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SONOGRAPHY

PRINCIPLES AND INSTRUMENTS

Frederick W. Kremkau

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Includes *Your New Paradigm for Understanding and Applying Sonographic Principles*

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CONTENTS

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Ultrasound: Sound We Don't Hear

LEARNING OBJECTIVES

After reading this chapter, the student should be able to do the following:

- Explain the concept of frequency and its importance in sonography.
- Define *ultrasound* and describe its behavior.
- Discuss how harmonics are generated.
- Compare continuous with pulsed ultrasound.
- Describe the weakening of ultrasound while it travels through tissue.
- Discuss the generation of echoes in tissue.

OUTLINE

KEY TERMS

Absorption
Acoustic
Acoustic variables
Amplitude
Attenuation
Attenuation coefficient
Backscatter
Bandwidth
Compression
Constructive interference
Continuous wave
Contrast agent
Coupling medium
Cycle
Decibel
Density
Destructive interference
Duty factor
Echo
Energy
Fractional bandwidth
Frequency
Fundamental frequency
Harmonics
Hertz
Impedance
Incidence angle
Intensity
Intensity reflection coefficient
Intensity transmission coefficient
Interference
Kilohertz
Longitudinal wave
Medium
Megahertz
Nonlinear propagation
Oblique incidence
Penetration
Period
Perpendicular
Perpendicular incidence
Power
Pressure
Propagation
Propagation speed
Pulse
Pulse duration
Pulse-repetition frequency
Pulse-repetition period
Pulsed ultrasound
Range equation
Rarefaction
Rayl
Reflection
Reflection angle
Reflector
Refraction
Scatterer
Scattering
Shear wave
Sound
Spatial pulse length
Speckle

KEY TERMS—cont'd

Specular reflection
Stiffness
Strength
Transmission angle
Transverse wave
Ultrasound
Wave
Wavelength

Sound is defined in two primary ways—experientially and physically. Experientially, it is what we hear with our human auditory system. Physically, it is what travels from the source of the sound to the listener. It is the latter concept that is relevant to our understanding of sonography. **Ultrasound** is similar to the ordinary sound we hear except that its **frequency** (discussed later in this chapter) is higher than the range of human hearing. While ultrasound travels through the human body, it interacts with the anatomy in ways that enable its use in diagnostic imaging. In this chapter, we consider what ultrasound is, how it is described, and how it travels through and interacts with human anatomy. After digesting this material, you will be prepared to learn in subsequent chapters how ultrasound is generated, received, and processed to produce anatomic, sonographic images and to detect and present motion and flow information.

SOUND

Waves

Diagnostic sonography uses ultrasound to produce images of anatomy, motion, and flow. Ultrasound is a form of sound. Through our sense of hearing, we experience sound daily. But what is sound physically? In spoken communication, sound is produced by a speaker and is heard by a listener. Sound travels from the speaker to the listener, so it is something that travels (i.e., propagates) through a **medium** such as air. But what is this sound that is traveling through air? Sound is a traveling variation in **pressure** (Figure 2.1,A). When the speaker speaks, variations in pressure are produced in the throat and mouth. These pressure variations travel through air to the listener, where they stimulate the auditory response in the ear and brain.

In more general terms, we can say that sound is a wave. A **wave** is a traveling variation in one or more quantities called wave variables. For example, a water wave is a traveling variation in water surface height. Dropping a pebble into a pond disturbs the surface of the water, causing it to move up and down. These up-and-down movements then travel across the surface of the pond so that motion, similar to that generated where the pebble entered the water, eventually occurs at the far shore. Similar to water waves, sound involves mechanical motion in the medium through which it travels. The pressure variations in the sound wave cause the particles of the medium to vibrate back and forth.

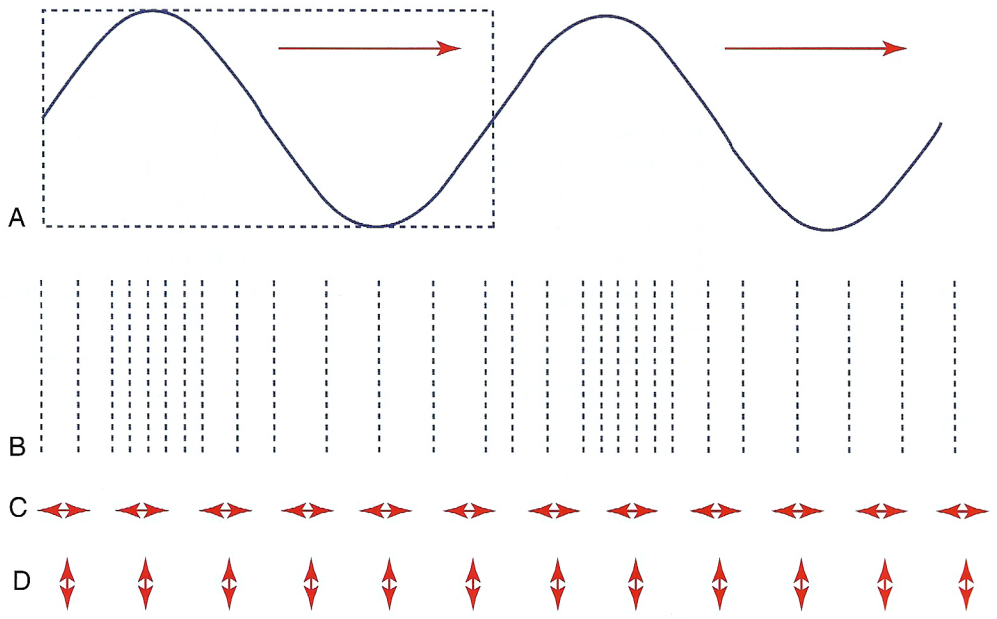

Figure 2.1 **A,** Sound is a traveling pressure variation. The box encloses one cycle of pressure variation. The pressure wave in this example is traveling to the right, as indicated by the arrows. **B,** Sound is also a traveling density variation. Regions of compression (high density) and rarefaction (low density) travel along with the high- and low-pressure regions of the wave. **C,** Particles vibrate back and forth in a sound wave. This vibratory motion is parallel to the direction of travel of the wave. Such a wave is called a longitudinal wave. Thus sound is a longitudinal, compressional pressure wave. **D,** A transverse (shear) wave involves motion perpendicular to the direction of wave travel.

A wave is a traveling variation of a quantity or quantities called wave variables.

