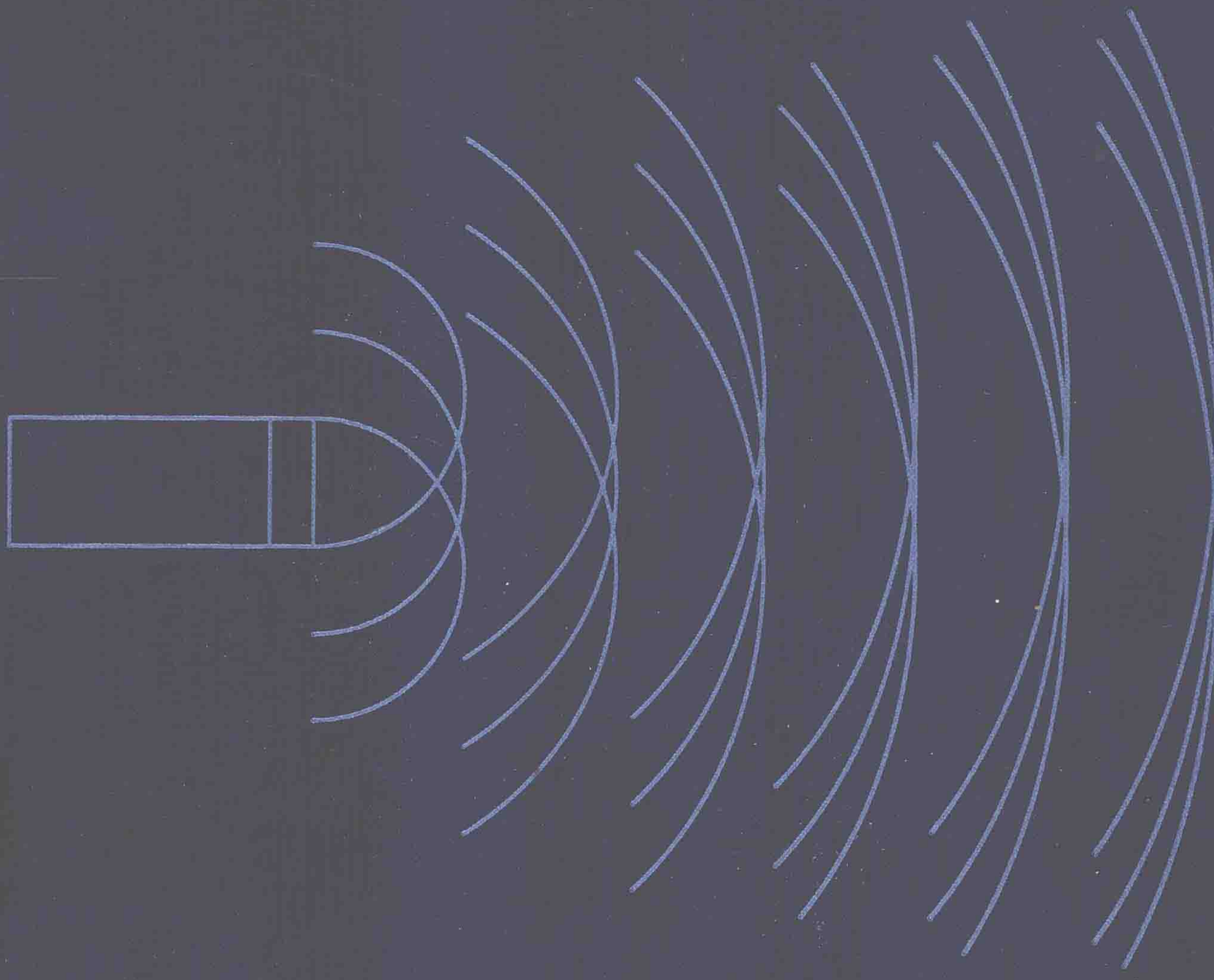
ULTRASOUND PHYSICS AND INSTRUMENTATION

SECOND EDITION



HYKES • HEDRICK • STARCHMAN

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ULTRASOUND PHYSICS AND INSTRUMENTATION

To our mothers
CATHERINE, EILEEN, and LOTTIE

PREFACE

This book addresses the needs of several groups of professionals involved in medical diagnostic ultrasound imaging. The primary intent of this textbook is to serve as a basis for instruction in ultrasound physics for diagnostic ultrasound technology students and radiology residents. However, the material presented will also benefit physicians and technologists in many medical specialties including obstetrics, cardiology, vascular surgery, urology, and surgery as well as veterinarians who use ultrasound equipment. The medical physicist and engineer can use the textbook as an introduction to ultrasound physics and instrumentation.

