BASICS OF BIOMEDICAL ULTRASOUND FOR ENGINEERS

HAIM AZHARI

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To the memory of
Elad Grenadier,
who was killed by terrorists on July 17, 2002,
at the age of 21.
And to the memory of his father
and my friend, Dr. Ehud Grenadier.
Blessed be their souls.

CONTENTS

PREFACE

This book partially summarizes the knowledge that I have accumulated during my 25 years of research and teaching in this fascinating field. This is actually the third edition of the book, but the first one to appear in English (the first two editions were published in Hebrew). I have tried my best to correct and improve the text based on comments that were given to me by the readers. Nevertheless, I presume that there are still quite a number of things to correct and improve. Thus, I would highly appreciate any comments sent to my E-mail address: Haim@BM.Technion.Ac.IL Kindly indicate "Ultrasound book—Comments" in the subject. Thank you in advance.

Haim Azhari

Haifa, Israel
September 2009

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I thank G_D for helping me complete this book and for making me meet the many good and talented people who have helped me learn this fascinating field.

I thank Dr. Kenneth Jassbey, who was my first teacher of ultrasound and my physician friends, Dr. Ehud Grenadier and Dr. Diana Gaitini, from whom I have learned the clinical side of ultrasound.

Many thanks are due to my students, past and present, from whom I have learned much. As Rabbi Hanina states in the Talmud, Taanit 7:70a: "I have learned a lot from my teachers, more than that from my friends, but most of all from my students."

I also thank Yifat Levy, Simona Beilin, and Alexandra Alexandrovich, who helped me convert my lecture notes to digital format. I also thank the faculty of Biomedical Engineering at the Technion IIT, for their administrative support.

Finally, many many thanks to my beloved family.

H. A.

INTRODUCTION

PRELUDE AND BASIC DEFINITIONS

From the day we are born we are trained to treat each of our body systems as a separate unit capable of performing one task. We see light with our eyes (actually our visual system). We hear sounds with our ears (our auditory system). We sense pressure and temperature with our somatosensory system and usually move things with our limbs. And here comes ultrasound and allows us to perform all these tasks with one modality. With ultrasound we can "see" the internal structure of the body. We can "hear" the speed of moving objects. We can sense and apply pressure to the extent of "crushing" kidney stones, and we can warm and "cook" tumors to destroy them noninvasively.

There is no doubt that ultrasound has helped humankind in many areas, and perhaps the most prominent one is medicine. There are many medical applications of ultrasound (see some mentioned in the following), and the potential of developing new applications is still quite large. The aim of this book is to introduce this fascinating area to a novice in the field and provide the basic "toolkit" of knowledge needed to use it and conduct research.

Let us begin with the very basic definitions:

Ultrasound—*Acoustic waves* (sound or pressure waves) propagating within a *matter medium* at frequencies exceeding the *auditory band*.

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As can be noted, this definition is based on three italic terms that need further clarification. Let us define the first term:

Acoustic Waves—A physical phenomenon during which *mechanical energy* is transferred through matter, without mass transfer, and which originates from a local *change* in the stress or pressure field within the medium.

The phenomenon that we are dealing with is in fact a process of "energy flow" from one place to another. This energy is *mechanical* in nature. It is embedded in the matter in the form of elastic strains (stemming from the spring-like behavior of the matter) and vibrations of molecules. Indeed, molecules of the medium do move when an acoustic wave passes through, but this motion is mostly localized. As stated above, this phenomenon is not associated with mass transfer. This corresponds mainly to solid or semisolid substances. It should be noted, however, that in fluids, a phenomenon called "acoustic streaming" may appear (see Chapter 12). But this is an effect stemming from the acoustic wave and not the wave itself (see Section 3.6 in Chapter 3).

