GRAY-SCALE ULTRASOUND:

A Manual for Physicians and Technical Personnel

BARTRUM – CROW

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W. B. SAUNDERS COMPANY
Philadelphia, London, Toronto

W. B. Saunders Company: West Washington Square
Philadelphia, PA 19105

1 St. Anne's Road
Eastbourne, East Sussex BN21 3UN, England

1 Goldthorne Avenue
Toronto, Ontario M8Z 5T9, Canada

Gray-Scale Ultrasound: A Manual for Physicians and Technical Personnel ISBN 0-7216-1548-1

Last digit is the print number: 9 8 7 6 5 4

To Sheila, Jane, and Ann.

ULTRASOUND: The wave of the future is here today.

PREFACE

Diagnostic ultrasound has come of age. In late 1973 abdominal and pelvic ultrasound was considered an interesting new imaging modality, but its use was confined to scattered medical centers throughout the world. At that time the number of technicians and physicians doing ultrasound was so small that literally "everybody knew everyone else," and information on technical and clinical developments circulated informally. There were no textbooks on the subject, no postgraduate courses, a single fledgling journal, a small and widely scattered literature, and only three hospitals in the United States offering any formal training in the field.

Then, in late 1974, gray-scale ultrasound scanners became commercially available. For the first time images looked like pictures instead of Rorschach ink blots. Physician interest was awakened. At the same time CT X-ray scanners dramatically proved the value of cross-sectional imaging. Ultrasound scanning was accepted as a vital part of the diagnostic armamentarium, something which should be available in the community hospital as well as the medical center.

This unprecedented demand for ultrasound services has revealed a dramatic shortage of training facilities for the continually increasing numbers of physicians and technologists involved in ultrasound. Several texts on scanning have been published and have helped fill this need. Unfortunately, most of these volumes were conceived and written during the era of bi-stable scanning and could not anticipate the rapid technologic equipment advances which have occurred. Also these texts are directed toward interpretation of ultrasound images and provide little information on the technique of producing scans of good quality. Postgraduate courses abound, but these also concentrate on image interpretation rather than image production. There are some in-residence "fellowship" training programs, but spaces are limited; and these programs cannot absorb the numbers of physicians and technologists entering the field.

In order to establish adequate standards for technicians in ultrasound the Registry of Diagnostic Medical Sonographers was established in 1975 and conducted the first qualifying examinations in June, 1976. Both a written and practical examination were required of candidates. We had the privilege of conducting some of these examinations and the results were distressing. While many of the candidates were highly knowledgeable and excellent sonographers, there was a large number who were insufficiently prepared to conduct a diagnostic examination of quality. All of the candidates expressed frustration at having no source for information and training in scanning. Most said that the physicians for whom they worked could not provide this information, as they themselves could not perform the examination from a technical standpoint.

Physicians seem frustrated by the same shortage of basic instruction material. For over two years we have offered a one- or two-week postgraduate fellowship for physicians in B-mode ultrasound. This course was designed for the community radiologist who had just acquired an ultrasound machine but didn't know how to turn it on. To make matters worse, he was often too busy with his practice to take off three or six months to travel some distance to take an intensive course on the subject. Sometimes he sent his favorite technician to a course instead, or tried to hire an experienced technician away from someplace else. This usually backfired: the favorite technician either came back poorly trained or, if well-trained, was quickly hired away by some other desperate physician. Perhaps even more frustrating were the situations in which the untrained physician was at the mercy of the well-trained technologist—although the physician signed the reports, his signature was meaningless because the technician actually performed and interpreted the examination. What we tried to offer in our brief two weeks was a firm footing in the realm of B-mode scanning; although our "graduates" did not leave as ultrasound experts, they left with enough knowledge to judge the technical merits of an ultrasound scan and even perform a credible examination themselves. They were equipped to continue to learn and expand their ultrasound knowledge. Well, things went nicely at first—just a few fellows now and then, but not enough to interfere seriously with our normal routine or disrupt our resident teaching. But business just kept on improving. Despite the fact that we did not advertise the fellowship, did not have a "glamour" name, and were located out in the boonies of New Hampshire, the demand for the fellowship outstripped our ability to provide it. Since we do not have a monopoly on ultrasound teaching, we assume this trend indicates an ever-increasing demand for basic B-mode ultrasound instruction.

