HANDBOOK OF

Medical Imaging

Volume 1. Physics and Psychophysics

Editorial Board

The cover illustration shows views of a knee obtained after trauma in which the conventional x-ray images show only minimal abnormality of the bone while the MRI shows more extensive injury to the bone and ligaments. See Chapter 12, p. 671, Effects of Anatomical Structure on Signal Detection, Ehsan Samei, William Eyler and Lisa Baron.

HANDBOOK OF Medical Imaging

Volume 1. Physics and Psychophysics

Jacob Beutel
Harold L. Kundel
Richard L. Van Metter
Editors

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Preface

During the last few decades of the twentieth century, partly in concert with the increasing availability of relatively inexpensive computational resources, medical imaging technology, which had for nearly 80 years been almost exclusively concerned with conventional film/screen x-ray imaging, experienced the development and commercialization of a plethora of new imaging technologies. Computed tomography, MRI imaging, digital subtraction angiography, Doppler ultrasound imaging, and various imaging techniques based on nuclear emission (PET, SPECT, etc.) have all been valuable additions to the radiologist's arsenal of imaging tools toward ever more reliable detection and diagnosis of disease. More recently, conventional x-ray imaging technology itself is being challenged by the emerging possibilities offered by flat panel x-ray detectors. In addition to the concurrent development of rapid and relatively inexpensive computational resources, this era of rapid change owes much of its success to an improved understanding of the information theoretic principles on which the development and maturation of these new technologies is based. A further important corollary of these developments in medical imaging technology has been the relatively rapid development and deployment of methods for archiving and transmitting digital images. Much of this engineering development continues to make use of the ongoing revolution in rapid communications technology offered by increasing bandwidth.

A little more than 100 years after the discovery of x rays, this three-volume *Handbook of Medical Imaging* is intended to provide a comprehensive overview of the theory and current practice of Medical Imaging as we enter the twenty-first century. Volume 1, which concerns the physics and the psychophysics of medical imaging, begins with a fundamental description of x-ray imaging physics and progresses to a review of linear systems theory and its application to an understanding of signal and noise propagation in such systems. The subsequent chapters concern the physics of the important individual imaging modalities currently in use: ultrasound, CT, MRI, the recently emerging technology of flat-panel x-ray detectors and, in particular, their application to mammography. The second half of this volume, which covers topics in psychophysics, describes the current understanding of the relationship between image quality metrics and visual perception of the diagnostic information carried by medical images. In addition, various models of perception in the presence of noise or "unwanted" signal are described. Lastly, the statistical methods used in determining the efficacy of medical imaging tasks, and ROC analysis and its variants, are discussed.

Volume 2, which concerns Medical Image Processing and Image Analysis, provides descriptions of the methods currently being used or developed for enhancing the visual perception of digital medical images obtained by a wide variety of imaging modalities and for image analysis as a possible aid to detection and diagnosis. Image analysis may be of particular significance in future developments, since, aside from the inherent efficiencies of digital imaging, the possibility of performing analytic computation on digital information offers exciting prospects for improved detection and diagnostic accuracy.

Lastly, Volume 3 describes the concurrent engineering developments that in some instances have actually enabled further developments in digital diagnostic imaging. Among the latter, the ongoing development of bright, high-resolution monitors for viewing high-resolution digital radiographs, particularly for mammography, stands out. Other efforts in this field offer exciting, previously inconceivable possibilities, e.g., the use of 3D (virtual reality) visualization for surgical planning and for image-guided surgery. Another important area of ongoing research in this field involves image compression, which in concert with increasing bandwidth enables rapid image communication and increases storage efficiency. The latter will be particularly important with the expected increase in the acceptance of digital radiography as a replacement for conventional film/screen imaging, which is expected to generate data volumes far in excess of currently available capacity. The second half of this volume describes current developments in Picture Archiving and Communications System (PACS) technology, with particular emphasis on integration of the new and emerging imaging technologies into the hospital environment and the provision of means for rapid retrieval and transmission of imaging data. Developments in rapid transmission are of particular importance since they will enable access via telemedicine to remote or underdeveloped areas.

As evidenced by the variety of the research described in these volumes, medical imaging is still undergoing very rapid change. The editors hope that this publication will provide at least some of the information required by students, researchers, and practitioners in this exciting field to make their own contributions to its ever-increasing usefulness.