Associated with pressure variations in a sound wave, density variations also exist. **Density** is the concentration of matter (mass per unit volume). Pressure, density, and particle vibration are called **acoustic variables** because they are quantities that vary in a sound wave (the term **acoustic** is derived from the Greek word for hearing). While sound travels through a medium, pressure and density go through **cycles** of increase and decrease, and particles of the medium oscillate in motion. At any point in the medium, pressure and density increase and decrease in repetitive cycles while the sound wave travels past that point. Regions of low pressure and density are called **rarefactions**, and regions of high pressure and density are called **compressions**. Compressions and rarefactions travel through a medium with a sound wave (see Figure 2.1,B). Sound requires a physical medium through which to travel; that is, it cannot pass through a vacuum. Sound is a mechanical, compressional wave in which back-and-forth particle motion is parallel to the direction of wave travel (see Figure 2.1,C). Such a wave is called a **longitudinal wave** or compressional wave.

The up-and-down motion of a water surface is **perpendicular** to the direction of wave travel. This type of wave is called a **transverse wave** or **shear wave** (see Figure 2.1,D). Electromagnetic waves such as light, radio, x-rays, and microwaves are transverse waves of electric and magnetic fields that involve no particle motion. The particle motion of sound waves is commonly parallel to the direction of wave travel (longitudinal wave), although in the case of shear-wave elastography, discussed later, the motion is transverse.

Sound is a traveling variation of acoustic variables.

Acoustic variables include pressure, density, and particle motion.

Sound is described by terms that are used to describe all waves. These terms include *frequency*, *period*, *wavelength*, *propagation speed*, *amplitude*, and *intensity*. Amplitude and intensity are covered in the later section on attenuation.

Frequency

Frequency (f) is a measurement of how often something happens. For example, there are 365 days in a year and 24 hours in a day. Frequency, as it relates to sound, is a count of how many complete variations (cycles) of pressure (or any other acoustic variable) occur in 1 second. As shown in Figure 2.1,A, pressure starts at its normal (undisturbed) value. This would be the pressure in the medium if no sound were propagating through it. While a sound wave travels through a medium, the pressure at any point in the medium increases to a maximum value, returns to normal, decreases to a minimum value, and returns to normal. This is a description of a complete cycle of variation in pressure as an acoustic variable.

A cycle is one complete variation in pressure or another acoustic variable.

The positive and negative halves of a pressure cycle correspond to compression and rarefaction, respectively. In other words, when the pressure is higher, the medium is denser (more tightly packed), and when the pressure is lower, the medium is less dense. While a sound wave travels past a point in the medium, this cycle of increasing and decreasing pressure and density is repeated over and over. The number of times it is repeated in 1 second is called *frequency* (Figure 2.2). Thus frequency is the number of cycles that occur per second. Frequency units include **hertz** (Hz), **kilohertz** (kHz), and **megahertz** (MHz). One hertz is one cycle per second. One kilohertz equals 1000 Hz. One megahertz equals 1,000,000 Hz.

Frequency is the number of cycles in a wave that occur in 1 second.

One hertz equals one cycle per second. The abbreviation for hertz is *Hz*.

One kilohertz equals 1000 cycles per second. The abbreviation for kilohertz is *kHz*.

One megahertz equals one million cycles per second. The abbreviation for megahertz is *MHz*.

Human hearing operates in a frequency range of approximately 20 to 20,000 Hz, although great variation exists on the upper frequency limit in individuals. Sound with a frequency of less than 20 Hz is called *infrasound* because its frequency is too low for human hearing (*infra* derives from the Latin word for *below*). Sound with a frequency of 20,000 Hz or higher is called *ultrasound* (*ultra* derives from the Latin word for *beyond*) because its frequency is too high for human hearing. Frequency is important in diagnostic ultrasound because of its impact on the resolution and **penetration** of sonographic images. Frequency is controlled by the choice of transducer and by the sonographic instrument.

Infrasound is sound of a frequency too low for human hearing.

Ultrasound is sound of a frequency too high for human hearing.

Period

Period (T) is the time that it takes for one cycle to occur (Figure 2.3). In ultrasound, the common unit for period is the microsecond (μs). One microsecond equals one-millionth of a second (0.000001 second). For example, the period for 5 MHz ultrasound equals 0.2 μs. Because 5 MHz ultrasound contains 5 million cycles in a second, each cycle has only one-fifth of a millionth of a second (0.2 μs) to occur. The

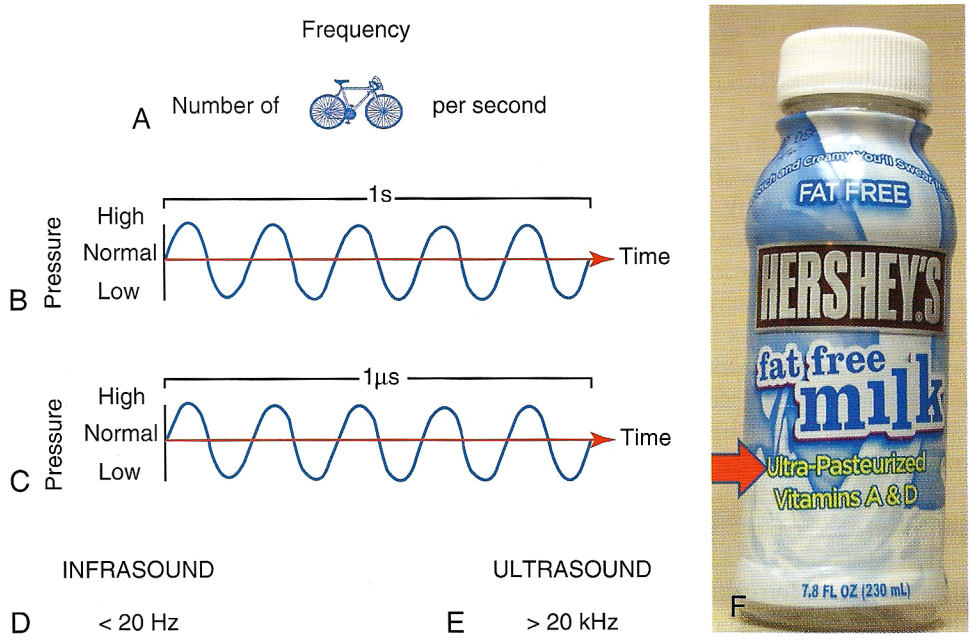

Figure 2.2 **A,** Frequency is the number of complete variations (cycles) that an acoustic variable (pressure, in this case) goes through in 1 second. **B,** Five cycles occur in 1 second; thus the frequency is five cycles per second, or 5 Hz. **C,** If five cycles occur within one-millionth of a second, also known as a microsecond (1 μs) (i.e., 5 million cycles occurring in 1 second), the frequency is 5 MHz. **D,** Infrasound is sound that human beings cannot hear because the frequencies are too low (less than 20 Hz). **E,** Ultrasound is sound that human beings cannot hear because the frequencies are too high (greater than 20 kHz). **F,** Ultra *(arrow)* is a prefix meaning "beyond."