It is these experiences which have motivated us to produce this book. Abdominal and pelvic ultrasonography is the most demanding of any imaging modality. In contrast to CT and radioisotope scanning, in which technician input is small, or conventional radiography for which most technical factors can be standardized, ultrasound image quality (and consequent diagnostic accuracy) is totally dependent upon the skill of the machine operator, be it technician or physician. It is obvious that unless both the technician and the physician involved in ultrasound are capable of producing high quality, reproducible scans which are free of artifacts, there is little value in establishing an ultrasound service.

This book is, therefore, directed to all those who are new to ultrasound scanning of the abdomen and pelvis and who plan to work in these areas. It discusses the many factors involved in organizing an ultrasound laboratory and generating scans of useful diagnostic quality. The material is rather dogmatic. This is by design. We certainly do not pretend that our way of scanning is the only way or necessarily the best way; in ultrasound, as any endeavor, "there is more than one way to skin a cat." We do know, however, that the techniques and methods described work for us and that they will work for others. We feel it is important for anyone beginning scanning to have a firm basis upon which to expand and experiment. Once the methods in this book are mastered, the ultrasonographer should continually modify and expand his technique until he evolves a method which works best for him.

There is little discussion of scan interpretation; other texts and journals cover this topic nicely and our bibliography lists some of these sources of information. The most difficult part of interpreting ultrasound scans is producing a technically adequate image and deciding what is real and what is artifact: we cover that problem in detail.

Similarly, there is little discussion of bi-stable scanning. Although still an extremely important adjuvant to many examinations, the general utility of bi-stable scanners is limited. Modern ultrasound is gray-scale ultrasound.

We have included a chapter on the technique of ultrasonically guided biopsy. Although not yet a widely used procedure, this exciting aspect of ultrasound has the potential for extending dramatically the medical diagnostic process.

Finally a brief word about style. It will quickly become apparent that we have abandoned the traditional medical discourse and substituted informal discussion. Although it may offend some readers we have chosen to do this for two reasons. First, we have written this book not only for the physician but also for the technician, medical student, and medical voyeur. To encompass this disparity of backgrounds, we have tried to avoid jargon and simplify explanations insofar as possible. Second, throughout our schooling we were "lectured at" and subtly resented it. We are all adults now: it is time to discuss things as partners rather than as masters and pupils.

But enough procrastination—off to the ultrasound lab!

ROYAL J. BARTRUM, JR.

HARTE C. CROW

ACKNOWLEDGMENTS

Any book is like an iceberg. The authors represent the tip; supporting them is a large group of unseen collaborators. We would like to note the following:

First and foremost, Sheila R. Foote, R.T., ultrasonographer extraordinaire and chief ultrasound technician at the Dartmouth-Hitchcock Medical Center. Coming from Groveton, New Hampshire (you have to see it to believe it), and starting with no ultrasound knowledge whatever, she is an inspiring example of how common sense, experience and dedication can lead to genuine expertise in scanning.

Our other ultrasound technicians, Carol Bailey, R.T., Kathy Horan, R.T., and Marty Keyes, R.T., have also provided both technical and moral support throughout this project.

Many trusting and patient folks consented to be models for scanning, among them Joyce Cilley, Donald Chakares, Laura Jo Helff, Patricia Huke, Martha McDaniel, Bruce Shaw, Gerard Smith, and Cindy Watson.

Valarie Page contributed the lucid diagrams which help unscramble our prose.

Betsy Youngholm and Linda Rondeau converted our hen-scratchings and garbled dictation to legible typescript.

Finally, George Vilk, of W. B. Saunders Company, provided considerable encouragement while showing uncommon patience at our continually late manuscripts.

To all, our heartfelt thanks.

R.J.B.

H.C.C.

