]. In contrast, acalculous cholecystitis is uncommon in the outpatient setting, accounting for only 5 to 15% of cases, while the majority of cases in the intensive care unit are unrelated to the presence of gallbladder stones [15].

In 1844, acalculous cholecystitis was first reported in a patient having died secondary to gallbladder perforation after a femoral hernia repair [16]. The overall incidence of acalculous cholecystitis has been estimated between 0.2 to 10% of critically ill patients and although the etiology unknown, is associated with prolonged fasting,

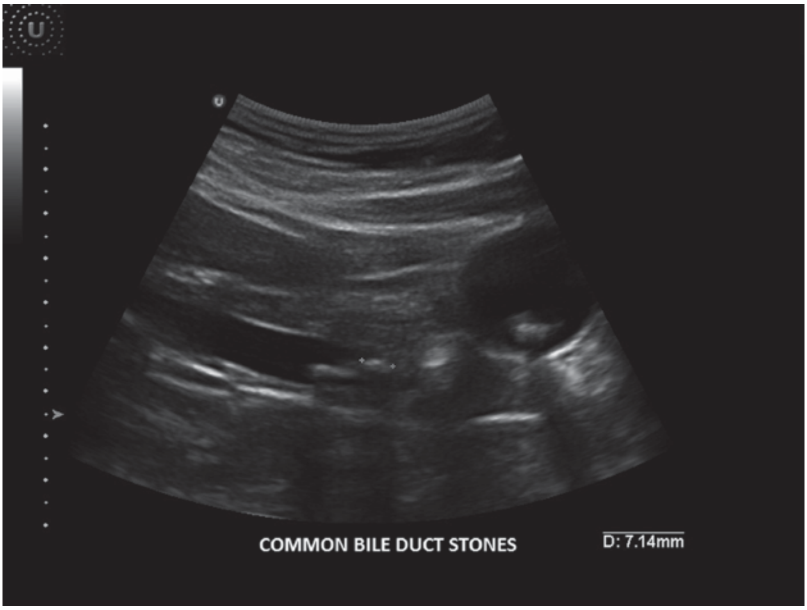

Fig. 5.5 Common bile duct stone

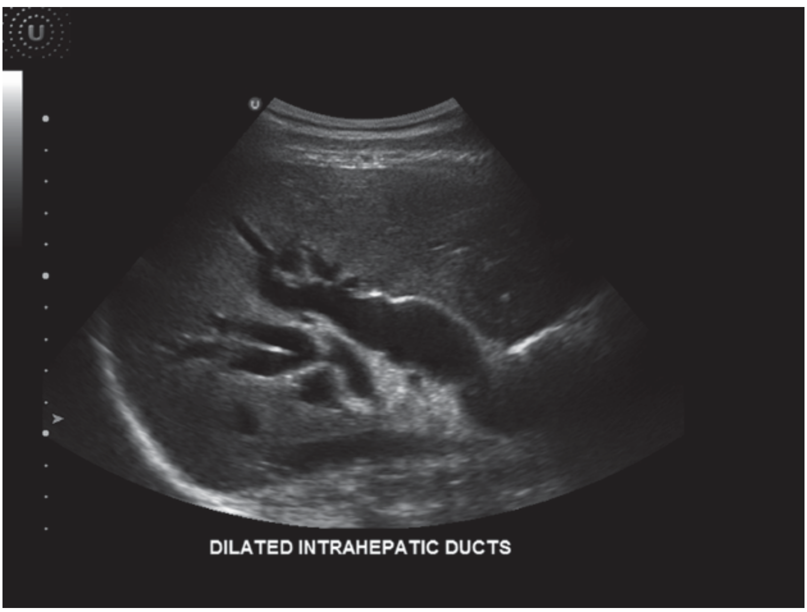

Fig. 5.6 Dilated intrahepatic ducts

use of total parenteral nutrition, trauma, major surgery, extensive burns, sepsis, multiple transfusions and shock [9, 15, 17]. Clinical diagnosis of acalculous cholecystitis is particularly difficult and often unrecognized in intensive care units because these patients are often mechanically ventilated, under sedation, or have undergone major surgery. In addition, traditional symptoms such as right upper quadrant pain and fever may be altogether absent [15]. In fact, it is estimated that 40 to 100 % of cases of acalculous cholecystitis are advanced, with gangrene, empyema or perforation at the time of diagnosis [15].

Ultrasound plays a critical role in the diagnosis of this condition as it is noninvasive, timely, and portable without ionizing radiation, all factors which are important in critically ill patients. In addition, the use of ultrasound allows for evaluation of surrounding structures such as the liver and kidney. The overall sensitivity and specificity reported for ultrasound in the diagnosis of acute cholecystitis both range from 80 to 88 % [18, 19].

Ultrasound findings common in this condition include a Murphy's sign, distended gallbladder, gallbladder sludge, pericholecystic fluid, and a thickened gallbladder wall [20]. Laing et al. first described an sonographic Murphy's sign as maximal tenderness when the sonographer presses the ultrasound directly against the visualized gallbladder in 1981 [21]. The sonographic Murphy sign alone however has a relatively love specificity and may altogether be absent, especially in acalculous cholecystitis [22]. Although gallbladder distention is not specific for cholecystitis, it is often seen in this condition and is indicative of either delayed emptying or functional or mechanical obstruction of the cystic duct. Gallbladder distention is defined on ultrasound as having a measurement of > 10 cm in length or > 4 cm in the transverse plane [9, 15]. Pericholecystic fluid can easily be identified on ultrasound, but can easily be confused with pre-existing ascites. The gallbladder wall is typically thickened in cholecystitis whether it is acalculous or calculous in nature. It is defined as a wall measurement greater than 3 mm, and ultrasound has been shown to be accurate within 1 mm in greater than 90 % of patients [23].

How to Evaluate the Gallbladder

In order for a complete sonographic evaluation of the gallbladder and biliary tree to be accomplished, both long axis and transverse views should be obtained with the patient in the supine condition, utilizing a 3.5- to 5.0-MHz transducer [24]. To aid localization of the gallbladder, place the transducer longitudinally at the level of the patient's right elbow, approximately between the 8th and 9th intercostal space along the anterolateral thoracic wall and have them take in a deep breath [12, 24]. This lowers the diaphragm and often drops the gallbladder into view. Once the gallbladder is in view, the transducer is manipulated to obtain both sagittal and transverse views. To obtain a transverse image, place the transducer in order to locate the right portal vein. Once this is in view, angle the transducer towards the patient's feet, which will bring the gallbladder into the image field [12]. If gallstones are identified, the patient must change positions in order to confirm mobility of the stones and rule out the presence of intraluminal polyps or masses. If bowel gas is interfering with the exam, placing the patient in a left lateral decubitus position may help. Since a distended gallbladder improves visualization, a patient should ideally be held NPO for 6 to 12 h prior to the examination. The gallbladder should be assessed for stones or masses as well as distention and wall thickening [12]. The extrahepatic bile ducts should also be assessed during an ultrasonic evaluation of the gallbladder. These are viewed also in the supine or left lateral decubitus position and should be evaluated for size and dilation. The normal common bile duct has echogenic walls and measures less than 10 mm [24].

Percutaneous Cholecystostomy

Percutaneous cholecystostomy was first described in 1980 by Dr. Radder as a treatment for gallbladder empyema [25]. Since then, this procedure has played an important role in the care of high-risk and critically ill patients. Although surgical cholecystectomy is the gold standard in the treatment of several gallbladder pathologies with a relatively low surgical morbidity and mortality, this does not hold true for all patients [26]. In the elderly and critically ill patients, the morbidity and mortality of surgical cholecystectomy is significant with rates reported between 14 and 30 %, which precludes traditional operative management [27–30]. It is in this select group of patients that percutaneous cholecystostomy is preferable because it can be performed under local anesthesia either in a radiology suite or in the intensive care unit under ultrasound guidance. In addition, it has been shown that this procedure can be performed by radiologists or surgeons, has few complications and a high success rate of over 95 % [31–34].

The technique for placement of a percuataneous cholecystostomy is the same whether it is placed in a radiology suite or at the patient's bedside in an intensive care unit setting. The patient's abdomen is prepped and draped in a sterile fashion. Conscious sedation is optional, which again is one of the advantages of this procedure. After the gallbladder has been localized via ultrasound, local anesthesia is obtained using 1 to 2 % lidocaine. A needle is then used to access the fundus of the gallbladder, either directly (transperitoneal approach) or through liver parenchyma (transhepatic approach). Once bile has been aspirated, a wire is placed through the needle, and the needle is then removed. Over this wire the tract is sequentially dilated, a 6- to 10-Fr catheter is then placed over the wire into the gallbladder fundus, the wire removed, and the catheter secured to the skin. Contrast can then be introduced through the catheter to confirm placement and evaluate patency of the cystic and/or common bile duct.

Although a low overall complication rate is associated with this technique, bowel injury, hemoperitoneum, pneumothorax, bile leakage, catheter occlusion and catheter dislodgement have all been described [32, 35]. There has been much discussion as to the methods of both the transperitoneal and transhepatic approaches. Both have been shown to be safe with similar overall complication rates [36, 37]. The transperitoneal approach is associated with a higher rate biliary leakage into the peritoneal space [38]. In contrast, the transhepatic approach is associated with better catheter stability and lower risk of an intraperitoneal bile leak [31]. However, the transhepatic approach should not be performed in patients with significant liver disease or coagulopathy, and complications such as intrahepatic bleeding and hemobiliary fistula have been reported [37, 39].

Renal Ultrasound

One of the most commonly injured organs in intensive care unit patients is the kidney. In addition, acute kidney injury is associated with an in hospital mortality rate ranging from 20 to 90 %, dependent upon severity [40, 41]. In fact, recent studies have shown that patient outcome can be significantly affected by even small declines in renal function [42, 43]. In 2004, in recognition of the many definitions of acute renal failure, renal impairment and acute kidney injury, the Acute Dialysis Quality Initiative developed a consensus definition of acute kidney injury known as the risk, injury, failure, loss and end-stage renal disease classification, also known as the RIFLE criteria [44]. According to the RIFLE criteria, up to two thirds of all ICU patients develop acute kidney injury [45]. Excluding patients with obstructive kidney failure, acute kidney injury in critically ill patients can be divided into categories of either functional or organic acute kidney injury. Functional or transient acute kidney injury results from decreased renal perfusion and therefore is reversible [46, 47]. However, organic or persistent acute kidney injury is defined by the presence of structural renal damage. The most common causes of acute kidney injury in the intensive care unit are hypotension, volume depletion, sepsis, and acute tubular necrosis [48].

Renal ultrasound is often recommended as part of the diagnostic evaluation in patients with azotemia and acute kidney injury. Gray scale ultrasound is a diagnostic tool that provides useful and valuable information about the kidneys and its collecting system. Information that can be obtained includes the size and appearance of the kidneys, presence and severity of hydronephrosis, and the presence of masses, cysts, stones and peri-nephric hematomas (Fig. 5.7).

Typically a 3.5-MHz or a 2- to 5-MHz multifrequency transducer is used to perform a renal ultrasound, with the patient in the supine position. At times, however, lateral decubitus or prone positioning may be required, dependent upon overlying bowel gas and the patient's body habitus. If possible, keeping the patient NPO for 8 h prior to examination is helpful in reducing the amount of bowel gas present [12]. The right kidney is often easier to visualize secondary to the abutting liver. The transducer is placed in the posterior axillary line and the kidney is evaluated in both longitudinal and transverse

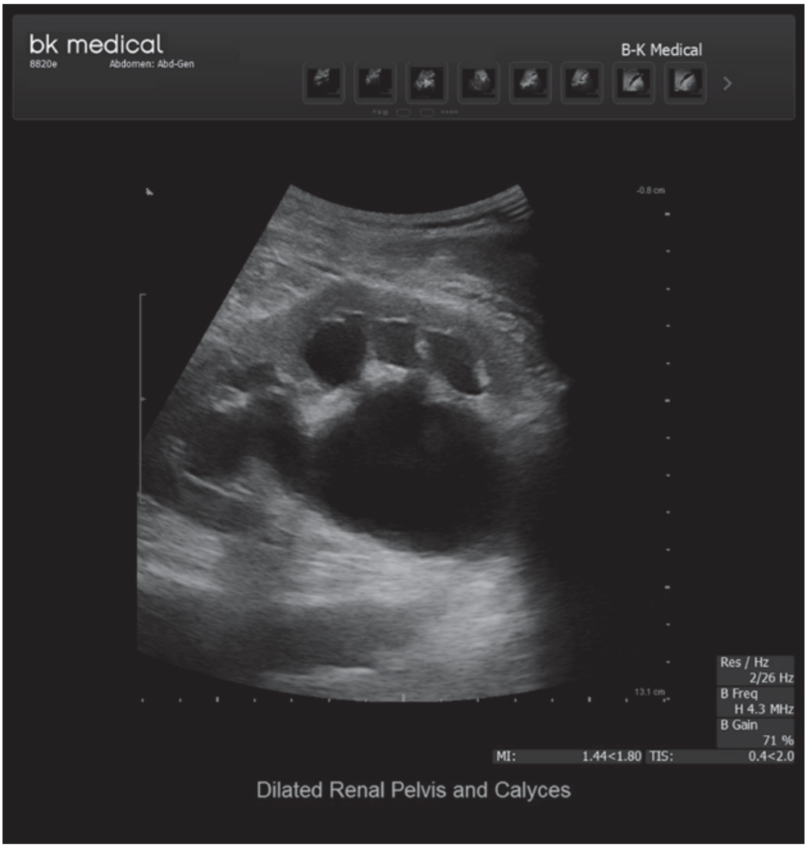

Fig. 5.7 Hydronephrosis

views. The longitudinal diameter of the kidney is measured, with normal ranges between 9 and 12 cm, dependent upon the patient's gender and overall size [49]. Parenchymal thickness is also measured in different areas of the kidney and averaged, with the normal thickness range between 1.5 and 1.8 cm [49]. These measurements help distinguish acute from chronic renal failure as kidney size is usually small with a thin cortex in chronic kidney disease [50]. Normal renal papillae are comparatively hypoechoic next to the renal parenchyma, and the collecting system difficult to visualize unless hydronephrosis is present. Stones are usually located in the calyx or ampulla, are very echogenic and have acoustic shadowing, but can be difficult to detect if less than 5 mm in size [49] (Fig. 5.8). Cystic and solid masses are also detectable on gray scale ultrasound, with cystic masses occurring more frequently. Cysts on ultrasound are characteristically hypoechoic with thin, clearly defined margins and have posterior acoustic enhancement [12]. Although the majority of renal cysts are round or oval in nature, irregular shapes are possible [12]. Masses differ from cysts in that they can be iso or hypoechoic, have loculations, and irregular margins. In addition, masses do not have posterior wall enhancement (Fig. 5.9).