The material in this book is based on lectures given to diagnostic ultrasound technology students and radiology residents. The physical principles that have applications to the clinical environment have been stressed. The operator's understanding of the basic physical principles and the factors affecting the presentation of the data influence the quality of the diagnostic information. It is, therefore, essential that all individuals who perform and/or interpret ultrasound scans understand the underlying physical principles.

The field of medical diagnostic ultrasound has expanded rapidly over the past decade. Although the basic physical principles have remained unchanged, significant advances in instrumentation have resulted in increased clinical use of this modality. Motion imaging techniques, particularly real-time and Doppler, have virtually eliminated static B-mode scanners. Duplex scanners that incorporate real-time imaging with nearly simultaneous Doppler capabilities are now commonplace. Computer processing techniques in color Doppler imaging have enabled two-dimensional blood flow information to be superimposed on the real-time image. The text has been revised and expanded to reflect these and other advances in medical diagnostic ultrasound instrumentation.

This edition has been divided into 11 chapters. Chapter 1 presents the basic physical principles of ultrasound in detail. This is an important chapter because these physical principles form the basis for understanding all ultrasonic scanning modes and are dramatically different from those that apply to diagnostic x-ray imaging. Basic instrumentation described in Chapter 2 includes transducer and scanner design based on the echo-ranging principle. Static imaging modes (A, B, gated and transmission) are discussed in Chapter 3. These instruments have been almost totally replaced with motion-imaging scanners (real-time, Doppler, and M-mode), which are described in Chapters 4, 5, and 6. Two-dimensional echocardiology is also presented in Chapter 6. Computers have played an important role in the development of instrumentation and thus digital processing techniques are discussed in Chapter 7. The usual end product of ultrasonic scanning is an image recorded on film or other media. An overview of image recording devices is presented in Chapter 8. As with other imaging techniques, ultrasound deposits energy into the body and thus has the potential for causing biological effects. Chapter 9 reviews the literature concerning the biological effects of ultrasound and the clinical safety concerns associated with medical diagnostic ultrasound. The quality of the recorded image must be maintained at a high level via an appropriate quality control program as set forth in Chapter 10. The last chapter summarizes image artifacts that can seriously jeopardize the diagnostic interpretation.

Problem-solving is an integral part of the learning process in physics and necessary for passing registry and certification examinations. Sample problems are incorporated throughout the text that illustrate important quantitative relationships. Analogies are used frequently to aid in explanation of physical principles. Review questions at the end of each chapter further emphasize important concepts.

An extensive glossary of ultrasonic terms is included. The appendix contains a comprehensive mathematics review and a short discussion of Fourier analysis, which is a computer processing technique in Doppler scanning. The comprehensive review test will thoroughly test the working knowledge of the reader.

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COLOR PLATES

The following color plates appear between pp. 270 and 271.

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Chapter 1

BASIC ULTRASOUND PHYSICS

INTRODUCTION

Sound is mechanical energy that is transmitted through a medium such as air. The term *mechanical* is defined as a physical change induced by a force. Periodic changes in the pressure of air are created by forces acting on molecules of air, causing them to oscillate back and forth about their mean or average positions. A pressure wave is transmitted from one location to another when vibrating molecules interact with neighboring molecules. The frequency of a wave is the number of vibrations at a point each second. This is discussed in the section Properties of Waves later in this chapter. Sound waves are those pressure waves that the human ear can detect. These waves oscillate at frequencies of 20 to 20,000 cycles/second (c/s); c/s is a unit also referred to as a hertz (Hz).