CONTENTS

Chapter 1

PRACTICAL PHYSICS

Do not skip this chapter! We hate physics just as much as you do, probably more. It would be wonderful if ultrasound scanners were totally standardized and automated so that all that was required to produce an image was simply to place the patient in front of the machine, push a button, and develop a picture. Alas, this is not the case at the present time. There is no field of medical imaging that is more dependent upon the skill of the machine operator than ultrasound scanning. And it is impossible to become a competent machine operator unless you know something about how the machine works.

We do not mean that you have to know enough physics to tear the scanner apart and rebuild the insides using leftover color TV parts, bubble gum, and a bobby pin; or that you have to be able to crystallize your own transducers on the kitchen stove. We mean only that you must have a basic understanding of what the ultrasound beam is, why an echo is produced, why artifacts exist, and what the various knobs on the machine do to the picture and why.

This is similar to the knowledge you must have to operate any mechanical contrivance adequately. The automobile is a good example. Most of us are not mechanics and don't know a piston from a pushrod or preignition from a marble in the ashtray, yet we do know a fair amount about the practical physics of the car. For instance, we know that gasoline is burned in the engine and produces energy to run the rest of the car. We know that this process is started by another form of energy, electricity in the battery, which runs the starter. Therefore if we turn the key and nothing happens we are more likely to suspect that the battery is dead rather than that the car is out of gas. Knowing this, we would ask someone to give us a push start rather than set off down the road, gas can in hand. Similarly if we were driving along and the car stopped, we would think the problem was more likely to be an empty gas tank than a dead battery.

It is this same general level of knowledge of the practical physics of ultrasound image production that is required. That is what this chapter is about—the physics of ultrasound for those who hate physics. We wish we could have put it at the end of the book—we know it is a bummer and a terrible lead-off topic, but unfortunately it is the basic platform upon which all ultrasound scanning rests and you simply must understand some of it before any other aspect of scanning will make much sense.

Enough procrastination. Getting into physics is like getting into an ice-cold swimming pool; the only way to do it is to hold your nose and jump.

THE PULSE-ECHO PRINCIPLE

B-mode ultrasonography is based on the pulse-echo principle. (We are going to discuss the term "B-mode" at some length later; for the moment it is enough to say that this term is a way of describing the information display system used almost exclusively in ultrasound scanning of any part of the body except the heart.)

A man stands on one side of a canyon and shouts "Hello!" toward the other side. This is the "pulse." That pulse travels through the air at the speed of sound (about 741 miles an hour) until it hits the opposite wall of the canyon where it is reflected back toward the man. Once the pulse has been reflected it becomes an "echo." The echo travels back to the man at the same speed of sound and, after a brief period of time, he hears the echo. We have all participated in this type of pulse-echo experience.

If the man has a stopwatch (and a small electronic calculator) he can use this pulse-echo to calculate how far it is to the other side of the canyon. He simply measures the time it took for his shout (the pulse) to be echoed back to him. Suppose this was 4 seconds. He consults his handy conversion table which tells him that 741 miles per hour is equivalent to 1087 feet per second. He then multiplies 1087 feet per second by 4 seconds and discovers that his "Hello" traveled 4348 feet. Since this represented two trips across the canyon (one for the pulse going and the other for the echo returning) he then divides by 2 and obtains 2174 feet as the distance to the other side of the canyon.

Now if the man got a kick out of measuring canyons this way, he would probably get tired of doing all these calculations every time he shouted. Instead he would sit down with a six-pack and do all of the calculations once for every possible time from 1 to, say, 20 seconds. He would then repaint the face of his stopwatch so that, instead of reading in seconds, it would read the number of feet to the echo source. Then he would be all set to measure canyons easily and quickly, using only his shout and the calibrated watch. Of course, his calibrated watch would be accurate only as long as the speed of sound was 1087 feet per second, but since the speed of sound in air doesn't vary much, at least when compared to the accuracy with which he can read his stopwatch, this problem isn't of much concern.

ULTRASOUND

Ultrasound imaging uses this same pulse-echo principle. A short pulse of ultrasound is emitted into the body. This pulse travels through the tissues at a constant speed until it encounters a reflecting surface. At such a surface some of the sound beam is reflected back toward the source; there it is received by the ultrasound scanner, which has been keeping track of the time and converting it to a distance in the same manner as the man and his calibrated stopwatch. However, instead of giving out the distance as a number, the scanner shows it as a dot or a spike on an oscilloscope or TV screen; the position of the spike is proportional to the distance the echo traveled. This enables us not only to measure the distance but to get a visual picture of it as well.