Beyond gray scale imaging, ultrasound is quickly becoming recognized as an integral part in the prevention and early detection of acute kidney injury as it is rapid, non-invasive, portable and repeatable. B-mode ultrasound is very valuable in assessing the anatomy of the kidney, but not its function. Although it is known that renal function is dependent upon renal blood flow and perfusion, the exact nature of the relationship between renal perfusion and acute kidney injury

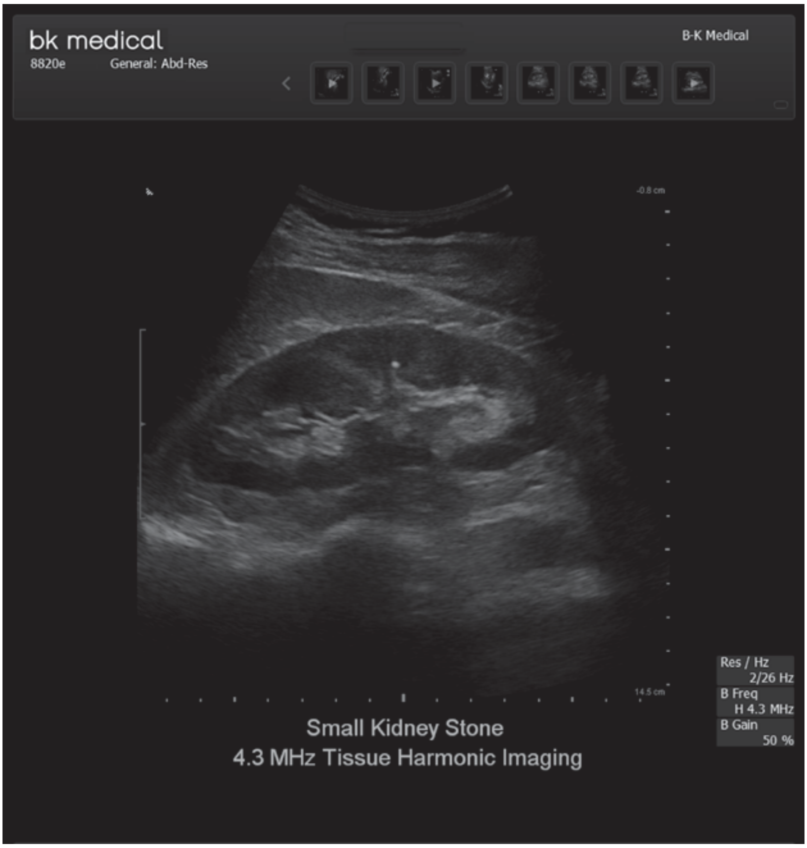

Fig. 5.8 Kidney stone

is not well understood. The current focus of research is the prevention and early diagnosis of acute kidney injury for which both Doppler and contrast enhanced ultrasound show promise.

Renal Doppler ultrasound and the calculation of a resistive index are being suggested as an important tool in the assessment of patients with acute kidney injury and changes in renal perfusion. The technique to perform a Doppler assessment of the kidneys, a 2- to 5-MHz transducer is used initially in B-mode to localize the kidney. One this has occurred, Doppler mode is used to then locate the renal vessels which divide into segmental and lobar arteries which then further branch into interlobar and then arcuate arteries. Either the interlobar or arcuate arteries are evaluated and three to five reproducible waveforms are obtained. These waveforms are then analyzed using the Resistive Index (RI) and each RI is then averaged. The RI is defined as the peak systolic shift minus the minimum diastolic shift, then this number is divided by the peak systolic shift. Although the overall normal range is age dependent, a normal RI is defined as less than 0.70. Studies have shown that the RI can be used to distinguish patients with transient RI and those with persistent RI [51, 52]. In addition, there are studies that suggest RI can be used to predict the development of acute kidney injury [53, 54].

Contrast-enhanced ultrasonography is a technique which employs micro-bubble based contrast agents to aid in the assessment of microvascular tissue perfusion. These microbubbles stay within the intravascular space as their size prevents diffusion through endothelium, and has shown to be safe in multiple clinical studies [46, 55–57]. The microbubbles then interact with the ultrasound waves and opacify the renal vascular

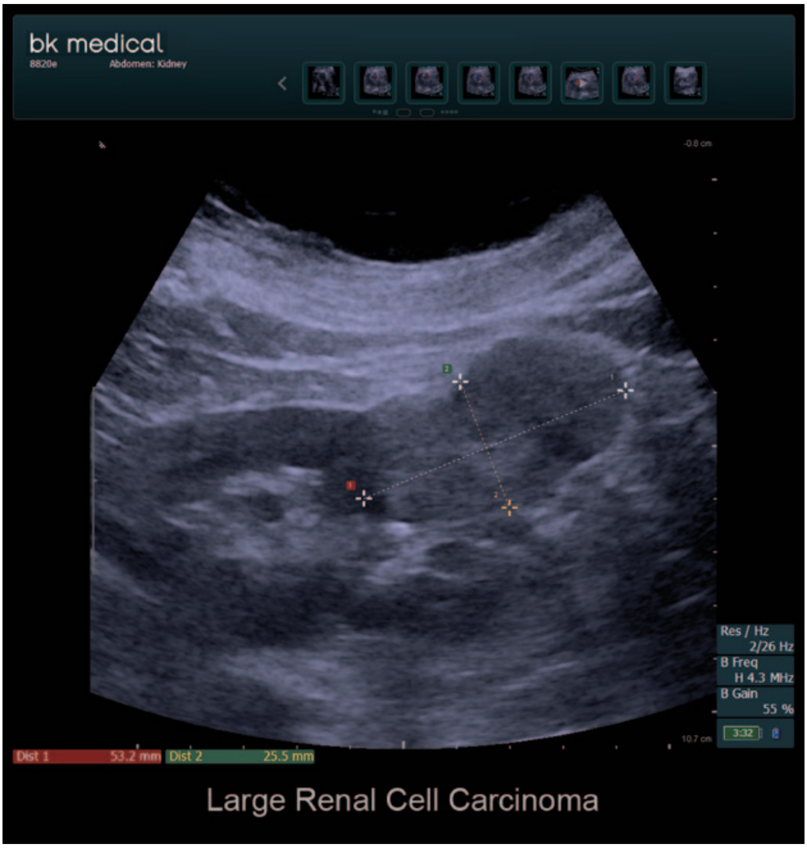

Fig. 5.9 Large renal cell carcinoma

bed, allowing for the microcirculation to be detected and analyzed [41]. The exact correlation between perfusion abnormalities demonstrated on contrast enhanced ultrasonography and the clinical entity of acute kidney injury has yet to be determined but is a current focus of study.

Bladder Ultrasound

Postoperative urinary retention is a common problem in the intensive care unit setting. Although this complication is often viewed as benign, it results not only in a prolonged hospital stay and increased patient costs, but even a single incident of overdistention can lead to permanent detrusor damage and chronic dysfunction of bladder emptying [58, 59]. Urethral catheterization is often used when postoperative urinary retention is suspected, however, catheterization is directly linked with the development of urinary tract infections, the most common nosocomial infection [9, 59].

Ultrasound has been shown to be an safe, rapid and noninvasive technique in the evaluation of patients with suspected urinary retention, especially in the intensive care unit setting where the typical physical examination utilizing inspection and palpation is likely to be impaired. Ultrasound can reliably provide an estimate of urine volume present in the bladder, which provides better information regarding the need for catheterization and preventing unnecessary catheterizations as well [58].

The technique is simple, utilizing a linear transducer cephalad to the pubic symphisis in the lower abdomen. The bladder is then evaluated in both the longitudinal and transverse planes. There are now commercially available ultrasound machines that will calculate urine volume based upon a few simple measurements. Although no consensus exists, most centers do recommend catheterization based upon estimated bladder volumes with a range of 300 to 500 mL.

Summary

- At miminum, an intensivist should acquire the skills to perform a FAST.
- Fluid is visualized as hypoechoic. In a hypotensive trauma patient, this fluid should be assumed to be blood until proven otherwise.
- The visualization of fluid can be useful to drain it (paracentesis).
- Evaluating the kidney, bladder, and gallbladder are good skills to obtain, but informal scanning does not replace formal ultrasound. Use your ultrasound exam as a complement to your physical exam, rather than a diagnostic test.
- Get familiar with the anatomy and scanning techniques, and perform the test in multiple healthy individuals until you obtain expertise.

Appendix

Video 5.1 Subxiphoid view of the pericardium and heart.
Video 5.2 FAST evaluation of the hepatorenal space.
Video 5.3 FAST evaluation of the splenorenal space.
Video 5.4 FAST evaluation: bladder view.

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Evaluation of Soft Tissue Under Ultrasound

6

David Evans

Soft Tissue Infections

Clinical Considerations

Soft tissue infections are commonly encountered in the critical care setting. Traditionally, physicians have relied on physical findings to make the diagnosis; however, it is difficult to discern cellulitis from abscess based on physical exam alone [1]. This has led some physicians to utilize imaging modalities like contrast-enhanced computer tomography to attempt to visualize soft tissue abscess. Ultrasound has proven an efficient aid for the detection, diagnosis, treatment of subcutaneous abscesses. The use of ultrasound improved the sensitivity for detecting underlying abscess from 78% on physical exam to over 97% [2]. Furthermore, ultrasound has shown to be far superior to CT for the detection of cutaneous abscess ($p = 0.0001$) [3]. Multiple studies have looked at the role of ultrasound in the management of cutaneous abscess and have shown a remarkable propensity for changing the management of the patient [4–6]. In this collection of studies management for soft tissue infections was changed up to 56% of the time when ultrasound was applied at the bedside. It was consistently found that in the patient subset in which the treating physician felt there was no underlying abscess the application of ultrasound identified deeper underlying abscess cavities.

D. Evans (✉)
Department of Emergency Medicine,
Virginia Commonwealth University,
52 Dillwyn Dr, Newport News, VA, USA
e-mail: evansdp@live.com

Anatomic Considerations

It is important that the provider has a detailed understanding of the underlying anatomy that is being evaluated. It is common for abscess cavities to abut arteries, veins, and nerves. If any doubt arises during the scanning process, it is advisable to compare with the unaffected contralateral side.

Technical Considerations

Evaluation of soft tissue infections should be performed with a high-frequency linear array transducer (5–15 MHz). Some extremely superficial infections will require some distance between the area of interest and the transducer. This can be accomplished with a mound of coupling gel, a stand-off pad, or a water bath. Occasionally, soft tissue infections extend deep into adjacent tissue planes and will be best visualized with the use of an alternate lower frequency transducer, such as a curvilinear or phased array transducer. The area of interest should be examined in at least two planes 90 degrees to each other. The depth should be set as to ensure the area of interest is well within the focal zone. Care should be taken to minimize the pressure of the transducer on the

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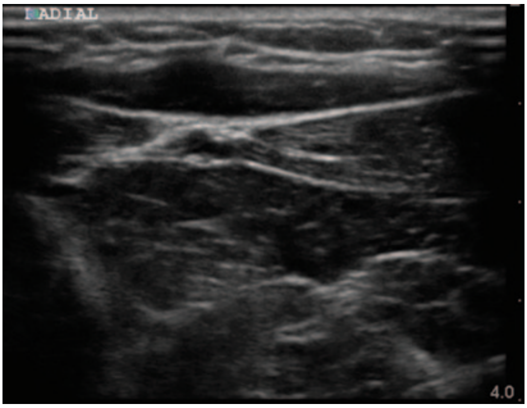

Fig. 6.1 Normal soft tissue of the volar surface of the distal lateral forearm

soft tissue as to not collapse or displace underlying structures.

Looking at Fig. 6.1, normal soft tissue structures are identified from superficial to deep. Closest to the transducer at the top of the screen is the skin with its thin hyperechoic homogenous appearance. Just distal to this is the subcutaneous layer made up mostly of fat, leading to a reticular pattern. In the center of the image the neuromuscular bundle is identified; the paired artery and vein appear anechoic in nature, while the radial nerve sitting just superior to the vessels is hyperechoic with grape-like clusters within it. Muscles are identified here and are relatively hypoechoic with hyperechoic striations. The humerus in the bottom left has a hyperechoic rim with posterior shadow.

Cellulitis

Sonography of cellulitic skin will show a thickened hyperechoic appearance to the skin (Fig. 6.2). The underlying tissue has a cobblestoned manifestation, which is classic for cellulitis (Fig. 6.3). Deep to this the tissue takes on a reticular pattern. It is important that abscess formation is ruled out during this exam. The entire area should be systematically scanned to evaluate for an abscess cavity.

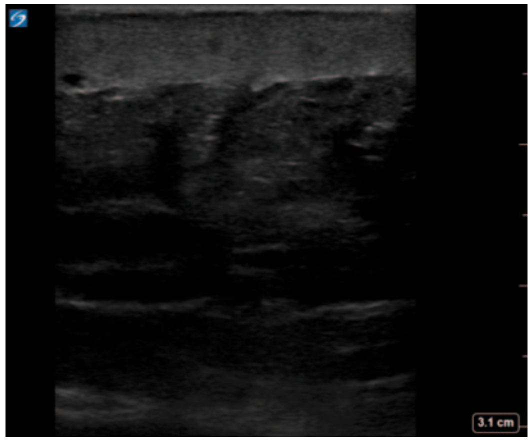

Fig. 6.2 Thickened hyperechoic skin in cellulitis

Fig. 6.3 Cobbelstoning of the distal medial surface of the lower extremity

Ultrasound may have some prognostic value in cellulitis. One small study showed that when a patient's scan contains only skin thickening without cobblestoning, the patient had higher rates of treatment success and faster recovery times [7].

Abscess

A subcutaneous abscess is identified most commonly as a discrete spherical area of hypoechoic fluid with surrounding hyperechoic rim and posterior acoustic enhancement (Fig. 6.4). It should be noted that abscesses can take on varying levels of echogenicity. For example, an infected sebaceous

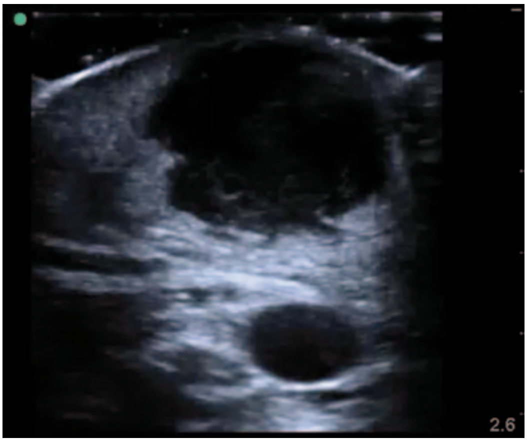

Fig. 6.4 Abscess cavity

cyst typically has a hyperechoic fluid collection and minimal posterior caustic enhancement. Care should be taken to note any septations within the cavity itself, identify any deeper abscesses that may exist, and document proximity to any neurovascular structure. Finally, color Doppler should be used to evaluate the cavity for any vascularity prior to incisional drainage (Fig. 6.5).

