PEDIATRIC ECHOCARDIOGRAPHY

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PREFACE

Echocardiography has become an important adjunct in the evaluation of pediatric patients, particularly neonates, with heart disease. Many of the early investigations using ultrasound dealt with, and undoubtedly will continue to deal with, descriptive anatomy although attention is now being directed to the assessment of cardiac performance. A pressing need for qualified pediatric echocardiographers exists; however, at this time, centers for training are severely limited and most individuals are self-taught.

The goal of this book is to provide the echocardiographer with an approach to the evaluation of cardiac disease in children. This approach is based upon a fundamental understanding of the technique and a thorough knowledge of the anatomy (normal as well as pathologic) and physiology of the heart. Individual cardiac defects have been grouped according to the hemodynamic effects produced by the lesion and discussed in terms of the specific echographic features common to each functional group.

All the echograms in this book, with two exceptions, were obtained with the use of single crystal transducers and represent six years of experience. Many echograms illustrating each defect have been included in order to provide an in-depth understanding of each anomaly. The examples selected generally represent the average record obtained in our laboratory although we strive to obtain technically optimal tracings in every patient. In addition, numerous anatomic illustrations and cineangiograms have been included to help illustrate and correlate the echographic features with the underlying anatomy.

Although two-dimensional echocardiographic systems are emerging, our experience with these techniques is limited. Hence, only a brief discussion of the two-dimensional systems is presented and the reader is referred to more detailed publications.

Echocardiography is an ideal technique for the study of patients because it is non-invasive, painless, and without known risk. When properly used and interpreted, the results are quite accurate. But the echographic examination is not simple. Individuals often have been discouraged after spending many frustrating hours trying to reproduce records of various conditions that have been published in the literature. This book is not intended to substitute for practical experience but rather to supplement it. I hope it will offer assistance to the experienced echocardiographer as well as the beginner.

Cincinnati, Ohio RICHARD A. MEYER

ACKNOWLEDGEMENTS

Although this book is a monograph, its preparation and completion would not have been possible without the combined efforts of innumerable persons. Many of these individuals will not be acknowledged because their contributions, although important and far reaching, frequently were subliminal. I apologize to those who deserve recognition but who were inadvertently omitted. However, I must mention several individuals who have had a profound influence on my echocardiographic experience and its application in congenital heart disease and who have been instrumental in the development of this book.

First and foremost to be acknowledged is Dr. Samuel Kaplan, my teacher, advisor, associate, boss, and friend, who recognized early in the development of this technique its potential value in assessing congenital cardiac defects. He has constantly supported my endeavors and been a source of encouragement not only in the preparation of this book but in the promotion of echocardiography as well. His tutelage will continue to be invaluable!

Dr. David Schwartz's superb knowledge of anatomy and his artistic ability have provided me with a vital and indispensable understanding of the echographic representations of complex cardiac defects. Many of the artistic illustrations that have been so helpful in the appreciation of the echocardiographic and anatomic relationships have been drawn by Dr. Schwartz or adapted from his sketches. His constant support and input are deeply appreciated.

Mrs. Joan Korfhagen has played an important role in the development of our echocardiographic laboratory. Her impeccable technique has produced most of the beautiful recordings in this book and permitted the diagnosis of many complex cardiac defects. Her enthusiasm and interest in pediatric echocardiography have made her an invaluable research assistant and teacher.

The fundamental concepts of ultrasound so crucial to the proper understanding and application of echocardiography when published in a medical text frequently are difficult to understand because the language is so foreign to the majority of readers. I am indebted to Mr. Russel Uphoff for the clarity and simplicity of his chapters which illustrate so well the basic principles of echocardiography. I hope that all echocardiographers reading this text, whether experienced or inexperienced, will benefit from these chapters as much as I have.

Special appreciation is given to Dr. Harvey Feigenbaum, who permitted me to visit his laboratory during my embryonic echocardiographic gestation. His early instruction, support, and continued influence are indispensable.

I have had the privilege of working with many physicians who have taken their training in the Division of Cardiology at the Cincinnati Children's Hospital Medical Center. Obviously, many echocardiographic developments are due principally to the efforts of these physicians, who include Kenneth Bloom, Stephen Hirschfeld, Wesley Covitz, Barry Baylen, Selwyn Milner, Gregory Johnson, Agustin Ramos, and Aluizio Stopa. Deep appreciation is expressed to Terry Dillon for his effort in collecting and collating the normal values.