Although the principle of ultrasonic pulse-echo diagnosis is the same as the echo in the canyon there are several practical differences. To understand these differences we need to know a little about sound.

All sound, be it ultrasound or the kind we hear, is actually a series of repeating pressure waves. It is convenient to think about these waves and illustrate them as sine wave forms, as shown in Figure 1–1. Line *A* shows a single wave or cycle. As we move along the horizontal axis, which represents time, the pressure starts at zero, rises to some peak, then falls back to zero and continues to a negative value before returning to zero. Line *B* shows a continuous wave form where a large number of the single waves have been strung together. The single wave is analogous to an extremely short beep of a car horn while the continuous wave represents the horn being stuck in the on position.

This simple wave form is not adequate to fully describe the sound, however. We must know more information about the

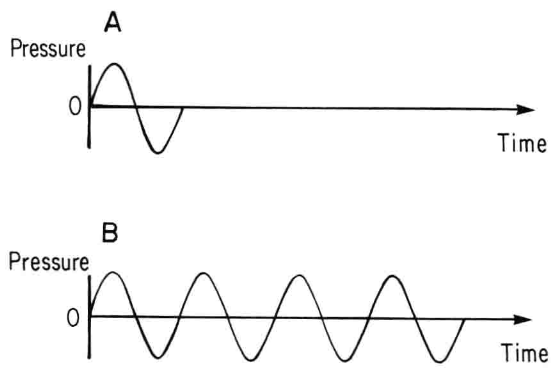

Figure 1–1. A diagrammatic representation of sound as a sine wave. *A*, A single wave or cycle. The horizontal axis is time; the vertical axis is pressure at a point in the medium through which the sound is traveling. The wave starts at zero pressure, rises to some positive value, then falls past zero to a negative value before returning to its starting position.

B, A continuous sound wave, made up of several single cycles linked together.

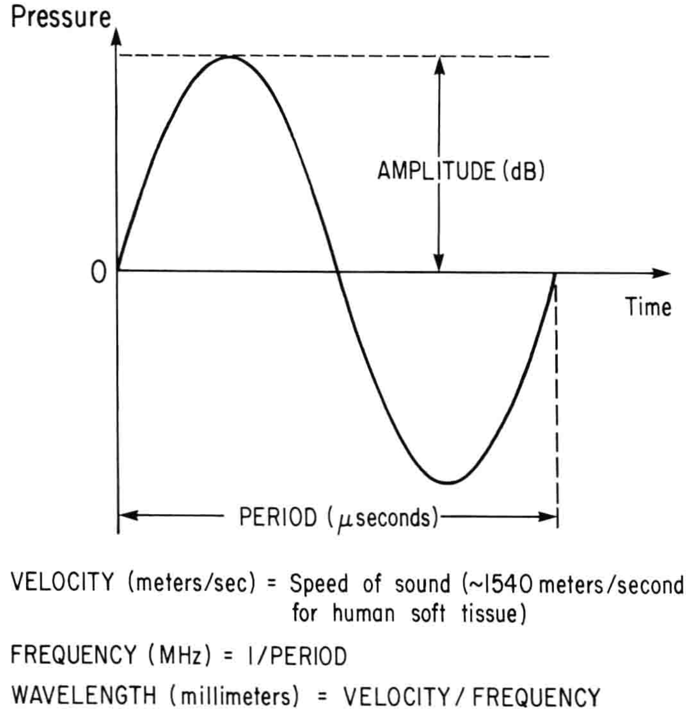

Figure 1–2. Some of the common parameters of a sound beam and the units in which they are commonly expressed.

wave before we can predict how it will behave. Therefore, several pieces of data are described for these waves (such data are called parameters of the wave). Some of the more important parameters are illustrated in Figure 1–2. The **period** is the time it takes to complete a single cycle. The **amplitude** is the peak pressure or height of the wave. This is a measure of the strength or "loudness" of the sound wave. A shouted "Hello" has a large amplitude while a whispered "Hello" has a small amplitude. We will use the words "power," "intensity," and "loudness" interchangeably with amplitude. While, in a strict physical sense, each of these terms has a slightly different meaning, for our purposes it will cause no errors to think of them as describing the same quantity.