The source of these waves is a *change* in the stress or pressure field within the medium—for example, a clap of hands or a knock with a hammer or an explosion. It is therefore understood that a *material* medium is needed to allow this energy to propagate and that acoustic waves, unlike electromagnetic waves, cannot propagate in vacuum. This implies that there is a strong relation between the properties of the medium (e.g., structure, elasticity, density, etc.) and the corresponding acoustic properties of the acoustic waves (e.g., speed of propagation, attenuation, possible wave types, etc.) passing through it.

Finally, we should explain why are these waves called ultrasonic. Well, in fact the physics describing ultrasonic waves is the same as the physics of sonic waves and subsonic waves. The spectral range of the human ear (the auditory band) is normally 20 Hz to 20 kHz (animals of course can hear other frequencies). It is merely more practical and a matter of convenience that we use in most of our medical applications frequencies exceeding 20 kHz. These frequencies are not detected by our auditory system and hence the range of higher frequencies is arbitrarily defined as "ultrasound." [It should be pointed out, however, that in Doppler-effect-based techniques (see Chapter 11), audible signals are the output of the process.]

THE ADVANTAGES OF USING ULTRASOUND IN MEDICINE

Ultrasound offers several advantages that make it attractive for medical applications. Let us note some of them:

A. *Hazardless Radiation.* As long as high intensities are not used (see Chapter 12), ultrasound is considered a safe and hazardless modality (see comments on safety in the following). This may be easily conceived by being aware of the fact that we are continuously “immersed” in an ocean of sounds. From the almost unheard sounds of our beating heart, through the music we hear from the radio to the loud noise of a passing jet airplane, we continuously absorb acoustic energy. Our body is “accustomed” to this energy. Even a baby in his mother’s womb is exposed to sounds. It is therefore understood why ultrasonic medical examination is the most popular imaging modality used during pregnancy. The fact that ultrasound is hazardless allows repeated examinations of the same patient with no risk using standard equipment [see, for example, declarations and restrictions published by the American Institute for Ultrasound in Medicine (AIUM) on the internet].

B. *High Sampling Rate.* Because the speed of sound, C, in most soft tissues (see Appendix A at the end of the book) is around 1540 m/sec and the typical ranges used in medical examinations are relatively short (0.1–25 cm), the time it takes a wave to cover such ranges is very short (on the order of several tens of microseconds). Consequently, many waves can be transmitted within a short time and gain sufficient information to follow dynamic changes occurring in “real time” within the body.

C. *Compact Transducers.* Most of the ultrasonic transducers used in medicine are made of piezoelectric crystals that are very compact. A typical imaging probe may have the size of a match box. Furthermore, very small crystals can be manufactured. These miniature crystals are sufficiently small to be placed atop minimally invasive surgery devices, or even atop catheters (e.g., intravascular ultrasound (IVUS); see Chapter 9), or even implanted within the body.

D. *A Single Transducer Can Be Used to Transmit and Receive Waves.* As piezoelectric transducers can both transmit and detect waves (see Chapter 8), the same element can serve as a source of waves at one time and then switched to serve as a sensor for detecting echoes at another time. This fact enables us to probe almost any region within the body (in an invasive or partially invasive manner).

E. *A Wide Variety of Parameters Can Be Measured.* Since the acoustic waves properties are strongly related to the properties of the medium in which they travel, there is a wide variety of parameters that can be measured. For example: speed of sound, attenuation, acoustic impedance, dispersion, nonlinearity, elasticity, and more. These parameters can be used to map and characterize tissues.

F. *Cost Effective.* Ultrasound systems do not require any RF shielded rooms as MRI does. The transducers commonly do not wear out and there is no need for films (as in X-ray systems). There is also no need for expensive and dangerous materials such as in nuclear medicine. On the contrary, the components are relatively inexpensive. Thus, ultrasound is an excellent choice also from the economical point of view. Therefore, it is a very popular modality and is available in numerous clinical sites all over the world.