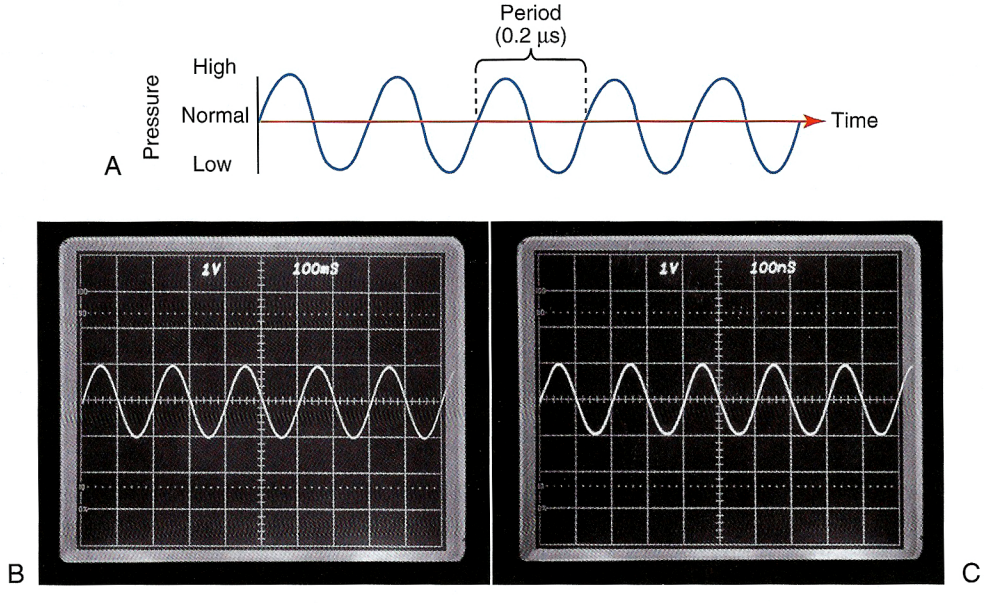

Figure 2.3 Period is the time it takes for one cycle to occur. **A,** Each cycle occurs in 0.2 μs, so the period is 0.2 μs. If one cycle takes 0.2 (or one-fifth) millionths of a second to occur, it means that 5 million cycles occur in 1 second, so the frequency is 5 MHz. **B,** Photograph of a tracing of a 5-Hz wave. The total screen width represents 1 second. One can see that five cycles occur in 1 second and that each cycle takes one-fifth (0.2) of a second to occur (period). If this were a pressure wave, it would be an example of infrasound (frequency is 5 Hz, i.e., less than 20 Hz). **C,** In this tracing, the total screen width is 1 μs. If five cycles occur in 1 μs, the period is 0.2 μs, and the frequency is 5 MHz, as in **A**. If this were a pressure wave, it would be an example of ultrasound (frequency greater than 20 kHz).

TABLE 2.1 Common Ultrasound Periods and Wavelengths in Tissue

Frequency (MHz)	Period (μs)	Wavelength (mm)[a]
2.0	0.50	0.77
3.5	0.29	0.44
5.0	0.20	0.31
7.5	0.13	0.21
10.0	0.10	0.15
15.0	0.07	0.10

[a]Assuming a (soft tissue) propagation speed of 1.54 mm/μs (1540 m/s).

importance of period will become apparent when **pulsed ultrasound** is considered in the next section. Table 2.1 lists common periods. Period decreases while frequency increases because, when more cycles are packed into 1 second, there is less time for each one. Indeed, period equals 1 divided by frequency.

$$T\ (\mu s) = \frac{1}{f\ (MHz)}$$

Period is the time that it takes for one cycle to occur.

If frequency increases, period decreases.

Wavelength

Wavelength (λ) is the length of space that one cycle takes up (Figure 2.4). If we could stop a sound wave, visualize it, and measure the distance from the beginning to the end of one cycle, the measured distance would be the wavelength of the sound wave. Wavelength is the length of a cycle from "front" to "back." More precisely, it could be called *cycle length,* but traditionally it has been called *wavelength.* For ultrasound, wavelength is commonly expressed in millimeters. One millimeter (1 mm) is one-thousandth of a meter (0.001 m). The importance of wavelength will be evident when detail resolution of images is considered. Table 2.1 lists common wavelengths in sonography.

Wavelength is the length of a cycle in space.

Propagation Speed

Propagation speed (c) is the speed with which a wave moves through a medium. For sound, **propagation** speed is the speed at which a particular value of an acoustic variable moves (Figure 2.5), at which a cycle moves, and at which the entire wave moves. All of these are the same speed. Relevant propagation speed units include meters per second (m/s) and millimeters per microsecond (mm/μs).

ADVANCED CONCEPT

Speed is the rate of change of position of an object. Speed is sometimes called velocity, although, strictly speaking, velocity is defined as speed with direction of motion specified. An example of wind speed might be 25 miles per hour (mph), but its velocity would be 25 mph out of the northwest.

Propagation speed is the speed at which a wave moves through a medium.

Wavelength depends on frequency and propagation speed. The relationship between the three is that wavelength is equal to propagation speed divided by frequency.

$$\lambda\ (mm) = \frac{c\ (mm/\mu s)}{f\ (MHz)}$$

This equation predicts that wavelength will decrease when frequency increases. This prediction is confirmed in Table 2.1. Later we will see that detail resolution improves with increasing frequency because of the decrease in wavelength.

If frequency increases, wavelength decreases.

