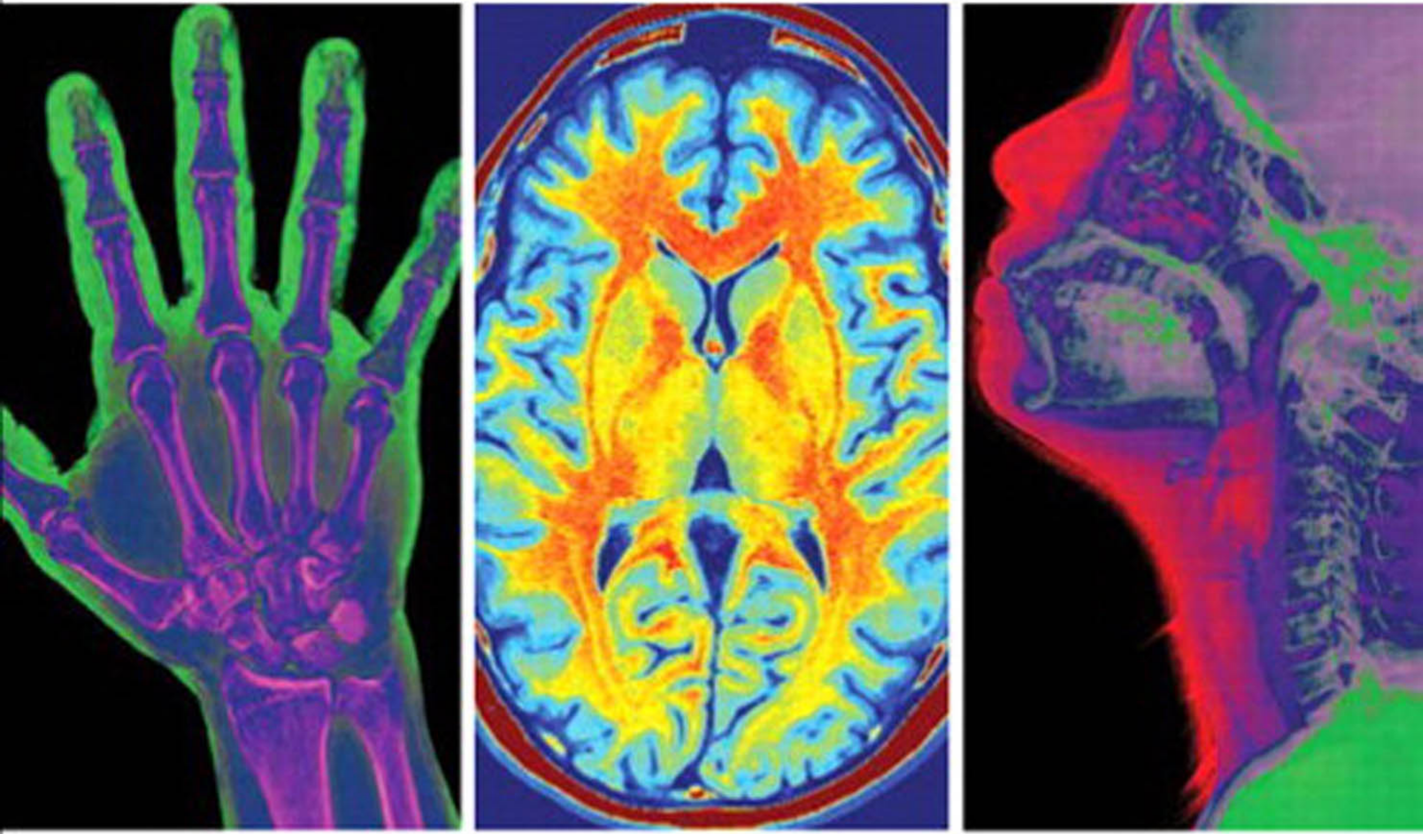
MEDICAL IMAGING

SIGNALS AND SYSTEMS

SECOND EDITION



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Medical Imaging Signals and Systems

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To our families
Carol, Emily, Ben, Mark, and David
Laura, Annie, and Beth
who help us see what's important and what's not.