Sound waves are mechanical in nature but are not restricted to transmission through air. However, they require an elastic, deformable medium for propagation, including gases, liquids, and solids. A solid is deformable because increased pressure applied to a solid causes a change in its shape. Elasticity is demonstrated by a return to the original shape when the pressure is lowered to the initial value. Sound waves are not electromagnetic radiation, as are light and x-rays. Electromagnetic radiation consists of alternating electrical and magnetic fields that are at right angles to one another and that propagate through a vacuum at the speed of light. Sound transmission cannot occur in a vacuum because no molecules are available to transfer the vibrations.

Ultrasound is defined as high-frequency mechanical waves that humans cannot hear; that is, they are mechanical waves having frequencies of greater than 20,000 Hz, or 20 kHz ($k = 10^3$). Infrasound refers to mechanical waves with frequencies of less than 20 Hz, which humans cannot hear. Ultrasound, infrasound, and sound have the same properties, and thus these terms are often used interchangeably in the description of physical interactions.

A pendulum having a small angle of displacement moves back and forth, displaying simple harmonic motion. The movement of a pendulum can be represented as a wave (Fig. 1-1). The location as a function of time can therefore be described using the wave equation

1-1

$$A = A_0 \sin(2\pi ft)$$

where A = amplitude at time t
A_0 = peak amplitude
f = frequency

The peak amplitude is the maximum distance from the rest position.

Sound waves are pressure or mechanical waves that result in the movement of the particles of a medium across or through their mean positions (Fig. 1-2). This movement is described mathematically by the wave equation (Equation 1-1) and can be illustrated by looking at the movement of a radio speaker. The radiofrequency wave received by the antenna is converted to an electronic signal, which drives the mechanical movement of the speaker. The speaker mechanically vibrates or oscillates back and forth at the frequency of the sound being produced (Fig. 1-3). The motion of a speaker can be visualized as a piston. When the speaker front moves forward, the air molecules immediately in front are pushed together, producing a region of increased air density, characterized by a small zone of increased pressure. The term *compression* describes the formation of the high-pressure region (Fig. 1-4).

If the speaker front is pulled back, a zone of decreased molecular density results. The term *rarefaction* describes the creation of a low-pressure region (Fig. 1-4). The regions of compression and rarefaction are passed through the medium by molecular interactions. The originally affected molecules collide with adjacent molecules to propagate the action of the speaker.

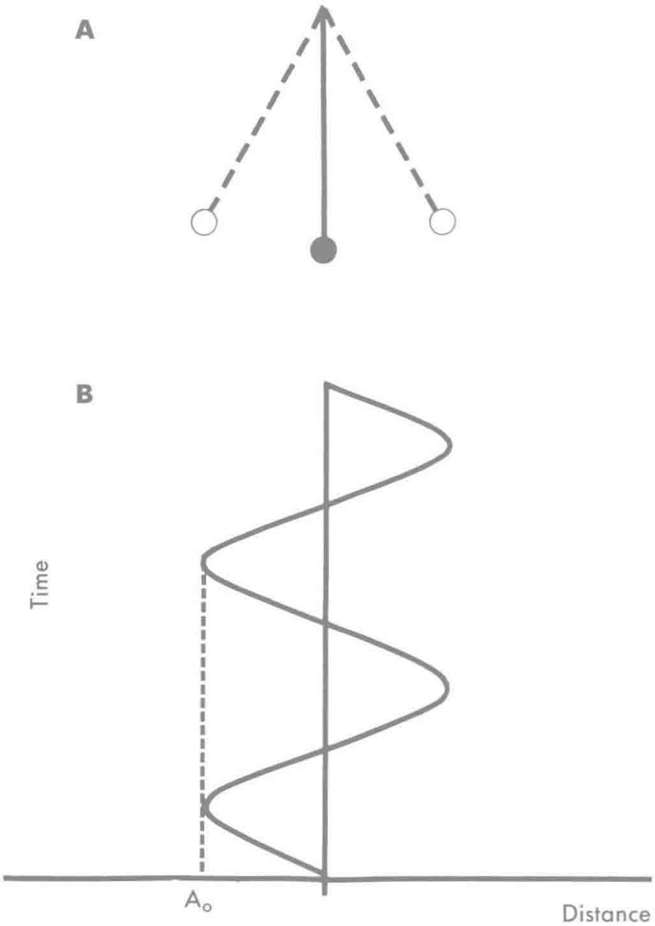

Fig. 1-1. Representation of pendulum motion. A, Oscillatory motion of a pendulum. B, Plot of pendulum displacement with time. The maximum displacement from the position at rest is designated A_o.