The **velocity** is the speed of the wave. The velocity depends on the type of material in which the wave is traveling. For instance, in air sound travels 741 miles per hour, which is equivalent to 331 meters per second (from here on we will use the metric system for all measurements). In stainless steel sound travels at 3100 meters per second. And in human soft tissue at 37° Centigrade (body temperature) sound travels at 1540 meters per second.

The **frequency** is the number of times the wave is repeated per second. The frequency is calculated by dividing the period (the time it takes to complete a single cycle) into 1.

Finally there is the **wavelength,** which is the distance the wave travels during a single cycle. The wavelength is calculated by dividing the velocity by the frequency.

Fortunately we will not have to be concerned with making all these calculations since only a very few different frequencies and wavelengths are used in ultrasound and it is easy to remember them.

Now we can see how ultrasound differs from the sound we hear. First, and most important, is frequency. Audible sound ranges in frequency from 16 to 20,000 cycles per second (a cycle per second is known as a Hertz; a million cycles per second is called a MegaHertz and is abbreviated MHz). Ultrasound is defined as any sound with a frequency of greater than 20,000 Hertz. In abdominal B-scanning we use sound frequencies ranging from 1 to 5 MHz.

The next consideration is velocity. Although velocity is independent of frequency and is determined by the medium in which the sound is traveling, there are practical differences. Since we hear sound in air, the velocity of audible sound is 331 meters per second. However, we use ultrasound in human soft tissue so the velocity in which we are interested is 1540 meters per second. (This is an average value; the actual velocities vary slightly from tissue to tissue, but these differences are so small that we can use the average value and not introduce any serious errors.)

The wavelengths of audible sound range from 2 to 200 centimeters while the wavelengths used in B-mode ultrasound range from 0.3 to 1.5 millimeters. (A millimeter is 1/10 of a centimeter; a Virginia Slims cigarette is 120 millimeters long.)

The amplitude or power of the ultrasound used for diagnosis is much smaller than that needed to shout "Hello." Since amplitudes vary so widely and since, for most purposes, we are not as concerned with the actual amplitude as with the relationship of one amplitude to another, a different type of measure of amplitude is used for sound. This is the decibel (dB) notation which is based on comparing the amplitudes of two different sound waves. We are all familiar with this type of measurement and use it every day. For example, in describing the virtues of a football quarterback we might say that quarterback A can throw the ball *twice as far* as quarterback B; or we say that a Mack truck weighs *ten times as much* as a Volkswagen. In neither case do we talk about the actual number of feet the football is thrown or the number of pounds the truck weighs. Of course, if we have in our mind some concept of how much a Volkswagen weighs (perhaps from tipping one over in our younger days) we could describe other vehicles in terms of how they compare to a Volkswagen and, at the same time, have some idea of their actual weight as well. In this sense a comparative measurement system can be used as if the numbers corresponded to some real quantity. Even though it is not really correct to use decibels as if they were some real and absolute measure of sound amplitude or power, it is useful and convenient to do so and will not introduce any errors into our thinking. So, we will often refer to the amplitude of ultrasound echoes as X number of decibels: the greater the number of decibels, the greater the amplitude (or the "louder") the echo.

Before we leave this topic of decibels, we should point out that this is a logarithmic system; that is, a decibel is defined as: $dB = 20 \log \frac{E_2}{E_1}$; where E_2 and E_1 are the actual measurements of the amplitudes of two different echoes.* Logarithmic scales are used whenever the quantities involved cover very large ranges; this enables widely different numbers to be easily compared. You have probably noticed already that 20 decibels corresponds to a factor of 10. Thus if echo A is 20 decibels louder than echo B, echo A has 10 *times* the amplitude of echo B. In a typical abdominal or pelvic ultrasound scan the echoes received from the soft tissues range in strength from 0 to 60 decibels. The actual amplitude range of these echoes is therefore 1 to 1000. (You have probably also figured out that quarterback A is 6 dB better than quarterback B and that a Mack truck is 20 dB heavier than a Volkswagen.)