A special note of thanks must go to the secretarial staff who did a remarkable job typing and assembling the manuscript. These individuals include Maureen Mack, Molly Kaplan, Maureen West, Mary Beth Feilhauer, Margie Deho, Audrey McLaughlin, and Grace Matthews.

RICHARD A. MEYER

CONTENTS

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Principles of Ultrasound

It is fair to ask why a book on diagnostic ultrasound should always start with a chapter on basic principles. The simple fact is that the echocardiographer, whether physician or technologist, can do a more effective job with an understanding of the modality. A knowledge of basic principles aids him from the selection of the proper transducer to the interpretation of the results. Such knowledge is particularly useful in the important matter of detecting—and discounting—acoustic artifacts.

A neophyte tends to be awed by the knowledge possessed by the experienced practitioner in his chosen field. In the case of ultrasound this need not be true. Ultrasound is nothing but a certain class of sound waves, and all of us are experienced with sound waves. Some concepts regarding sound that are common knowledge to all who have grown up with a sense of hearing and a moderate penchant for observation are:

Sounds May Be Loud (Intense) or Soft (Weak). Intense sounds are produced by a powerful source such as an explosion or a jet plane. However, a soft sound may be weak because it comes from a weak source or because it has traveled a long distance. Also, a sound may be attenuated (weakened) by interposing a sound-deadening material between the source and the observer. (Notice how sound is defined in terms of the observer—in fact, purists maintain there is no sound without someone to hear it.)

Sounds Vary in Frequency. This is most apparent in music; sounds are said to have a high pitch or a low pitch. In music, pitch (frequency) is so important that it is the primary parameter for defining a tone. At this point it is appropriate to consider what it is that determines the frequency or pitch of the tone. Sound is usually produced by something vibrating—in a musical instrument it may be a string, a reed, a diaphragm, or a combination of these. The rate of vibration determines the frequency or pitch of the tone that is produced. The frequency at which the sound source vibrates is determined by its physical characteristics—its size, its mass, and its tightness.

Sound Has a Finite Velocity. Not only does sound have a finite velocity but also it is slow enough to be detected by the human sensing apparatus. Perhaps, the commonest example is the fact that thunder arrives at a point perceptibly later than does the light from the lightning bolt.

High Frequency and Low Frequency Sounds Travel at the Same Velocity. If all frequencies did not travel at the same velocity, band music would become increasingly disorganized as one moved away from it. A corollary of this observation is that sounds travel at the same velocity regardless of their intensities.

Low Frequency Sound Waves Travel Better and Farther than High Frequency Sounds. A common example of this phenomenon is the fact that a jet engine screams when one is close to it but sounds thunderous from a distance. Notice also that inside the plane one hears only the low frequency sounds. The high frequencies are attenuated by the sound insulation of the fuselage.

Sound Waves Reflect from an Object upon Which They Impinge. This fact has given rise to the special term *echo,* which is defined as "the sound produced by the reflection of sound waves from an opposing surface." (Funk & Wagnall) It goes without saying that this phenomenon is the basis for the whole field of echocardiography. Unfortunately, just as a shout in mountainous terrain may be repeated many times, echoing in diagnostic ultrasound does not necessarily stop after a single reflection. These multiple reflections are the cause of one of the commonest types of artifacts encountered in echocardiography.

The Interpretation Given a Sound Depends Greatly upon the Observer. This is an outgrowth of the fact that one of the principal uses of sound is for communication. The same sound may have a completely different connotation for two listeners. Thus, the music your radio produces for you is apt to be considered noise by your neighbor. Notice the unpleasant, undesirable context of the term *noise*—more about this later.

Perhaps, it would be easier to understand the behavior of sound waves if they could be observed directly. Unfortunately they cannot. However, some appreciation of sound waves can be learned from waves on the surface of water. Although the analogy has its limits, water waves have two advantages; they can be seen and their velocity is slow enough so that observation is facilitated. If a pebble is dropped into a quiet pool of water, a wave front emanates in all directions from the source of the

