1 Fundamentals

Introduction

To become versed in the language of ultrasonography, it is necessary to review some of the basic principles of physics. The wave physics principles of ordinary (i.e., audible) sound apply to ultrasound (US) and its applications as well. Thus, to create a foundation for further discussions, a number of definitions and basic concepts are presented here.

Basic definitions and physics principles

Amplitude is the peak pressure of a wave (Figure 1.1). Measured in decibels (dB), this can describe the volume (or "loudness") of audible sound or the strength of the echo in ultrasound.

Ultrasound machines can measure the intensity (amplitude) of the returning echo; analysis of this information affects the brightness of the echo displayed on the screen. Strong returning echoes translate into bright or white areas on the screen (known as *hyperechoic*). Weak returning echoes translate into dark gray or black areas on the screen (known as *hypoechoic* or *anechoic*, respectively). The "gray scale" of diagnostic ultrasonography is the range of echo strength as it correlates to colors on a black–white continuum (Figure 1.2).

Velocity is defined as the speed of the wave. It is constant in a given medium and is calculated to be 1540 m/s in soft tissue (i.e., the *propagation speed* of soft tissue is 1540 m/s). Using this principle, an ultrasound machine can calculate the distance/depth of a structure by measuring the time it takes for an emitted ultrasound beam to be reflected back to the source (Figure 1.3). Sonar, as used on submarines, is based on this same principle.

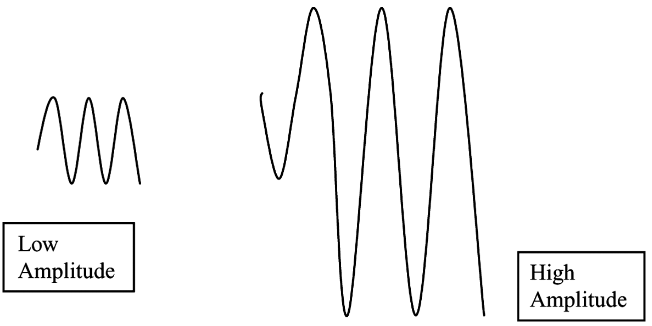

Figure 1.1 Low- and high-amplitude sound waves.

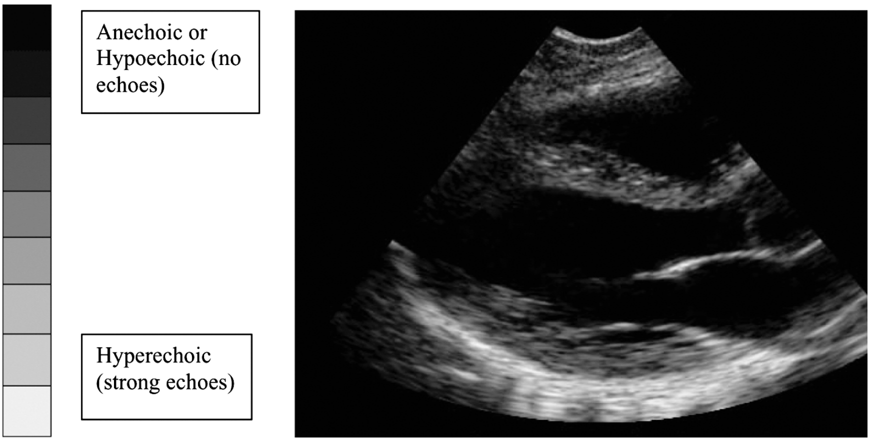

Figure 1.2
Most ultrasound machines have 256 shades of gray, corresponding to the returning amplitude of a given ultrasound wave.

Frequency is the number of times per second the wave is repeated. One hertz (Hz) is equal to one wave cycle per second. Audible sound has frequencies from 20 to 20 000 Hz. By definition, any frequencies above this range are referred to as ultrasound. The frequencies used in diagnostic ultrasound typically range from 2 to 12 MHz (1 MHz = 1 million Hz).