INTERACTION OF ULTRASOUND AND TISSUE

Sound traveling through air, such as the "Hello" of our friend, the canyon measurer, has a pretty uncomplicated life. It simply zips across the canyon, hits the far wall, and comes rebounding back. About the only really noticeable change is that the sound gets weaker as it travels, so the echo is not nearly as loud as the shout. When an ultrasonic pulse is sent into the soft tissues of the body, however, it undergoes continuous modification.

The most significant change is attenuation. Although not a scientifically rigorous definition, we shall consider **attenuation** to be the progressive weakening of the sound beam as it travels through tissue. Thus, the farther through the tissue the sound travels,

*This definition of the decibel is used when electric power is involved, and since echoes produce electric signals, this is the definition used in diagnostic ultrasound. For other purposes the decibel is defined as: $dB = 10 \log \frac{P_2}{P_1}$.

the weaker it gets. The attenuation of ultrasound is dependent on many factors, including the wavelength of the sound, the type and density of the tissue, the degree of heterogeneity of the tissue, and the number and type of echo interfaces in the tissue. It is impossible to predict accurately the degree of attenuation for something as complex as human tissue. Nevertheless, it is no great problem to measure the attenuation in a laboratory (the amplitude of the sound beam is measured at varying distances in a tissue and the difference, after some mathematical manipulation, becomes the attenuation).

Attenuation measurements have been made for many different human tissues with many different frequencies of ultrasound. These figures are available in textbooks on the physics of ultrasound. The actual numbers are of no great concern to the average clinical ultrasonographer, but it is useful to remember the following general rule of thumb: the "average" attenuation of an ultrasound beam in human soft tissue is 1 dB per centimeter per MHz. This means that an ultrasound beam with a frequency of 1 MHz loses 1 dB of amplitude for every centimeter it travels. A 2.25 MHz beam loses $2.25 \times 1 = 2.25$ dB for every centimeter it travels and a 5 MHz beam loses $5 \times 1 = 5$ dB per centimeter. We must remember that each echo received has actually traveled *twice* as far as the distance to the reflecting surface since it has made a trip to the reflecting surface and back to the source. Therefore, we must multiply the attenuation by 2 if we wish to know how much an echo from any given depth has been attenuated.

(Just to make sure we all have this straight before going on, we will now have a short quiz. *The question:* "An ultrasound beam with a frequency of 3.5 MHz is directed into the liver and an echo is received from a depth of 6 centimeters. How much has this echo been attenuated?" *The answer:* "Attenuation is estimated as 1 dB per centimeter per MHz. 1 dB $\times$ 3.5 MHz = 3.5 dB per centimeter. The echo came from 6 centimeters but it actually traveled 12 centimeters—6 going out and 6 coming back—so we multiply 3.5 dB per centimeter $\times$ 12 centimeters = 42 dB. The echo was attenuated by 42 dB.")

How does attenuation of an ultrasound beam occur? Primarily through three processes: absorption, reflection, and scattering.

Absorption occurs when energy in the sound beam is captured (or absorbed) by the tissue. Most of this energy is converted to heat in the tissue. It is this process which is the basis for ultrasound diathermy, a common therapeutic use of ultrasound. At the low energy levels used in diagnostic ultrasound, the biologic effect of absorption is negligible, however.

Reflection is the redirection of a portion of the ultrasound beam back toward its source. Reflection gives rise to echoes and forms the basis of diagnostic ultrasound scanning. Whenever the sound beam passes from a tissue of one acoustic impedance to a tissue of a different acoustic impedance, a small portion of the beam will be reflected and the remainder will continue on. We shall take a closer look at this process in a minute.

Scattering occurs when the beam encounters an interface which is irregular and smaller than the sound beam. As the name suggests, the portion of the beam which interacts with this interface is "scattered" in all directions. This is similar to what happens to a cream pie when it is thrown in a face—the cream is splattered in many directions. There is no reason for the clinical ultrasonographer to know much about scattering other than that it occurs. Since the interfaces which produce scattering are small, only a small percentage of the beam is involved. (The portion of the beam which is "scattered" directly backward will return to the transducer and produce an echo—known as a non-specular reflection.)

