DIAGNOSTIC USES OF ULTRASOUND

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PREFACE

Ultrasound has assumed ever-increasing importance in medicine since its introduction as a method of soft-tissue imaging less than two decades ago. Not until the late 1950s did it become an accepted diagnostic modality; since then, the various uses of ultrasound have multiplied exponentially. Two pathways have been followed: a technical effort directed toward the development of more sophisticated instrumentation, and an empirical approach emphasizing the application of ultrasound to practical problems in medicine. Technical advances have resulted in complex equipment with new capabilities, some not yet appropriate for general use. Empirical studies have added many valuable and practical new procedures to our diagnostic armamentarium.

In this book we have attempted to organize the available material on the practical diagnostic uses of ultrasound using the simplest proven methods available. This book is intended not only as an introduction to the practical uses of ultrasound but also as a manual that can easily be used by those interested in establishing ultrasonic techniques in their institutions. Therefore we have avoided a discussion of complex instrumentation and theoretical objectives. It is organized so that a reader interested in a particular field may find all pertinent information in one chapter. A bibliography of recommended references is provided at the end of each chapter for those desiring more detailed information.

Each chapter contains a complete and simplified description of the established methods in use. Ultrasonic patterns (echograms or ultrasonograms) obtained with each technique are presented with as much representative variation as possible. Experimental as well as pathologic data are provided only where needed to clarify particular points of conflict. Problems most commonly encountered are explained with illustrations showing how to avoid these possible sources of error.

In short, we have endeavored to provide physicians as well as technicians with a basic book on diagnostic ultrasound that can be used as a reference source and as a manual providing the information needed to perform all the established ultrasonic diagnostic procedures as simply and accurately as possible.

CONTENTS

Marvin C. Ziskin

1

Basic Principles

THE NATURE OF ULTRASOUND

Sound is a mechanical vibration that is transmitted through matter and ultrasound is one of its forms. Sound is perceptible to the human ear* if the frequency of vibration is between 16 and 20,000 Hz.** Sound with a frequency above 20,000 Hz is called ultrasound, and if the frequency is below 16 Hz it is called infrasound. This classification, although convenient, is quite arbitrary from both biologic and physical points of view. Many animals, such as bats, dogs, and dolphins, can hear sounds considerably higher in frequency than 20,000 Hz. Furthermore, few humans can hear frequencies above 16,000 Hz. From the physical point of view, there are no qualitative distinctions among the categories of sound; the only distinctions are those of quantity.

Propagation of Sound

Sound is propagated in the form of a mechanical vibration of the particles of the medium through which it travels. Unlike electromagnetic waves, such as light or x-rays, sound cannot travel through a vacuum. For the purpose of understanding sound propagation, it is helpful to consider matter consisting of an arrangement of particles or molecules in which each particle is connected to its neighbors by

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*Strictly speaking, sound is perceived by the person. The ear is merely a sensor.

**The term Hertz is now the preferred term for "cycles per second." Its abbreviation is Hz. One kiloHertz (1 kHz) equals 1,000 cycles per second and one megaHertz (1 MHz) equals one million cycles per second.

elastic bands as shown in Figure 1-1. Now if one of the particles is displaced to the left, the elastic band attached to its neighbor on the right will be stretched. If the displaced particle is then released, it will be pulled back to its original position by the stretched elastic band. However, because of its inertia, it will overshoot and continue moving to the right until stopped by the elastic band on the left. The particle will then move to the left until restrained by the stretching of the elastic band on the right. In this manner, the particle vibrates back and forth from its resting position. The vibration would continue indefinitely were it not for frictional forces that act in all materials. The frictional forces cause the amplitude of each cycle of vibration to be smaller than the preceding cycle. The energy utilized in overcoming the friction is converted into heat.

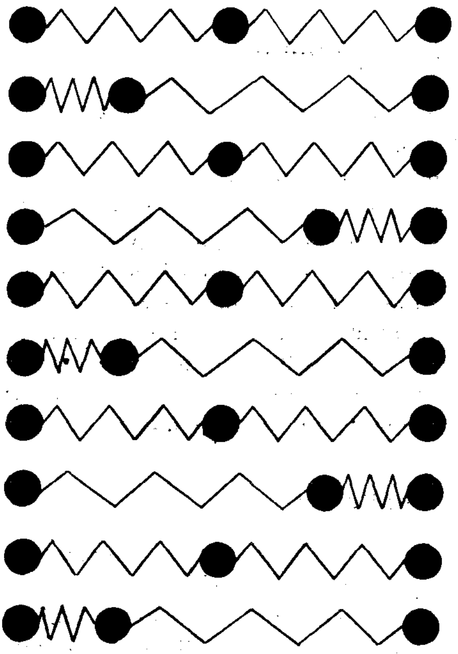

Fig. 1-1. Motion of a vibrating particle is shown. Each successive horizontal row represents a successive instant in time. The top row shows the resting position of a particle and its nearest neighbors. The next row shows a displacement of the particle to the left. When released, the particle will continue to vibrate back and forth about its resting position.