An example of the relationship among frequency, wavelength, and propagation speed is seen by comparing Figures 2.3,C; 2.4; and 2.5. In these figures, frequency is 5 MHz, wavelength is 0.31 mm, and propagation speed is 1.54 mm/μs. These values apply to the same wave because they are a compatible set according to the following equation:

$$\lambda\ (mm) = \frac{c\ (mm/\mu s)}{f\ (MHz)} = \frac{1.54\ mm/\mu s}{5\ MHz} = 0.31\ mm$$

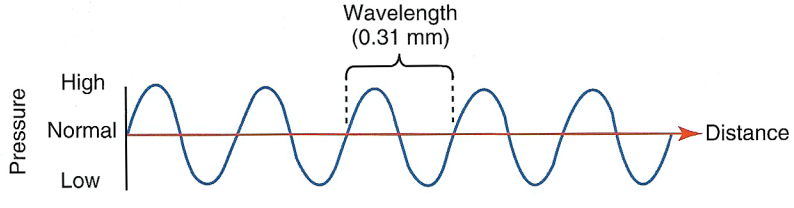

Figure 2.4 Wavelength is the length of space over which one cycle occurs. In this figure, each cycle covers 0.31 mm. Thus the wavelength is 0.31 mm. This figure differs from Figures 2.2 and 2.3 in that the horizontal axis represents distance rather than time. For a propagation speed of 1.54 mm/μs and a frequency of 5 MHz, the wavelength is 0.31 mm.

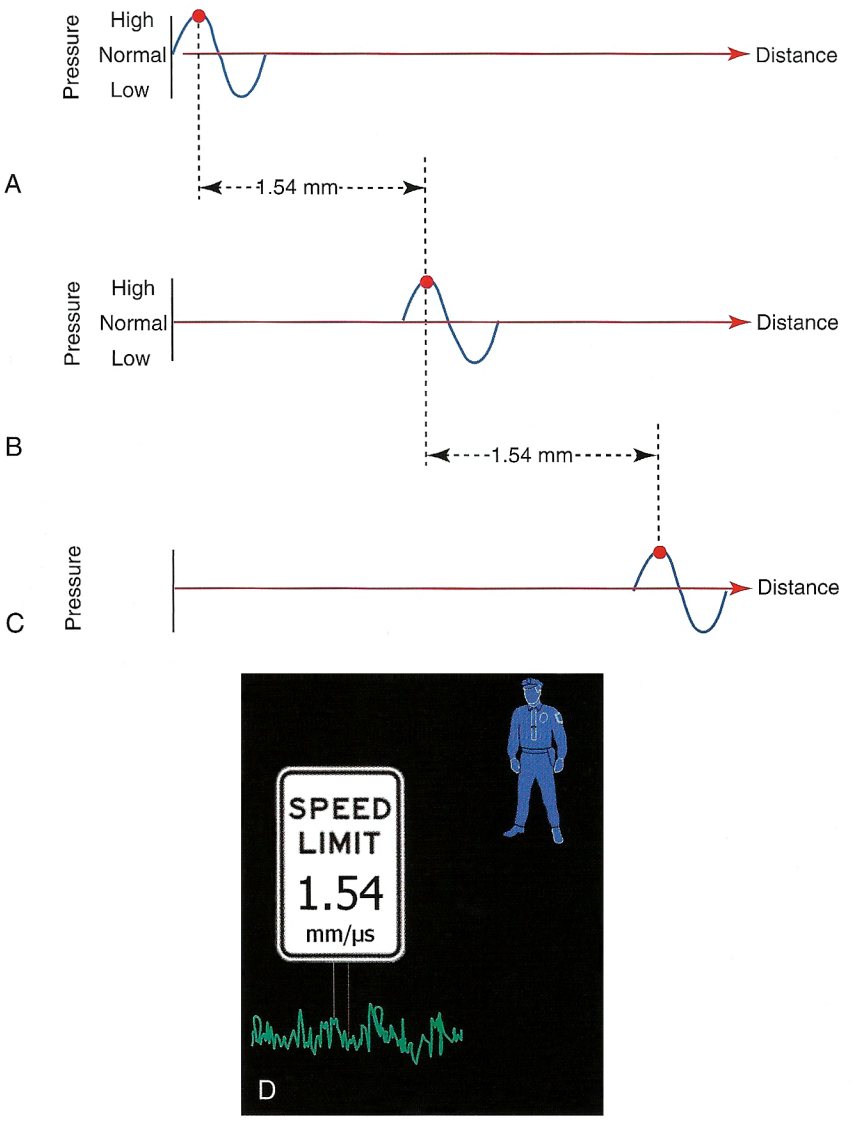

Figure 2.5 Propagation speed is the speed with which a particular value of an acoustic variable (also the rest of the cycle and, indeed, the entire wave) travels through a medium. **A,** The movement of a maximum (identified by the *red dot*) is shown in this figure. **B,** 1 μs after A. **C,** 1 μs after B and 2 μs after **A**. The maximum (dot) moves 1.54 mm in 1 μs and 3.08 mm in 2 μs. The propagation speed is 1.54 mm/μs. The propagation speed in this figure (1.54 mm/μs), when divided by the frequency in Figure 2.3, C (5 MHz), equals the wavelength in Figure 2.4 (0.31 mm). **D,** Propagation speeds in soft tissue average 1540 m/s, or 1.54 mm/μs.

Propagation speed is determined by the medium, primarily its stiffness (hardness). **Stiffness** is the resistance of a material to compression. Stiffness is the inverse of compressibility; that is, a compressible material such as a sponge has low stiffness, and a stiff (hard) material such as a rock has low compressibility. Stiffer media have higher sound speeds. Thus propagation speeds are lower in gases (which are highly compressible), higher in liquids, and highest in solids (which are nearly incompressible). The average longitudinal propagation speed in soft tissues is 1540 m/s, or (in more relevant units for our purposes) 1.54 mm/μs. Values for soft tissues range from 1.44 to 1.64 mm/μs. Not surprisingly, because soft tissue is mostly water, these values are similar to those for liquids such as water. Shear waves travel much more slowly than longitudinal waves. Shear wave propagation speeds in tissues range from 0.5 to 10 m/s.

Propagation speeds are highest in solids and lowest in gases.

The average propagation speed of sound in soft tissues is 1.54 mm/μs.

In lung tissue, because it contains gas, the propagation speed of sound is much lower than in other soft tissues. However, this difference is not important because ultrasound does not penetrate air-filled lung tissue well enough for imaging. In bone, because it is a solid, propagation speeds are higher (3–5 mm/μs) than in soft tissues. Soft tissue propagation speeds are within a few percent of the average, so the average can be assumed for all soft tissues with little error. Fat is farthest from the average, about 6% lower. Propagation speed is important

because sonographic instruments use it to accurately locate echoes on the display.