The most common error a novice sonographer makes is to misidentify an enlarged lymph node for an abscess. Lymph nodes generally have a hypoechoic appearance with an internal hyperechoic mushroom-like structure that should demonstrate flow on color Doppler (Fig. 6.6). Another possible pitfall is a soft tissue mass such as a lipoma. Lipomas generally are hyperechoic spherical masses, but lack thickening of the skin or posterior acoustic enhancement (Fig. 6.7). Felons are difficult to image due to the small surface area of the distal digit, but with use of a water bath the area can be successfully visualized (Fig. 6.8).

Necrotizing fasciitis represents a true surgical soft tissue emergency, in which time to diagnosis is critical. Unfortunately, it is often a clinical diagnosis, as traditional imaging techniques have proven to be insensitive. Ultrasound can help in the early recognition and diagnosis of necrotizing fasciitis [8, 9]. Typically, the subcutaneous layer will show edema and cobblestoning as with cellulitis; however, in necrotizing fasciitis there should be a pre-fascial fluid collection just above the deep fascial plane measuring greater then 4 mm (Fig. 6.9). Depending on the organism responsible for the infection subcutaneous air may be present.

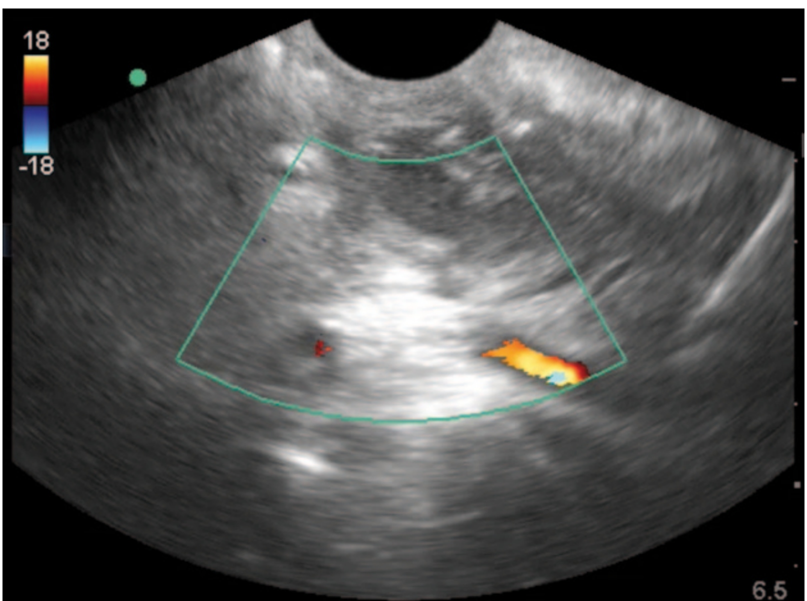

Fig. 6.5 Peritonsilar abscess with carotid artery seen posterior to abscess cavity

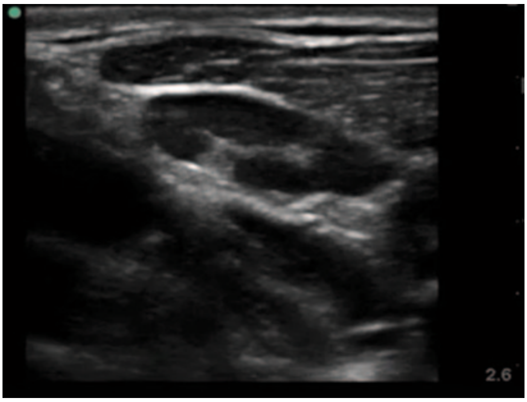

Fig. 6.6 Normal lymph node

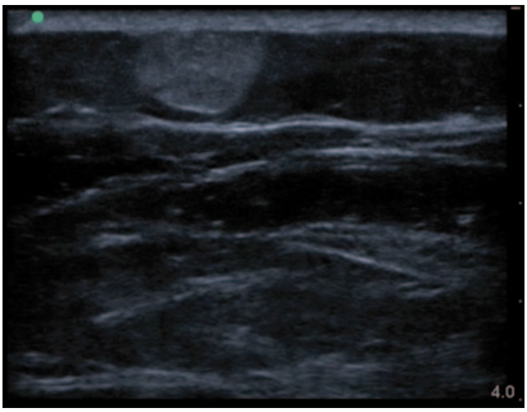

Fig. 6.7 Lipoma

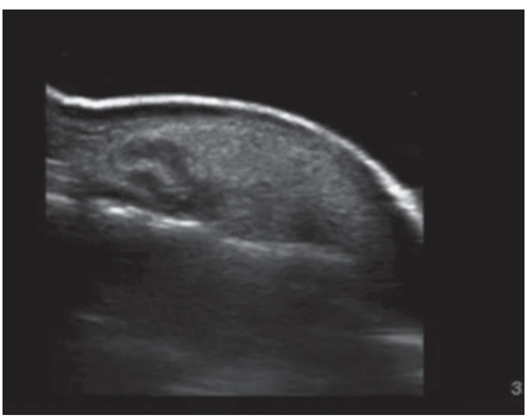

Fig. 6.8 Felon imaged in a water bath

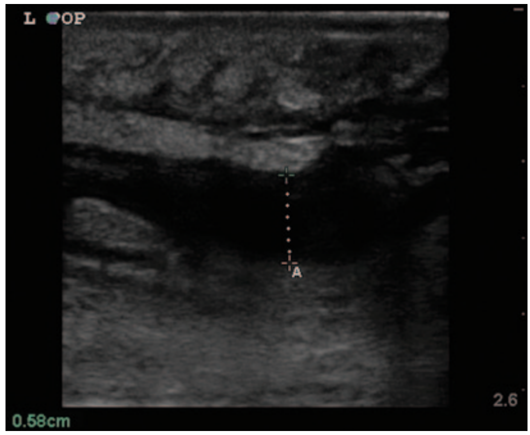

Fig. 6.9 Pre-fascial fluid collection seen in necrotizing fasciitis

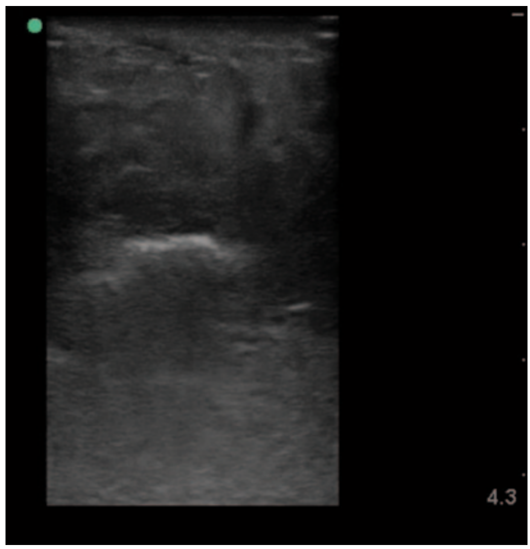

Fig. 6.10 Hyperechoic subcutaneous air with dirty posterior shadow

This is seen as an area of hyperechogenicity within the subcutaneous layer with "dirty" posterior shadowing and reverberation artifact (Fig. 6.10).

Summary

- Having knowledge of the anatomy you are evaluating is indispensable.
- Use the high-frequency probe for superficial structures.

- Use ultrasound as a tool to improve your clinical skills. Soft tissue infections remain a clinical diagnosis.

Foreign Body Recognition

Clinical Consideration

Wounds contaminated with foreign bodies represent a particular difficulty for the provider. Even with careful examination foreign bodies are routinely missed on exam [10, 11]. These missed foreign bodies represent a disproportional amount of medico-legal litigation and monetary awards [12, 13]. Missed foreign bodies can lead to poor wound healing, cellulitis, and systemic infection [14–16]. Typically, plain films are performed to evaluate for the possibility of foreign bodies. Levine et al.'s review of 490 cases showed x-rays missed 25 % of all glass objects and 93 % of wood [17]. These radiolucent materials have both a high miss rate and a high propensity for infection.

Ultrasound has shown to be an efficient modality at detecting these radiolucent foreign bodies with up to 95 % sensitivity [18–21]. Once the object has been identified ultrasound can be utilized to guide its removal. This procedural use of ultrasound improves time to detection and outcomes [20, 22, 23]. Given that ultrasound provides a low-cost, real-time, noninvasive way to evaluate and treat foreign bodies with higher sensitivity than other imaging modalities, it can be said that ultrasound has become the imaging modality of choice for the detection, localization, and removal of foreign bodies.

Anatomic Considerations

The provider should have an understanding of the underlying anatomy of the affected area. It is common that foreign bodies occur in the hands and feet, so it is prudent to have an understanding of these areas, in particular. It is advisable to evaluate the contralateral uninjured area if any question exists.

Technical Considerations

The exam should be performed with a high-frequency linear array transducer (5–15 MHz). It is important to image the suspected foreign body in both longitudinal and cross-sectional planes. Most foreign bodies are relatively superficial and may require some distance between the transducer and the object. This distance places the object of interest within the transducer;s optimal focal zone. The best way to gain distance between a superficial object and the transducer is the use of a water bath [24, 25]. If the location of the foreign body prohibits the use of water bath, a standoff pad or mound of coupling gel can be used to obtain the proper amount of distance from the object. Once the depth is optimized, the surrounding anatomical structures should be identified with particular attention paid to any neurovascular structures.

Foreign Body

Foreign bodies can have a variety of appearances on ultrasound depending on the physical characteristics of the object, the length of time the object has been retained, and any surrounding infection. In Fig. 6.11, a piece of wood is identified in the transverse view. Note the wood's hyperechoic nature with small posterior caustic shadow and surrounding tissue edema and inflammation. In

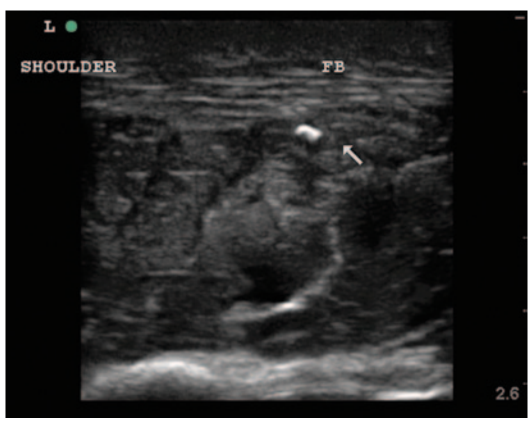

Fig. 6.11 Transverse image of wooden foreign body

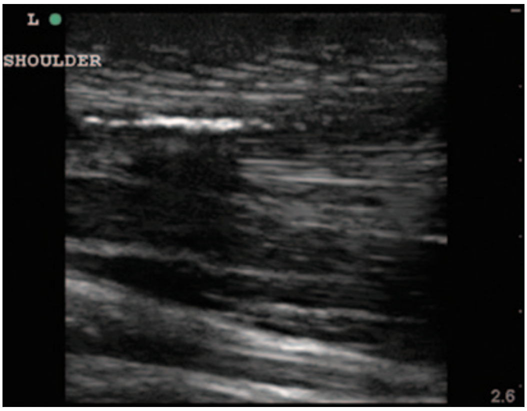

Fig. 6.12 Longitudinal image of wooden foreign body

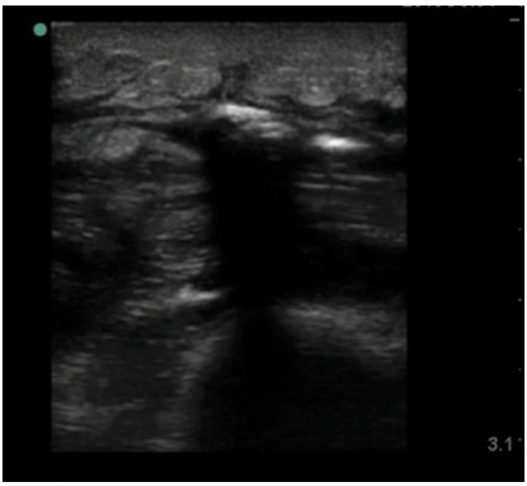

Fig. 6.13 Transverse image of paper foreign body with surrounding cellulitis

Fig. 6.12, the same wooden object is seen in the longitudinal plane. Here the posterior shadow is more prominent due to the larger surface area of the object being imaged. In Fig. 6.13, a large hyperechoic foreign body is identified with signs of surrounding cellulitis. This image represents a tightly rolled up piece of paper that an inmate had been stabbed with several days prior to presenting to the emergency department. These sonograms are in contrast to the metal foreign body seen in Fig. 6.14, with a reverberation artifact. Once the object has been identified, local anesthesia can be infiltrated into the area and a decision can be made as to whether to retrieve the object.

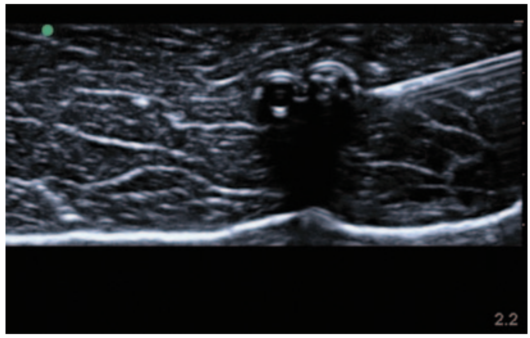

Fig. 6.14 Metal needle in longitudinal view

Musculoskeletal Injuries

Ultrasound has revolutionized the provider's ability to diagnosis and treat musculoskeletal injuries. The advent of high-resolution ultrasound imaging and advanced soft tissue software has enabled ultrasounds to achieve resolution of musculoskeletal structures once only obtainable with magnetic resonance imaging. This has led to widespread use within the orthopedic, sports medicine, rheumatology communities [26, 27]. In this section we will only cover a few of the many uses of ultrasound to evaluate musculoskeletal injuries including tendon and muscle tears, dynamic evaluation of tendons, joint dislocations, and joint injection/aspiration.

Anatomical Considerations

Musculoskeletal structures tend to be superficial in nature, thus lending themselves to sonographic evaluation. Tendons are made of parallel collagen fibers forming a single homogenous bundle. Each of these bundles is surrounded by endotendon, which is in turn bound together by the epitendon. The entirety of the tendon is surrounded by a double-walled synovial sheath.

Prior to sonographic evaluation of the joint space, the provider should have a detailed understanding of articulations, overlying tendons, and surrounding neurovascular structures.

Technical Considerations

In general, a high-frequency linear array transducer (5–15 MHz) should be used to image these superficial musculotendinous structures. Certain areas like the Achilles tendon are superficial and not conducive to a water bath due to their location. It is suggested for these to use a standoff pad.