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Preface

Although the underlying principles of medical imaging have not changed in the nine years since the first edition of this book was published, the instrumentation and practices have continued to evolve and improve. This second edition maintains the *signals and systems* focus of the first edition, with up-to-date descriptions of instrumentation. We still cover the most important *imaging modalities* in radiology: projection radiography, x-ray computed tomography, nuclear medicine scintigraphy and emission tomography, ultrasound imaging, and magnetic resonance imaging. But we now provide additional material on digital radiography, multi-row detector CT systems, 3D ultrasound, both functional and diffusion-weighted magnetic resonance imaging, and much more. As before, we expect the reader to be familiar with signals and systems, which are usually covered in the sophomore year of most engineering curricula, and with elementary probability. Freshman courses in physics, chemistry, and calculus are also assumed.

As with the first edition, the book is organized into parts emphasizing key overall conceptual divisions. Part I introduces basic imaging principles, including an introduction to medical imaging systems in Chapter 1, a review of signal processing (with emphasis on two-dimensional signals) in Chapter 2, and a discussion of image quality in Chapter 3. Our presentation of the theory of medical imaging systems is strongly based on continuous signals; however, a development of discrete signals is included to permit discussions on sampling and implementation. Issues of image quality, including resolution, noise, contrast, geometric distortion, and artifacts are described in a general context here, and are revisited within each modality in subsequent chapters.

Part II describes key modalities in radiographic imaging. It begins in Chapter 4 with a brief presentation of the physics of radiography, including the generation and detection of ionizing radiation and its effect on the human body. Chapter 5 describes projection radiography systems, including chest x-ray, fluoroscopy, and mammography systems. As in all subsequent chapters, coverage focuses on signals, including only enough physics and biology to motivate the modality and provide a model for the analysis. Chapter 5 also presents the mathematics of *projection imaging*, a very fundamental idea in medical imaging. Chapter 6 covers x-ray computed tomography, expanding on the instrumentation and mathematics of projection imaging and introducing the concept of image reconstruction in medical imaging. Computed tomography produces true *tomograms* (images of cross sections of the body) rather than projections of the body.

Part III presents the physics and modalities of nuclear medicine imaging. Chapter 7 describes the physics of nuclear medicine, focusing primarily on the concept of radioactivity. The major modalities in nuclear medicine imaging are described in Chapter 8, which covers planar scintigraphy, and Chapter 9, which covers emission computed tomography.

Part IV covers ultrasound imaging. It begins in Chapter 10 with a brief presentation of the physics of sound, and continues in Chapter 11 with the various imaging modes offered within this rich modality. Part V covers magnetic resonance imaging. Chapter 12 presents the physics of nuclear magnetic resonance, and Chapter 13 continues with a presentation of various magnetic resonance imaging techniques.

We have used the first edition of this book for a one-semester upper-level/graduate course on medical imaging systems. In order to cover the material in one semester, we routinely skip some material in the book, and we move at a very brisk pace. Although it was very tempting to add more depth in modern instrumentation, reconstruction methods, and diagnostic uses of medical imaging, we feel that this breadth of material could not be covered in one semester with sufficient depth, and would be inconsistent with our primary goal of providing a unified view of medical imaging from a signals and systems point of view. On the other hand, we feel that this book could be used as the basis for a two-semester course, perhaps by covering Parts I–III in the first semester and Parts IV–V in the second semester. A two-semester approach would allow instructors to use supplementary materials for additional depth in the physics and instrumentation of medical imaging, or to present current research topics.

Medical imaging is very visual—just ask any radiologist. Although the formalism of signals and systems is mathematical, we understand the advantages offered through visualization. Therefore, the book contains many images and diagrams. Some are strictly pedagogical, offered in conjunction with the exposition or an example problem. Others are motivational, revealing interesting features for discussion or study. Special emphasis is made to provide biologically relevant examples, so that the important context of medical imaging can be appreciated by students. Many images have been added or replaced in this edition, in order to provide better coverage of current use and to provide reference images to help explain features and qualities of the various modalilties.

New to This Edition

The second edition of this book arose primarily from the need to provide updates to the technology and methods in medical imaging systems, which have undergone substantial development since the first edition. At the same time, we were able to incorporate changes to the organization of the book and to improve certain aspects of pedagogy. Instructors and students alike now have more modern material from the core medical imaging modalities while still maintaining the signal processing perspective in a unified treatment of medical imaging signal and systems.