ADVANCED CONCEPT

The propagation speed in any medium depends on the density (ρ) and stiffness of the medium. By density, we mean *mass density,* which is the mass per unit volume. The stiffness is the resistance to compression, also called the hardness or the bulk modulus of elasticity (B). The reciprocal of bulk modulus is the compressibility of a medium. Specifically, propagation speed depends on the bulk modulus-density ratio:

$$c\ (m/s) = \left[\frac{B\ (N/m^2)}{\rho\ (kg/m^3)}\right]^{1/2}$$

This relationship predicts that an increase in bulk modulus increases propagation speed and that an increase in density decreases propagation speed. If we compare gases, liquids, and solids, we find that generally more dense materials have higher propagation speeds, not lower. The reason is that higher-density materials generally have higher stiffness also, and the stiffness differences between materials are generally greater than the density differences. Thus the stiffness differences dominate the effect on the propagation speed so that, in general, solids have higher propagation speeds than liquids, and liquids have higher speeds than gases.

Harmonics

The dependence of propagation speed on pressure causes strong sound (pressure) waves to change shape while they travel (Figure 2.6) because the higher-pressure portions of the wave travel faster than the lower-pressure portions. This movement produces a wave that originally has a smooth curve shape (called *sinusoidal;* illustrated in Figure 2.6,A) that progresses toward a nonsinusoidal shape (see Figure 2.6,C). Propagation in which speed depends on pressure and the shape of the wave changes is called **nonlinear propagation.** A continuous (not pulsed) sinusoidal waveform is characterized by a single frequency (equal to the number of cycles per second). Any other wave shape contains additional frequencies that are even and odd multiples of the original frequency. The original frequency is called the **fundamental frequency.** The even and odd multiples are called *even* and *odd* **harmonics**, respectively. A frequency analysis of the wave in Figure 2.6,A, would yield a single (fundamental) frequency such as 2 MHz. Analysis of parts B and C would reveal, in addition to fundamental frequency, harmonics such as 4, 6, and 8 MHz. While the shape becomes less sinusoidal, the harmonics become stronger. Therefore they are stronger in part C than in part B. The use of harmonic frequency echoes (harmonic imaging is discussed later) improves the quality of sonographic images.

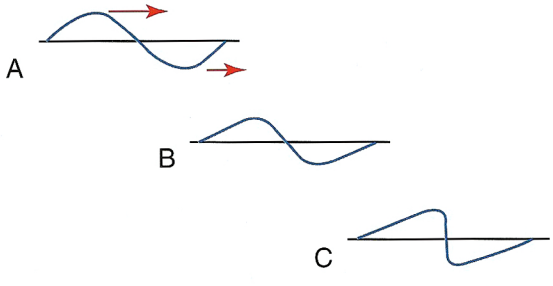

Figure 2.6 In nonlinear propagation, propagation speed depends on pressure. **A,** Higher-pressure portions of the wave travel faster than the lower-pressure portions. **B–C,** Thus the wave changes shape while it travels. This change from the initial sinusoidal shape introduces harmonics that are even and odd multiples of the fundamental frequency.

Harmonics are even and odd multiples of fundamental frequency.

PULSED ULTRASOUND

Thus far we have discussed terms (*frequency, period, wavelength,* and *propagation speed*) that are sufficient to describe **continuous wave** (CW) ultrasound in which cycles repeat indefinitely. For sonography and most of Doppler ultrasound, pulsed ultrasound is used rather than CW. Pulsed ultrasound is not on continuously. An ultrasound pulse is a few cycles of ultrasound. **Pulses** are separated in time with gaps of no ultrasound. Ultrasound pulses are described by some additional parameters that we will now discuss.

With continuous wave ultrasound, cycles repeat indefinitely. Pulsed ultrasound consists of pulses separated by gaps in time. A pulse is a few cycles of ultrasound.

Pulse-Repetition Frequency and Period

The term *frequency,* when unqualified, is the number of cycles occurring per second for a CW. For a pulsed wave, it is the number of cycles per second that would occur if it were a CW. When qualified with the adjectives *pulse-repetition,* **pulse-repetition frequency** (PRF) is the number of *pulses* that occur in 1 second (Figure 2.7). Diagnostic ultrasound involves a few thousand pulses per second, so PRF is commonly expressed in kHz. One kHz equals 1000 Hz. Frequency (the number of cycles per second) and PRF (the number of pulses per second) are independently controlled by the sonographic instrument.

The term *period,* when unqualified, refers to the time for one cycle to occur. When qualified with the adjectives *pulse-repetition,* **pulse-repetition period** (PRP) refers to the time from the beginning of one pulse to the beginning of the next (Figure 2.8). Its common units are milliseconds (ms, or one-thousandth of a second). The PRP is the reciprocal of PRF. The PRP decreases while PRF increases because, when more pulses occur in a second, the time between them decreases.

$$PRP\ (ms) = \frac{1}{PRF\ (kHz)}$$

PRF is controlled automatically by sonographic instruments to satisfy requirements that are discussed later. With Doppler techniques, the operator controls PRF, which is also described in later chapters. PRF is important because it determines how quickly images are generated. For example, with a PRF of 5 kHz,