When a particle is set into vibration, it also affects the neighboring particles via the elastic band connections. As shown in Figure 1-2, displacement of a particle to the left will cause its right-hand neighbor to move to the left. This neighboring particle will in turn cause its own right-hand neighbor to move to the left. The process continues until this leftward displacement progresses throughout all of the particles in the material lying in the direction of movement. The net effect of this series of sequential movements is the propagation of a wave energy.

If the elastic connections were rigid, all of the particles would move at the exact same time and be in perfect synchrony. However, because of the elastic nature of these connections, there is a finite delay before the motion of a particle can force its neighbor to move. The stiffer the elastic connections, the shorter the delay and the more rapid will be the propagation of the vibration.

It should be noted that although the vibrational energy is transmitted through the material, there is no net movement of the medium. That is, the total displacement of each particle is limited to just short distances about its resting position.

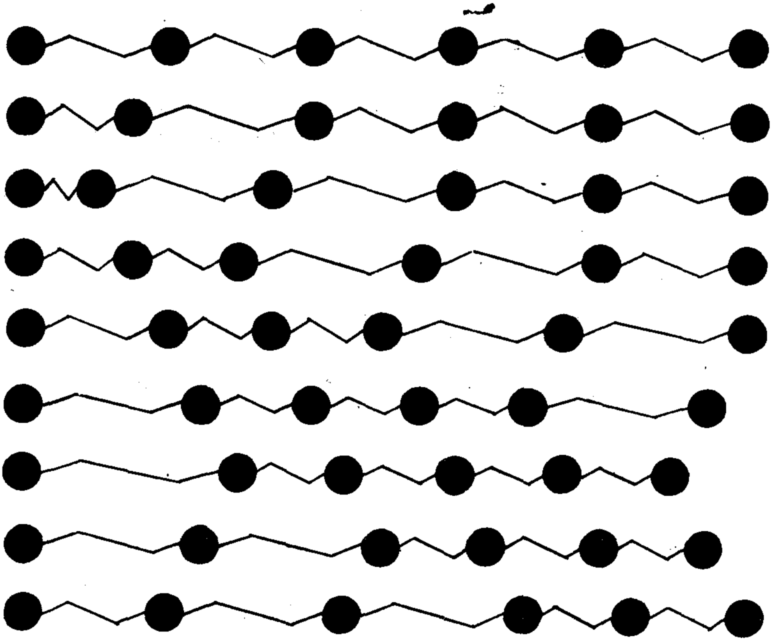

Fig. 1-2. Propagation or particle motion is shown. The particle on the far left is held fixed. Each row represents a successive instant in time. See text for explanation.

Types of Waves

In the preceding description, the particle vibration occurred in the direction of sound propagation. Sound with this type of particle motion is called a longitudinal sound wave. Transverse waves occur when the particle motion is perpendicular to the direction of sound propagation.

Although all materials can support longitudinal waves, only solids can support transverse waves. With the sole exception of compact bone, the tissues of the body behave acoustically as though they were fluids. Consequently, longitudinal waves are by far the predominant form of sound energy in medical application. In this book, all discussions of sound waves will relate solely to longitudinal waves unless stated otherwise.

Figure 1-3 shows a longitudinal wave traveling through a medium. Because the particles of the medium are not vibrating in perfect synchrony, the distances between neighboring particles are not constant. At any instant in time, there are regions in which the interparticle distances are very small and regions where these distances are quite large. The local pressure within the medium is directly proportional to the concentration of particles and therefore will be greatest in those regions where the interparticle distances are smallest. The upper portion of Figure 1-3 shows a graph of the pressure variation associated with the sound wave. Note that the associated pressure wave varies in a sinusoidal manner and that its peaks correspond to the regions of greatest particle concentration within the medium.