It is important to have an in-depth understanding of what normal musculoskeletal structures should look like on ultrasound. The skin should appear as a thin hyperechoic layer immediately at the top of the image. The subcutaneous layer will take on a reticular appearance due to the fat in this layer, and varies in thickness based on the patient's body mass index. Deep to this layer we will find muscle, tendons, fascia, bones, and neurovascular structures in varying degrees. Muscle takes on a hypoechoic appearance with characteristic hyperechoic striations on longitudinal view (Fig. 6.15) and speckled appearance in transverse (Fig. 6.16). The thin fascial layers separating the muscles should follow the muscle and appear intensely hyperechoic on ultrasound. Tendons appear hyperechoic and linear in nature in long axis (Fig. 6.17) [28]. In short axis the tendon will appear to be of moderate echogenicity with hyperechoic bundles giving tendon its signature echotexture (Fig. 6.18). Due to the intricate design of tendons, they display a particular imaging artifact called anisotropy. Anisotrophy occurs due to an increased angle of incidence; when the beam angle is anything less than perpendicular, the

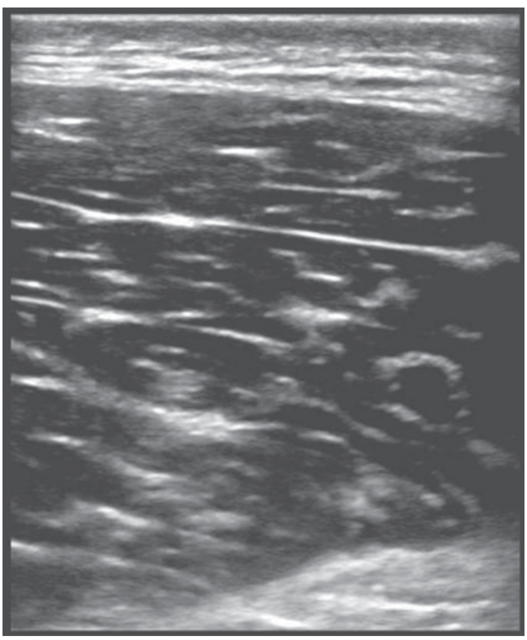

Fig. 6.15 Muscle in longitudinal view

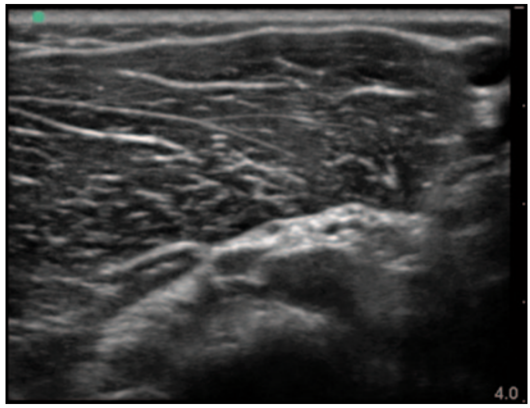

Fig. 6.16 Muscle in transverse view

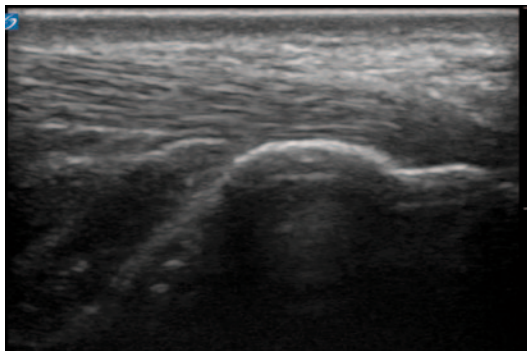

Fig. 6.17 Long axis of Achilles tendon insertion on calcaneus

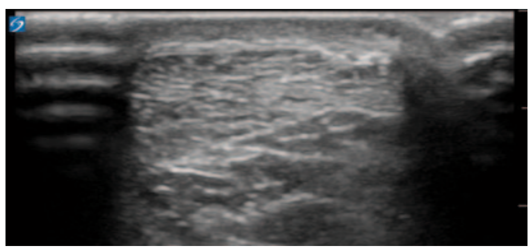

Fig. 6.18 Short axis of Achilles tendon

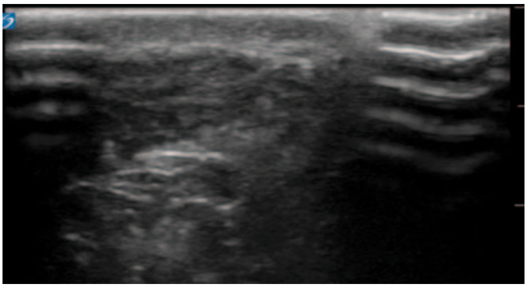

Fig. 6.19 Short axis of Achilles tendon displaying anisotropy

hyperechoic tendon appears hypoechoic due to beam refraction (Fig. 6.19). This is important because the majority of tendon injures will appear hypoechoic. To overcome this artifact, the sonographer should adjust the angle and watch for resolution of the hypoechoic defect. If the defect remains, it is indeed a tendon injury [29]. Bone will appear to have an intensely hyperechoic rim with posterior shadowing. Nerves will appear as hyperechoic grape-like clusters and typically are adjacent to anechoic blood vessels.

Tenosynovitis

Prior to intrinsic tendon damage occurring many overuse injuries produce synovitis, fluid, and hypoechoic edema in the surrounding structures. On sonography tenosynovitis is seen as tendon thickening, fluid within the synovial sheath, and pain on compression with the transducer. It is important to rule out any joint space effusion prior to making the diagnosis of tenosynovitis, because some joints communicate with the adjacent synovium. Thus, the diagnosis of tenosynovitis can only be made if the fluid collection is localized to the tendon sheath itself.

Tendinopathy

Tendinopathy can be caused by degenerative changes, impingement, or overuse. On ultrasound the tendon will begin to show signs of thickening, followed by a loss of fibrillar pattern,

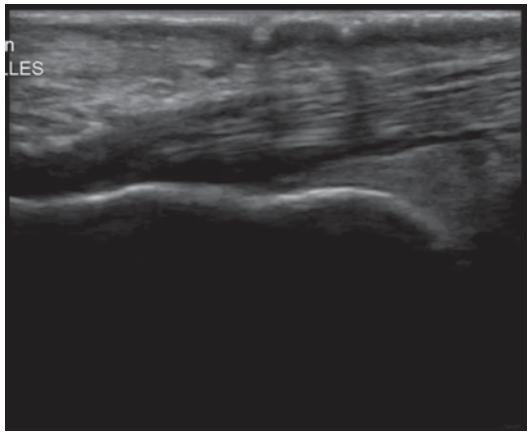

Fig. 6.20 Achilles tendon showing tendinopathy

and eventually areas of hypoechogenicity will form within the tendon itself (Fig. 6.20). If these areas of hyoechoic tendon are found on exam, a full dynamic tendon exam should be performed to evaluate for any tendon disruption [30].

Tendon Disruption

Tendons can have partial or complete tears, and typically occur in the setting of underlying tendinopathy. The injured area of the tendon is typically separated by hypoechoic fluid and hematoma (Fig. 6.21). Dynamic imaging can elucidate whether full disruption of the tendon exists [31].

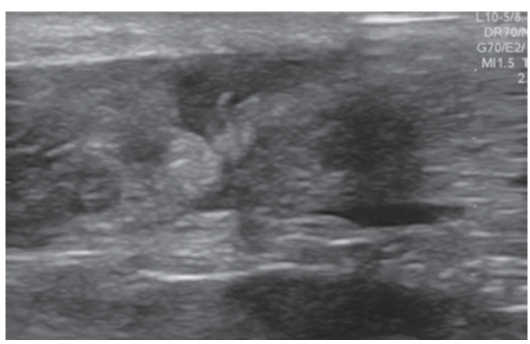

Fig. 6.21 Achilles tendon showing tendon ruptured

Joint Dislocation

Joint dislocations are commonly encountered in the emergency setting. Approximately 50 % of all large joint dislocations involve the glenohumeral joint [32]. Until recently, plain radiographs have been the imaging modality of choice for shoulder dislocations. Current studies have demonstrated the distinct advantages ultrasound has over plain radiographs for both anterior and posterior glenohumeral dislocations [33–35]. Ultrasound allows for rapid, real time evaluation of the joint space. Once the joint space has been evaluated and a dislocation has been identified, ultrasound can be used to inject the joint with anesthetic [36]. Once anesthetized, the joint can then be reduced under ultrasound guidance [37].

Anterior shoulder dislocations arise from an inferiorly directed force pushing the humeral head out of the inferior portion of the glenoid fossa. After the head has disarticulated the more powerful pectorals and biceps muscles pull the head anteriorly. Posterior and inferior dislocations are far more rare then anterior dislocations.

Imaging of the glenohumeral joint is best accomplished with a curvilinear transducer set to a high frequency setting (5 MHz). The sonographer should stand at the patients back with the patients arm adducted and supported. The transducer should be placed parallel and inferior to the scapular spine with the indicator to the patient's left, at the level of the glenoid. The depth should be adjusted to ensure both the glenoid and the humeral head are visible. The humeral head will appear as a hyperechoic circular structure lateral to the glenoid. In the setting of an anterior shoulder dislocation the humeral head will be visible deep to the glenoid, and hyperechoic clot can be visible in the joint space (Fig. 6.22). Once the dislocation has been identified, anesthetic can be placed in the joint space under direct guidance. Once anesthetized and the joint is reduced, ultrasound can be used to confirm reduction. With the same technique, the transducer is placed posteriorly on the patient and if the reduction is successful the humeral head will be seen abutting the glenoid (Fig. 6.23). Slight internal-external rotation of the adducted arm will show the rotational articulation between the humeral head and glenoid fossa.

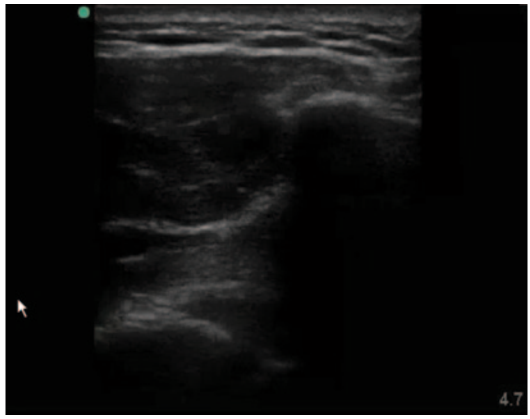

Fig. 6.22 Anterior glenohumeral dislocation

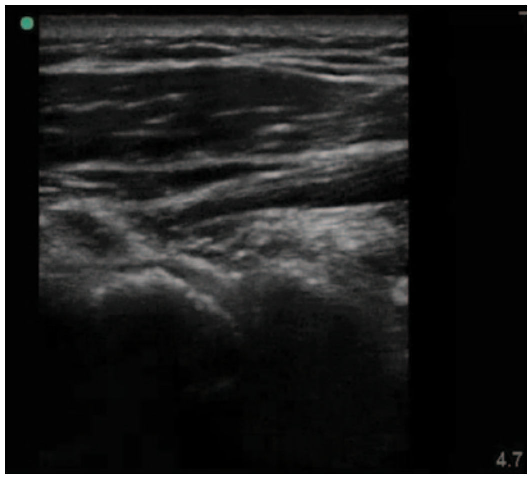

Fig. 6.23 Reduced glenohumeral dislocation

Joint Aspiration/Injection

Painful swollen joints are a commonly encountered condition, which sometimes requires synovial fluid analysis. While anatomical landmark-based techniques have been traditionally taught, radiology and other specialties have been performing ultrasound-guided arthrocentesis for decades [38, 39]. Ultrasound-guided joint aspirations and injections have proven superior to landmark-based techniques [40, 41]. Most joints are

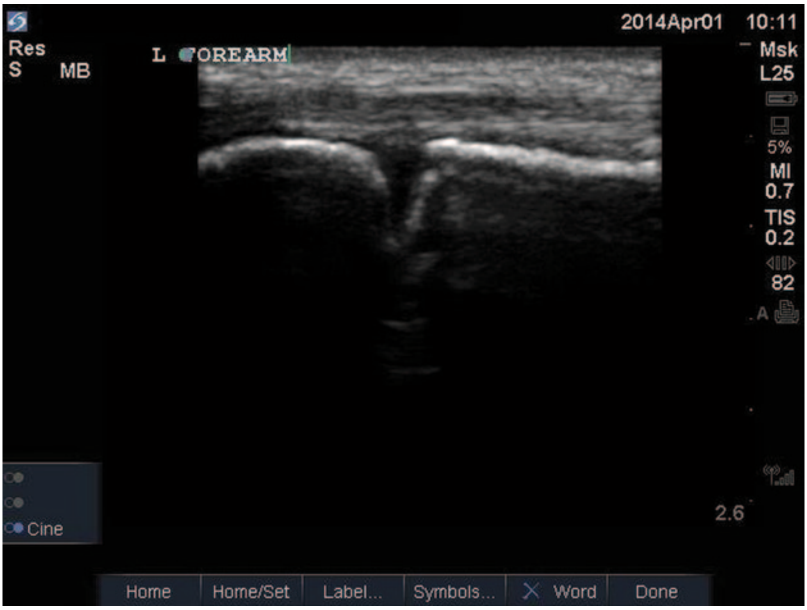

Fig. 6.24 Normal radiohumeral joint

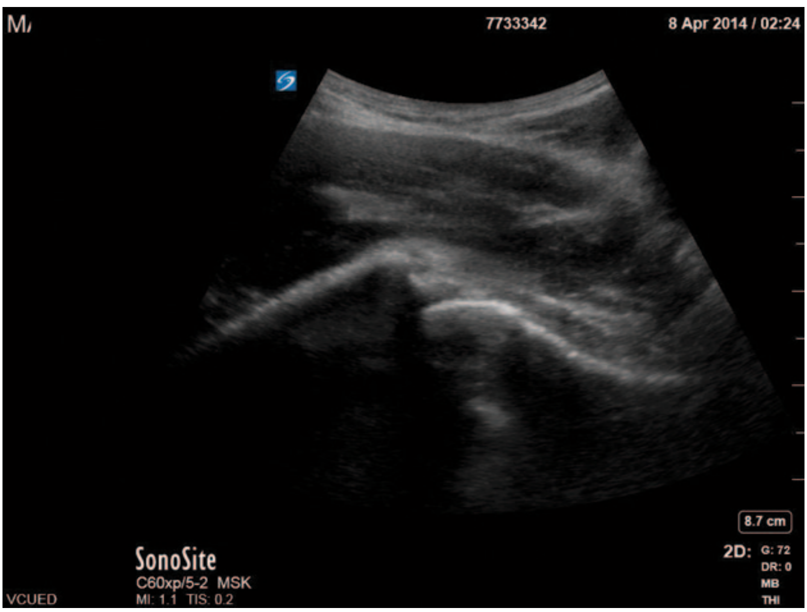

Fig. 6.25 Normal longitudinal hip sonogram

superficial, and can imaged with a standard high-frequency linear array transducer (Fig. 6.24); however, some deeper joints, like the adult shoulder and hip, are best imaged with the curvilinear transducer (5 MHz). A familiarity with the joint anatomy is recommended prior to beginning the exam. When performing the sonographic evaluation of the hip, the patient is placed supine with the leg slightly abducted and externally rotated. The transducer is placed in the longitudinal plane with the indicator pointed cranial. The femoral neck, head, and acetabulum are identified by the hyperechoic rim (Fig. 6.25). The anechoic cartilage on the femoral head is identified. At the

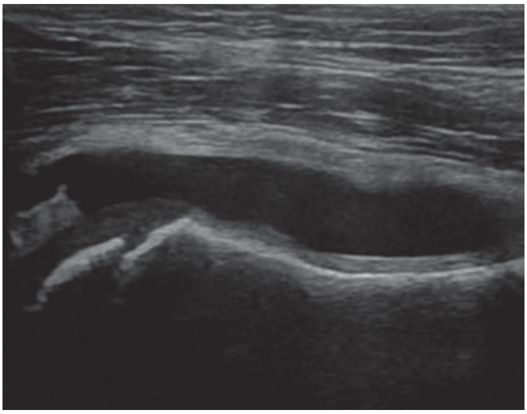

Fig. 6.26 Hip effusion in child

angle of the femoral head and neck lies the joint space being evaluated. An effusion is generally defined as a 2-mm increase, when compared to the asymptomatic hip, in the distance from the cortical echo to the joint capsule or as a convex bulging joint capsule with a fluid stripe greater then 5 mm (Fig. 6.26). If an effusion is noted, a needle can be placed in plane with the transducer under sterile conditions. The sonographer should note the position of the femoral vessels prior to aspiration. This can be performed by turning the transducer 90° and insuring the vessels lay well out of the path of the needle [41, 42].