The most significant changes to this new edition include:

- Completely rewritten overview sections including many new images to better motivate and explain the core modalities that use x-rays, radioactivity, ultrasound, and nuclear magnetic resonance.
- New sections on digital radiography systems and mammography in projection radiography.
- A new section on multi-row detectors in computed tomography.

- A new section on iterative reconstruction in emission tomography in nuclear medicine.
- New sections on nonlinear wave propagation and harmonic imaging in ultrasound imaging.
- New development and presentation of imaging equations in planar scintigraphy, single photon emission computed tomography, and positron emission tomography.
- New sections on three-dimensional imaging, noise, and speckle in ultrasound imaging.
- New sections on susceptibility weighted imaging, functional magnetic resonance imaging, and diffusion magnetic resonance imaging in magnetic resonance imaging.
- Reorganization of the chapters on signals and systems and image quality to encourage a better pedagogical flow.
- Many new problems, added primarily to the chapters having relatively fewer problems in the first edition. There are a total of 261 problems in this second edition.

Acknowledgments

Many students, friends, colleagues, and teaching assistants contributed to this book through discussions and critiques. We wish to thank Elliot R. McVeigh and John I. Goutsias, who co-taught our course at Johns Hopkins University during the early years and helped draft the first edition of the book. We are grateful to Drs. Avneesh Chhabra, Harvey Ziessman, Peter Calabresi, and David Yousem for providing several clinical images (and their descriptions) and to Vince Blasko and Beatrice Mudge for providing several images depicting artifacts that can arise in clinical imaging. Xiao Han, Xiaodong Tao, Li Pan, Vijay Parthasarathy, Tara Johnson, Minnan Xu, Abd El-Monem El-Sharkawy, Kahaled Abd-Elmoniem, Lotta Ellingsen, Jing Wan, Snehashis Roy, Harsh Agarwal, Issel Lim, Xian Fan, Nan Li, Sahar Soleimanifard, Nathanel Kuo, Jeffrey Pompe, Min Chen, Chuyang Ye, and Zhen Yang contributed problems and solutions, Dhruv Lamba helped find new images, and Aaron Carass fixed many LaTeX problems. We are grateful for the images provided to us by GE Healthcare, Philips Healthcare, and Osirix. We thank J. Webster Stayman for reviewing the digital radiography section. We would also like to thank six anonymous reviewers who provided comments on their experiences with the first edition, which provided a basis for many of the changes we have made to this edition, and five anonymous reviewers who reviewed a draft of this edition, which helped us to better balance material in several sections. Finally, we would like to thank Dr. William R. Brody, who inspired the creation of the course out of which this book emerged.

Jerry L. Prince
Jonathan M. Links

PART I

Basic Imaging Principles

Overview

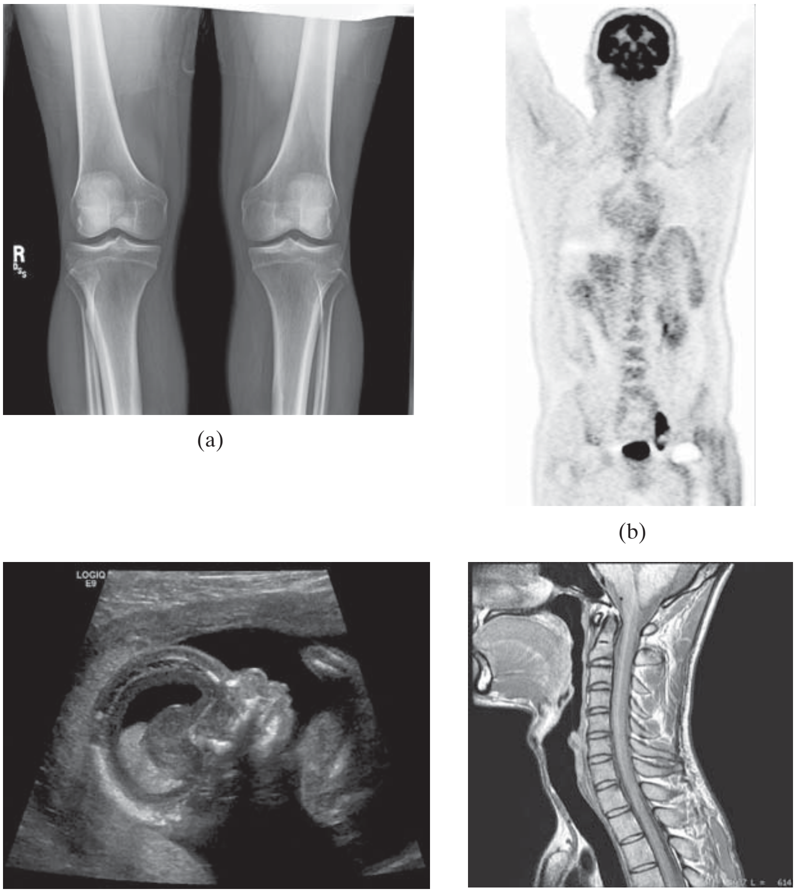
What does the human body look like *on the inside*? The smart answer: It depends on how you look at it. The most direct way to look inside the human body is to cut it open, for example, through surgery. A refinement of this procedure might be to use an endoscope, essentially a light tube that is "threaded" through the body, which conveys an image to a display device. Both methods offer direct optical viewing, but also involve cutting the body, putting something in it, or both. These are *invasive techniques*, which cause (potential) damage or trauma to the body.