High-frequency sound waves generate high-resolution pictures. High-frequency sound waves use more energy because they generate more waves, which send back more echoes over short distances to the machine, creating detailed pictures of shallow depth (Figure 1.4). However, because they lose energy more rapidly, high-frequency ultrasound waves do not penetrate long distances. Conversely, lower-resolution waves conserve energy. Although they do not create pictures of equally high resolution, they are able to penetrate deeper into tissue. Imagine sitting near a high-fidelity stereo system. Your ears will note great detail in the high-frequency (treble) range, and less detail in the low-frequency (bass) range. This is why "tweeters" should be aimed at the listener while the subwoofer can be placed anywhere. Downstairs from the speakers, the treble drops off entirely and only the bass remains. Thus, frequency correlates directly to resolution and inversely to penetration in audible sound as well as ultrasound.

Wavelength is the distance the wave travels in a single cycle. Because velocity must remain constant in a given medium, wavelength is inversely related to frequency (velocity = frequency × wavelength). Therefore, high frequency decreases wavelength (and thus penetration), and lower frequency increases wavelength (and thus penetration).

Attenuation is the progressive weakening of a sound wave as it travels through a medium. The attenuation coefficients for different tissue densities in the body are shown in Table 1.1.

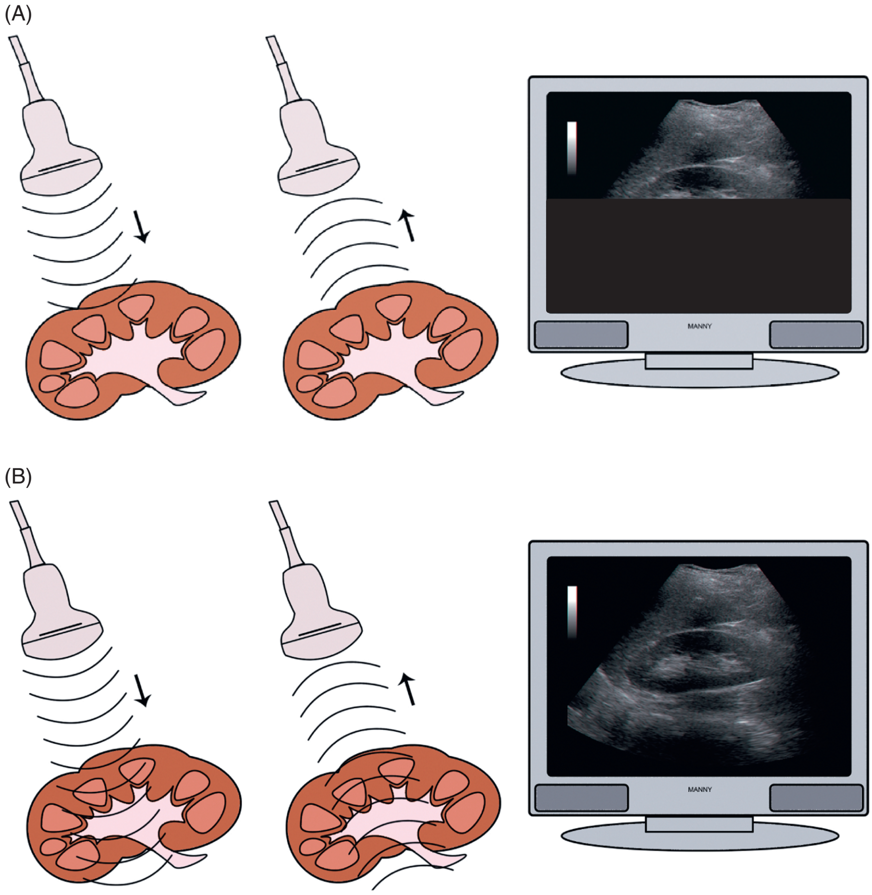

Figure 1.3

(*A*) The near field of the screen shows objects closest to the probe. (*B*) The far field of the screen shows images further from the probe. Courtesy of Dr. Manuel Colon, University of Puerto Rico Medical Center, Carolina, PR.