Summary

- Use the high-frequency probe.
- Gain expertise in performing ultrasound before intervening.
- The angle of the probe might change your visualization and your perception of the structures visualized. Since ultrasound is a dynamic examination, you will be able to overcome this obstacle by scanning the area in different angles before intervening.
- Maintain sterile technique when performing any ultrasound-guided procedure.

Abdominal Wall Hernia

Clinical Considerations

Abdominal wall hernias can occur in multiple different locations. Abdominal wall sonography is a fast, inexpensive, and accurate way to assess for abdominal wall hernias, making it the first-line tool for investigating the for the presence of hernias [43]. Approximately 4 % of all abdominal surgeries have a delayed complication of hernia and are therefore routinely encountered in the emergency setting [44]. Typically, hernias are diagnosed from the patient's history and physical; however, sometimes the patient's history is inconclusive or the physical exam is limited by external factors like obesity or hernia location. Spigelian hernia occurs through a slit-like defect in the anterior abdominal wall adjacent to the semilunar line, a curved tendinous line placed on either side of the rectus abdominis. Because a spigelian hernias are typically covered by the external oblique aponeurosis, it is difficult to appreciate on physical exam [45].

Anatomical Considerations

General knowledge of the surface anatomy of the abdominal wall and the expected location of hernias is essential to provide an anatomical framework within which to look for pathology. The abdominal wall is composed of skin, superficial fascia, fat, muscles, transversalis fascia, and the parietal peritoneum. The panniculus adiposus or Camper's fascia is made up of fat deposits in the superficial fascial layer. Scarpa's fascia is deep to this, and contains more fibrous tissue. The muscular layer gives strength to the abdominal wall with its four paired muscles and their respective aponeuroses. The lateral abdominal wall contains the oblique muscles: the external, internal, and transverse abdominal muscles. The aponeurosis of these three muscles joins together to surround the more midline rectus abdomens muscles, then fuse medially to form the line alba, a single central fascial layer [46].

Technical Consideration

Abdominal wall is best evaluated with linear array transducer (5–15 MHz) in the lean patient and a curvilinear transducer (2–5 MHz) in the patients of larger body habitus. The patient should be scanned in the supine position to start and if no pathology is appreciated, intermittent valsalva maneuver or standing position should be utilized to better elucidate an pathology. Typically, the abdominal wall is broken into three main regions: the midline region, the paramedian region, and the inguinal region. The midline region contains the linea alba medially, which appears as a hyperechoic structure bordered on each side by lateral rectus muscles. Beneath the rectus muscles lays the thin hyperechoic peritoneal membrane. The bowel adjacent to the peritoneum can be seen peristalsing with pockets of echoic fluid and hyperechoic commit tails (Fig. 6.27).

The peramedian region is located where the edge of the lateral rectus meets the aponeuroses of the lateral abdominal wall muscles. This area is called the spigelian fascia, and it is where spigelian hernias occur. Particular attention should be paid to the area inferior to the umbilicus, at the level of the line arcuata, as this is where spigelian hernias occur more frequently.

The inguinal region is located on the lower portion of the anterior abdominal wall, with the thigh inferiorly, the pubic tubercle medially, and the anterior superior iliac spine superiolaterally. The hypoechoic psoas muscle will be noted laterally [47].

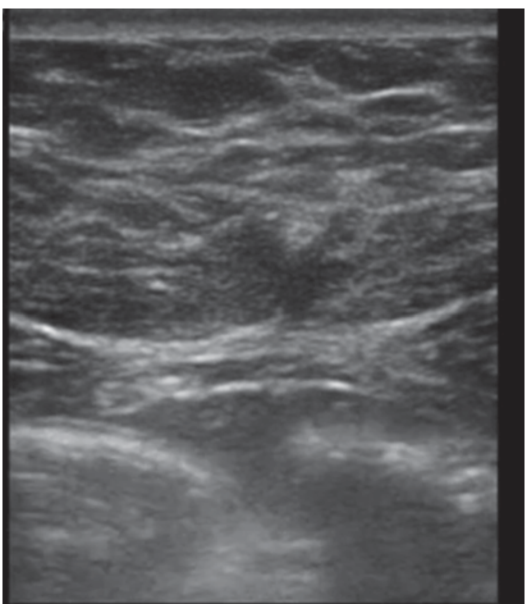

Fig. 6.27 Transverse image through the linea alba

Abdominal Wall Hernia

Abdominal wall hernias are diagnosed sonographically by visualizing the hypoechoic bowel moving through a fascial defect (Fig. 6.28). The presence of peristalsis helps to identify the hernia as bowel. In cross-section the bowel will take on a target sign with an outer hypoechoic muscular layer and a hyperechoic mucosal layer.

Sonographic diagnosis of strangulated hernias can be difficult. Doppler analysis of the hernia can show reduced flow, but is unreliable and technically difficult to perform [48]. Fortunately, bowel obstruction typically occurs prior to strangulation and this can be readily assessed with ultrasound. The sonographic findings of an obstructed bowel include dilated fluid-filled bowel loops with hyperechoic air moving within the fluid, typically in a back-and-forth pattern [9, 50, 51].

Many times the fascial defect is not directly under the area of maximal bulge created by the

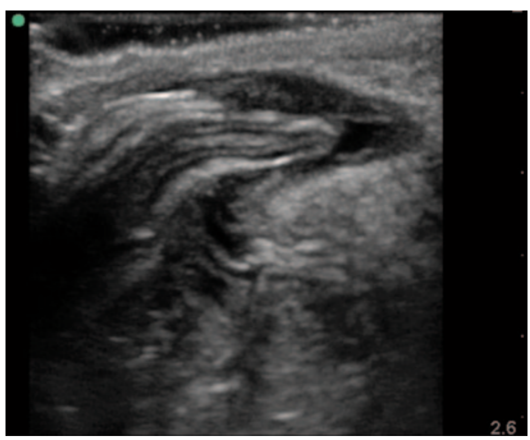

Fig. 6.28 Longitudinal image of anterior wall hernia through fascial defect

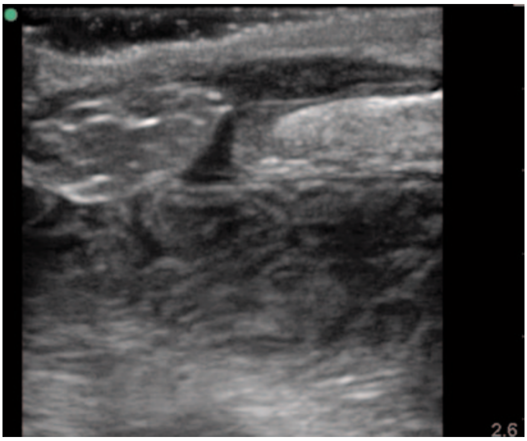

Fig. 6.29 Successful reduction of hernia through fascial defect

hernia. Ultrasound can be used to find the location of the fascial defect and directly observe the reduction (Fig. 6.29).

Summary

- Select the probe depending on the body habitus of your patient. The deeper you need to visualize the lower frequency you need to choose.
- Valsalva can help in better visualization of fascial defects.

Fractures

Clinical Considerations

While not typically considered the method of choice for detecting fractures, this is by convention alone. The interface of the relatively hypoechoic soft tissue to the hyperechoic cortex of bone makes it an ideal indication for ultrasound. Studies have shown that for nasal bone fractures ultrasound has a much higher sensitivity than plain radiographs, thus making it the test of choice [52]. Rib fractures are a common ailment in the setting of trauma, with studies showing plain radiographs to be less than 25 % sensitive, while ultrasound sensitivity is greater than 80 % [53–55]. One study showed that in patients with suspected rib fractures, ultrasound showed fractures twice as often as standard chest radiography [56].

Ultrasound is not limited to diagnosis alone; it can be utilized to help reduced fractures. Chen et al. showed that in the pediatric population ultrasound had a 97 % sensitivity and 100 % specificity for forearm fractures. Once fractures were identified, ultrasound was used to reduce the fracture with a 92 % success rate [57]. This ability to reliably identify and help reduce fractures in real time with an inexpensive, lightweight, portable machine has led to its use in the austere environments of space, submarines, and the wilderness [58–60].

Anatomical Considerations

The rib exam should be conducted around the area of the patient’s tenderness. The rib will be found just beneath the skin, subcutaneous layer and overlying muscle. The anterior portion of the ribs joins the costal cartilage prior to articulating with the sternum. It should be noted that ribs 6 to 10 join together prior to their insertion on the sternum. Nasal bones are found at the dorsum of the nose and the frontal process of the maxilla laterally. The nasal bones join the maxilla laterally at the nasomaxillary suture line and join the frontal bone superiorly at the nasofrontal suture line. Long bones are round and located deeper than either nasal bones or ribs.

Technical Considerations

Evaluations of the ribs should be performed with a linear array transducer (5–15 MHz) with a generous amount of coupling gel. Attention should be paid to the amount of pressure applied to the injured area so as to reduce the pain of the exam. The exam is generally begun with the ribs imaged in short access over the point of maximal tenderness. This should appear as a hyperechoic semicircle with a posterior shadow. The caudal portion of the rib will display the neuromuscular bundle of the intercostal artery and nerve.

Just deep to the rib, the pleural line can be seen as a hyperechoic line with a sliding appearance and scattered comet tails or B-lines. Once a disruption is seen, the rib should be imaged in its longitudinal plane. Care should be taken to follow the angled surface of the rib. Imaging of the nasal pyramids should be performed with a high-frequency liner array transducer (5–15 MHz). Again, a large amount of coupling gel should be used during the exam due to the superficial nature of the bone. The transducer should be placed superiomedially along the lateral nasal pyramid bilaterally, and paramedially to midline to fully evaluate the nasal bone. The cortex should be superficial and appear hyperechoic with a posterior shadow. Long bones are best examined with a linear array transducer (5–15 MHz) when possible; however, due to the depth required to fully evaluate certain bones a curvilinear transducer (2–5 MHz) is sometimes required. Long bones are best imaged in the longitudinal approach and the transducer slid across the entire length of the bone. It is important to visualize the bone from multiple orientations when possible so as to not miss greenstick fractures. The cortex should again appear as a hyperechoic line with a posterior shadow.

Rib Fractures

Rib fractures will appear as a discontinuation in the anterior cortex of the bone (Fig. 6.30). There is typically a small hypoechoic hematoma surrounding the fracture line [61]. If pressure is applied to the transducer, there should be movement and widening of the fracture in real time. When rib fractures are identified, the underlying pleural space should be evaluated for pneumothorax and the underlying lung should be evaluated for pulmonary contusion.

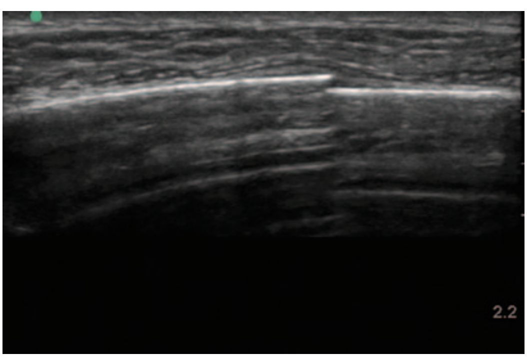

Fig. 6.30 Rib fracture

Nasal Fractures

Nasal bone fractures will be clearly delineated by the same discontinuity of the hyperechoic cortex as rib fractures. The nasal bones sit more superficially then the ribs and care should be taken to ensure proper depth. The fracture area will be surrounded by a hypoechoic hematoma (Fig. 6.31).

Long Bone Fractures

Long bone fractures will show the typical appearance of a separation in the anterior cortex of the bone with surrounding hematoma. If significant displacement is identified, the ultrasound can be performed after a reduction attempt to ensure proper alignment of the cortex (Fig. 6.32 and 6.33).

Maxillary Sinusitis

Clinical Considerations

It is common for intubated patients in the ICU setting to develop maxillary sinusitis [62, 63]. Maxillary sinusitis is a known risk factor for the development of fever and sepsis within the ICU [64, 65]. Unfortunately, the diagnosis of sinusitis by radiographs is difficult because of the low sensitivity of plain films. In a comparison between computer tomography and Waters' view the weighted mean sensitivity for diagnosis of any abnormality in the maxillary sinus was 67.7 %, specificity 87.6 %, accuracy 78.6 %, positive predictive value 82.5 % and negative predictive value 76.9 % [66].