The beauty of medical imaging is that we can see inside the human body in ways that are less invasive than surgery or endoscopy. In some cases—for example, magnetic resonance imaging (MRI) and ultrasound imaging—the methods are completely *noninvasive* and risk-free so far as we know. In other cases—for example, projection radiography, x-ray computed tomography (CT), and nuclear medicine—there is some risk associated with the radiation exposure, even though these methods are considered noninvasive as well.

Fundamentally, these medical imaging techniques mean that we do not need to cut the body or put a physical device into it in order to "see inside." Of perhaps even greater importance, these techniques allow us to see things that are not visible to the naked eye in the first place. For example, functional magnetic resonance imaging (fMRI) allows us to obtain images of organ perfusion or blood flow, and positron emission tomography (PET) allows us to obtain images of metabolism or receptor binding. In other words, the various imaging techniques allow us to see inside the body in different ways—the "signal" is different in each case and can reveal information which the other methods cannot. Each of these different methods is a different *imaging modality*, and the "signals" that arise are intrinsically different. This hearkens back to the opening question: What does the human body look like on the inside? The answer: It depends on the measured signal of interest.

In this book, we use a *signals and systems* approach to explain and analyze the most common imaging methods in radiology today. We want to answer the question: What do the images look like and why? We will discover that medical imaging physics allows us to image certain parameters of the body's tissues, such as reflectivity in ultrasound imaging, linear attenuation coefficient in computed tomography, and hydrogen proton density in magnetic resonance imaging. These physical parameters, which one can think of as "signals" within the body, represent the input signal into an imaging system. In medical imaging, the "object" or "signal" arising from the patient depends on the physical processes governing a given imaging modality. Thus, a given patient represents an ensemble of different objects or signals. In considering a given medical image, it is thus important to start with the physics that underlie the creation of signals from the patient for that modality. Accordingly, each part of this book is organized such that the first chapter describes the relevant physics, and subsequent chapters describe those modalities based on the specific physical processes of that part.

The first output of any medical imaging system is based on physical measurements, which might be returning echoes in an ultrasound system, x-ray



(a) (b) (c) (d)

Figure I.1
The four main medical imaging signals discussed in this book: (a) x-ray transmission through the body, (b) gamma ray emission from within the body, (c) ultrasound echoes, and (d) nuclear magnetic resonance induction. The corresponding medical imaging modalities are projection radiography, planar scintigraphy, ultrasound imaging, and magnetic resonance imaging. All images courtesy of GE Healthcare.

intensities in a CT system, or radio frequency waves in an MRI system. The final output in this system is created through *image reconstruction*, the process of creating an image from measurements of signals. The overall quality of a medical image is determined by how well the image portrays the true spatial distribution of the physical parameter(s) of interest within the body. Resolution, noise, contrast, geometric distortion, and artifacts are important considerations in our study of image quality. Ultimately, the clinical utility of a medical image involves both the image's quality and the medical information contained in the parameters themselves.