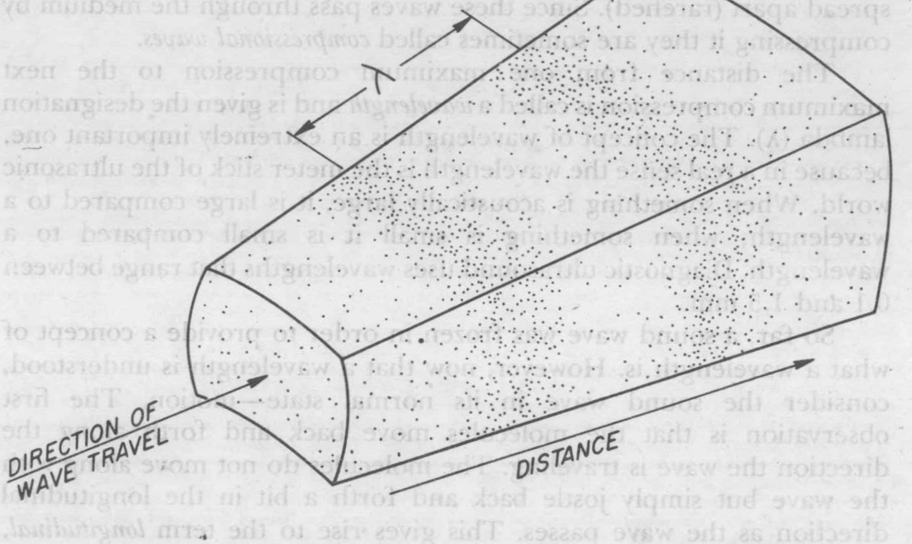

Fig. 1–1. Section of sound field showing compression and rarefaction of molecules of medium.

disturbance. This wave front is similar to that produced by a point sound source except that the sound wave truly travels in all directions, not being limited to the plane of the water surface. If the source of the disturbance is large and uniform as, for example, wind blowing across an open lake, the wave fronts will be parallel to one another and will all travel in a single direction.*

In order to become a really effective echocardiographer, a little more appreciation of the principles of sound than those just discussed is needed. Ultrasound is defined, with typical human egomania, as sound waves above the range of human hearing, that is, with a frequency above 20,000 cycles per second (c.p.s.). Nowadays, 1 c.p.s. is often called 1 Hertz (Hz) after the German physicist; thus, 20,000 c.p.s. = 20,000 Hz or 20 kilohertz (KHz) and 1,000,000 c.p.s. = 1 megahertz (MHz).

Next it would be appropriate to study a sound wave more closely, but this is difficult to do with something that is moving at 1500 meters (m.)/second (sec.). Assume that the sound wave could be frozen—stopped in its tracks—and a section of the sound field examined (Fig. 1–1). There are regions where the molecules of the medium are

*For the reader interested in pursuing the matter of water waves in greater depth, Rachel Carson has an excellent nontechnical chapter on the subject in her book *The Sea Around Us.*[1]

compressed together, interspersed with regions where the molecules are spread apart (rarefied). Since these waves pass through the medium by compressing it they are sometimes called *compressional waves*.

The distance from one maximum compression to the next maximum compression is called a *wavelength* and is given the designation lambda (λ). The concept of wavelength is an extremely important one, because in a real sense the wavelength is the meter stick of the ultrasonic world. When something is acoustically large, it is large compared to a wavelength; when something is small it is small compared to a wavelength. Diagnostic ultrasound uses wavelengths that range between 0.1 and 1.5 mm.

So far, a sound wave was frozen in order to provide a concept of what a wavelength is. However, now that a wavelength is understood, consider the sound wave in its normal state—motion. The first observation is that the molecules move back and forth along the direction the wave is traveling. The molecules do not move along with the wave but simply jostle back and forth a bit in the longitudinal direction as the wave passes. This gives rise to the term *longitudinal,* which is often used to refer to the type of sound wave which propagates through gases and liquids. This differentiates it from other types of sound waves in which the molecules move transversely and which propagate well only in solids.[2] These sound waves are not important in medical applications of ultrasound.

Since the sound wave is now moving, with the proper techniques, its velocity can be measured. The velocity varies depending on the medium through which the sound wave is traveling—in general, in gases it is slow, in liquids moderate, and in solids rapid. In water (saline) the velocity is about 1500 m./sec. Fortunately, soft body tissues are acoustically similar to saline solution in this respect. Velocity through fat is about 6 percent slower than through saline solution, whereas other soft tissues fall within a 4 percent range, just above 1500 m./sec. It may seem that 1500 m./sec. is pretty swift, but actually the speed of sound is comfortably slow so that with modern electronic techniques no particular problem is encountered when measuring the transit times found in the human body.

