DIAGNOSTIC ULTRASOUND

Imaging and Blood Flow Measurements

SECOND EDITION

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K. Kirk Shung
University of Southern California
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Dedication

This book is dedicated to my wife,

Linda, and three children,

Albert, Simon, and May, and their spouses,

Rini, Jenny, and Chris.

Contents

Preface

The field of medical imaging is advancing at a rapid pace. Imaging modalities such as x-ray radiography, x-ray computed tomography (CT), ultrasound, nuclear imaging, magnetic resonance imaging (MRI), and optical imaging have been used in biology and medicine to visualize anatomical structures as large as the lung and liver and as small as molecules. Ultrasound is considered the most cost-effective among them all. It is used routinely in hospitals and clinics for diagnosing a variety of diseases and is considered the tool of choice in obstetrics and cardiology because it is safe and capable of providing images in real time. New applications in preclinical or small animal imaging and cellular imaging are being explored.

Although there have been many clinical books published for ultrasound, very few technical books are available. Over the past 35 years, this has been a major problem for the author in teaching a graduate course in ultrasonic imaging at the Department of Bioengineering, Pennsylvania State University, and the Department of Biomedical Engineering, University of Southern California. It is for this purpose that this book was written. The book is intended to be a textbook for a senior-level or first-year graduate-level course in ultrasonic imaging in a biomedical engineering, electrical engineering, medical physics, or radiological sciences curriculum. An attempt has been made to minimize mathematical derivation and to place more emphasis on physical concepts. In this edition, several chapters, including the chapter on transducers, were greatly expanded. Chapter 1 gives an overview of the field of ultrasonic imaging and its role in diagnostic medicine relative to other imaging modalities. Chapters 2 and 3 describe the fundamental physics involved and a crucial device in ultrasound, ultrasonic transducers, respectively. Conventional imaging approaches and Doppler measurements are given in Chapters 4 and 5. More recent developments, including contrast imaging and 4D imaging, are described in Chapters 6 to 9. In Chapter 10, current status and standards on ultrasound bioeffects are reviewed. Chapter 11 discusses methods that have been used to measure ultrasonic properties of tissues. This chapter is optional and may be eliminated at the discretion of the instructor. At the end of each chapter a list of relevant references and further reading materials is given.

Material contained in the book should be more than sufficient for a one-semester graduate- or senior-level course.

The book should also be of interest to radiologists with some technical background and practicing engineers and physicists working in the imaging industry.

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About the Author

K. Kirk Shung obtained a Ph.D. in electrical engineering from University of Washington, Seattle, in 1975. He is a Dean's Professor in Biomedical Engineering, an endowed position, at University of Southern California and has been the director of NIH Resource Center on Medical Ultrasonic Transducer Technology since 1997.

Dr. Shung is a life fellow of IEEE and a fellow of the Acoustical Society of America and American Institute of Ultrasound in Medicine. He is a founding fellow of American Institute of Medical and Biological Engineering. Dr. Shung received the IEEE Engineering in Medicine and Biology Society Early Career Award in 1985 and was the coauthor of a paper that received the best paper award for *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* (UFFC) in 2000. He was selected as the distinguished lecturer for the IEEE UFFC society for 2002-2003. In 2010 and 2011, he received the Holmes Pioneer Award in Basic Science from American Institute of Ultrasound in Medicine and the academic career achievement award from the IEEE Engineering in Medicine and Biology Society.

Dr. Shung has published more than 500 papers and book chapters. He is the author of a textbook *Principles of Medical Imaging* published by Academic Press in 1992 and a textbook *Diagnostic Ultrasound: Imaging and Blood Flow Measurements* published by CRC press in 2005. He co-edited a book *Ultrasonic Scattering by Biological Tissues* published by CRC Press in 1993. Dr. Shung is currently serving as an associate editor of *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, *IEEE Transactions on Biomedical and Engineering*, and *Medical Physics*. Dr. Shung's research interest is in ultrasonic transducers, high frequency ultrasonic imaging, ultrasound microbeam, and ultrasonic scattering in tissues.

chapter one

Introduction

1.1 History

The potential of ultrasound as an imaging modality was realized as early as the late 1940s, when several groups of investigators around the world utilizing sonar and radar technology developed during World War II started exploring medical diagnostic capabilities of ultrasound (Goldberg and Kimmelman, 1988). John Wild and John Reid in Minnesota developed a prototype B-mode ultrasonic imaging instrument and were able to demonstrate the capability of ultrasound for imaging and characterization of cancerous tissues in the early 1950s at frequencies as high as 15 MHz. John Wild's pioneering effort and accomplishment were recognized with the Japan prize in 1991. At the same time, Douglas Howry and Joseph Holms at the University of Colorado at Denver, apparently unaware of the effort by Wild and Reid, also built an ultrasonic imaging device with which they produced cross-sectional images of the arm and leg. In Japan, starting in the late 1940s, medical applications of ultrasound were explored by Kenji Tanaka and Toshio Wagai. Two Japanese investigators, Drs. Shigeo Satomura and Yasuhara Nimura, were credited for the earliest development of ultrasonic Doppler devices for monitoring tissue motion and blood flow in 1955. Virtually simultaneously with the work going on in Japan and in the United States, Drs. Inge Edler and Hellmuth Hertz at the University of Lund in Sweden worked on echocardiography, an ultrasound imaging technique for imaging cardiac structures and monitoring cardiac functions. In parallel with these developments in the diagnostic front, William Fry and his colleagues at the University of Illinois at Urbana worked on using a high-intensity ultrasound beam to treat neurological disorders in the brain. The primary form of ultrasonic imaging to date has been that of a pulse-echo mode. The principle is very similar to that of sonar and radar. In essence, following an ultrasonic pulse transmission, echoes from the medium being interrogated are detected and used to form an image. Many terminologies used in ultrasound are imported from the field of sonar and radar. Although pulse-echo ultrasound had been used since the 1950s to diagnose a variety of medical problems, it did not become a widely accepted diagnostic tool until the early 1970s, when gray-scale ultrasound with nonlinear echo amplitude to gray-level mapping was introduced. Continuous-wave (CW) and pulsed-wave (PW) Doppler ultrasound devices for measuring blood flow also became available during that time. Duplex ultrasound scanners that combined both functions, allowing the imaging of anatomy and the measurement of blood flow with one single instrument, soon followed. Today, ultrasound is the second most utilized diagnostic imaging modality in medicine (second only to conventional x-ray) and is a critically important diagnostic tool of any medical facility.