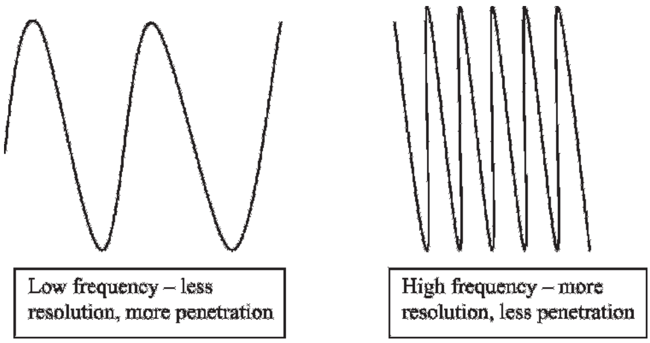

Figure 1.4

Low- and high-frequency sound waves.

Table 1.1 Attenuation coefficients for body tissues

Tissue	Attenuation coefficient	Ultrasound characterisitics
Air	4500	Poor propagation, sound waves often scattered
Bone	870	Very echogenic (reflects most back, high attenuation)
Muscle	350	Echogenic (bright echo)
Liver/kidney	90	Echogenic (less bright)
Fat	60	Hypoechoic (dark echo)
Blood	9	Hypoechoic (very dark echo)
Fluid	6	Hypoechoic (very dark echo, low attenuation)

Several factors contribute to attenuation: the density of the medium, the number of interfaces encountered, and the wavelength of the sound. Diagnostic ultrasound does not transmit well through air and bone because of scatter and reflection. However, ultrasound travels well through fluid-containing structures such as the bladder. Attenuation also occurs as sound encounters interfaces between different types of media. If a tissue is homogeneous and dense, then the number of interfaces is reduced and less attenuation occurs. If a tissue is heterogeneous and less dense, then more attenuation occurs.

Reflection is the redirection of part of the sound wave back to its source. *Refraction* is the redirection of part of the sound wave as it crosses a boundary between different media (or crosses tissues of different propagation speeds such as from muscle to bone). *Scattering* occurs when the sound beam encounters an interface that is relatively small or irregular in shape (e.g., what happens when sound waves travel through air or gas). *Absorption* occurs when the acoustic energy of the sound wave is contained within the medium.

Resolution refers to an ultrasound machine's ability to discriminate between two closely spaced objects. Figure 1.5 shows two points that are resolved as distinct by a machine with higher resolution (the paired dots) and the same structures visualized by a machine with lower resolution (the two dots are seen as a single indistinct blob). *Axial resolution* refers to the ultrasound machine's ability to differentiate two closely spaced echoes that lie in a plane parallel to the direction of the traveling sound wave. Increasing the frequency of the sound wave will increase the axial resolution of the ultrasound image. *Lateral resolution* refers to the ultrasound machine's ability to differentiate two closely spaced echoes that lie in a plane perpendicular to the direction of the traveling sound wave. In some portable ultrasound machines, the focal zone (or narrowest part of the ultrasound beam)

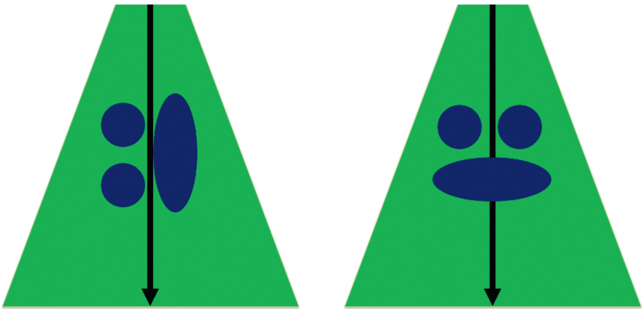

Figure 1.5
Axial resolution (*left*) improves with higher frequency. Lateral resolution (*right*) improves with narrow bandwidth (focal zone).

is automatically set over the mid-range of the screen. However, some machines have a button that allows you to shift that narrow part of the beam up and down.

Finally, *acoustic power* refers to the amount of energy leaving the transducer. It is set to a default in most diagnostic ultrasound machines to prevent adverse biologic effects, such as tissue heating or cell destruction. This is to adhere to the ALARA or "as low as reasonably acceptable" principle – meaning the lowest amount of energy is used to obtain the information clinically needed to care for the patient. Therapeutic ultrasound operates differently from the diagnostic ultrasound discussed so far in that it purposely uses the heating properties of ultrasound to affect tissue. Often, therapeutic ultrasound is used in physical therapy or rehabilitation after orthopedic injuries to help mobilize tissue that has been scarred.