The molecules vibrate back and forth through their mean positions (a distance of only several microns). A micron is equal to 10^{-6} meters. Molecules do not travel from one end of the medium to the other; that is, there is no flow of particles. Rather, the effect is transmitted over long distances because of the neighbor-to-neighbor interactions. This molecular motion is necessary for sound transmission, which explains why sound cannot be transmitted through a vacuum.

Ultrasound is defined as high-frequency (greater than 20 kHz) mechanical waves. The wave energy mechanically moves particles of a medium so that they vibrate in a relatively uniform fashion, similar to the rhythmic oscillations of the speaker.

TYPES OF WAVES

Waves are divided into two basic types: longitudinal and transverse. Longitudinal waves are those in which particle motion is along the direction of the wave energy propagation. That is, the molecules vibrate back and forth in the

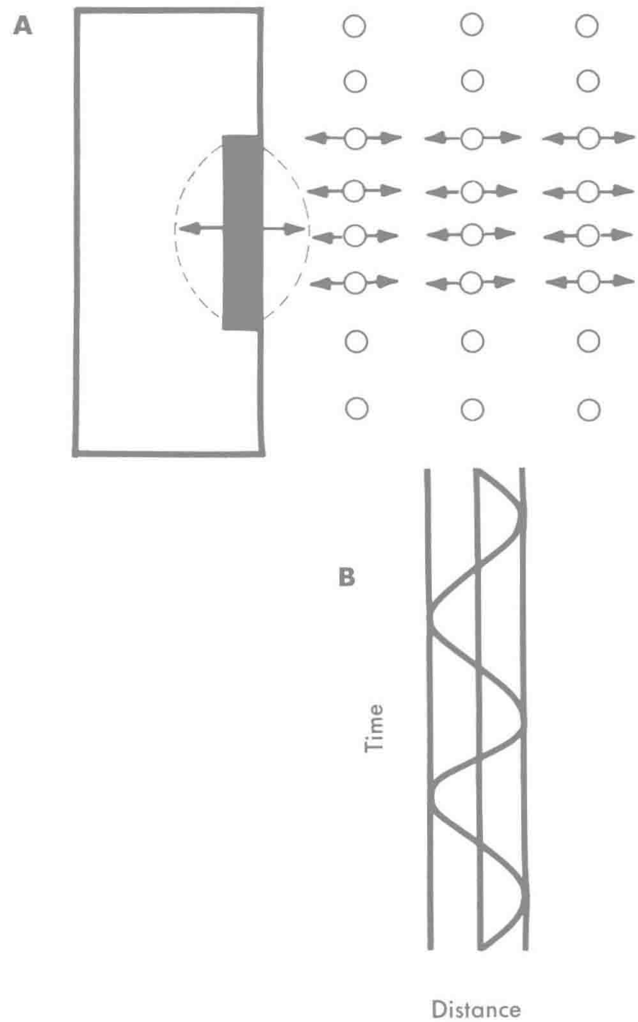

Fig. 1-2. Concept of molecular motion. A, Simple harmonic motion of air molecules produced by piston source. B, Plot of molecular displacement with time.

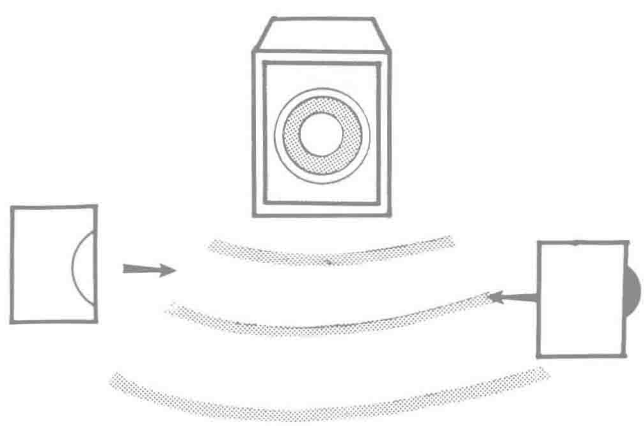

Fig. 1-3. Drawing of molecular motion induced by a speaker in which rarefactions *(open areas)* and compressions *(shaded areas)* are shown.