The best way to study ultrasonic waves is to insert a small microphone or other transducer (p. 10) into the sound field and let the wave pass by, recording its pressure variations. The resulting electric voltage is shown in Figure 1–2. If the transducer is accurate, the voltage will be a true electric representation of the pressure variation in the medium as the sound wave passes. By convention, compression is upward and rarefaction is downward with time along the horizontal axis. Now it is possible to measure electrically the number of pressure peaks

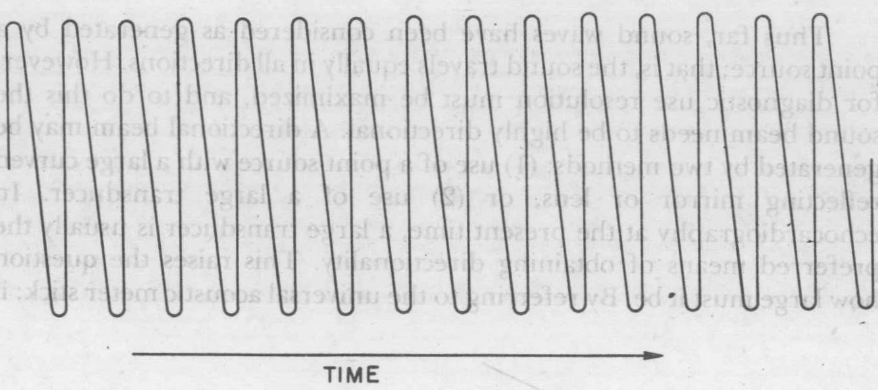

Fig. 1–2. Electric voltage produced by a transducer immersed in a sound field.

that pass the transducer in 1 sec., and thus derive the frequency of the sound wave. It is for this reason, principally, that transducers are rated by frequency rather than by wavelength, since it is difficult to measure wavelength electrically using conventional methods.

Fortunately, once the velocity of the sound wave in the medium is known, wavelength can be derived from frequency by application of the simple geometric formula:

$$\lambda = \frac{V}{f}$$

where V = velocity (m./sec.), λ = wavelength (m.), and f = frequency (Hz). For medical work in soft tissue the formula can be simplified even more. All that has to be done to obtain the wavelength in millimeters is to divide the frequency in megahertz into 1.5. Thus a transducer operating at 1.5 MHz produces a sound wave with a wavelength of 1 mm., a transducer operating at 3.0 MHz produces a sound wave with a λ = 0.5 mm., and so on. In view of the simplicity of the wavelength-frequency relationship, any echocardiographer can easily determine the wavelength of the energy being used in a procedure.

The importance of knowing the wavelength is that wavelength dictates the resolution with which the sound is capable of defining a structure. It is only when the frequency of a sound wave is raised to at least 1 MHz that the wavelength becomes small enough to be useful for medical diagnosis. This explains why low frequency sound waves are inadequate for this purpose.

Thus far, sound waves have been considered as generated by a point source; that is, the sound travels equally in all directions. However, for diagnostic use resolution must be maximized, and to do this the sound beam needs to be highly directional. A directional beam may be generated by two methods: (1) use of a point source with a large curved reflecting mirror or lens, or (2) use of a large transducer. In echocardiography at the present time, a large transducer is usually the preferred means of obtaining directionality. This raises the question how large must it be. By referring to the universal acoustic meter stick: it