Basic instrumentation

Ultrasound devices all use the same basic principle for generating ultrasound waves and receiving the reflected echoes. This principle is made possible by a property that quartz and some other compounds, both natural and synthetic, possess called the *piezoelectric effect*. The piezoelectric effect refers to the production of a pressure wave when an applied voltage deforms a crystal element. Moreover, the crystal can also be deformed by returning pressure waves reflected from within tissue. This reflected deformation generates an electric current that the machine translates into a pixel. As mentioned, this pixel's gray shade depends on the strength or amplitude of the returning echo and thus the strength of the electric current it generates.

Many different arrangements of this basic piezoelectric transducer/probe have been developed (Figure 1.6). For example, a convex probe has crystals embedded in a curved, convex array. The further the beams have to travel, the more the ultrasound beams fan out. This reduces lateral resolution in deeper tissue. It also produces a sector- or pie-shaped image. A linear array probe (Figure 1.7) has crystals embedded in a flat head. As a result, the

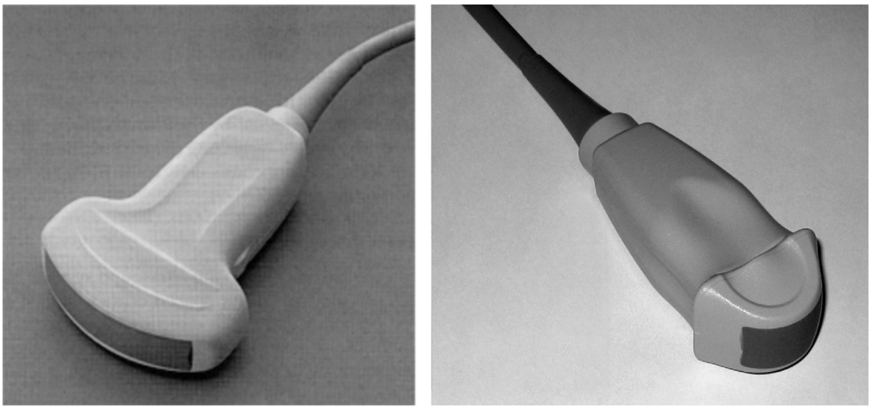

Figure 1.6
Curvilinear probe on left, microconvex probe on right.

Figure 1.7
Linear probe.

ultrasound beams travel in a straight line. Because the ultrasound beams are directed straight ahead, a rectangular image is produced. Probes come in different sizes or "footprints" because sometimes smaller probes are needed to sneak through ribs or other structures that are not ultrasound-friendly. The phased-array probe (Figure 1.8) serves this purpose well and is often employed for cardiac and abdominal scanning.

Finally, each probe has a range of frequencies it is capable of generating. Usually, linear probes have higher frequency ranges and curved probes have lower frequency ranges. One exception to this is the intercavitary probe used in obstetric and gynecologic ultrasound (Figure 1.9). Although it has a curved footprint, it also uses higher-frequency ultrasound to obtain high-resolution pictures of smaller structures close to the probe.

Figure 1.8
Phased-array probe.

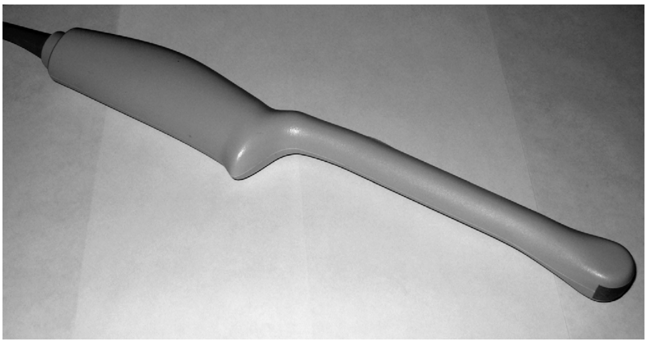

Figure 1.9
Intracavitary probe.

Using the transducer/probe

When scanning with the transducer, use adequate amounts of ultrasound gel to facilitate maneuvering the transducer and to optimize the quality of images obtained. Any air between the probe and the surface of the skin will cause sound waves traveling through that space to scatter, and the strength of the returning echoes will decrease.