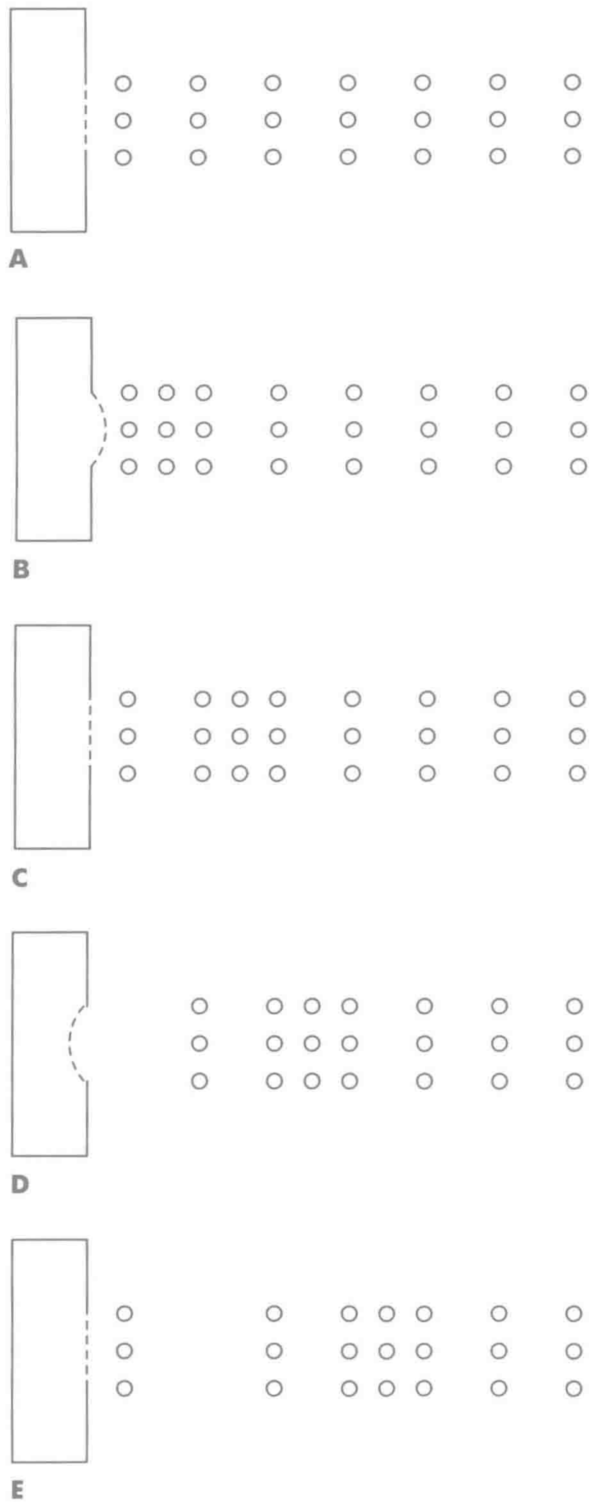

Fig. 1-4. Influence of a speaker motion on surrounding air molecules. **A**, Undisturbed medium with no speaker motion. **B**, Speaker moving outward, compressing the medium. **C**, Speaker returns to original position as region of compression advances. **D**, Speaker moves inward, creating rarefaction in the medium. **E**, Speaker returns to original position as regions of compression and rarefaction advance in the medium.