Figure I.1 shows the four main medical imaging signals discussed in this book: (1) x-ray transmission through the body, (2) gamma ray emission from within the body, (3) ultrasound echoes, and (4) nuclear magnetic resonance induction. Part II covers modalities that use x-ray transmission signals, Part III covers modalities that use gamma ray emission, Part IV covers modalities that use ultrasound signals, and Part V covers magnetic resonance imaging, which uses signals that arise from nuclear magnetic resonance. The specific medical imaging modalities depicted in Figure I.1 are (1) projection radiography, (2) positron emission tomography, (3) ultrasound imaging, and (4) magnetic resonance imaging.

In Figure I.1, parts (a) and (b) represent two-dimensional *projection* images of the three-dimensional human body. A projection is created as a two-dimensional "shadow" of the body, a process that is illustrated in Figure I.2. Figures I.1(c) and (d) are slices within the body. Figure I.3 depicts the three

Figure I.2
The creation of a two-dimensional projection through the body. In this case, x-rays are transmitted through a patient creating a radiograph.

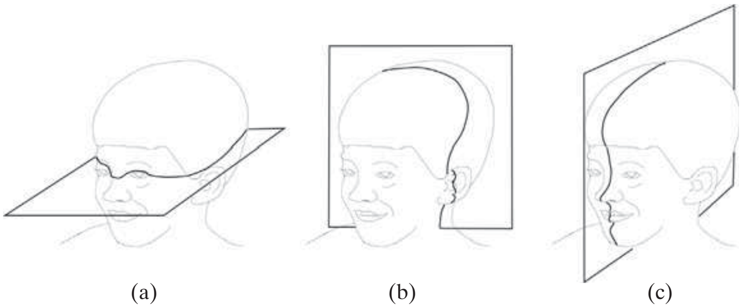


Figure I.3
The three standard orthogonal tomographic or slice or section views: (a) axial or transaxial or transverse, (b) coronal or frontal, and (c) sagittal.

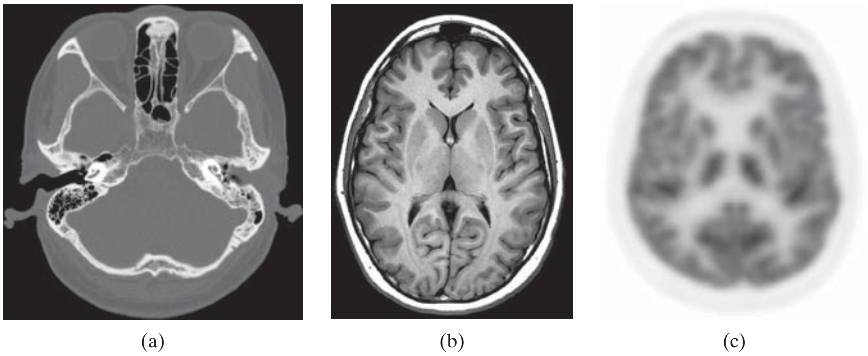


Figure I.4
Representative transverse slice through the brain from three different imaging modalities: (a) computed tomography, (b) magnetic resonance imaging, and (c) positron emission tomography.

standard orientations of slice (or *tomographic*) images, *axial*, *coronal*, and *sagittal*. Figure I.1(d) is a sagittal slice, while Figure I.1(c) is an *oblique* slice, that is, an orientation not corresponding to one of the standard slice orientations.

Figure I.4 also shows slice images. In this case, each image is a transverse slice, oriented perpendicular to the head and body axis through the brain. Each image is obtained from a different imaging modality: (a) computed tomography, (b) magnetic resonance imaging, and (c) positron emission tomography. Even though each image depicts (a slice through) the brain, the images are strikingly different, because the signals giving rise to each image are themselves strikingly different. In this part of the book, we study the common signal processing concepts that relate to all imaging modalities, setting the groundwork for adding the physical differences that account for the different appearances of the imaging modalities, and hence their different uses in medicine.

CHAPTER 1

Introduction

In this book, we take a signals and systems approach to the characterization of medical imaging. As discussed in the Overview, there are a variety of signals in which we are interested; ultimately, this interest stems from the biological and medical significance of these signals in patients with various diseases. In practice, these signals are transformed into images via medical imaging modalities. In this chapter, we begin to consider these modalities and their characteristics.

