1 Fundamentals

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. 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 the wave (Figure 1.1). When applied to ordinary sound, this term correlates with the loudness of the sound wave. When applied to ultrasound images, this term correlates with the intensity of the returning echo.

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 a bright or white dot on the screen (known as *hyperechoic*). Weak returning echoes translate into a black dot on the screen (known as *hypoechoic* or *anechoic*). 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 1,540 m/s in soft tissue (i.e., the *propagation speed* of soft tissue is 1,540 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). (This is likened to the use of sonar devices by submarines.)

Frequency is the number of times per second the wave is repeated. One Hertz 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 10 MHz (1 MHz = 1 million Hz).

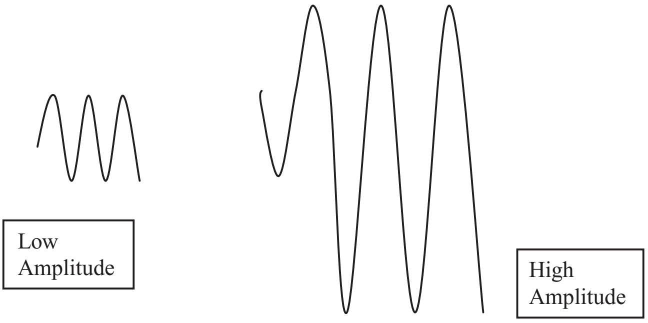

Figure 1.1
Low- and high-amplitude sound waves.

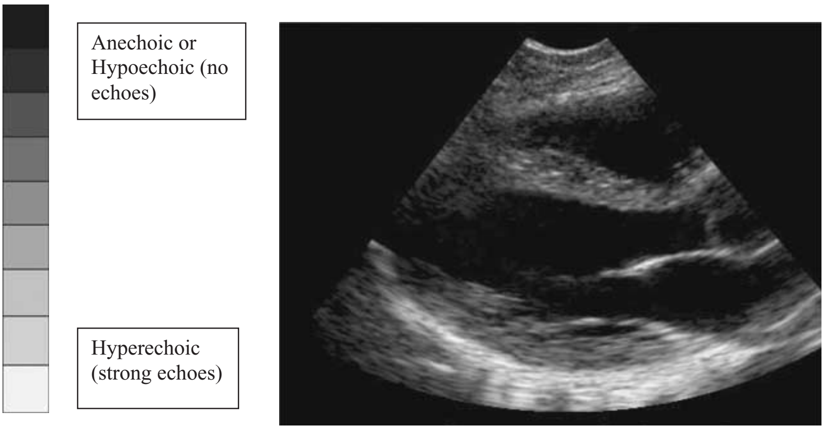

Figure 1.2

Most ultrasound machines have 256 shades of gray that correspond to the returning amplitude of a given ultrasound wave.

Figure 1.4 shows that 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. However, because they lose energy more rapidly, high-frequency ultrasound does not penetrate long distances. Conversely, lower-resolution waves conserve energy, and although not creating pictures of equally high resolution, they are able to penetrate deeper into tissue.

Wavelength is the distance the wave travels in a single cycle. Wavelength is inversely related to frequency because of the principle 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. Following is the range of attenuation coefficients for different tissue densities in the body:

Air	4,500	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 type of 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