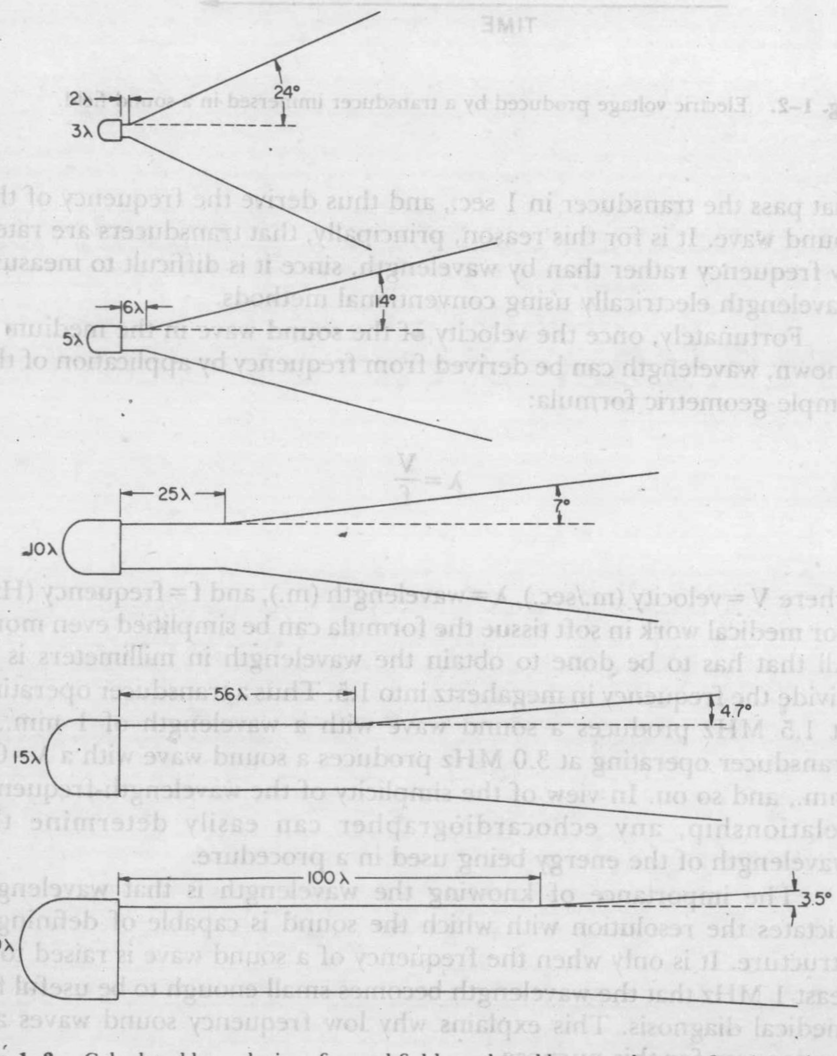

Fig. 1–3. Calculated boundaries of sound field produced by transducers of various sizes.

must be large with respect to a wavelength in the medium through which the sound is to propagate.

A more exact idea of the effect of transducer size can be obtained from Figure 1–3, which illustrates the outer boundary of the sound beam for transducers with diameters of 3, 5, 10, 15, and 20 λ. It is apparent that a transducer with a diameter of at least 10 λ is needed for good directionality, and for most purposes a diameter of 20 λ is even better. Notice that the field pattern is divided into two sections—a cylindrical near field* and a conically shaped far field. Figure 1–3 can be used to estimate the field pattern of almost any unfocused medical transducer. With a few commonly used transducers as examples, the calculations are:

AEROTECH MODEL SMT 22 DN
2.25 MHz, 13 mm. diameter

$$\lambda = \frac{1.5}{2.25} = 0.67 \text{ mm.}$$

$$\text{The diameter in wavelengths} = \frac{13}{0.67} = 19.4\ \lambda.$$

Thus this transducer has a beam pattern similar to that of Figure 1–3E (20 λ). The near field extends to 100 λ or 100 × 0.67 = 67 mm. The near field diameter is 13 mm., and the far field has a total divergence of 7 degrees.

HOFFREL MODEL 348
5 MHz, 6.5 mm. diameter

$$\lambda = \frac{1.5}{5} = 0.3 \text{ mm.}$$

$$\text{The diameter in wavelengths} = \frac{6.5}{0.3} = 21.6\ \lambda.$$

Again, this transducer has a beam pattern similar to that of Figure 1–3E (20 λ). From the figure it is found that the near field extends to 100 λ or 30 mm. The near field diameter is 6.5 mm., and the total beam divergence is 7 degrees.

*Actually, the near field is a complex interference pattern, which fortunately is not a matter of great significance in diagnostic work.

HOFFREL MODEL 343
2.25 MHz, 6.5 mm. diameter

$$\lambda = \frac{1.5}{2.25} = 0.67 \text{ mm.}$$

$$\text{The diameter in wavelengths} = \frac{6.5}{0.67} = 9.7\ \lambda.$$

This transducer has a beam pattern similar to that of Figure 1–3D (10 λ). From this pattern it is seen that the near field extends 25 λ or 16.7 mm. The total angle of divergence is 14 degrees.