A GENERAL STATEMENT ON SAFETY

As stated above, ultrasound—if used properly—is safe. After so many years of use and gained experience, it can be categorically stated that diagnostic ultrasonic devices that comply with the current standards and regulations impose no danger to the examined patient. (This issue is further elaborated in Chapter 12.) However, like in many other things in life, abuse is not recommended, especially when babies and sensitive organs are examined. Generally speaking, it can be stated that the safe performance zone is determined mainly by two factors: (i) the intensity of the acoustic energy used (which is measured in W/cm^2) and (ii) exposure time. In Fig. I.1 a chart based on a graph published by the AIUM Bioeffects Committee in 1976 [1] is depicted. Although this chart is obsolete, it provides a good visual concept of safety limits. This chart maps the safe zone (shaded area) in the intensity–exposure time plane (the scale is logarithmic for both parameters). The exposure limits set at that time by the AIUM allowed a maximal transducer output intensities (see term: spatial peak temporal average in Chapter 12) of 100 mW/cm^2 for exposure durations exceeding 500 sec. Higher intensities up to 50 W/cm^2 could be used with shorter exposure times, provided that they are kept within the shaded area shown.

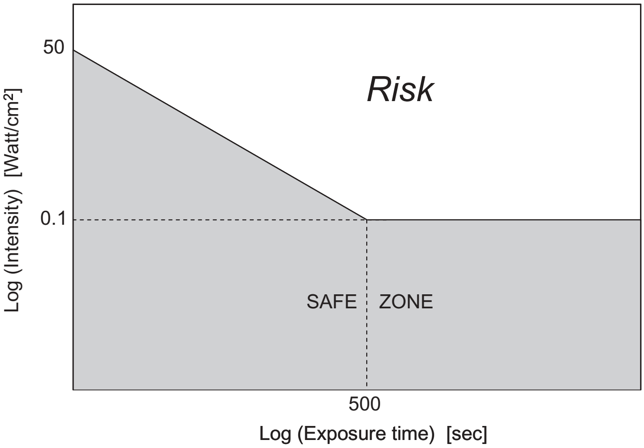

Figure I.1. Schematic chart based on a graph published by the AIUM in 1976 [1]. This chart maps the zone (shaded area) considered to be safe at that time in the intensity–exposure time plane. The scale is logarithmic for both parameters. For current limits see, for example, reference 2.

Current limits set by various regulatory institutes include more parameters and allow higher intensities for long exposure durations. The present limit set by the American FDA is 720 mW/cm^2 for a parameter called *spatial peak temporal average intensity*. (For additional indices see Chapter 12.) These limits naturally refer to imaging systems. For therapeutic applications, such as hyperthermia [3] or lithotripsy [4], much higher intensities must to be used. Consequently, some damage to normal tissues should be expected.

SOME COMMON APPLICATIONS OF ULTRASOUND

As noted above, there are currently many applications of ultrasound in medicine, and new applications are frequently suggested. The main application today is ultrasonic imaging. This modality offers rapid and convenient tools for acquiring images of soft tissues. Using ultrasonic images, sizes and distances within organs can be measured (e.g., the heart's left ventricular diameter and the diameter of the eye), pathological tissues (e.g., cysts and tumors) can be identified and characterized, kidney and gall stones can be detected, and volumes and areas can be calculated.

In pregnancy monitoring, ultrasound is a convenient key tool, which allows frequent follow-ups and assessment of the baby's development and allows the parents today to "see" their baby's face in 3D (see example in Chapter 9). Ultrasound also plays a major role in cardiovascular diagnosis. Using the Doppler effect, blood flow in various vessels and through the heart's valves can be imaged. Duplex imaging allows the physician to combine an anatomical image with a color-coded flow/motion map. Miniaturization allows intravascular (IVUS) imaging and invasive plaque analysis.

Hard tissues such as bones and teeth pose a technical challenge due to their high reflectivity and attenuation of acoustic waves. There are a few commercial systems available in the market today for bone assessment and for dental applications, but this market is still not dominant.