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Part I. Physics

Introduction to Part I

During the last half of the twentieth century, Medical Imaging has undergone a series of revolutionary changes. These have not only been driven by advances in the underlying science and technology, but by changes in the needs of health care providers. The diagnostic quality of images available to physicians as well as the variety and scope of available imaging technologies has expanded beyond what could have been imagined fifty years ago. The pace of this change is still accelerating. In part this revolution is attributable to advances in our fundamental understanding of the physical phenomena on which the imaging technologies are based. But the useful application of this understanding has been enabled by an increasing availability of computational power and high-speed data communications. Networked computational resources have been harnessed to support both the increasing pace of scientific research and, more importantly, to handle the vast amounts of data that digital imaging technologies require.

The best-known advances in medical imaging have applied digital imaging technology to previously unexploited physical measurables. Here the fortuitous combination of physical understanding and ever-increasing, widely available computational power have enabled the development and widespread adoption of ultrasound imaging, tomography, and magnetic resonance imaging. Further improvements and extensions of the scope of these imaging modalities are the subject of many ongoing research and development efforts. More speculative efforts are aimed toward discovering new “signals” that can be utilized for diagnostic purposes.

Even as new imaging technologies have found their place in medical diagnosis, classical x-ray projection radiography itself is undergoing a revolution. This began with the development of commercial Computed Radiography systems in the 1980s. At first large and expensive, technological advances have steadily reduced size and cost, while the usefulness of digital images has increased due to the ever-expanding information technology infrastructure in medicine. Here technological advances and the challenges of providing health care to a greater number of people more efficiently than ever before are driving revolutionary change. Research is now concentrated on the development of flat panel digital detectors whose possible applications range from digital mammography to conventional diagnostic radiography and fluoroscopy. Ultimately these detectors will lower the cost and increase the availability of diagnostic imaging thereby completing the transition to a totally digital medical imaging environment where image information will be better utilized to guide patient care.

Concurrent with all of these changes, our understanding of imaging science, largely derived from information theoretic considerations developed during the 1950s, has developed to the point where it can effectively guide system optimization. This initially allowed conventional x-ray imaging systems to be optimized well beyond their prior capabilities. Now with the separation between image capture and image display enabled by digital imaging technology, we pursue the heretofore unavailable opportunity of independently optimizing these two subsystems. This will bring image quality closer than ever before to the currently understood fundamental limits.

As we begin the new century, this volume provides a snapshot of our current understanding of the physics of medical imaging written by authors who have contributed significantly to its development. The first three chapters describe the fundamental physics and imaging science on which x-ray projection radiography is based. Together these provide the basis for the ongoing improvements and new developments aimed at optimizing the performance of these imaging systems. The unifying signal-to-noise concepts described are now accepted as the technology-independent absolute criteria by which progress is measured for all imaging modalities. These lead naturally to a discussion of the exciting developments in detector technology for digital radiography. Therefore, the next two chapters describe the most recent developments in flat panel detectors for digital mammography and general projection x-ray imaging. The most exciting imaging technologies to emerge in this information age allow us to fully visualize the three-dimensional structure of human anatomy. They are the focus of the final three chapters in Part I. Of these, the first two describe current practices incorporating the latest developments in magnetic resonance imaging and computed tomography. They are followed, in the final chapter, by a description of recent developments in volume ultrasound imaging.

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Richard L. Van Metter

CHAPTER 1
X-ray Production, Interaction, and Detection in Diagnostic Imaging

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1.1 X-ray production

1.1.1 Definitions and mechanisms

X rays and γ rays are forms of electromagnetic radiation that are energetic enough that when interacting with atoms, they have the potential of liberating electrons from the atoms that bind them. When an atom or molecule is stripped of an electron, an ion pair forms, consisting of the negatively charged electron (e^-) and the positive atom or molecule. X rays and γ rays, therefore, are forms of *ionizing radiation*, and this feature fundamentally distinguishes these rays from the rest of the electromagnetic spectrum.