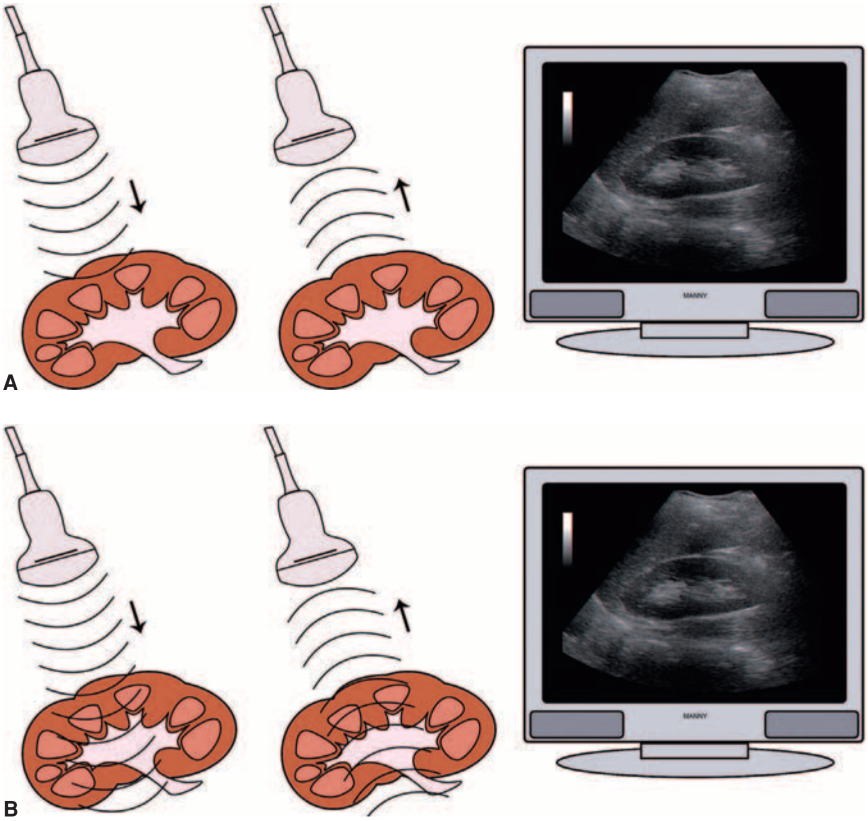

Figure 1.3
(a) The near field of the screen shows objects closest to the probe. (b) The far field of the screen shows images further from the probe. Courtesy of Dr. Manuel Colon, University of Puerto Rico Medical Center, Carolina, Puerto Rico.

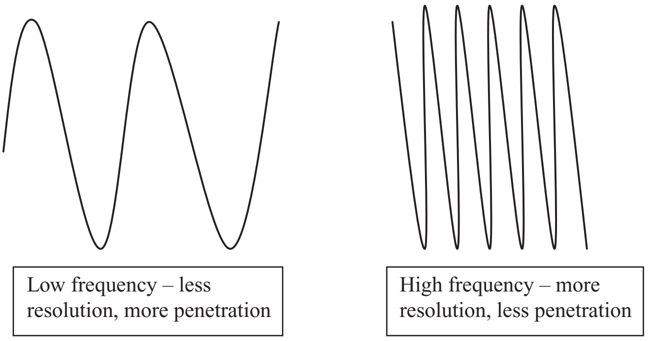

Figure 1.4
Low- and high-frequency sound waves.

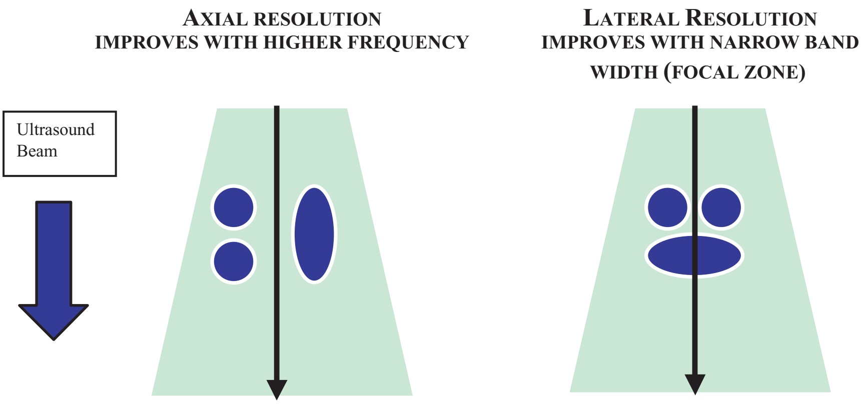

Figure 1.5

Axial resolution improves with higher frequency. Lateral resolution improves with narrow bandwidth (focal zone).

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 of 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 smaller 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. The following images represent 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 (Figure 1.5). In most portable ultrasound machines, the machine self-adjusts the focal zone (or narrowest part of the ultrasound beam) automatically over the midrange 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 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, natural and synthetic) possesses 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 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 farther 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 ultrasound beams travel in a straight line. Because the ultrasound beams are directed straight ahead, a rectangular image is produced.

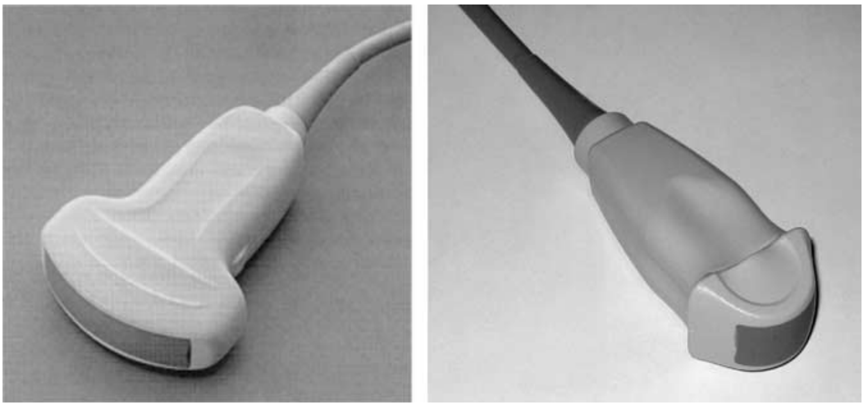

Figure 1.6
Curvilinear probe on left, and microconvex probe on right.