Ultrasound is also commonly used in physiotherapy where it is used for warming inner tissue layers in order to help accelerate the healing process. In the past few years a renaissance of an idea that had been presented in the 1940s has started. The idea is to use high-intensity focused ultrasound (HIFU) to ablate tumors noninvasively [3]. There are several commercially available systems today for treating the breast, the uterus, and the prostate. Other applications combining HIFU with MRI and other imaging modalities guidance are under investigation.

Another application of ultrasound is in lithotripsy, which has become a routine clinical procedure. By focusing high-intensity acoustic bursts on kidney stones, these stones are disintegrated and washed out of the body through the urinary tract.

Other applications utilize acoustic waves to disintegrate blood clots (acolysis) and to increase the permeability of the skin and internal membranes for drug delivery. In addition, it has been demonstrated that ultrasound can be used to insert large molecules into cells for gene therapy (see Chapter 12).

It has also been suggested to use ultrasound for cosmetic applications. There were several start-up companies who have developed ultrasonic hair-removing devices. And there are at least two companies today that have developed systems for removing fat (lypolyses) and for body contouring (i.e., reshaping the body).

These are just demonstrative applications of the potential of ultrasound in medicine. Although this field is almost a century old, it continues to flourish.

WHAT IS IT THAT WE NEED TO KNOW?

After we have been introduced to the field, let us define in general terms what it is that we need to know in order to be able to use ultrasound properly. For that purpose, consider the general schema shown in Fig. I.2. In this figure a schematic layout of ultrasonic waves "flow" through and out of the body is depicted. For simplicity, let us restrict our discussion to two dimensions. Usually, we have a source of acoustic waves or an array of such sources that transmit waves into the body (represented schematically by the "transmitter" box). In most cases we have control over the temporal profile and the timing of the transmitted waves (designated here as $F(t, x, y)$). It is important to note that in certain applications the source may be positioned within the body. As a result of the interaction between the waves and the tissue, part of the acoustic energy is absorbed as a function of time and location: $B(t, x, y)$. Part of the energy passes through the body to the other side: $T(t, x, y)$. And the rest is scattered to various directions: $S(t, x, y)$. The properties of the tissues combined

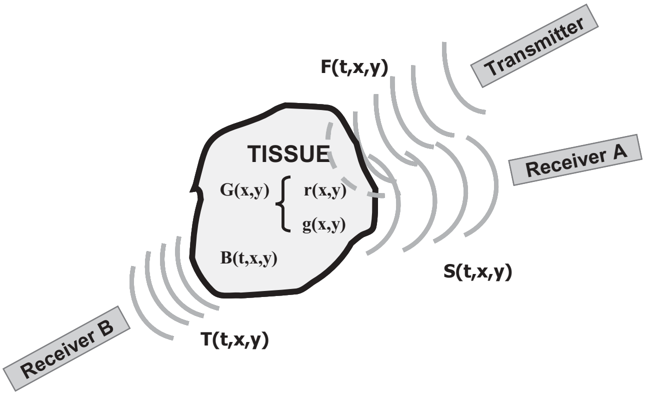

Figure I.2. Schematic layout of ultrasonic waves "flow" through and out of the body. A transmitted wave can pass though the organ and be detected on the other side. Scattered waves (echoes) can be detected at different positions around the body.

with its geometry $G(x, y)$ determine the energy division between these three types of mechanisms and their temporal and spatial profiles. By measuring $T(t, x, y)$ and/or $S(t, x, y)$, we try to characterize the tissue properties $G(x, y)$. For example, in a pulse–echo imaging process we try to map the geometry $g(x, y)$, whereas in a tissue characterization process we may focus our analysis on the reflectivity properties of the tissue: $r(x, y)$. And during a therapeutic process we may need to know the tissue's absorption properties.