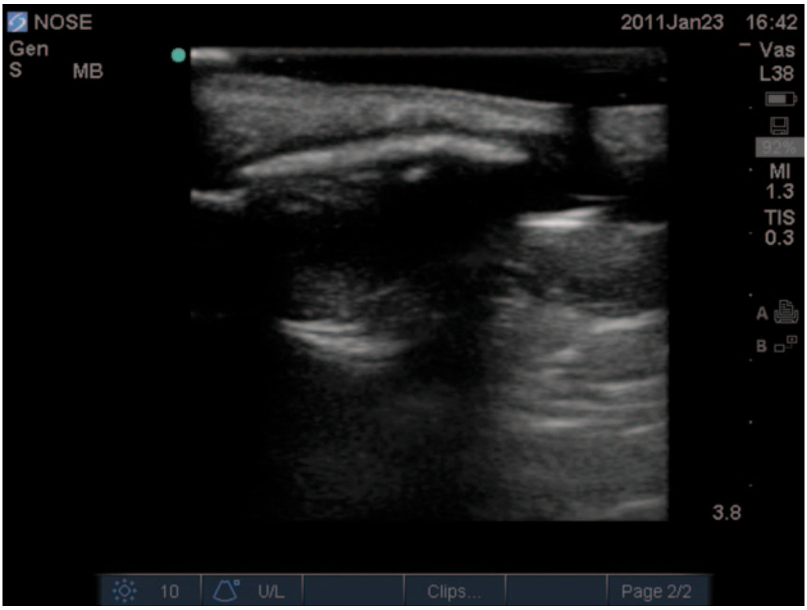

Fig. 6.31 Comminuted displaced nasal bone fracture

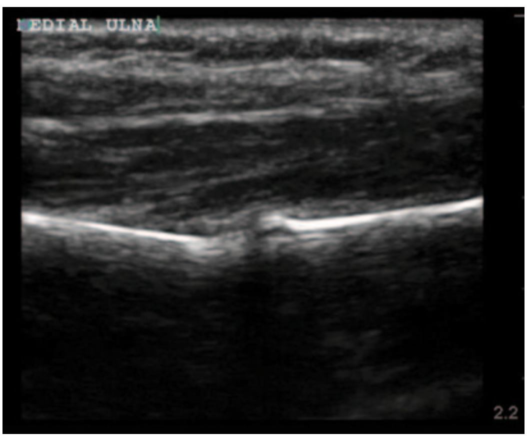

Fig. 6.32 Mid-shaft ulnar fracture

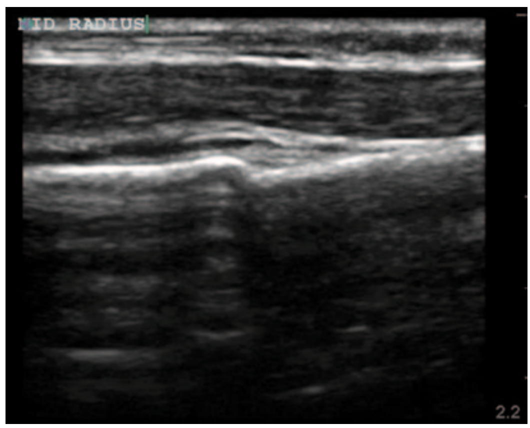

Fig. 6.33 Mid-shaft radial greenstick fracture

Anatomical Considerations

The maxillary sinus is the largest of the four paranasal sinuses. The paired maxillary sinuses are located below the cheeks, above the teeth, and on the sides of the nose. The maxillary sinuses are shaped like pyramids and each contain three cavities that point lateral, medial, and inferior. The borders of the orbit are made up of the zygoma laterally, nasal wall medially, hard palate inferiorly, and inferior orbit superiorly. The anterior wall of the maxillary sinus sits superficial and makes it amenable to ultrasound. Typically, the posterior wall, which sits approximately 2 to 4 cm deep to the anterior wall, is not visible on ultrasound. If the sinus cavity becomes fluid-filled the posterior wall becomes readably identified on ultrasound.

Technical Considerations

Evaluation of the sinus cavity can be performed with a linear array transducer (5–15 MHz) or a

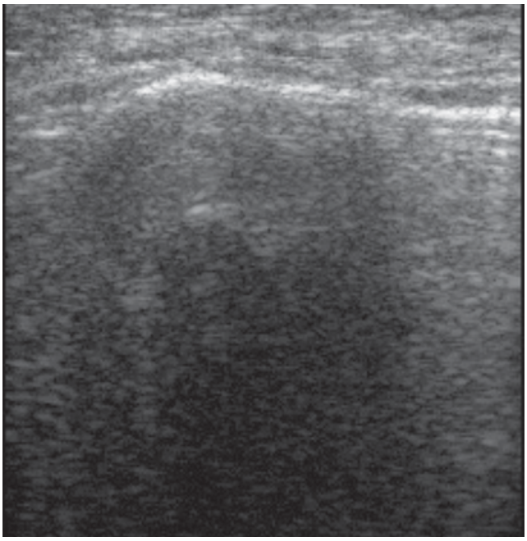

Fig. 6.34 Normal maxillary sinus ultrasound

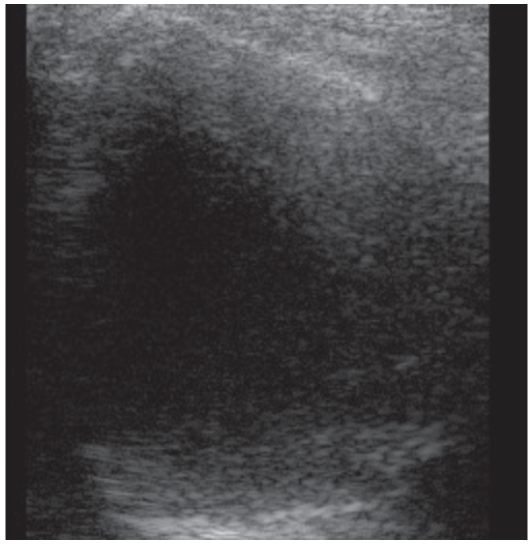

Fig. 6.35 Sonographic evidence of posterior wall of maxillary sinus indicating sinusitis

phased array transducer (3–5 MHz). It is advisable to have the patient seated in the semi-recumbent position in order to maximize the fluid interface with the anterior wall. The depth should be set to the appropriate setting of 5 to 7 cm, and the sinus cavity should be imaged in both the sagittal and transverse planes. In the normal sinus the anterior wall will be visible as a highly echoic linear structure just beneath the skin surface (Fig. 6.34). There is typically some resonance artifact visible deep to the anterior wall. The posterior wall with not be visible in the normal air-filled sinus cavity.

Maxillary Sinusitis

Sinus fluid is identified by the presence of the posterior wall on sonography (Fig. 6.35). Radiographic evidence of fluid collection within the sinus has a strong correlation with the presence of maxillary sinus infection [62]. Ultrasound is used to detect fluid within the sinus cavity and thereby diagnosis sinusitis. The occurrence of ventilator-associated bronchopneumonia in patients undergoing prolonged mechanical ventilation can be prevented by the systematic search for and treatment of nosocomial sinusitis [67]. Hilbert et al. showed that bedside ultrasound had a sensibility, specificity, positive predictive value, and negative predictive value of 100, 96.7, 98.6, and 100 % respectively in intubated ICU patients when compared to computer tomography [68].

Summary

- Ultrasound is an adjunct for diagnosing fractures.
- Expertise is acquired by performing multiple examinations and learning what looks normal and abnormal.
- Once you acquire expertise ultrasound could be of benefit diagnosing fractures since it will avoid radiation exposure and transporting the patient to different places in the hospital.

Assessment of the Airway

Clinical Considerations

Ultrasound can be used to obtain information regarding the supraglottic, glottic, and infraglottic structures. A detailed understanding of the larynx is required to fully appreciate the structures identifiable on bedside ultrasound and its complete clinical utility. Ultrasound can be used to (1) identify fractures of the hyoid bone or the thyroid cartilage, (2) evaluate vocal cord motion, and (3) confirm endotracheal intubation.

Anatomic Considerations

The thyroid cartilage is a broad cartilaginous structure composed of two intersecting laminae that meet in the midline at approximately 90 degrees. The thyroid cartilage becomes calcified with age, which can decrease ultrasound transmission. Inferior to the thyroid cartilage lays the cricoid cartilage, which forms a ring around the airway and is attached to the thyroid cartilage by the cricothyroid ligament. Superior to the thyroid cartilage lays the ossified hyoid bone, which is attached to the thyroid via the thyrohyoid membrane. Deep to the thyrohyoid membrane lays the epiglottis, which gives way to the mucinous vestibular folds or false vocal cords. The true cords lay deep to the thyroid cartilage [69].

Technical Considerations

The airway should be imaged with a high-frequency linear array transducer (5–15 MHz). Choosing a transducer with a smaller footprint can also be beneficial as some larger footprints will have trouble in patients with short necks. Due to the curved nature of the larynx copious amount of compelling gel should be applied as to maximize the transducer-soft tissue interface.

Hyoid Bone

The hyoid bone should imaged in the transverse plane with the neck extended (Fig. 6.36). Due to its thinness nearly the entire hyoid bone can be seen in one image. Fracture of the hyoid bone will be seen as a disruption of the hyperechoic cortex with a step off-like pattern. A hypoechoic hematoma may be identified surrounding the fracture.

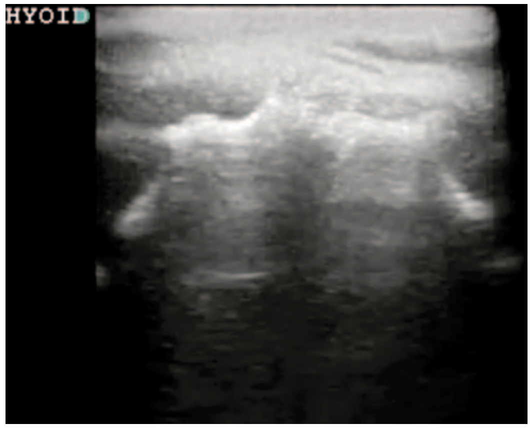

Fig. 6.36 Transverse image of hyoid bone

Thyroid Cartilage

The thyroid cartilage should be imaged in the transverse plane and the paramedical sagittal plane in the supine position with the neck hyperextended. It will appear as an upside-down "V"-shaped structure of varying echo-intensity (Fig. 6.37). It can be relatively hypoechoic in the young to hyperechoic in the elderly. The hypoechoic strap muscles sit just anterior to the cartilage. Depending on the level of calcification of the thyroid cartilage, fractures of the cartilage may not be readily apparent. Signs of hypoechoic hematoma may be the indicator of cartilaginous disruption.

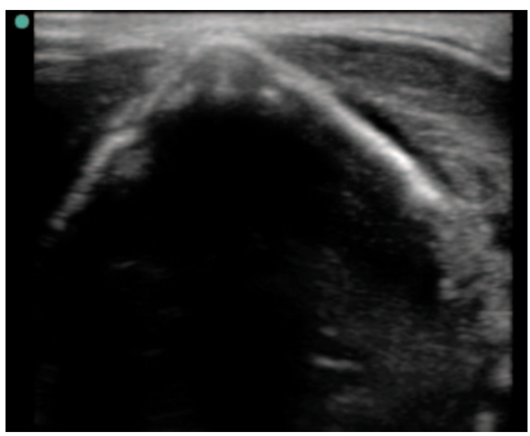

Fig. 6.37 Transverse image of thyroid cartilage

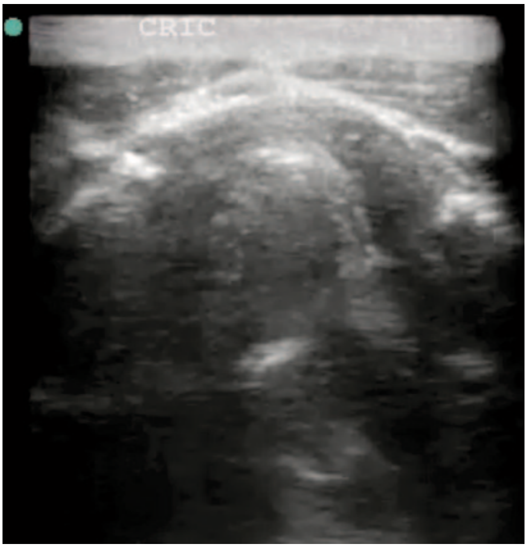

Fig. 6.38 Transverse image through the cricoid membrane of vocal folds

Vocal Cords

The vocal cords can be imaged in the transverse plane by imaging directly through the thyroid cartilage (Fig. 6.38). If the cartilage has developed calcification, making it hard to image through, the superior approach through the thyrohyoid membrane can be used. The transducer is placed in the transverse orientation just cranial to the thyroid cartilage and angled downward. The arytenoid cartilage is easily identified in this approach.

The patient can be asked to perform prolonged vocalization exercises such as saying "eeeeee." This will cause medialization of the vocal cords and elevate the glottis. This can help to evaluate for any asymmetry in vocal cord movement. A paralyzed vocal cord can appear in a lower position and shorter than the normal cord. Also, if the paralyzed cord is in the medial position this will be readily apparent on real-time imaging [70, 71].

Endotracheal Intubation

Real-time evaluation of the endotracheal attempt can be monitored by the left paramedian transverse approach. The hypoechoic esophagus should be visualized just to the left of the trachea. As the intubation attempt is being made, if the endotracheal tube passes into the esophagus instead of the trachea, the hyperechoic double-walled lining of the anterior surface of the tube can be immediately identified with an intense posterior shadow (Fig. 6.39). If the endotracheal tube passes into the trachea the esophagus will remain normal in appearance (Fig. 6.40) [72, 73]. Once the tube has been placed, confirmation above the carina can be determined by the presence of sliding lung bilaterally [74, 75].

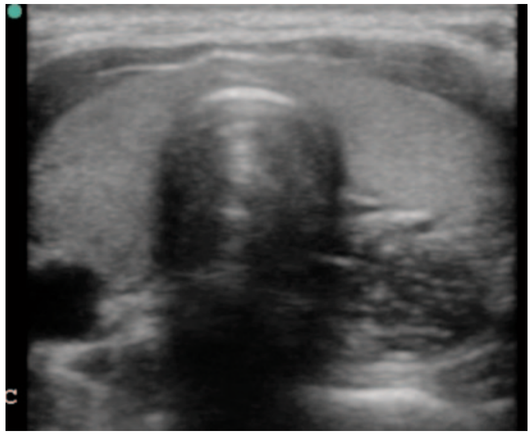

Fig. 6.39 Transverse image of trachea and esophagus that has been distended by carbonated beverage

Fig. 6.40 Transverse view of endotracheal tube cuff in the trachea

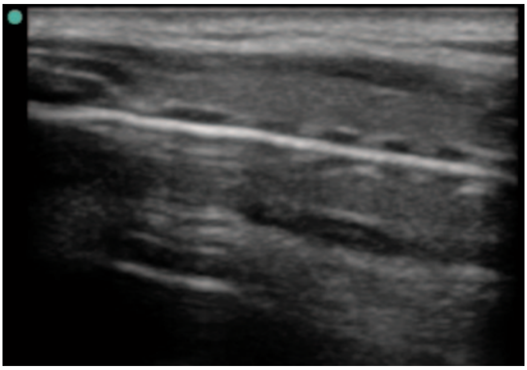

Fig. 6.41 Longitudinal view of cricothyroid membrane

In the event of a failed airway, ultrasound can also be used to proper locate the cricothyroid membrane (Fig. 6.41) [76]. The liner array transducer is used in the linear orientation medially to identify the membrane. In the Curtis et al. study it took less than 4 s to identify the cricothyroid membrane, and less than 30 s to place an incision, pass a gum elastic bougie and secure a 6.0 endotracheal tube [77].