Figure 1.7
Linear probe.

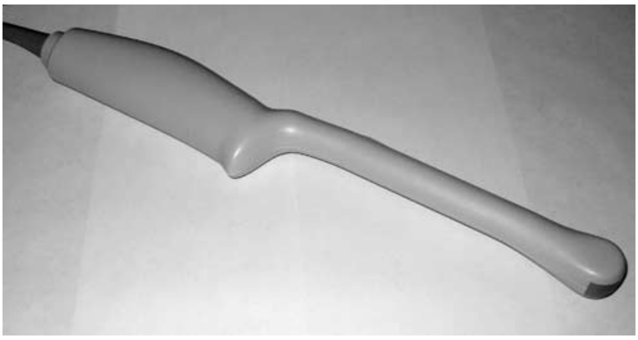

Figure 1.8
Intercavitary probe.

Probes also come in different sizes or "footprints" because sometimes you will need smaller probes to sneak through ribs or other structures that are not ultrasound-friendly. 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 1.8). Although it has a curved footprint, it also uses higher-frequency ultrasound to obtain high-resolution pictures of smaller structures close to the 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 mean that sound waves traveling through that space will scatter and the strength of the returning echoes will decrease. In addition, several scanning planes should be used whenever imaging any anatomic structure. This means that it is always important to image structures in two planes (i.e., transverse and longitudinal)

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Figure 1.9 Screen markers are found on the top of the screen, usually on the left for emergency ultrasound applications. Courtesy of Emergency Ultrasound Division, St. Luke's–Roosevelt Hospital Center, New York, New York.

because we are looking at three-dimensional structures with two-dimensional images.

Probe 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 1.9). Objects located near the probe marker on the transducer will appear near the probe marker on the screen. Objects opposite the probe marker will appear on the other side of 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 will have different probe positions (180 degrees different) 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 (Figure 1.10). 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 the figure in three different orientations (short side, long side, and facing out of the page), with its beam colored green to illustrate the concept.

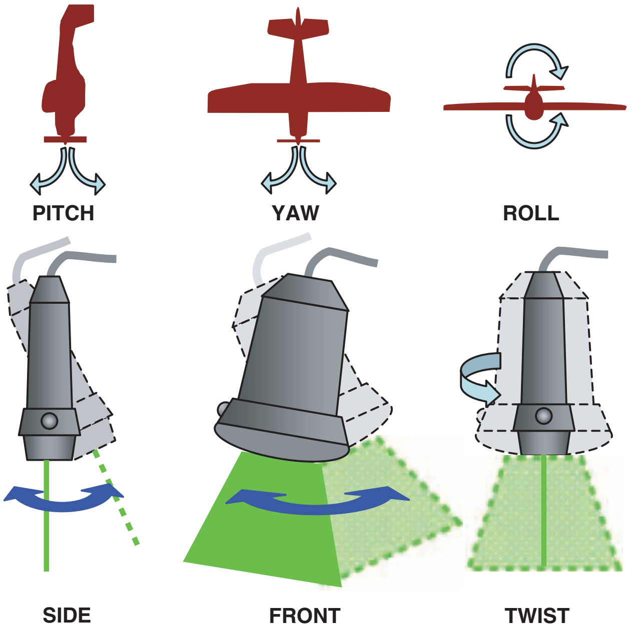

Figure 1.10
Orienting the probe in three dimensions.

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 1.11), 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 1.12) 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 1.13) is obtained by positioning the transducer laterally. The probe marker is still pointed to the patient's head so the cephalad

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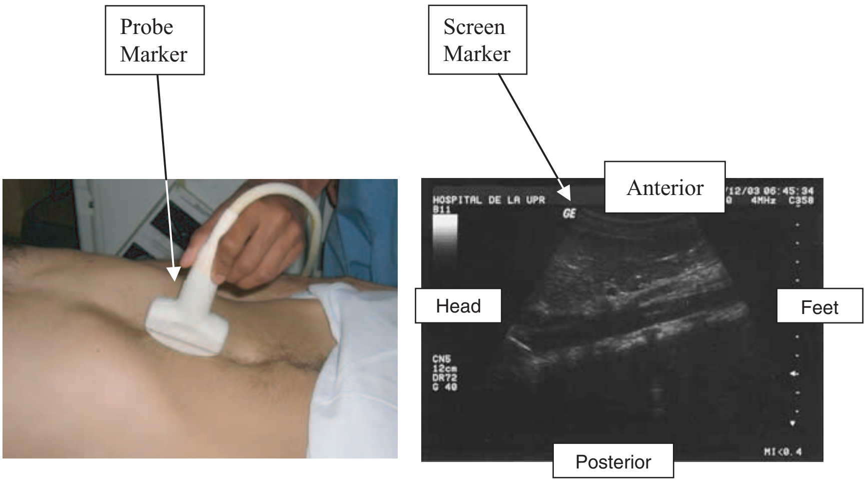

Figure 1.11
Longitudinal probe position.