In order to be able to perform these tasks, we must be very well familiarized with the connections and relations between the medium's properties and the properties of acoustic waves passing though it. Furthermore, we need to know what are the currently available techniques for transmitting and handling these waves in order to use them effectively. *And that is what this book is all about.*

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CHAPTER 1

WAVES—A GENERAL DESCRIPTION

Synopsis: This chapter deals with the basic definitions of waves in general and acoustic waves in particular. The objective of this chapter is to "touch base" with wave properties and their mathematical description. We shall start with a qualitative description and define the various types of waves. We shall examine what properties can be used to describe waves, introduce the wave equation in a homogeneous medium, learn about "group" and "standing" waves, and describe in detail spherical and cylindrical waves. Finally, we shall study the wave equation in a nonhomogeneous medium and the Born and Rytov approximations associated with its solution.

(*Note:* It is likely that many of the items presented in this chapter are trivial or familiar to most readers. Thus, a reader who is well aquatinted with the material may hop to the next chapter.)

1.1 GENERAL DEFINITIONS OF WAVES—A QUALITATIVE DESCRIPTION

When a mechanical wave propagates through matter, energy is transferred from one location to another [1, 2]. However, this energy is not associated with mass transfer. For example, one may consider the propagating waves formed when moving an end point of a jumping rope or when the first piece from a set of dominoes aligned in a row falls down. Clearly, energy is transferred by motion of matter, but mass is not really transferred from one location to another. The nature of the propagating wave is determined by the type of perturbation causing it to appear but also and mainly by the properties of the

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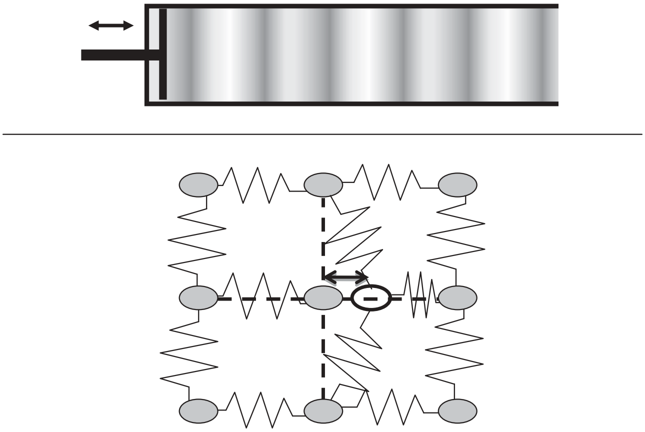

Figure 1.1. Schematic depiction of two possible configuration of mechanical wave propagation. **(Top)** The wave propagation direction is limited to only one direction. **(Bottom)** Although the small masses' motion is horizontal, waves can propagate along the vertical direction as well.

media through which it travels. For clarity, let us observe the two examples shown in Fig. 1.1:

Example 1. A cylinder filled with gas or fluid has a piston on its left side. At a certain time point the piston is pushed back and forth. Consequently, a pressure wave will propagate through the gas or fluid along the cylinder's axis. In this case the wave may be considered as one-dimensional.

Example 2. A matrix consisting of springs and spherical masses is at rest. At a certain time point, one mass is pushed back and forth. As a result, the masses along the line of perturbation will vibrate and a mechanical wave will propagate through the matrix. However, in this case the perturbation will also be associated with deformation of springs from both sides of the moving mass. Hence, one may expect mechanical waves to propagate along directions that are perpendicular to the induced motion as well.

From Example 2, one can conclude that several types of waves, each characterized by different properties, can be generated at the same time and even from the same perturbation. (This issue will be discussed in Chapter 4, where wave propagation in solids is analyzed.) Also, it is important to note that the motion direction of the particles constituting the medium does not have to align with the wave propagation direction. Using this fact, we can apply a preliminary division of wave types based on the relation between the wave propagation direction and the motion direction of the particles constituting the medium (see also Fig. 1.2):