An electromagnetic wave of frequency ν has an energy proportional to ν, with the constant of proportionality given by Plank's constant, h:

$$E = h\nu, \tag{1.1}$$

where $h = 4.135 \times 10^{-15}$ eV-s. For *diagnostic* medical x-ray imaging, the range of x-ray energies incident upon patients runs from a low of 10,000 eV (10 keV) to about 150 keV. In terms of wavelengths:

$$\lambda = \frac{c}{\nu}, \tag{1.2}$$

where c is the speed of light (2.997925×10^8 m/s). The range of wavelengths corresponding to diagnostic imaging span from about 0.1 nm (at 12.4 keV) to 0.01 nm (at 124 keV), compared to the visible spectrum spanning from about 400 nm (violet) to 650 nm (red). The electromagnetic spectrum is illustrated in Figure 1.1.

X rays and γ rays have different spectral characteristics, but fundamentally an x ray of energy E is exactly the same as a γ ray of energy E. By definition, γ rays originate from the nucleus of the atom, whereas x rays originate at the atomic level of the atom. Gamma rays are given off by radioactive isotopes such as technetium 99m, thallium 201, and iodine 131. A complete discussion of γ rays, which are the rays of interest in nuclear medicine imaging, is beyond the scope of this chapter.

X rays can be produced by several different methods, such as by synchrotrons, by channeling sources, by free electron lasers, etc. The most common x-ray production technology used in the vast majority of the radiology departments around the world, however, is the standard x-ray tube which emits bremsstrahlung as well as characteristic x rays. These processes are discussed below.

1.1.2 Bremsstrahlung radiation

According to classical theory, if a charged particle is accelerated it will radiate electromagnetic energy. When energetic electrons are incident upon a metal target (as in an x-ray tube), the electrons interact with the coulomb field of the nucleus of the target atoms and experience a change in their velocity, and hence undergo deceleration. *Bremsstrahlung radiation* ("braking radiation") is produced by this

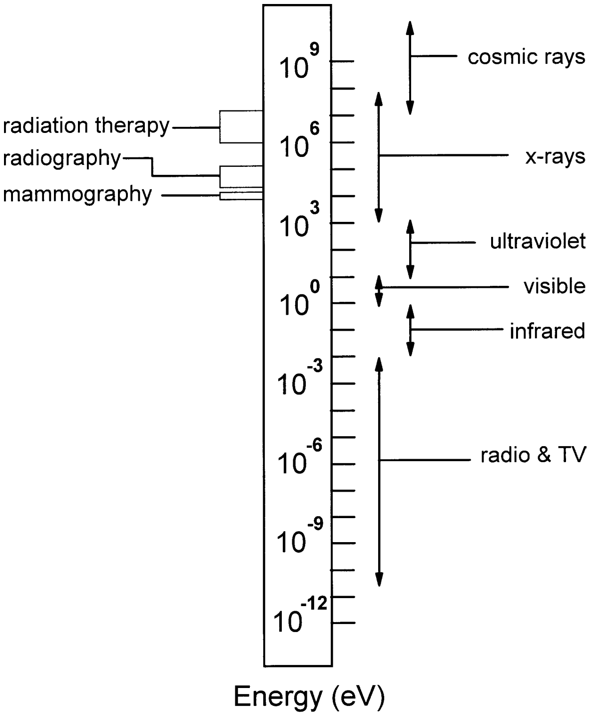

Figure 1.1: The electromagnetic spectrum is illustrated. X rays are at the high-energy, short-wavelength end of the EM spectrum. Cosmic rays of 100 GeV and higher have been observed.

process. The total intensity of bremsstrahlung radiation (integrated over all angles and all energies) resulting from a charged particle of mass m and charge ze incident onto target nuclei with charge Ze is proportional to:

$$I_{\text{bremsstrahlung}} \propto \frac{Z^2\, z^4\, e^6}{m^2}. \tag{1.3}$$

The bremsstrahlung efficiency is markedly reduced if a massive particle such as a proton or alpha particle is the charged particle. Relative to an electron, protons and α particles are over 3 million times less efficient (1836^{-2}) than electrons at producing bremsstrahlung x rays. Electrons therefore become the practical choice for producing bremsstrahlung. The Z^2 term in Eq. (1.3) also indicates that bremsstrahlung production increases rapidly as the atomic number of the target increases, suggesting that high-Z targets are preferred.

Bremsstrahlung production is illustrated in Figure 1.2. In Figure 1.2(a), incident electrons are shown passing near the target atom nucleus, and bremsstrahlung x rays of different energies (E_1, E_2, and E_3) are emitted. Electrons with only a grazing incidence of the atomic coulomb field (e.g., e_1^- in Figure 1.2(a)) give off