The regions of greatest particle concentration are called condensations, and the regions of lowest particle concentration are called rarefactions. As the sound wave travels through the medium, the

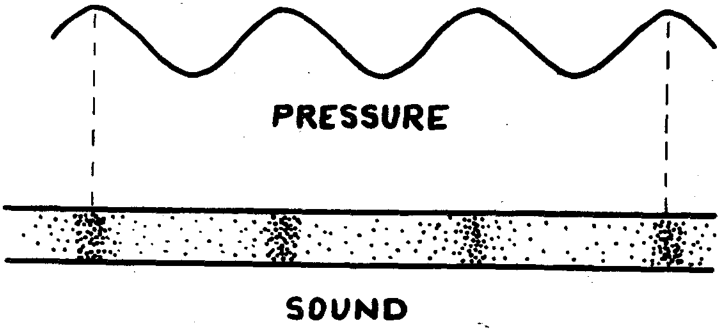

Fig. 1-3. Longitudinal sound wave and corresponding pressure variation is illustrated. Propagation is toward the right.

interparticle distances change in such a way that regions of low concentration become more concentrated and vice versa. However, the distances between the condensations and rarefactions remain constant and regular. The net effect appears as though the entire picture in the lower portion of Figure 1-3 has moved in the direction of propagation.

Velocity of Sound

The velocity of sound depends on two properties of the medium through which it travels: the elasticity and the density. The exact relationship is expressed in the equation:

$$v = \sqrt{\frac{E}{\rho}},$$

where v is the velocity, E is the elasticity, and ρ is the density of the medium. Density is defined as mass per unit volume and expressed in units of g/cc.

Elasticity is the measure of stiffness of the elastic connections between the particles of a material. Contrary to the common notion of elasticity, to a physicist the stiffer the elastic band, the greater the elasticity.

The precise nature of E will depend on the type of wave and whether the medium is a gas, liquid, or solid. For longitudinal waves in solids, Young's modulus of the solid would be used as the value for E. Young's modulus is defined as that increment in pressure required to produce a corresponding fractional increase in length. For longitudinal waves in gases and liquids, the adiabatic bulk modulus of the fluid would be used for the value of E. The bulk modulus is that increment in pressure required to produce a corresponding fractional decrease in volume. The term adiabatic implies that no heat was transferred to the surrounding matter in the process.

Elasticity, and therefore the velocity, is affected by temperature and pressure. The relationship of velocity to these variables is somewhat complicated and empirically determined. However, the total influence of these variables within the biologic range is relatively small, and, therefore, temperature and pressure can usually be ignored in medical ultrasonics.

Velocity of sound is virtually independent of frequency. Therefore, the velocity of ultrasound is exactly the same as that of audible sound for any material.

Table 1-1 gives the velocity of sound through various common materials. These measurements were performed at standard atmos-

Table 1-1
Sound Velocities

Material	Velocity (m/sec)
Nonbiologic	
Air	*331*
Pure water	*1,430*
Sea water	*1,510*
Plastic	*2,500*
Metal	*5,000*
Biologic	
Fat	*1,450*
Vitreous humor of eye	*1,520*
Human soft tissue, mean value	*1,540*
Brain	*1,541*
Liver	*1,549*
Kidney	*1,561*
Spleen	*1,566*
Blood	*1,570*
Muscle	*1,585*
Lens of eye	*1,620*
Skull bone	*4,080*

pheric pressure and at room temperature (17°–25°C). It should be noted that the velocity in one type of soft tissue is very nearly the same as that of another, and also close to that of water. As far as acoustics is concerned, soft tissue behaves as a liquid. In contrast, compact bone behaves as a solid, and sound velocity in bone is approximately three times greater than it is in soft tissue.

Frequency

Frequency is the rate at which something oscillates and is expressed in units of Hertz. The frequency of a sound wave is the frequency at which the particles of the medium vibrate. With respect to the associated pressure wave, this corresponds to the number of pressure peaks that pass a given point in 1 sec. Sound frequencies employed in medical applications range from 1 to 15 MHz. However, in some ophthalmologic applications, frequencies as high as 30 MHz have been used.

EFFECT OF FREQUENCY

The frequency has an important influence on the shape of a sound beam. The widening of a sound beam as it travels is called divergence. For any given sound source, the higher the frequency the smaller the divergence (Fig. 1-4). The divergence also depends on the diameter of the sound source. The exact relationship will be described later. Ideally, a beam used as a diagnostic probe should be very narrow and have no divergence. This would provide the best lateral resolution, which will be discussed below.

Wavelength

The wavelength of a sound wave is defined with respect to the associated pressure wave. It is the distance from one pressure peak to the next pressure peak (Fig. 1-5). In medical applications, wavelengths range from 0.1 to 1.5 mm.