It is important to hold the probe such that it does not slip from your grasp or slide around on the patient's gel-covered skin. Holding the probe with the first three to four fingers of your hand allows the fourth or fifth finger and heel of the hand to provide a stable platform for scanning. Thus, less pressure needs to be applied to maintain position on the skin surface without slipping. Holding the probe as you would a pencil is a good first pass at comfortable probe handling (Figure 1.10).

Finally, several scanning planes should be used whenever imaging any anatomic structure. It is always important to image structures in at least two planes (e.g., transverse and longitudinal), because we are looking at three-dimensional structures with two-dimensional images.

Figure 1.10
Holding the probe.

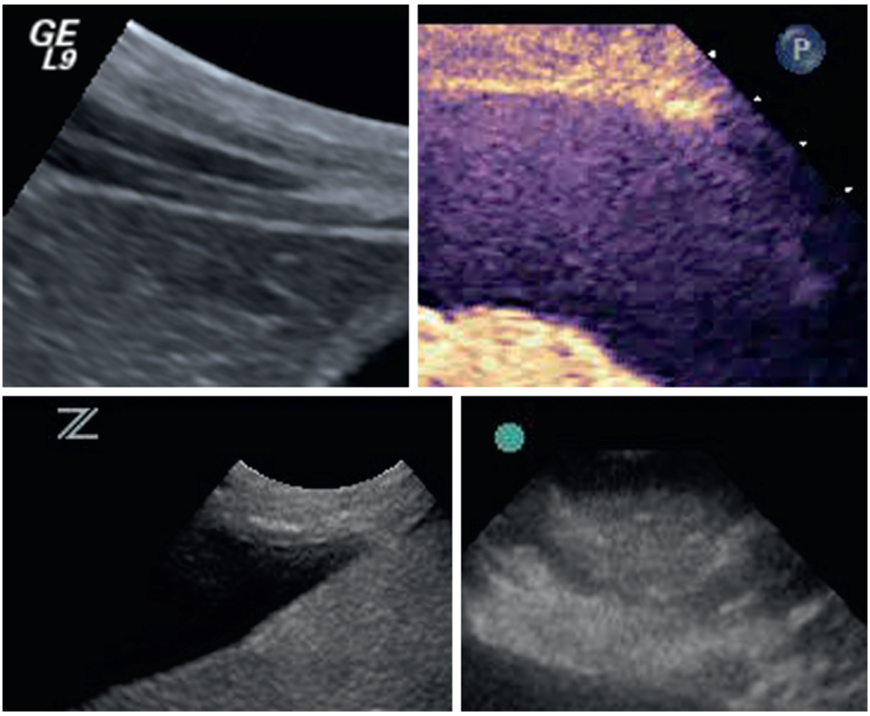

Figure 1.11
Screen markers are found on the top of the screen, usually on the left for emergency ultrasound applications. Different vendors use different symbols as markers. Clockwise from top left: GE, Philips, SonoSite, Zonare.

Probe and screen markers

One of the first principles to remember is that every probe has a raised marker or indentation on it that correlates to the side of the screen with a dot, the ultrasound manufacturer's logo, or some other identifier (Figure 1.11). Objects

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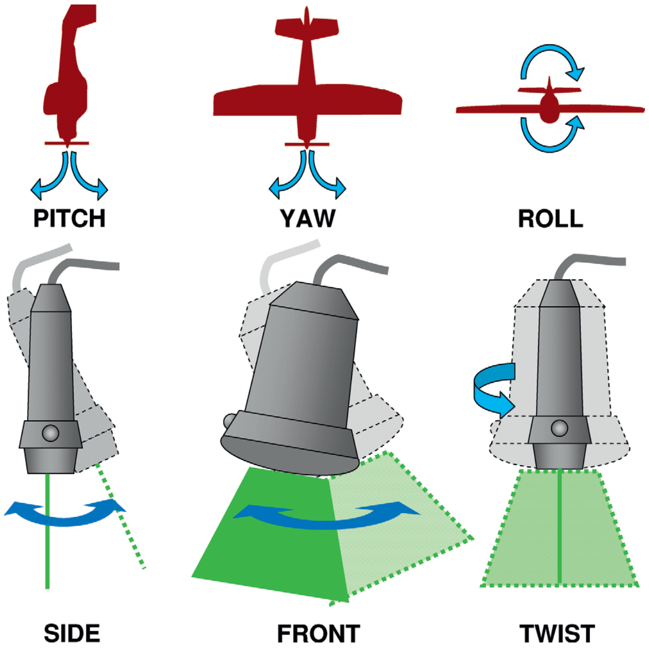

Figure 1.12 Orientation of the probe in three dimensions.

located near the probe marker on the transducer will appear near the screen marker on the screen. Objects opposite the probe marker will appear on the other side from the screen marker.