REFLECTION AND ECHO PRODUCTION

We need to examine the process of ultrasonic reflection and echo production in a little detail since it is the basis of B-mode scanning. Also there seems to be a great deal of confusion and misconception concerning this phenomenon, particularly in regard to "resolution" of ultrasound systems.

Reflection occurs—that is, an echo is produced—whenever the ultrasound beam passes from a tissue of one acoustic impedance to a tissue of a different acoustic impedance. This is also known as crossing an acoustic impedance mismatch or as crossing an acoustic interface. The large number of terms used to describe this probably helps account for the confusion. We will refer to this as an acoustic interface or simply "interface." An **interface** occurs whenever two tissues of differing acoustic impedance are in contact with each other.

Now all we need to know is what is "acoustic impedance"? Elementary, my dear Watson. The **acoustic impedance** of a tissue is the product of the density of the tissue and the speed of sound in the tissue. This is often written as: $Z = p \times c$, where Z = the acoustic impedance, p = the density of the tissue, and c = the speed of sound in the tissue. But the speed of sound in soft tissues is assumed to be a constant (1540 meters per second) so that the only thing which affects the acoustic impedance is the density of the tissue. This simplifies matters greatly. For our purposes we can assume that the acoustic impedance is the same thing as the density of a tissue; therefore, an interface occurs every time tissues of different density are in contact with each other. It takes only very small density differences to make an interface: water, blood cells, fat, liver cells, bile, bile duct walls, blood vessel walls, and connective or fibrous tissue all have sufficiently differing densities to create interfaces. This is one of the reasons ultrasound has proved so useful in abdominal and pelvic examinations: there is a tremendous amount of information about the soft tissues in the ultrasound beam. (The X-ray beam, by contrast, cannot differentiate these small differences in density; water, blood cells, liver cells, bile, bile ducts, blood vessels, and connective and fibrous tissue all appear gray to the X-ray. Even though CT body scanners have excellent resolution, the picture quality is limited by the very small density differences, too small to be detected by X-ray.)

When the sound beam crosses an interface, only a small percentage of it is reflected. The remainder continues on through the tissues where it can be reflected by other interfaces. The amount of sound which is reflected at an interface determines how much amplitude the returning echo will have or how "loud" the echo will be. This amount depends on how great the difference is between the two acoustic impedances which make up the interface. If the difference is very small, only a small percentage of the sound will be reflected; if the difference is large, a large portion will be reflected.

It would seem logical that large echoes would be desirable, but actually this is not the case. Ideally only enough of the beam should be reflected to enable the echo to be detected by the scanner; we want the rest of the beam to be available for creating other echoes. If too large a portion of the beam is reflected at an interface (producing a very loud echo), there is too little of the sound left to produce echoes from other interfaces deeper in the tissue. This is why ultrasound scanners cannot "see" through bowel gas or bone. The difference in acoustic impedance between soft tissue and gas or bone is very large, so large in fact that most of the beam is reflected and none is left to continue deeper. For example, at a soft tissue–bone interface about 70 per cent of the beam is reflected. It takes only two interfaces like this to exhaust the sound. For a soft tissue–gas interface the percentage is over 99 per cent. We can see that bone and gas are the ultrasonic equivalent of a stone wall; nothing gets through them. We should also notice that we are talking about percentage reflection. No matter how powerful the ultrasound beam, the same percentage will be reflected. If we use a louder beam we will get a louder echo but we won't penetrate the gas or bone. It's the same situation as shining a light at a mirror—no matter how bright the light you cannot see through the mirror: you just get a lot of glare. This is important because many people seem to believe that they can blast the sound beam through bowel gas by turning up the power. Although turning up the power makes more echoes, these echoes are mostly artifacts and have no relation to the underlying tissue. Because the problem of artifacts is so great we shall discuss it in greater detail in Chapter 5.

(*Extra reading for aggressive students department:* Why are the acoustic impedances of soft tissue and gas or bone so different? You'll remember that acoustic impedance, Z, is actually the product of