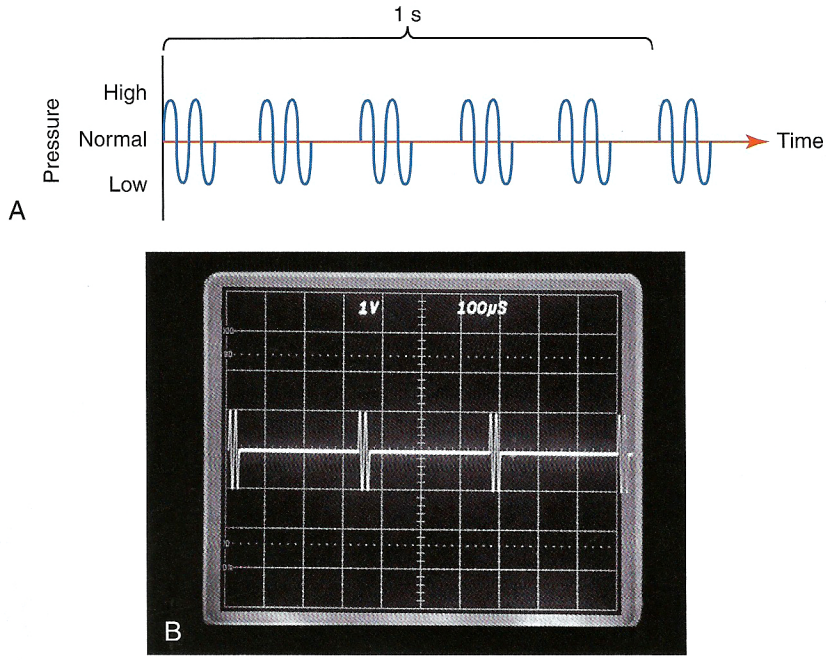

Figure 2.7 Pulse-repetition frequency (PRF) is the number of pulses that occur in 1 second. **A,** Five pulses (containing two cycles each) occur in 1 second; thus, the PRF is 5 Hz. **B,** In this photograph, three pulses occur in 1 ms (or one-thousandth of a second); thus, the PRF is 3 kHz. The total scaled screen width is 1 ms.

5000 pulses are produced each second, generating 5000 scan lines per second. If, for example, each image has 100 scan lines, 50 images will be produced per second. Later this will be called *frame rate,* and it will determine how well rapidly moving structures can be followed.

PRF is the number of pulses that occur in 1 second.

PRP is the time from the beginning of one pulse to the beginning of the next one.

If PRF increases, PRP decreases.

Pulse Duration

Pulse duration (PD) is the time that it takes for one pulse to occur (see Figure 2.8). PD is equal to the period (T, the time for one cycle) times the number of cycles in the pulse (n) and is expressed in microseconds. Sonographic pulses are typically two or three cycles long. Compared with longer ones, shorter pulses improve the quality of sonographic images. Doppler ultrasound pulses are typically 5 to 30 cycles long.

$$PD\ (\mu s) = n \times T\ (\mu s)$$

Sonographic pulses are typically two or three cycles long. Doppler pulses are typically 5 to 30 cycles long.

PD decreases if the number of cycles in a pulse is decreased or if the frequency is increased (reducing the period). The instrument operator chooses the frequency.

PD is the time for a pulse to occur.

If frequency is increased, period is decreased, reducing PD. If the number of cycles in a pulse is reduced, PD is decreased. Shorter pulses improve the quality of sonographic images.

Duty Factor

Duty factor (DF) is the fraction of time that pulsed ultrasound is on (see Figure 2.8,D). Continuous wave ultrasound is on 100% of the time. Pulsed ultrasound, by definition, is not on all of the time. The DF indicates how much of the time the ultrasound is on. Longer pulses increase the DF because the sound is on more of the time.

DF is the fraction of time that pulsed ultrasound is on.

DF is the fraction of the PRP that the sound is on. The remainder of the time to the next pulse is the listening time for reception of echoes that will form a scan line on the instrument display. Higher PRFs increase the DF because there is less listening time between pulses. Thus the DF increases with increasing PD or PRF. DF has no units because it is a fraction with time in both the numerator and denominator. Thus the DF is simply expressed as a decimal, such as 0.10 or 0.25, or as a percentage, such as 10% or 25%. The importance of the DF will become evident when intensities and safety issues are discussed later. The DF is equal to PD divided by the PRP, because PD represents the amount of time that the sound is on, and the PRP is the time from one pulse to the next. Thus the ratio of the two represents the fraction of time that pulsed ultrasound is on.

REVIEW

The following key points are presented in this chapter:

- Sound is a wave of pressure and density variations and particle vibration.
- Ultrasound is sound that has a frequency greater than 20 kHz.
- Frequency denotes the number of cycles occurring in 1 second.
- Harmonic frequencies are generated while sound travels through tissue.
- Wavelength is the length of a cycle in space.
- Propagation speed is the speed of sound through a medium.
- The medium determines propagation speed.
- The average propagation speed of sound through soft tissue is 1.54 mm/μs.
- Pulsed ultrasound is described by PRF, PRP, PD, DF, and SPL.
- Amplitude and intensity describe the strength of sound.
- Attenuation is the weakening of sound caused by absorption, reflection, and scattering.
- Attenuation increases with frequency and path length.
- The average attenuation coefficient for soft tissues is 0.5 dB/cm for each megahertz of frequency.
- Imaging depth decreases with increasing frequency.
- Impedance is the density of a medium multiplied by propagation speed.
- When sound encounters boundaries between media with different impedances, part of the sound is reflected, and the remainder is transmitted into the second medium.
- With perpendicular incidence, and if the two media have the same impedance, there is no reflection.
- The greater the difference in the impedances of the media at a boundary, the greater is the intensity of the echo that is generated at the boundary.
- With oblique incidence, the sound is refracted at a boundary between media for which propagation speeds are different.
- Incidence and reflection angles at a boundary are always equal.
- Scattering occurs at rough media boundaries and within heterogeneous media.
- Contrast agents are used to enhance echogenicity in sonography and Doppler ultrasound.
- Pulse-echo round-trip travel time (13 μs/cm) is used to determine the distance to a reflector.

EXERCISES

Answers appear in the Answers to Exercises section at the back of the book.

1. A wave is a traveling variation in quantities called wave _____.
   a. lengths
   b. variables
   c. cycles
   d. periods
2. Sound is a traveling variation in quantities called _____ variables.
   a. wave
   b. pressure
   c. density
   d. acoustic
3. Ultrasound is sound with a frequency greater than _____ Hz.
   a. 2
   b. 15
   c. 20,000
   d. 1540
4. Acoustic variables include _____, _____, and particle motion.
   a. stiffness, density
   b. hardness, impedance
   c. amplitude, intensity
   d. pressure, density
5. Which of the following frequencies is in the ultrasound range?
   a. 15 Hz
   b. 15,000 Hz
   c. 15 kHz
   d. 30,000 Hz
   e. 0.004 MHz
6. Which of the following is *not* an acoustic variable?
   a. pressure
   b. propagation speed
   c. density
   d. particle motion
7. Frequency is the number of _____ an acoustic variable goes through in a second.
   a. cycles
   b. amplitudes
   c. pulse lengths
   d. Duty factors
8. The unit of frequency is _____, which is abbreviated as _____.
   a. hertz, Hz
   b. megahertz, MHz
   c. kilohurts, khts
   d. cycles, cps
9. Period is the _____ that it takes for one cycle to occur.
   a. length
   b. amplitude
   c. time
   d. height
10. Period decreases while _____ increases.
    a. wavelength
    b. pulse length
    c. frequency
    d. bandwidth
11. Wavelength is the length of _____ over which one cycle occurs.
    a. time
    b. space

c. propagation
d. power

12. Propagation speed is the speed with which a(n) _____ moves through a medium.
a. wave
b. particle
c. frequency
d. attenuation