For the most part, bedside ultrasound keeps the screen marker on the left-hand side of the screen. However, formal echocardiography is performed with the marker on the right-hand side of the screen, so most machines have a button that lets you flip the screen marker back and forth. This manual describes all images with the marker on the left to keep machine settings constant. It is important to know this fact, because echocardiographers often employ different probe positions (180 degrees rotated from the descriptions in this book) based on their different screen settings.

Proprioception

As one grows more comfortable with scanning, the probe and ultrasound beam become an extension of the arm. It becomes natural to understand that moving your hand a certain way yields predictable changes in the image orientation. For novice users, it is helpful to review the standard orientation of the probe. Like any object working in three dimensions, the probe (and therefore the ultrasound beam) can be oriented in an *x*, *y*, or *z* axis. A simple analogy would be the orientation of an airplane. An ultrasound transducer is pictured in Figure 1.12 in three different orientations (short side, long side, and facing out of the page), with its beam colored green to illustrate the concept.

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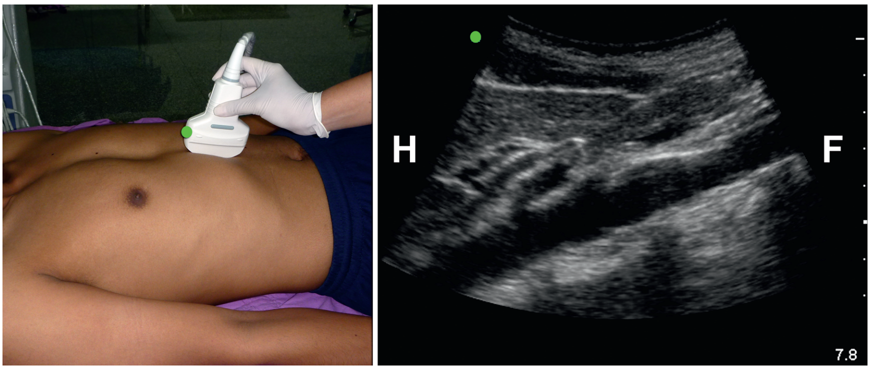

Figure 1.13
Longitudinal probe position. The probe marker and screen marker are highlighted in green.

Pitch refers to movement up or down. For a transducer in a transverse orientation on the abdomen, this would refer to tilting or "fanning" the probe toward the head or feet. *Yaw* refers to a side-to-side turn. This would correspond to angling the same probe left or right toward the patient's flanks. Finally, *roll* refers to spinning on a central long axis. If this motion is done with the aforementioned probe, the transverse orientation would become sagittal. At first, focus on moving the probe in one plane at a time, and note the impact on the image. Novice users often become disoriented when they believe that they are moving in one plane but are truly twisting through multiple axes at once.

Probe positioning when scanning

When obtaining a longitudinal or sagittal view (Figure 1.13), the transducer is oriented along the long axis of the patient's body (i.e., the probe marker is pointed toward the patient's head). This means that you will see the cephalad structures on the side of the screen with the marker (here, on the left side).

The transverse or axial view (Figure 1.14) is obtained by orienting the transducer 90 degrees from the long axis of the patient's body, producing a cross-sectional display. For the vast majority of indications, the probe marker should be oriented toward the patient's right. Again, if the marker is pointed to the right, the structures on the right side of the body will appear on the side of the screen with the marker.

The coronal view (Figure 1.15) is obtained by positioning the transducer laterally. The probe marker is still pointed to the patient's head so the cephalad structures are on the left side of the screen (marker side). The structures closest to the probe are shown at the top of the screen, and as the beam penetrates, the tissues furthest from the probe are at the bottom of the screen.