The wavelength is symbolized by the greek letter lambda, λ. From the physicist's point of view, the wavelength is of utmost importance, since it determines the theoretical limit for the resolving capability of a sound beam.

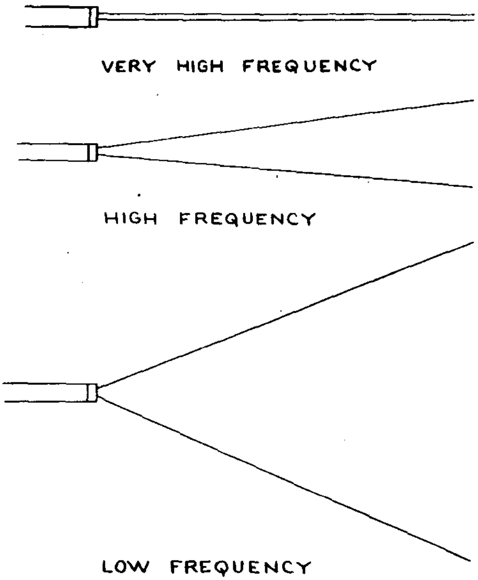

Fig. 1-4. Effect of frequency on beam divergence is shown.

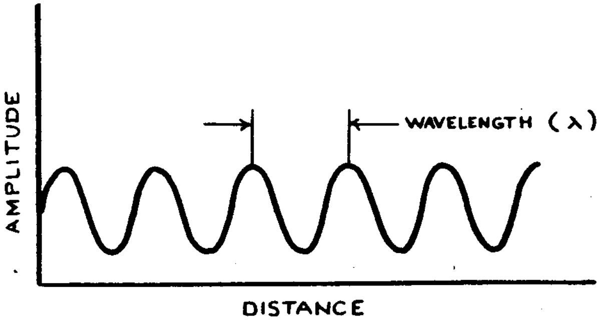

Fig. 1-5. Graphical definition of wavelength is illustrated.

Velocity, frequency, and wavelength are interrelated. The equation describing the relationship is:

$$v = f\lambda$$

where v is the velocity, f is the frequency, and λ is the wavelength. This equation permits one to calculate any one of these three variables if the other two are known.

EXAMPLE

You wish to calculate the wavelength of a 2-MHz sound wave in blood. (The velocity of sound in blood is 1570 m/sec.) The solution would be:

$$\lambda = \frac{v}{f} = \frac{1570 \text{ meters/sec}}{2 \text{ MHz}}$$

$$= \frac{1570}{2 \times 10^6} \text{ meters} = 785 \times 10^{-6} \text{ meters}$$

$$= 785 \times 10^{-3} \text{ mm}$$

$$= 0.785 \text{ mm.}$$

Resolution

Resolution is the ability to identify two objects as being distinct entities. The greater the resolution, the closer the two objects can be and still be recognized. There are two types of resolution to consider in using ultrasound as a diagnostic probe: lateral resolution and axial resolution.

LATERAL RESOLUTION

Lateral resolution, sometimes termed azimuthal resolution, is the ability to distinguish objects in a line perpendicular to the axis of the sound beam. It is measured by the distance between two objects when they are just resolvable by the sound beam. As shown in Figure 1-6, lateral resolution is inversely proportional to beam width. The beam width depends on the diameter of the sound source, the frequency of the sound, and for a diverging beam the distance from the source.

AXIAL RESOLUTION

Axial resolution, sometimes termed depth resolution, is the ability to distinguish two objects on a line parallel to the sound beam. It is measured as the distance between objects when they are just resolvable. The wavelength determines the theoretical limit for axial resolution. That is, objects closer than one wavelength apart cannot be

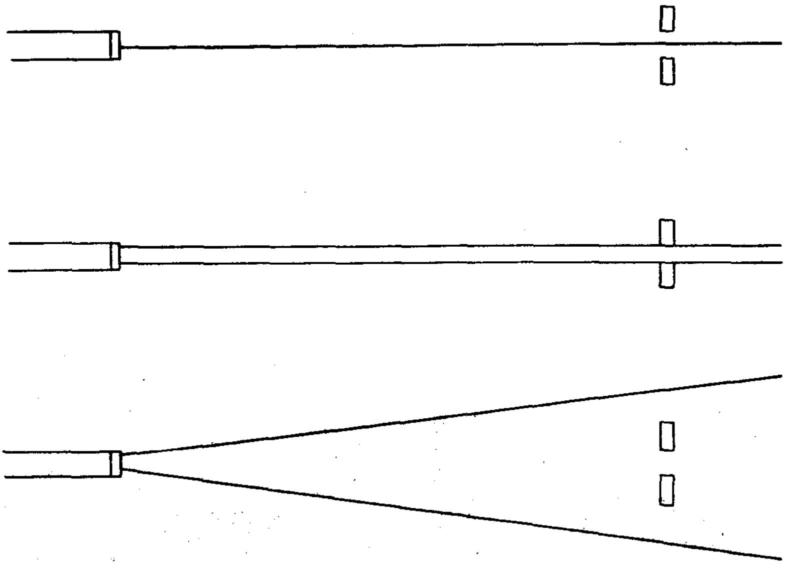

Fig. 1-6. Effect of beam width on lateral resolution is shown:

$$\text{Lateral Resolution} = \frac{1}{\text{Beam Width}}$$

The wide beam is incapable of resolving the two objects. The medium-sized beam just resolves and the very narrow beam easily resolves the two objects.

resolved (Fig. 1-7). Since wavelengths employed in diagnostic usage range from 0.1 to 1.5 mm, anatomic surfaces closer together than these distances will not be distinguished. Therefore, individual cells cannot be identified by ultrasound, whereas anatomic organs and tissue layers can.

Because of beam width and resolution considerations, the frequencies employed for diagnostic applications are at least 1 MHz. From these considerations alone, the higher the frequency the better. However, 15 MHz is the practical upper limit, since the penetration of ultrasound decreases with increasing frequency.

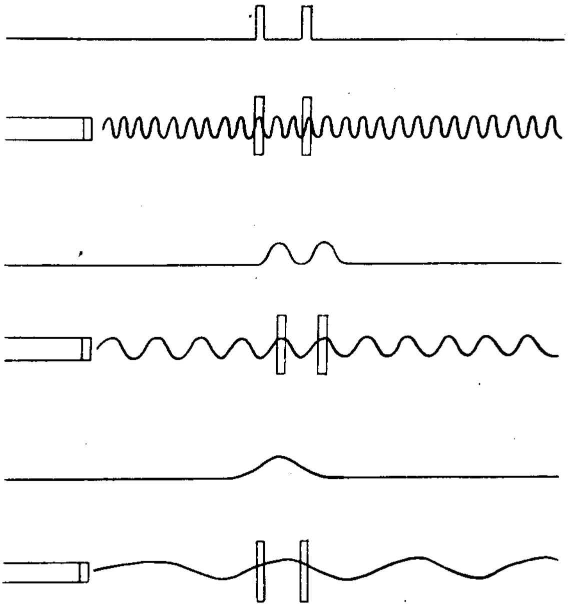

Fig. 1-7. Effect of frequency on axial resolution is illustrated. Three ultrasonic beams of differing frequencies are shown traversing two objects. Above each ultrasound beam is shown the echo pattern obtained with that beam. The low frequency beam cannot resolve the two objects. Both the medium and high frequency beams do resolve the two objects. Furthermore, the high frequency beam provides the best portrayal of the objects.

Intensity

It takes energy to initiate a sound wave. The energy is imparted to the particles to cause their resulting movement. Power is the rate at which this energy is propagated past an imaginary surface perpendicular to the sound beam. The unit of power is the watt.

Intensity is defined as power per unit area and is the appropriate measurement for the "strength" of ultrasound beams. It is measured in units of W/sq cm, or, for low intensities, in mW/sq cm.

Table 1-2 shows the intensity ranges of ultrasound used for various medical applications. The intensities used for diagnostic applications range from 1 to 50 mW/sq cm and are approximately 100 times lower than those used for therapeutic applications.

Sometimes it is desirable to compare two intensities. Because the ratio of two intensities can vary over a very large range, it has been found convenient to express this comparison by the logarithm of the ratio. The unit, the logarithm of the ratio of two intensities, is called the bel in honor of Alexander Graham Bell, the inventor of the telephone. However, it is the decibel, one tenth the size of a bel, that has become the standard unit used today.

The intensity of a sound beam, with respect to some reference intensity level, is then expressed as:

$$\mathrm{dB} = 10 \log_{10} \left(\frac{I}{I_o} \right),$$

where dB stands for decibels, I is the intensity of sound, and I_o is the intensity of reference.

Unless stated otherwise, the reference intensity level is understood to be 10^{-16} W/sq cm, the intensity of the faintest sound perceptible to the human ear. For example, sound with an intensity one million

Table 1-2
Ultrasonic Intensities

Medical Application	Intensity
Surgical	>10 W/sq cm
Therapeutic	1–3 W/sq cm
Diagnostic	0.001–0.05 W/sq cm