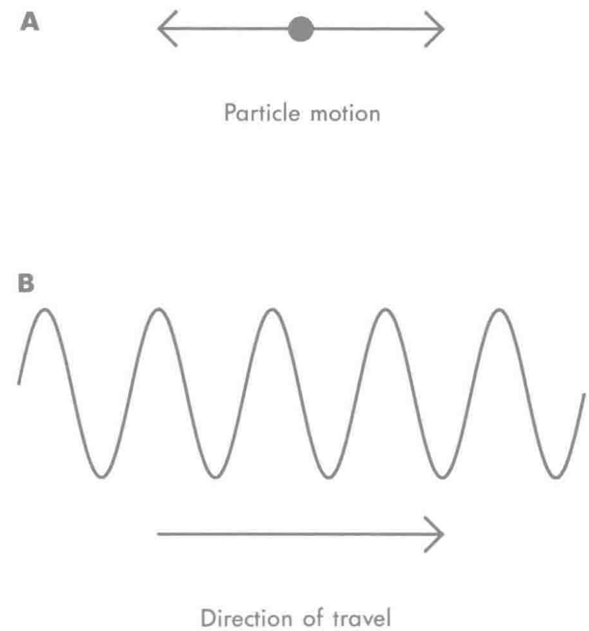

Fig. 1-5. Longitudinal wave. **A**, Molecular (particle) motion. **B**, Direction of travel of the wave is in the same direction as particle motion.

same direction in which the wave is traveling (Fig. 1-5). Sound waves are longitudinal.

Transverse waves are those in which the motion of the particles is perpendicular to the direction of propagation of the wave energy. The wave motion resulting from a stone thrown in the water is an example of a transverse wave. The water molecules vibrate up and down, similar to a cork floating on the water, as the wave moves away from the point of origin across the surface of the water. An example of a transverse wave is shown in Figure 1-6.

Bone is the only biological tissue that can cause the production of transverse waves, which are sometimes referred to as shear waves or stress waves.

PROPERTIES OF WAVES

Waves have certain physical characteristics that are used to describe them. Table 1-1 lists common descriptors, and the corresponding symbols are employed throughout the text. Each descriptor is introduced and discussed in this chapter.

When particle displacement is plotted versus distance, the wavelength of a wave, λ, is the distance from crest to crest or from trough to trough (Fig. 1-7). A more formal definition of wavelength is the length of one complete wave cycle (Fig. 1-7). A cycle is a sequence of changes in the amplitude that recur at regular intervals. Amplitude in this context describes the displacement from the mean position. The complete course of amplitude variations beginning at one crest is repeated at the next crest. Wavelength is

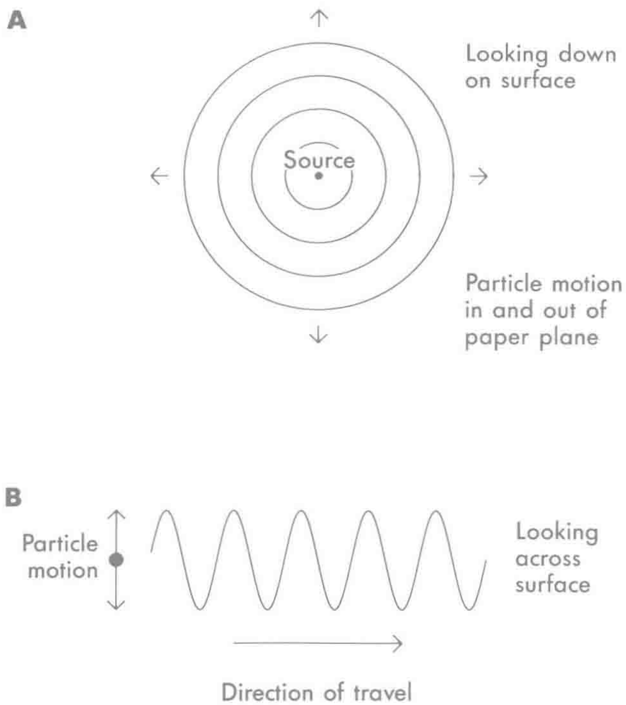

Fig. 1-6. Transverse wave. Direction of travel is radially outward from the sound source **A**, which produces particle motion perpendicular to the direction of travel **B**.

Table 1-1. List of physical descriptors and symbols

Descriptor	Symbol
Absorption coefficient	α
Acoustic impedance	Z
Acoustic power	W
Acoustic pressure	p
Attenuation coefficient	a
Compressibility	β
Density	ρ
Frequency	f
Instantaneous intensity	i
Intensity attenuation coefficient	μ
Particle displacement	s
Particle velocity	u
Period	τ
Reflection coefficient	α_R
Transmission coefficient	α_T
Velocity of sound	c
Wavelength	λ

expressed in units of meter (m), centimeter (cm), or millimeter (mm).