1.1 History of Medical Imaging

The first published medical image was a radiograph of the hand of Wilhelm Conrad Roentgen's wife in December 1895. Roentgen had been experimenting with a Crooke's tube (the forerunner of today's x-ray tube) and noticed that "a new kind of rays" (hence, *x-rays*) were emitted that could expose a photographic plate even when optically shielded. It was immediately obvious to Roentgen that his discovery could have a profound impact in medicine. Indeed, the first clinical use of x-rays occurred only two months later, in February 1896. The use of x-rays became widespread, and both static and dynamic (*fluoroscopic*) techniques were developed. Here, a *static* technique refers to an image taken at a single point in time, whereas a *dynamic* technique refers to a series of images acquired over time.

For many decades, these *planar* (i.e., two-dimensional projection) radiographs were the only medical images being produced. Ultimately, radiography was extended into transmission computed tomography, or *cross-sectional* imaging. Godfrey Hounsfield produced the first true computed tomography (CT) scanner in 1972 at EMI in England. He used mathematical methods for image reconstruction developed a decade earlier by Allan Cormack of the United States. Hounsfield and Cormack shared the Nobel Prize in Medicine in 1979. Many radiologists consider CT scanning to be the most important development in medical imaging since Roentgen's original discovery.

As radiography arose from the discovery of x-rays, nuclear medicine arose from the discovery of radioactivity by Antoine Henri Becquerrel in 1896. Initially, radionuclides were used in cancer therapy rather than in medical imaging. The concept of using radioactive *tracers* to study physiology was introduced by George de Hevesy in 1923; de Hevesy is considered the father of nuclear medicine. A radiotracer is a radioactively labeled drug that mimics a biological compound of interest; the distribution of the radioactivity implies the distribution of the drug. Early studies with radiotracers used conventional nonimaging radiation detectors to roughly determine amounts of radioactivity in various body regions. In 1949, Benedict Cassen at UCLA started the development of the first imaging system in nuclear medicine, the *rectilinear scanner*. The modern *Anger scintillation camera* was developed by Hal Anger at UC Berkeley in 1952. The element of the most commonly used radionuclide in nuclear medicine, technetium-99m, was discovered in 1937 by Carlo Perrier and Emilio Segre; its first use in medicine was in 1961.

The interaction of acoustic waves with media was first described by Lord John Rayleigh over one hundred years ago in the context of the propagation of sound in air. Modern ultrasound imaging had its roots in World War II Navy sonar technology, and initial medical applications focused on the brain. Ultrasound technology progressed through the 1960s from A-mode, B-mode, and M-mode scans to today's two-dimensional (2-D) Doppler, three-dimensional (3-D), and nonlinear imaging systems.

The phenomenon of *nuclear magnetic resonance*, from which magnetic resonance imaging (MRI) arises, was first described by Felix Bloch and Edward Purcell; they shared the 1952 Nobel Prize in Physics. This work was extended by Richard Ernst, who received the Nobel Prize in Chemistry in 1991. In 1971, Raymond Damadian published a paper suggesting the use of magnetic resonance (MR) in medical imaging; in 1973, a paper by Paul Lauterbur followed. Lauterbur received the Nobel Prize in Medicine in 2003, along with Peter Mansfield, who developed key methods in MRI.

1.2 Physical Signals

In this book, we consider the detection of different physical signals arising from the patient and their transformation into medical images. In practice, these signals arise from four processes:

- Transmission of x-rays through the body (in projection radiography and CT)
- Emission of gamma rays from radiotracers in the body (in nuclear medicine)
- Reflection of ultrasonic waves within the body (in ultrasound imaging)
- Precession of spin systems in a large magnetic field (in MRI)

Radiography, CT scanning, and nuclear medicine all make use of electromagnetic energy. Electromagnetic energy or waves consist of electric and magnetic waves traveling together at right angles. Wavelength and frequency are inversely related; frequency and energy are directly related. The electromagnetic spectrum spans the frequency range from zero to that of cosmic rays; only a relatively small portion of this spectrum is useful in medical imaging. At long wavelengths—for example, longer than 1 angstrom—most electromagnetic energy is highly attenuated by the body, prohibiting its exit and external detection. At wavelengths shorter than about 10^{-2} angstroms, the corresponding energy is too high to be readily detected.