13. Wavelength is equal to _____ _____ divided by _____.
a. propagation speed, frequency
b. media density, stiffness
c. pulse length, frequency
d. wave amplitude, period

14. The _____ and _____ of a medium determine propagation speed.
a. amplitude, intensity
b. wavelength, period
c. impedance, attenuation
d. density, stiffness

15. Propagation speed increases if _____ is increased.
a. amplitude
b. frequency
c. density
d. stiffness

16. The average propagation speed in soft tissues is _____ m/s or _____ mm/μs.
a. 10, 3
b. 1540, 1.54
c. 3, 10
d. 1.54, 1540

17. Propagation speed is determined by the _____.
a. frequency
b. amplitude
c. wavelength
d. medium

18. Place the following classifications of matter in order of increasing sound propagation speed.
a. gas, solid, liquid
b. solid, liquid, gas
c. gas, liquid, solid
d. liquid, solid, gas

19. The wavelength of 7-MHz ultrasound in soft tissues is _____ mm.
a. 1.54
b. 0.54
c. 0.22
d. 3.33

20. Wavelength in soft tissues _____ while frequency increases.
a. is constant
b. decreases
c. increases
d. weakens

21. It takes _____ μs for ultrasound to travel 1.54 cm in soft tissue.
a. 10
b. 0.77
c. 154
d. 100

22. Propagation speed in bone is _____ that in soft tissues.
a. lower than
b. equal to
c. higher than
d. 10 m/s greater than

23. Sound travels fastest in _____.
a. air
b. helium
c. water
d. steel

24. Solids have higher propagation speeds than liquids because they have greater _____.
a. density
b. stiffness
c. attenuation
d. propagation

25. Sound travels most slowly in _____.
a. gases
b. liquids
c. tissue
d. bone

26. Sound is a _____ _____ wave.
a. mechanical expressional
b. electromagnetic transverse
c. electromagnetic longitudinal
d. mechanical longitudinal

27. If propagation speed is doubled (a different medium) and frequency is held constant, the wavelength is _____.
a. decreased
b. doubled
c. halved
d. unchanged

28. If frequency in soft tissue is doubled, propagation speed is _____.
a. decreased
b. doubled
c. halved
d. unchanged

29. If wavelength is 2 mm and frequency is doubled, the wavelength becomes _____ mm.
a. 4
b. 1
c. 2.5
d. unchanged

30. Waves can carry _____ from one place to another.
a. information
b. density
c. impedance
d. speed

31. From given values for propagation speed and frequency, _____ can be calculated.
a. amplitude
b. impedance
c. wavelength
d. intensity

32. If two media have different stiffnesses, the one with the higher stiffness will have the higher propagation speed. True or false?
33. The second harmonic of 3 MHz is _____ MHz.
    a. 2
    b. 3.2
    c. 6
    d. 9
34. Odd harmonics of 2 MHz are _____ MHz.
    a. 1, 3, 5
    b. 2, 4, 6
    c. 6, 9, 12
    d. 6, 10, 14
    e. 10, 12, 14
35. Even harmonics of 2 MHz are _____ MHz.
    a. 1, 3, 5
    b. 2, 4, 6
    c. 4, 8, 12
    d. 6, 10, 14
    e. 10, 12, 14
36. Nonlinear propagation means that _____.
    a. the sound beam does not travel in a straight line
    b. propagation speed depends on frequency
    c. harmonics are not generated
    d. the waveform changes shape while it travels
37. In nonlinear propagation, additional frequencies appear that are _____ and _____ multiples of the fundamental frequency. They are called _____.
    a. double, triple, harmonics
    b. double, triple, subharmonics
    c. odd, even, harmonics
    d. odd, even, subharmonics
38. If the density of a medium is 1000 kg/m^3 and the propagation speed is 1540 m/s, the impedance is _____ rayls.
    a. 1540
    b. 2540
    c. 540
    d. 1,540,000
39. If two media have the same propagation speed but different densities, the one with the higher density will have the higher impedance. True or false?
40. If two media have the same density but different propagation speeds, the one with the higher propagation speed will have the higher impedance. True or false?
41. Impedance is _____ multiplied by _____ _____.
    a. density, propagation speed
    b. frequency, oblique incidence
    c. wavelength, propagation speed
    d. attenuation, PD
42. The abbreviation CW stands for _____.
    a. corrected waveform
    b. continuous window
    c. continuous wave
    d. contrast waveform
43. PRF is the number of _____ occurring in 1 second.
    a. cycles
    b. pulses
    c. periods
    d. wavelengths
44. Pulse-repetition _____ is the time from the beginning of one pulse to the beginning of the next.
    a. frequency
    b. time
    c. duration
    d. period
45. The PRP _____ while PRF increases.
    a. increases
    b. decreases
    c. is unchanged
    d. is undetermined
46. PD is the _____ it takes for a pulse to occur.
    a. frequency
    b. time
    c. duration
    d. period
47. SPL is the _____ of _____ that a pulse occupies while it travels.
    a. length, time
    b. length, space
    c. amount, amplitude
    d. intensity, energy
48. _____ is the fraction of time that pulsed ultrasound is actually on.
    a. Pulse duration
    b. Pulse intensity
    c. Duty factor
    d. Duty frequency
49. PD equals the number of cycles in the pulse multiplied by _____.
    a. frequency
    b. period
    c. wavelength
    d. amplitude
50. SPL equals the number of cycles in the pulse multiplied by _____.
    a. frequency
    b. period
    c. wavelength
    d. amplitude
51. The DF of continuous wave sound is _____.
    a. 1
    b. undefined
    c. 1540
    d. 10
52. If the wavelength is 2 mm, the SPL for a three-cycle pulse is _____ mm.
    a. 6
    b. 0.6
    c. 0.4
    d. 1