Summary

- The gold standard to evaluate placement of the endotracheal tube is capnography. Ultrasound can be extremely useful, especially in cases where capnography can be decreased for other reasons such as a patient with declining cardiac output and perfusion (code situation).
- When evaluating the airway use a high-frequency probe.
- It is useful to become familiar with the sonographic appearance of airway anatomy in elective situations to prepare yourself better for an urgent situation.

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7 Other Important Issues: Training Challenges, Certification, Credentialing and Billing and Coding for Services

Kazuhide Matsushima, Michael Blaivas and Heidi L. Frankel

Introduction

As ultrasound has become increasingly important in the diagnosis and treatment (through image-guided interventions) of ICU patients, practitioners must acquire and interpret the images appropriately. Expert statements regarding competency and ultrasound training have been published by different societies and organizations [1–3]. The American College of Chest Physicians (ACCP) and the La Société de Réanimation de Langue Française (SRLF) have collaborated to define the competencies in critical care ultrasonography [4]. They defined the elements of critical care ultrasonography to include the following: pleural ultrasonography, lung ultrasonography, abdominal ultrasonography and vascular ultrasonography (guidance of vascular access and diagnosis of venous thrombosis). Of note, they emphasized that competence is different from certification. The Society of Critical Care Medicine (SCCM) published the comprehensive review regarding the use of ultrasound in critical care medicine [5, 6]. Recently, an SCCM Task Force has provided training objectives for critical care ultrasound (CCU) and Advanced Critical Care Echocardiography (ACCE) [7]. It recognized ACCE as a more advanced skill and developed recommendations for achieving competence.

CCU: Knowledge

1. Physical principles of ultrasound image formation and pulse-wave, continuous, and color Doppler
2. Artifacts and pitfalls
3. Operation of ultrasound machines, including controls and transducers
4. Equipment handling, calibration, bioeffects safety, infection control, and electrical safety
5. Data management, including image storage, integration with hospital image management systems, reporting, quality assurance process
6. Ergonomics of ultrasound exam in intensive care unit environment
7. Indications, contraindications, limitations, and potential complications of critical care ultrasound and echocardiography

K. Matsushima (✉)
Department of Surgery, University of Southern California, LAC+USC Medical Center, 1200 N. State street, Inpatient tower (C), Rm C5L100, Los Angeles, CA 90033, USA
e-mail: mkazu45@gmail.com

M. Blaivas
Department of Emergency Medicine, St. Francis Hospital, PO Box 769209, Roswell, GA 30076, USA
e-mail: mike@blaivas.org

Department of Medicine, University of South Carolina, Columbia, SC, USA

H. L. Frankel
32427 sea raven drive Rancho Palos Verdes, CA 90275
e-mail: heidileefrankel@gmail.com

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8. Normal sonographic anatomy of each relevant modality and organ system
9. Standard windows and views for each relevant modality
10. Incorporation and integration of focused transthoracic with other modalities of hemodynamic monitoring
11. Knowledge of normal and abnormal right and left ventricular size and systolic function
12. Knowledge of normal and abnormal cardiac atrial size
13. Ability to identify signs of chronic cardiac disease
14. Estimation of central venous pressure and limitation of ultrasound estimation
15. Ultrasound manifestations of pericardial effusion and signs of tamponade and limitation of ultrasound diagnosis of tamponade
16. Ultrasound manifestations of septic shock and differentiation between severe hypovolemia and vasodilatory state
17. Ultrasound manifestation of severe hypovolemia and understanding of the limitation of assessment of "fluid status" with ultrasound
18. Ultrasound manifestations of pneumothorax and understanding of the limitation in diagnosis of pneumothorax
19. Ultrasound characterization of pleural effusion
20. Ultrasound manifestations of venous thrombosis of lower extremities
21. Incorporation of cardiac ultrasound in Advanced Cardiac Life Support (ACLS) protocols
22. Principles of needle/wire guidance with ultrasound for bedside procedures, including vascular access, thoracentesis, paracentesis, and tube thoracotomy

CCU: Skills

1. Ability to operate ultrasound machines and utilize their controls to optimize image quality
2. Ability to recognize common ultrasound artifacts (e.g. reverberation, side lobe, mirror image)
3. Ability to select an appropriate probe for a given ultrasound examination
4. Ability to insert transesophageal echocardiography probe in anesthetized, tracheally intubated patient (if this competence is desired)
5. Ability to incorporate ultrasound examinations in the bedside management of critically ill or injured patients during cardiopulmonary arrest or in shock
6. Ability to perform basic transthoracic echocardiography and differentiate normal from markedly abnormal cardiac structures and function
7. Ability to recognize marked changes in global left systolic function
8. Ability to recognize marked hypovolemia
9. Ability to recognize gross valvular lesions and dysfunction
10. Ability to detect significant pericardial effusions
11. Ability to rule out pneumothorax in patients with normal chest walls
12. Ability to assess pleural effusion: size, location, degree of loculation
13. Ability to assess alveolar/interstitial syndrome
14. Ability to recognize large deep venous thrombosis in femoral veins
15. Ability to incorporate ultrasound in patient resuscitation during cardiopulmonary arrest without interfering with ACLS protocols or interrupting chest compressions.
16. Ability to communicate ultrasound findings to other healthcare providers, the medical record, and patients
17. Recognize when referral to or consultation with other specialists is necessary
18. Ability to recognize complications of various critical care ultrasound applications
19. Ability to guide bedside procedures with ultrasound (e.g., vascular access, thoracentesis, paracentesis, arthrocentesis)

ACCE: Knowledge

1. All knowledge needed to perform critical care ultrasound
2. Advanced knowledge of artifacts and pitfalls in interpretation.

3. Knowledge of comprehensive transthoracic and/ or transesophageal echocardiography views
4. Detailed knowledge of qualitative and quantitative echocardiography
5. Detailed knowledge of heart-lung interactions in spontaneously breathing and mechanically ventilated patients
6. Detailed knowledge of diseases of the heart relevant to care of critically ill or injured patients (e.g., dynamic left ventricular outflow tract obstruction, systolic anterior motion of the mitral valve, pericardial constriction, restrictive cardiomyopathy, ischemic cardiomyopathy, mitral or aortic stenosis)
7. Detailed knowledge of normal and abnormal left ventricular systolic function, including segmental wall motion abnormalities
8. Detailed knowledge of normal and abnormal left ventricular diastolic function
9. Detailed knowledge of normal and abnormal right ventricular function, including the appearance of acute and chronic pulmonary hypertension, right ventricular infarct, pulmonary heart failure, tricuspid annular plane systolic excursion, right ventricular fractional area change
10. Detailed knowledge of commonly encountered complications of acute coronary syndrome
11. Detailed assessment of hemodynamic significance of valve dysfunction
12. Detailed knowledge of tamponade physiology, including flow variation in the right and left hearts, chamber collapse, inferior vena cava plethora
13. In-depth knowledge of applications of critical care echocardiography in evaluating fluid responsiveness
14. Knowledge of anatomy, physiology, and implications of intracardiac and intrapulmonary shunts
15. Knowledge of echocardiographic manifestations of intracardiac masses and thrombi
16. Detailed knowledge of other diagnostic modalities relevant in hemodynamic management of critically ill or injured patients

ACCE: Skills

1. All the skills needed in basic critical care ultrasound
2. Ability to perform comprehensive transthoracic and/or transesophageal echocardiography exam
3. Ability to quantify flows and pressures across various cardiac chambers
4. Ability to acquire comprehensive hemodynamic data
5. Ability to quantify systolic and diastolic left ventricular function
6. Ability to quantify right ventricular systolic function
7. Ability to recognize subtle left ventricular wall motion abnormalities
8. Ability to quantify normal and abnormal native and prosthetic valvular function
9. Ability to evaluate hemodynamic consequences of pericardial effusion and tamponade
10. Ability to assess fluid responsiveness in spontaneously breathing and mechanically ventilated patients using validated echocardiographic dynamic indices of preload
11. Ability to assess for the presence of intracardiac and intrapulmonary shunts
12. Ability to assess for intracardiac masses and thrombi
13. Ability to recognize limitations and inaccuracies of the chosen modality and identify additional diagnostic modalities necessary for the management of a critically ill patient, and recognize situations when referral to specialist is required

Training and Proficiency

Two potential pathways exist for physicians to complete training for the ultrasound in the ICU– either fellowship-based (particularly for younger practitioners) or practice-based. Different requirements in licensing, board-certification, and the duration of didactics have been suggested by SCCM for trainees in each pathway (Tables 7.1 and 7.2). These also address differential training

Table 7.1 Training pathways in critical care ultrasound with focused cardiac ultrasound

Requirements	Fellowship pathway	Practice experience pathway
Current license to practice medicine	Required	
Current medical board certification	Certified or eligible	
Specific training/experience in critical care	Fellowship in critical care medicine or 24 months of clinical experience in critical care medicine, with at least 25 % of clinical time dedicated to care of critically ill patients for the last 2 years of practice	
Didactics	Curriculum during fellowship training	20 h of continuing medical education, AMA[a] Category 1 credits or their equivalent; credits should be obtained while acquiring practical experience in critical care ultrasound
Spectrum of pathology	Broad, including main diagnoses within each core application	
Examination of special competence	Not required	

[a] American Medical Association

Table 7.2 Training pathways in advanced critical care echocardiography

Requirements	Fellowship pathway	Practice experience pathway
Current license to practice medicine	Required	
Current medical board certification	Certified provider	
Specific training/ experience in critical care	Fellowship in critical care medicine or 24 months of clinical experience in critical care medicine, with at least 25 % of clinical time dedicated to care of critically ill patients for the last 2 years of practice	
Didactics	Curriculum during fellowship training	40 h of AMA[a] Category 1 credits or their equivalent; credits should be obtained while acquiring practical experience in advanced critical care echocardiography
Spectrum of pathology	Full spectrum of critical care diagnosis	
Examination of special competence	Required	

[a] American Medical Association

paradigms, number of examinations and format of competency examination.

Comprehensive ultrasound training courses for each level of physicians have been conducted by several professional societies. These courses generally consist of a didactic session and a hands-on skill session over a period of one or more days. The American College of Surgeons (ACS) provides an ultrasound education program for surgeons and surgical trainees [8]. A focused ECHO/ ICU ultrasound application module introduces fundamental skills including ultrasound-guided central line insertion, thoracic and vascular imaging and focused echocardiography. The SCCM offers basic, advanced and pediatric critical care ultrasound courses. The American College of Chest Physicians (CHEST) has also developed various critical care ultrasonography courses for intensivists [9]. These courses include on-line submission of video clips is required after completion of an internet-based tutorial and hands-on training. The required content of images includes cardiac, thoracic, abdominal and vascular (deep veins) views. Upon successful completion of the course, a certificate of completion program is issued. How satisfactory completion of these courses relates to credentialing remains to be determined [10].

Certification

Certification is the process whereby an external agency recognizes competence in a discipline or set of skills. Often, this agency is a specialty board (e.g., The American Board of Surgery) that sets criteria for certification usually involving an examination. Other agencies that grant certification may not be housed under the domain of the specialty board. For ultrasound, SCCM and the American College of Emergency Physicians (ACEP) do not recommend certification for basic critical care ultrasound (CCUS). However, they do recommend certification for ACCE. At present, there is not an examination and board that addresses ACCE. The National Board of Echocardiography (NBE) does issue certification for intraoperative transesophageal echocardiography. Preliminary discussion has occurred between various critical care societies and the NBE for ACCE certification (personal communication). However, at present, no such certification exists.

Number of Examinations to Attest to Competency

By extrapolating from work on intraoperative and office-based echocardiography, SCCM developed recommendations for ACCE and CCUS examinations to ensure competency. Of course, this is highly provider-dependent. Some practitioners may develop competency well before the recommended targets, others may require additional experience. SCCM recommends interpretations of at least 400 ACCE examinations—200 of which must be personally performed. During the training period, 50 annual examinations should be performed. Table 7.3 provides SCCM's recommended requirements for competence in CCUS.

Credentialing

Practitioners who perform hospital-based procedures must conform to their scope of practice as outlined in a formal credentialing process. Credentialing serves to assess and confirm the qualifications of a licensed or certified health care practitioner [11]. The American Medical Association (AMA) policy statement regarding privileging for ultrasound imaging states that (1) ultrasound imaging is within the scope of practice of appropriately trained physicians, (2) broad and diverse use and application of ultrasound imaging technologies exist in medical practice, (3) privileging of the physician to perform ultrasound imaging procedures in a hospital setting should be a function of hospital medical staffs and should be specifically delineated on the Department's Delineation of Privileges form, (4) each hospital medical staff should review and approve criteria for granting ultrasound privileges based upon background and training for the use of ultrasound technology and strongly recommends that these criteria are in accordance with recommended training and education standards developed by each physician's respective specialty [12].

The ACEP issued its first edition of ultrasound guidelines a decade ago [13]. These guidelines recommended implementing a transparent, high quality, verifiable and efficient credentialing system as an integral component of building an ultrasound program. The SCCM Ultrasound Certification Task Force has provided the key components of credentialing in ultrasound for critically ill patients as follows [7]:

Table 7.3 Recommended requirements for competence in critical care ultrasound

Type of Ultrasound	Application	Minimum number interpreted	Minimum number personally performed
Diagnostic	Basic critical care echocardiography	50	30
	Pleural/pulmonary ultrasound	30	20
	Focused abdominal ultrasound	30	20
	Vascular ultrasound	30	20
Procedural	Vascular access	10	10
	Thoracentesis/thoracostomy	5	5
	Pericardiocentesis	5	5
	Paracentesis	5	5
	Other needle guidance procedures	5	5

- Departments should follow the specialty-specific guidelines for the credentialing and privileging process.
- Department should grant CCUS and ACCE privileges separately.
- Each department should choose which core critical care ultrasound applications are relevant to its critical care environment, should decide whether to credential for ACCE, and should track critical care providers in the use of these applications by following a continuous quality improvement process.
- Providers applying for privileges in CCUS and ACCE should complete the necessary training.
- Privileges in ACCE should require testamur or certification status on an exam of special competence.
- Credentialed providers should demonstrate clinical competence during each reappointment (at least every 2 years) and actively participate in continuous quality improvement as they do with other procedures and techniques in which they are credentialed.