A further constraint must be placed on the sound wave in order to use it effectively for echo work. Its length must be restricted so that it becomes a pulse rather than a long wave train as shown in Figure 1–2. The necessity for this can be appreciated by recalling what happens with echoes in the mountains. If instead of a single shout the shout is continuous, the returning echoes will be obscured by the continuing outgoing sound. Exactly the same problem is encountered when a long wave train is used to excite the transducer—echoes from near structures are obscured by the outgoing sound waves (Fig. 1–4A). This problem is

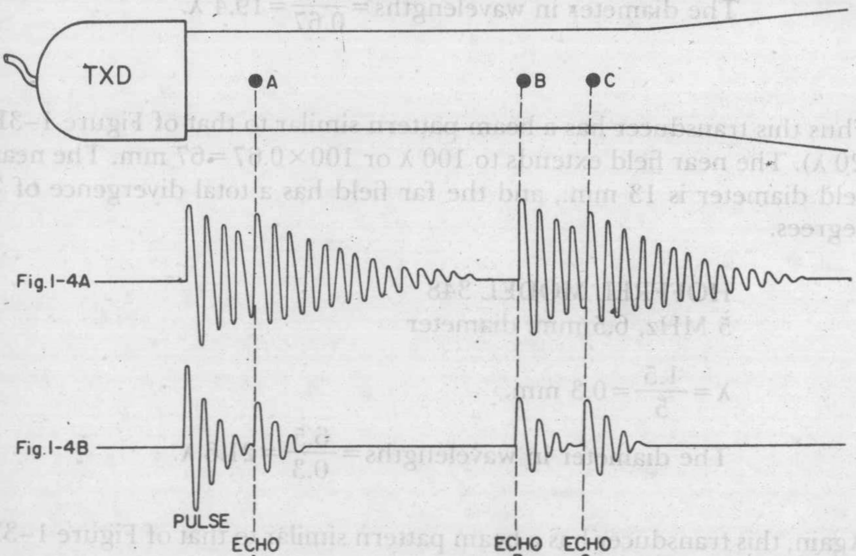

Fig. 1–4. Effect of length of wave train on ability of system to detect a target (A) close to the transducer (TXD) and to differentiate two closely spaced targets (B and C) located along the axis of the beam.

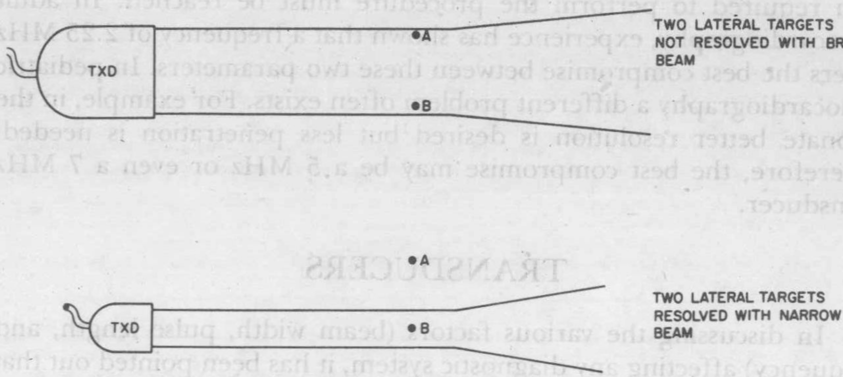

Fig. 1–5. Effect of transducer beam width on the ability of the system to discriminate between two closely spaced, laterally disposed objects (A and B). TXD = transducer.

prevented by shortening the wave train to 3 or 4 cycles (Fig. 1–4B). (Since it is desirable to use a short pulse one might ask why not shorten the wave train to a single half cycle. In some nondestructive testing applications this is done. However, in medical diagnostics the reduction in sensitivity that results is generally intolerable.) This kind of wave train is produced by designing the transducer so that it is inherently heavily damped.

One other parameter remains to be determined—a suitable wavelength. In order to do this resolution must be considered. Resolution is the ability of the system to differentiate between two closely spaced small objects. In present-day ultrasonic systems, the resolution obtained depends on whether the objects are longitudinally or laterally disposed with respect to the beam. Along the beam (axially) the resolution is determined by the length of the transmitted pulse as shown in Figure 1–4. If the pulse is 3 or 4 cycles long the axial resolution will be about 3 or 4 λ. In a similar manner the lateral resolution is determined by beam width of the transducer (Fig. 1–5). Since a beam width of 10 to 20 λ is necessary to obtain good directionality of the transducer, this is the order of magnitude of lateral resolution that can be expected.

Two conclusions can be reached from the previous discussion. The first is that axial resolution is three to five times better than lateral resolution. Second, in order to obtain the best resolution, wavelength must be as small as possible. From the formula on page 5, it can be seen that the wavelength (λ) can be reduced by increasing frequency. Unfortunately, the limitation observed with audio frequency sound (high frequencies do not penetrate as well as low frequency sound) is encountered. Thus, a compromise between resolution and the penetra-