In this book, we express energy in units of *electron volts* (eV), where 1 eV is the amount of energy an electron gains when accelerated across 1 volt potential. We will concentrate on electromagnetic radiation whose wavelengths correspond to energies of roughly 25–500 keV.

Ultrasound imaging utilizes sound waves, and considerations of attenuation and detection are similar to those above. Image resolution is not adequate when wavelengths longer than a couple of millimeters are used, and attenuation is too high for very short wavelengths. An ideal frequency range for ultrasound in medical imaging is 1–20 MHz, where 1 Hz = 1 cycle/second.

The signal in MRI arises from the precession (like the motion of a child's top or dreidel) of nuclei of the hydrogen atom—that is, protons. When placed in a large magnetic field, collections of protons, termed *spin systems*, can be set into motion by applying radio frequency (RF) currents through wire coils surrounding the patient. Although these spin systems precess at RF frequencies (64 MHz is typical), the primary signal source is not from radio waves, but from the Faraday induction of currents in the same or different wire coils.

1.3 Imaging Modalities

The medical imaging areas we consider in detail in this book are projection radiography, CT, nuclear medicine, ultrasound imaging, and MRI. An *imaging modality* is a particular imaging technique or system within one of these areas. In this section, we give a brief overview of these most common imaging modalities.

Projection radiography, CT, and nuclear medicine all use ionizing radiation. The first two transmit x-rays through the body, then use the fact that the body's tissues selectively *attenuate* (reduce) the x-ray intensities to form an image. These are termed *transmission* imaging modalities because they transmit energy through the body. In nuclear medicine, radioactive compounds are injected into the body. These compounds or *tracers* move selectively to different regions or organs within the body, emitting gamma rays with intensity proportional to the compound's local concentration. Nuclear medicine methods are *emission* imaging modalities because the radioactive sources emit radiation from within the body.

Ultrasound imaging transmits high-frequency sound into the body and receives the echoes returning from structures within the body. This method is often called *reflection* imaging because it relies on acoustic reflections to create images. Finally, MRI requires a combination of a high-strength magnetic field and radio frequency Faraday induction to image properties of the proton nucleus of the hydrogen atom. This technique is called *magnetic resonance imaging* since it exploits the property of nuclear magnetic resonance.

1.4 Projection Radiography

Projection radiography includes the following modalities:

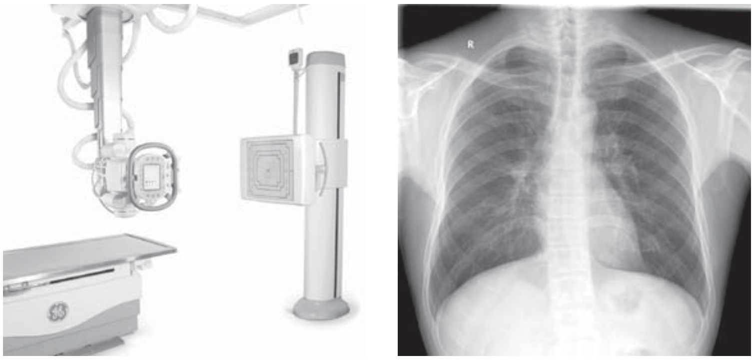
- *Routine diagnostic radiography*, including chest x-rays, fluoroscopy, mammography, and motion tomography (a form of tomography that is not *computed* tomography)

- *Digital radiography*, which includes all the scans in routine radiography, but with images that are recorded digitally instead of on film
- *Angiography*, including universal angiography and angiocardiography, in which the systems are specialized for imaging the body's blood arteries and vessels
- *Neuroradiology*, which includes specialized x-ray systems for precision studies of the skull and cervical spine
- *Mobile x-ray systems*, which are small x-ray units designed for operating rooms or emergency vehicles
- *Mammography*, which includes film-based or digital-based systems optimized for breast imaging

All of these modalities are called "projection" radiography because they all represent the projection of a 3-D object or signal onto a 2-D image.