Amplitude refers to a change in magnitude of a physical entity and can be applied to either the pressure in the medium, the density in the medium, the particle displacement, or the particle velocity, when describing the properties of waves. The term *amplitude* has other applications, such as to characterize the size of the voltage pulse delivered to or

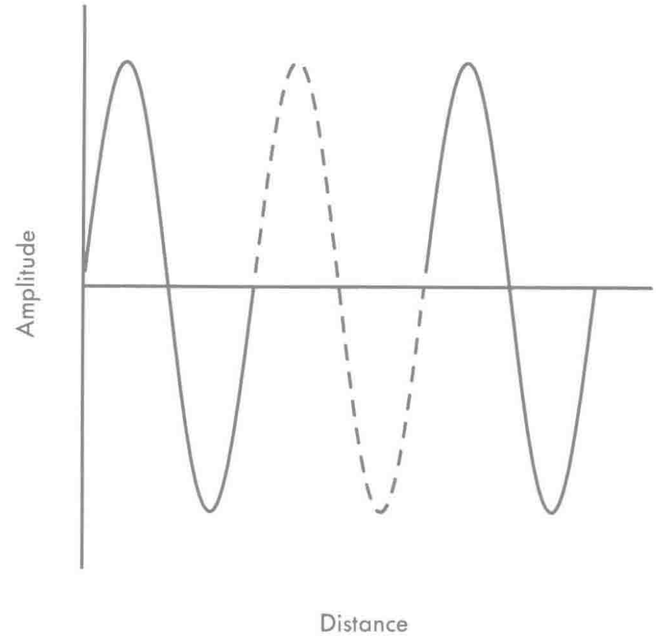

Fig. 1-7. Amplitude of particle displacement plotted as a function of distance of wave travel. The wavelength is defined as the distance from crest to crest or from trough to trough. The wavelength is also defined as one complete wave cycle *(dotted line)*.

induced in the crystal of the transducer (discussed later). Unless indicated otherwise, the term *amplitude* is used to describe particle displacement as a property of waves. When the amplitude is plotted as a function of time, the period of the wave, τ, is defined as the time necessary for one complete cycle or the time from crest to crest or from trough to trough (Fig. 1-8). The unit of the period is the second (s).

The frequency of a wave, *f*, is the number of cycles passing a given point in one unit of time (usually 1s) and corresponds to the inverse of the period ($1/\tau$). The unit of frequency is the hertz, which is equal to 1 cycle per second (c/s).

The speed at which a wave propagates through the medium is called the acoustic velocity, *c*. The velocity of sound is determined by the rate at which the wave energy is transmitted through the medium, which depends on the density and compressibility of the medium. Note that the acoustic velocity is not the same as the particle velocity (*u*), which refers to the speed at which the particles vibrate back and forth across their mean positions. It should be emphasized that a medium must be present in order for sound to propagate. This medium must also be elastic; that is, the medium must have the ability to deform temporarily and then reform to its original shape.

The velocity of sound in the medium is inversely proportional to the square root of the density of the medium, $\sqrt{\rho}$; that is, the denser the medium, the slower the velocity of sound:

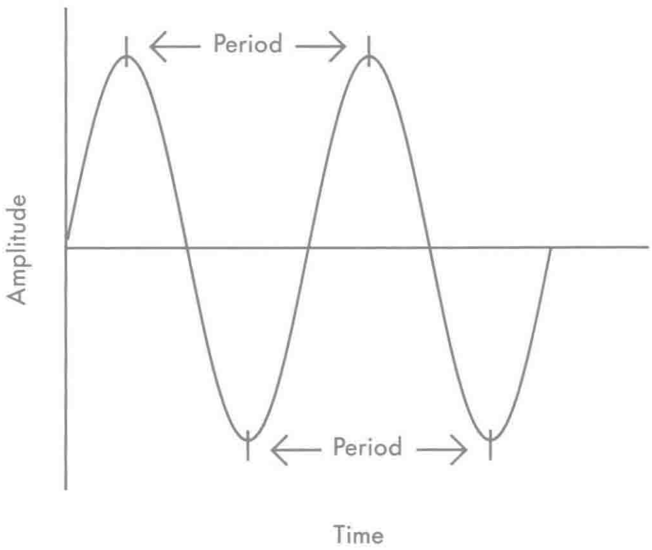

Fig. 1-8. Amplitude plotted versus time of wave travel, demonstrating the period of the wave.