Although ultrasound has been in existence for more than 40 years and is considered a mature technology by many, the field is by no means in a stagnant state. Technical advances are constantly being made. The introduction of contrast agents, harmonic imaging, flow and tissue displacement imaging, multidimensional imaging, and high-frequency imaging are just a few examples. In this book, these new developments, along with fundamental physics, instrumentation, system architecture, biological effects of ultrasound, and clinical applications, will be discussed in detail.

1.2 Role of ultrasound in medical imaging

Ultrasound not only complements the more traditional approaches such as x-ray, but also possesses unique characteristics that are advantageous in comparison to other competing modalities, such as x-ray computed tomography (CT), radionuclide emission tomography, and magnetic resonance imaging (MRI). More specifically, ultrasound (1) is a form of nonionizing radiation and is considered safe to the best of present knowledge, (2) is less expensive than imaging modalities of similar capabilities, (3) produces images in real time, unattainable at the present time by any other methods, (4) has a resolution in the millimeter range for the frequencies being clinically used today, which may be made better if the frequency is increased, (5) can yield blood flow information by applying the Doppler principle, and (6) is portable and thus can be easily transported to the bedside of a patient.

Ultrasound also has several drawbacks. Chief among them are that (1) bony structures and organs containing gases cannot be adequately imaged without introducing specialized procedures, (2) only a limited window is available for ultrasonic examination of certain organs such as the heart and neonatal brain, (3) it is operator skill dependent, and (4) it is sometimes impossible to obtain good images from certain types of patients, including obese patients.

The many advantages that ultrasound is capable of offering have allowed it to become a valuable diagnostic tool in such medical disciplines as cardiology, obstetrics, gynecology, surgery, pediatrics, radiology, and neurology, to name just a few. The relationship among ultrasound and other imaging modalities is a dynamic one. Ultrasound is the tool of choice in obstetrics primarily because of its noninvasive nature, its cost-effectiveness, and its real-time imaging capability. This role will not change in the foreseeable future. Ultrasound also enjoys similar success in cardiology, demonstrated by the fact that echocardiography is a training that every cardiologist must have. The future of ultrasound in cardiology, however, is not as rosy as in obstetrics because while ultrasound is progressing at a rapid rate, other competing imaging modalities, such as multislice spiral CT and MR, are also making great strides in improving the image acquisition rate and image quality. Ultrasound may lose ground in certain areas, but it may gain in other areas. Ultrasound mammography is an example of gradually gaining importance in breast cancer imaging. Nevertheless, at a time of heightened public concern with health care costs, the cost-effectiveness of an imaging tool is a crucial factor in planning diagnostic strategies. Diagnostic ultrasound is particularly attractive in this respect and is likely to remain a major diagnostic modality for many years to come.

Although the pace of development in therapeutic ultrasound has not been as striking as diagnostic ultrasound, significant progress has also been made in the past decades. These efforts have been primarily focused on developing better devices for hyperthermia, frequently in combination with chemotherapy or radiotherapy, for the treatment of tumors, and for high-intensity focused tissue ablation.

1.3 Purpose of the book

This book is written based upon the notes for a graduate course on ultrasound imaging that the author has been teaching at the Department of Bioengineering, Pennsylvania State University, and the Department of Biomedical Engineering, University of Southern California, since 1979. In the 2nd edition several chapters are expanded and updated. The book is intended to be a textbook for a senior- to graduate-level course in ultrasonic imaging. It should also be useful for physicists, engineers, clinicians, and sonographers who are interested in learning more about the technical side of diagnostic ultrasound as a reference.

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Figure 2.23 A stationary observer perceives a change in frequency of a wave

emitted by a moving source toward the observer resulting from a change in

wavelength from λ to λ’. (a) The source is stationary. (b) The source is moving at

a velocity v.

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Figure 3.59 (Continued) Experimental arrangement for measuring cross talk of a

transducer during (a) transmission and (b) reception.

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Figure 6.22 A comparison of B-mode and B-flow images obtained from a carotid

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Geared micromotor N S Ultrasonic transducer Scanning mirror Optical

ber Jewel bearings Magnetic coupling Front view of the transducer Piezoelectric element Optical

ber

Figure 9.24 A hybrid PA-ultrasound endoscopic probe.

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