The common element in all of these systems is the *x-ray tube*. As we will see in Chapter 5, the x-ray tube generates an x-ray pulse in an approximately uniform "cone beam" (shaped like a cone) geometry. This pulse passes through the body and is attenuated by the intervening tissues. The x-ray intensity profile across the beam exiting from the body is no longer uniform—shadows have been created by dense objects (such as bone) in the body. This intensity distribution is revealed using a scintillator, which converts the x-rays to visible light. Finally, the light image on the scintillator is captured either on a large sheet of photographic film, a camera, or solid-state detectors.

The most common modality in projection radiography is the chest x-ray; a typical unit is shown in Figure 1.1(a). Here, the x-ray tube is located on the column projecting down from the ceiling. The scintillator and detector can be located either in the pedestal unit on the right or in the table itself. The radiologic technologist stands at a console not shown, protected by lead, but able to see through a window. A typical chest x-ray is shown in Figure 1.1(b). This image shows the spine, ribs, heart, lungs, and many other features radiologists are trained to identify and interpret. A key feature of this image is that structures located at different depths in the body are overlaid (or superimposed) on the 2-D image. For example, we can see both front and back ribs in the chest x-ray in Figure 1.1(b). This is a property of projection imaging, and it is common to



(a) (b)

Figure 1.1
(a) A chest x-ray unit and (b) a chest x-ray image. *Source*: Courtesy of GE Healthcare.

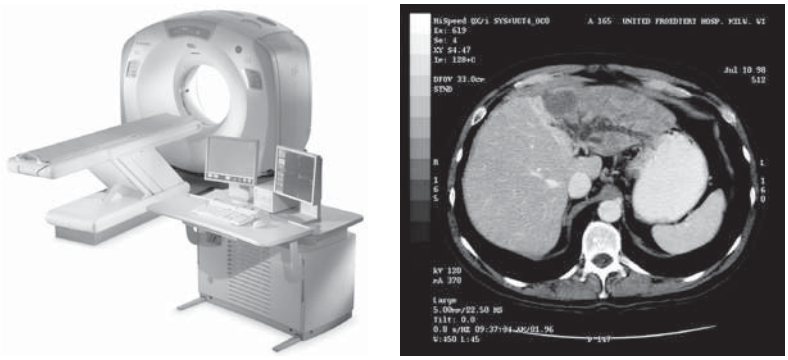
all projection radiographic methods. True *tomography*, the imaging of a 2-D slice of the 3-D body, cannot be directly accomplished using any modality in projection radiography. More details about projection radiography are given in Chapter 5.

1.5 Computed Tomography

As in projection radiography, CT uses x-rays. Unlike projection radiography, however, CT collects multiple projections of the same tissues from different orientations by moving the x-ray source around the body. CT systems have rows of digital detectors whose signals are input directly to a computer, and these signals are used to reconstruct one or more cross sections (slices) of the human body. In this way, although CT systems acquire projections that represent a "shadow" of the body, they generate truly tomographic images after reconstruction.

The important historical phases in CT development are *single-slice CT*, *helical CT*, and *multiple-row detector* CT (MDCT). Single-slice CT systems acquire data within a single plane and reconstruct only one plane per rotation. In helical CT systems, the x-ray tube and detectors continuously rotate around in a large circle, while the patient is moved in a continuous motion through the circle's center. From the patient's perspective, the x-ray tube carves out a helix; hence, the name helical CT. The importance of this technique is in its ability to rapidly acquire 3-D data, such as a whole body scan, in less than a minute. In MDCT systems, there are many rows of detectors used to rapidly gather a *cone* of x-ray data, comprising a 2-D projection of the 3-D patient. When the x-ray source and detectors revolve rapidly around the patient (one to two revolutions per second), very quick (near real-time) 3-D imaging is possible using these CT scanners.

A typical CT scanner is shown in Figure 1.2(a). In the center of the picture, we can see the cylindrical opening in which the patient lies; a patient table is also visible. Around the cylindrical opening is a housing containing both the x-ray tube and the detector array. The gantry holding these components is capable of spinning rapidly around the patient. The computer displays and keyboard in the foreground are used for entering patient data and viewing images. Although CT images can be printed on paper or film, the images are completely digital in nature since they are computed from the measured projections. The CT image



(a)

(b)

Figure 1.2
(a) A CT scanner and (b) a CT image of a slice through the liver.
Source: Courtesy of GE Healthcare.