$$c \propto 1/\sqrt{\rho}$$

where c = velocity
ρ = density of the medium

The density is the mass of the medium per unit volume. As the density of the medium is increased, more mass is contained within a given volume. For particles with increasingly larger mass, more force is required to produce molecular motion; once molecules are moving, more force is required to stop the molecules. This is particularly true for the rhythmic starting and stopping required to produce sound transmission. Thus on the basis of density alone, one would expect sound (ultrasound) to have a greater velocity in air (low density) than in bone (high density).

The velocity is also inversely proportional to the square root of the compressibility of the medium, $\sqrt{\beta}$:

$$c \propto 1/\sqrt{\beta}$$

Compressibility indicates the fractional decrease in volume when pressure is applied to the material. The easier a medium is to compress, the higher the compressibility. Dense materials, such as bone and other solids, are very difficult to reduce in volume. This low compressibility predicts a high velocity of sound in bone. In contrast, because the gas molecules in air are far apart and are easily brought closer together (i.e., compressibility is high), one would expect the velocity of sound in air to be low.

The reciprocal of the compressibility is given a special name, the *bulk modulus*. Consequently, the velocity is directly proportional to the bulk modulus. As the bulk modulus increases—and the compressibility decreases—the velocity of sound in the medium becomes faster. Some authorities refer to this property as the stiffness of the medium.

Combining compressibility and density into one equation, the acoustic velocity for a particular medium is determined by:

1-2

$$c = \frac{1}{\sqrt{\beta\rho}}$$

If the density could be increased without affecting the compressibility, then Equation 1-2 predicts that the speed of sound would decrease. Compressibility and density of a particular substance are interdependent; a change in density is coupled with a larger and opposing change in the compressibility. Because compressibility varies more rapidly, this parameter becomes the dominant factor in Equation 1-2. The overall effect is commonly summarized by the statement that, as the density increases, the speed also increases. As shown in Table 1-2, the velocity of sound in air is 330 m per second (m/s), whereas the velocity of sound in bone is 4,080 m/s. Compressibility is the key factor in determining the relative acoustic velocity, because bone is less compressible than air.

Another comparison of density and compressibility affects can be made by looking at two different liquids. Water has a density of 1 g per cubic centimeter (1 g/cm^3), and mercury has a density of 13.6 g/cm^3. On the basis of density alone, water would have a velocity of sound $\sqrt{13.6}$ times faster than mercury. The compressibility of water is 13.4 times higher than mercury (water is more easily compressed), which tends to cancel the density effect. The velocities for water and mercury are similar (Table 1-2). In fact, all liquids tend to transmit ultrasound at the same velocity. In the transference of sound, soft tissue behaves in a manner similar to liquids; the acoustic velocities for various tissue types do not vary by more than a few percent.

In general, because the compressibility is low, more dense media (most solids) have greater velocities than do less dense media (liquids or gases). This is one of the reasons (the second reason will soon become evident) that cowboys and Indians used to put their heads on the ground or the railroad tracks to listen for buffalo or trains in the old John Wayne movies. Sound travels faster in media denser than air because of reduced compressibility.

The average velocity of ultrasound in tissue is 1540 m/s. A slight dependence on the temperature of the medium and on the frequency is exhibited. The velocity of ultrasound waves in water at 20°C is 1480 m/s. If the temperature of the water is increased to 37°C, the velocity becomes 1520 m/s. For a few degrees shift in temperature, the change in velocity in water is small. Room temperature fluctuations are not a problem with respect to clinical applications because the body is maintained at a nearly constant temperature. However, sound propagation in phantoms is very dependent on temperature. For example, a mixture of 8% ethanol with water at room temperature mimics the velocity in tissue at 37°C. A temperature change of one degree in