53. The SPL in soft tissue for a two-cycle pulse of frequency 5 MHz is _____ mm.
a. 6
b. 0.6
c. 0.4
d. 1

54. The PD in soft tissue for a two-cycle pulse of frequency 5 MHz is _____ μs.
a. 6
b. 0.6
c. 0.4
d. 1

55. For a 1-kHz PRF, the PRP is _____ ms.
a. 6
b. 0.6
c. 0.4
d. 1

56. For Exercises 54 and 55 together, the DF is _____.
a. 0.0004
b. 0.004
c. 0.04
d. 0.4

57. How many cycles are there in 1 second of continuous wave 5-MHz ultrasound?
a. 5
b. 500
c. 5000
d. 5,000,000
e. None of the above

58. How many cycles are there in 1 second of pulsed 5-MHz ultrasound with a DF of 0.01 (1%)?
a. 5
b. 500
c. 5000
d. 5,000,000
e. None of the above

59. In Exercise 58, how many cycles did pulsing eliminate?
a. 100%
b. 99.9%
c. 99%
d. 50%
e. 1%

60. For pulsed ultrasound, the DF is always _____ 1.
a. less than
b. greater than
c. equal to

61. _____ is a typical DF for sonography.
a. 0.1
b. 0.5
c. 0.7
d. 0.9

62. Amplitude is the maximum _____ that occurs in an acoustic variable.
a. time
b. variation
c. distance
d. frequency

63. Intensity is the _____ in a wave divided by _____.
a. amplitude, power
b. area, power
c. power, amplitude
d. power, area

64. A unit for intensity is _____.
a. mW/cm^2
b. MHz/cm^2
c. cm/MHz
d. mm/cm^2

65. Intensity is proportional to _____ squared.
a. mW
b. watts
c. attenuation
d. amplitude

66. If power is doubled and area remains unchanged, intensity is _____.
a. unchanged
b. halved
c. doubled
d. quadrupled

67. If area is doubled and power remains unchanged, intensity is _____.
a. unchanged
b. halved
c. doubled
d. quadrupled

68. If both power and area are doubled, intensity is _____.
a. unchanged
b. halved
c. doubled
d. quadrupled

69. If amplitude is doubled, intensity is _____.
a. unchanged
b. halved
c. doubled
d. quadrupled

70. If a sound beam has a power of 10 mW and a beam area of 2 cm^2, the spatial average intensity is _____ mW/cm^2.
a. 10
b. 2
c. 20
d. 5

71. Attenuation is the reduction in _____ and _____ as a wave travels through a medium.
a. amplitude, intensity
b. amplitude, wavelength
c. intensity, speed
d. amplitude, speed

72. Attenuation consists of _____, _____, and _____.
a. amplitude, intensity, power
b. amplitude, wavelength, power
c. absorption, reflection, scattering
d. scattering, amplitude, speed

Compilation of Equations

For convenient reference, the equations in this book are compiled here.

Chapter 2

$$T\,(\mu s) = \frac{1}{f\,(MHz)}$$

$$\lambda\,(mm) = \frac{c\,(mm/\mu s)}{f\,(MHz)}$$

$$PRP\,(ms) = \frac{1}{PRF\,(kHz)}$$

$$PD\,(\mu s) = n \times T\,(\mu s)$$

$$DF = \frac{PD\,(\mu s)}{PRP\,(\mu s)} = \frac{PD\,(\mu s) \times PRF\,(kHz)}{1000}$$

$$SPL\,(mm) = n \times \lambda\,(mm)$$

$$I\,(mW/cm^2) = \frac{P\,(mW)}{A\,(cm^2)}$$

$$a\,(dB) = a_c\,(dB/cm) \times L\,(cm)$$

$$a\,(dB) = \tfrac{1}{2}\,(dB/cm\text{-}MHz) \times f\,(MHz) \times L\,(cm)$$

$$z\,(rayls) = \rho\,(kg/m^3) \times c\,(m/s)$$

$$IRC = \frac{I_r\,(W/cm^2)}{I_i\,(W/cm^2)} = \left[\frac{(z_2 - z_1)}{(z_2 + z_1)}\right]^2$$

$$ITC = \frac{I_t\,(W/cm^2)}{I_i\,(W/cm^2)} = 1 - IRC$$

$$\theta_i\,(degrees) = \theta_r\,(degrees)$$

$$d\,(mm) = \tfrac{1}{2}\,[c\,(mm/\mu s) \times t\,(\mu s)]$$

Chapter 3

$$f_o\,(MHz) = \frac{c_t\,(mm/\mu s)}{2 \times th\,(mm)}$$

$$AR\,(mm) = \frac{SPL\,(mm)}{2}$$

$$LR\,(mm) = w_b\,(mm)$$

Chapter 4

$$pen\,(cm) \times PRF\,(kHz) \leq 77\,(cm/ms)$$

$$PRF\,(Hz) = n \times LPF \times FR\,(Hz)$$

$$pen\,(cm) \times n \times LPF \times FR\,(Hz) \leq 77{,}000\ cm/s$$

Chapter 5

$$Q\,(mL/s) = \frac{\Delta P\,(dyne/cm^2)}{R\,(poise)}$$

$$R\,(g/cm^4\text{-}s) = 8 \times L\,(cm) \times \frac{\eta\,(poise)}{\pi \times [r^4(cm^4)]}$$

$$Q\,(mL/s) = \frac{\Delta P\,(dyne/cm^2) \times \pi \times d^4\,(cm^4)}{128 \times L\,(cm) \times \eta\,(poise)}$$

$$\Delta P = 4(v_2)^2$$

$$f_D\,(kHz) = f_R\,(kHz) - f_o\,(kHz) = f_o\,(kHz) \times \frac{[2 \times v\,(cm/s)]}{c\,(cm/s)}$$

$$v\,(cm/s) = \frac{77\,(cm/ms) \times f_D\,(kHz)}{f_o\,(MHz)}$$

$$f_D\,(kHz) = \frac{[f_o\,(kHz) \times 2 \times v\,(cm/s) \times (\cos\theta)]}{c\,(cm/s)}$$

$$v\,(cm/s) = \frac{[77\,(cm/ms) \times f_D\,(kHz)]}{[f_o\,(MHz) \times \cos\theta]}$$

$$FR_m\,(Hz) = \frac{77{,}000\,(cm/s)}{pen\,(cm) \times LPF \times n}$$

Chapter 7

$$NL\,(kHz) = \tfrac{1}{2} \times PRF\,(kHz)$$

Chapter 9

$$MI = \frac{p_r\,(MPa)}{[f\,(MHz)]^{1/2}}$$