Billing and Coding

To obtain reimbursement for the ultrasound studies in the ICU, proper documentation of procedures needs to be performed for each case. A documented report should include the indications of the study using International Classification of Diseases (ICD) codes, utilized technique, findings, and interpretation by the credentialed physician. Storage of the key images can be performed on printed paper or digital file incorporated in the radiology system. Further, the identification of each procedure should be appropriately performed using the CPT codes and CPT code modifiers for the billing purposes.

CPT is the medical nomenclature widely used to report medical procedures and services [14]. All physicians who perform a bedside ultrasound in the ICU should be familiar with the CPT code. The CPT codes for the commonly performed ultrasound studies are listed below;

- Diagnostic
  - Focused cardiac ultrasound, transthoracic: 93308
  - Pleural/pulmonary ultrasound: 76604
  - Focused Assessment with Sonography for Trauma (FAST), Extended FAST (EFAST): 93308 for the cardiac examination, 76705 for the abdominal examination, 76604 for the thoracic examination
  - Vascular ultrasound for the deep vein thrombosis: 93971
- Procedural
  - Vascular access guidance: 76937
  - Thoracentesis guidance: 76942
  - Paracentesis guidance: 49083
  - Pericardiocentesis guidance: 76930
  - Arthrocentesis guidance: 76942
  - Abscess aspiration guidance: 76942

A limited ultrasound study is often performed by physicians in the ICU. This is because the ultrasound studies are normally focused on a certain anatomical area to answer clinical questions. While a complete study is defined as one which an attempt is made to visualize and diagnostically evaluate all of the major structures within the anatomic description, a limited study is defined as one that addresses only a single area or single diagnostic problem. There are generally different CPT codes for a complete study and a limited study. For example, 93308 is for a limited transthoracic echocardiography defined as "Echocardiography, transthoracic, real-time with image documentation (2D), includes M-mode recording, when performed, follow-up or limited study." For a complete study of cardiac ultrasound, 93306 and 93307 are the CPT codes defined as "Echocardiography, transthoracic, real-time with image documentation (2D), includes M-mode recording, when performed, complete, with spectral Doppler echocardiography, and with color flow Doppler echocardiography (93306) or without spectral or color Doppler echocardiography (93307)."

The CPT modifiers are used to provide the additional and more accurate information regarding a procedure and service. It is a crucial part of successful coding and billing for the ultrasound studies in the ICU to use the appropriate modifiers. Commonly used modifiers for ultrasound procedures include:

- **Professional component (-26 modifier)**: For professional services or procedures, typically reported for ultrasound studies performed and interpreted by the physicians in the ICU.
- **Reduced services (-52 modifier)**: Reported when the physicians reduced or eliminated a portion of service and procedure.
- **Distinct procedural service (-59 modifier)**: Reported for services or procedures that are not typically reported together, but are appropriate under certain circumstances.
- **Repeat procedure by same physician (-76 modifier)**: Reported for a repeat procedure by the same physician on the same date such as a repeat FAST exam for trauma patients.
- **Repeat procedure by another physician (-77 modifier)**: Reported for a repeat procedure by another physician in a different specialty or different group on the same date.

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Clinical Applications of Ultrasound Skills

8

Paula Ferrada MD FACS

Introduction

Since the wide availability of ultrasound technology, physicians everywhere have incorporated the use and training of this technique [1–5]. For the critical care physician, ultrasound has become an essential tool for guiding therapy [6–10].

Although in most instances the care of the critically ill happens in the confines of a specialized unit, critical care must be brought to all scenarios as a lifesaving strategy [11].

Directing therapy with ultrasound, especially in the unstable patient, requires training and initiative; and it can be done in the operating room, emergency room, in any place where necessary [4, 12].

In underserved areas of the world, where other technologies are not readily available, ultrasound might be the only choice for interrogating fluid status, cardiac function, intra-abdominal bleeding or any life-threating emergency [13, 14].

Emergency medicine has led the way for training of non-radiologists and non-cardiologists in ultrasound and echocardiography[15, 16]. Surgeons, especially those of us that are also critical care physicians, need to approach the subject of learning this technique more enthusiastically, for the only way to have a voice in the matter is to speak the same language [1, 7–9, 15–28]. Surgeons described the use of ultrasound to evaluate for intra-abdominal fluid while treating trauma patients, and how these teachings are included in the Advanced Life Support Training available for all providers [27]. There is no reason why any subspecialty should fall behind in the learning of this technique, especially since its use is directed to life-saving maneuvers. In fact, learning point-of-care ultrasound should be inclusive of nurses, paramedics, medical students, any provider who at one point can use this tool to achieve better patient outcome [29–31].

Critical conditions such as respiratory decompensation and hypotension are frequently encountered in the intensive care setting [32, 33]. Respiratory insufficiency can occur rapidly, and is not necessarily prone to an early or accurate diagnosis with the traditional radiological tools available [34–36]. The accuracy of lung ultrasound has been established for the diagnosis of pneumothorax, lung consolidation, alveolar-interstitial syndrome, and pleural effusion [2, 37–41].

Ultrasound can also be a useful tool to evaluate hemodynamic deterioration [42]. A problem-oriented cardiac evaluation is not only feasible, but lifesaving, in many situations, including hypovolemia, right-sided cardiac failure, decreased left ventricular function and the presence of

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Prof. P. Ferrada MD FACS (✉)
Critical Care and Emergency Surgery, Virginia Commonwealth University, 1200 E Broad St, Richmond, USA
e-mail: pferrada@mcvh-vcu.edu

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hemodynamically significant pericardial effusion [4, 7, 8, 43–45].

One of the few disadvantages of these techniques is that is operator-dependent. The aim of the previous chapters is to breach the knowledge gap. This chapter explains the applications when treating a hypotensive patient, offering basic and advanced concepts on a practical, user-friendly approach.

Clinical Applications

When treating an unstable patient a useful first view is the subcostal or subxyphoiod cardiac window. This window gives the operator immediate information regarding the fluid status, contractility and presence of effusion.

Hypovolemia and Trauma

A hyperdynamic heart as well as a flat IVC can be interpreted as hypovolemia (Video 8.1). This video shows an IVC that belongs to a patient relatively hypotensive while observing a splenic laceration. On this particular case, obtaining these views allowed the clinician to expedite surgical intervention.

An empty or hyperdynamic heart is also indicative of hypovolemia. Video 8.2 shows an empty left ventricle. This patient also had an obvious pericardial effusion.

If there is evidence of hypovolemia in the ultrasound, resuscitation should be started immediately, and the use of ultrasound can help in finding the cause. The operator can complete a FAST rapidly and evaluate the abdomen and the chest for fluid (Videos 8.3 and 8.4). Using the same probe, a rapid evaluation of the pleura can be possible. For this decrease the depth in the image. Absence of comet tails and pleural movement will give the diagnosis of pneumothorax.

Pump Issues

If the heart shows decreased contractility on the left side on this view, the operator can change therapy by starting inotropes (Video 8.5). This video belongs to a patient who was found down and was brought to the trauma bat with the presumption of trauma. Since he had poor left ventricular function, it is obvious that massive fluid resuscitation was contraindicated in his care; however, without the cardiac view it would be impossible to predict that the cause of hypotension was not hypovolemic shock.

If there is dilation of the right side of the heart, this might indicate acute pulmonary hypertension. In our critically ill population, this is most likely a sign of pulmonary embolism, and anticoagulation would be immediately indicated (Video 8.6). This clip belongs to a patient that after multiple orthopedic operations became acutely hypotensive. Obtaining this quick cardiac evaluation allowed us to start anti-coagulation immediately to treat a pulmonary embolism without waiting for a confirmatory test that would require traveling.

A pericardial effusion in the setting of hypotension can be interpreted as tamponade, especially if it is compressing the right side of the heart (Video 8.7). As a pitfall in trauma even a small effusion can be sign of a life-threating injury to the heart; and in some cases if the defect in the pericardium is large or if the pericardium has been previously violated (CABG), the blood would drain into the thoracic space rather than accumulating in the pericardium (Video 8.8). The last video with a very small effusion belongs to a patient that had blunt cardiac rupture of the right ventricle. He had a CABG 3 years prior so all the blood was drained to the left chest.

Desaturation

On a patient with low saturation the ultrasound can also be an invaluable tool.

The phased array probe can be used to evaluate the base of the lungs as well as the pleura for consolidation, effusion or pneumothorax. Video 8.9 shows a pneumothorax; compare it to the chest x-ray of the same patient in Fig. 8.1. A CT scan of the same patient (Fig. 8.2) shows the pneumothorax not to be as insignificant as pre-

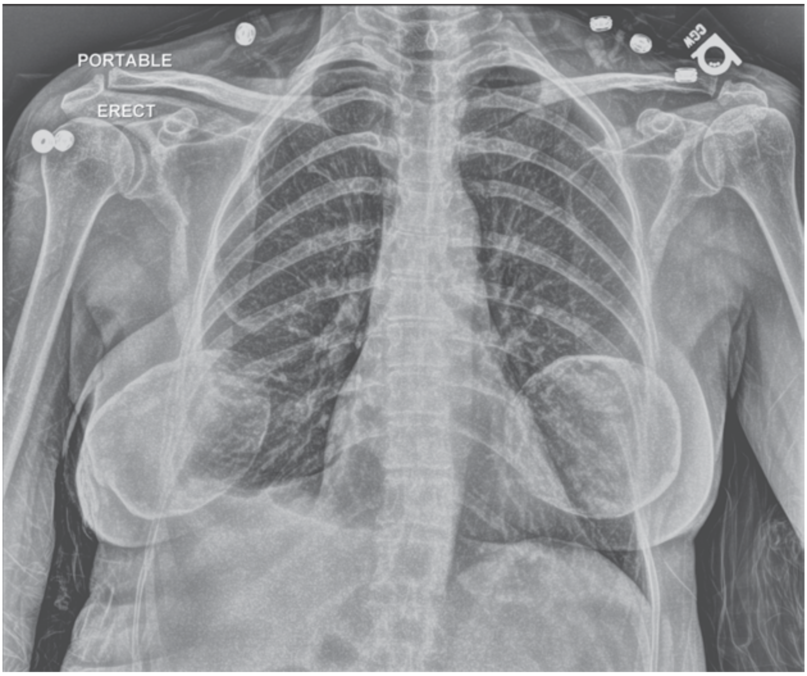

Fig. 8.1 This is the chest x-ray of an occult pneumothorax. This image belongs to the same patient in Video 8.9

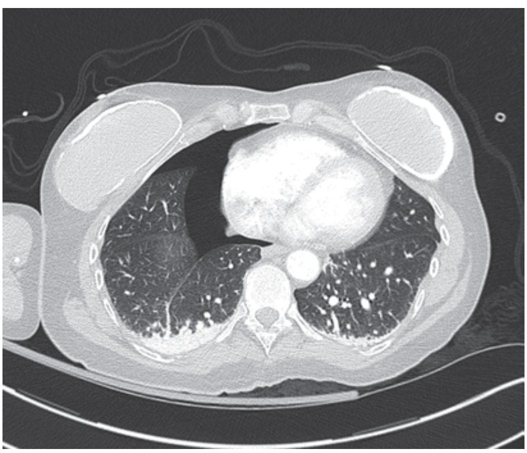

Fig. 8.2 This CT scan shows the pneumothorax not to be as insignificant as previously believed to be on the x-ray. The image belongs to the same patient in Fig. 8.1 and Video 8.9

viously believed to be on the x-ray. Video 8.10 shows a pleural effusion on a patient with acute desaturation while in the ICU that required emergent re-intubation; compare it to the chest x-ray taken the same day, before extubation Fig. 8.3.

Summary

Ultrasound has many applications, especially when evaluating a patient whose clinical status is deteriorating. Expertise is required to trust the examination in these late stages of resuscitation. Therefore, previous training and experience in performing this test in healthier individuals will come in handy.

Appendix

Video 8.1 A flat IVC. In the setting of hypotension this image is diagnostic of hypovolemia.
Video 8.2 A hyperdynamic heart. In the setting of hypotension, a hyperdynamic heart should be considered a sign of hypovolemia.
Video 8.3 Positive EFAST in Morrison's pouch. On a hypotensive trauma patient, this fluid is blood until proven otherwise.
Video 8.4 Positive EFAST for intrathoracic fluid. On a hypotensive trauma patient, this fluid is blood until proven otherwise.

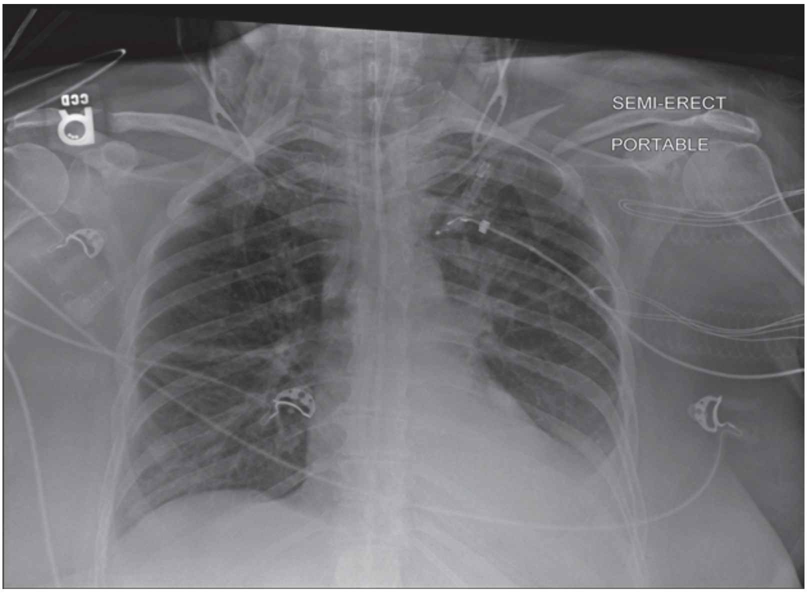

Fig. 8.3 This is a chest x-ray showing pleural effusion. It belongs to the same patient on Video 8.10. The ultrasound video shows how a large pleural effusion can look moderate or small on portable x-ray

Video 8.5 Poor contractility.
Video 8.6 Right-sided cardiac dysfunction.
Video 8.7 Cardiac tamponade. Notice the complete compression of the right-sided cardiac structures.
Video 8.8 This video shows a pericardial effusion and a pleural effusion. In this case it was an injury to the right ventricle decompressing into the thoracic cavity.
Video 8.9 Pneumothorax. This video shows the lung point sign demarcating the penumothorax.
Video 8.10 Pleural effusion.

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