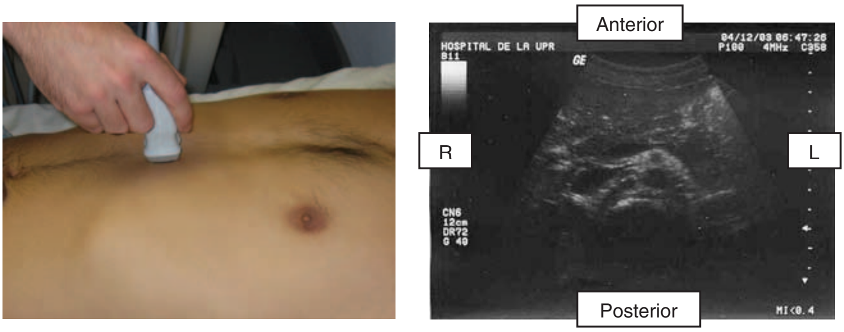

Figure 1.12
Transverse probe position.

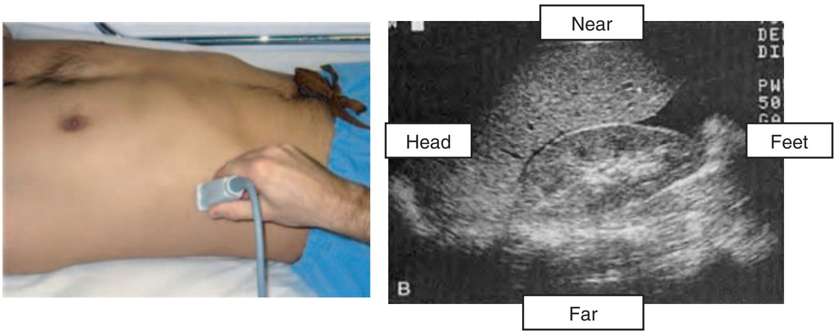

Figure 1.13
Coronal probe position.

structures are on the left side of the screen (marker side). In this view, the structures closest to the probe are shown on the top of the screen, and as the beam penetrates, the tissues furthest from the probe are on the bottom of the screen.

Understanding the Formed Image

To review, a number of conventions have been almost universally adopted for translating the electrical information generated by the transducer into an image on a display screen. We say "almost" because, as mentioned previously, cardiologists have reversed their screen marker; instead of placing it on the left side of the screen, they place it on the right. Because bedside ultrasound includes abdominal and other imaging, we leave the marker on the left side and teach you to hold the probe 180 degrees reversed from the cardiology standard when doing bedside cardiac imaging. By doing this, the images you create will appear the same as the cardiologists' on the screen.

Again, to obtain these conventional views, you must know the orientation of the transducer's beam. The convention is that the probe indicator or marker should be to the patient's right or the patient's head. The screen marker should be on the left of the screen (see figures in previous section).

Adjusting the Image

Some ultrasound machines allow the operator to choose where to focus the narrowest part of the ultrasound beam. By adjusting the *focal zone* (Figure 1.14), you can optimize lateral resolution. Focus is usually adjusted by means of a knob or an up/down button on the control panel.

Focal depth is usually indicated on the side of the display screen as a pointer. By moving the pointer to the area of interest, the beam is narrowed at that

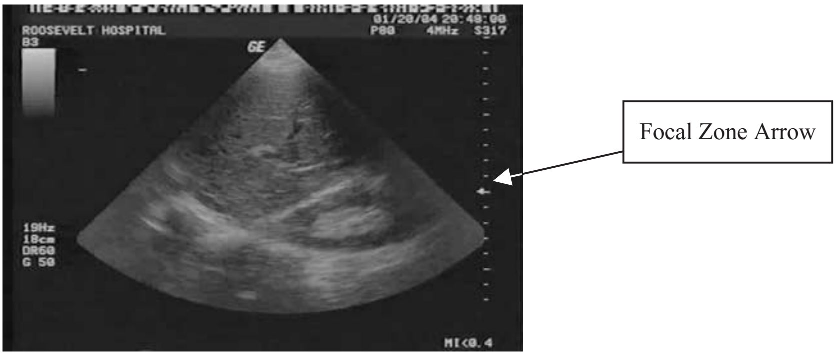

Figure 1.14
Focal zone. Courtesy of Emergency Ultrasound Division, St. Luke's–Roosevelt Hospital Center, New York, New York.