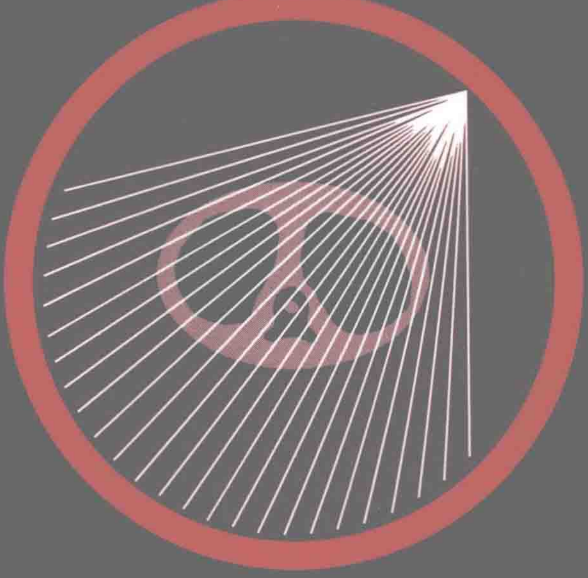
THE ESSENTIAL PHYSICS OF MEDICAL IMAGING



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DEDICATION

All accomplishments are inexorably tied to those who support and encourage the efforts of the creator. To that end this book is dedicated to my father Norman T. Bushberg whose wisdom, guidance, and love have been a constant source of inspiration. I also wish to express my deepest appreciation and love to Lori Crow and my family who were always there with a kind word or a helping hand just when I needed it most.

J.T.B.

To Spoon and T-spoon . . . for your support, patience, and understanding.

J.A.S.

To my family, especially my grandmother Mrs. Pearl Ellett Crowgey, and my teachers, especially my high school mathematics teacher Mrs. Neola Waller, and Drs. James L. Kelly, Roger Rydin, W. Reed Johnson, and Denny D. Watson of the University of Virginia.

E.M.L.

To my brother, Richard.

J.M.B.

FOREWORD

As a clinician I am usually suspicious of physics books. Radiology residents typically approach physics with the enthusiasm that they would accord to having been given an extra 4 months of night and weekend call. With this in mind, it is clear that a physics text needs to be carefully designed, written, and reviewed.

Dr. Bushberg and his colleagues have succeeded in presenting a clear text that covers all areas of diagnostic imaging. A number of current texts cover only one area of physics and the residents often purchase several texts by different authors in order to have a complete grasp of the subject matter. A particularly strong point of this book is the development process that has taken several years, bringing the text from a syllabus used and critiqued by residents into a final polished form. It gives me great pleasure to introduce this book since I have encouraged its gestation and birth into the published world.

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PREFACE

Medical imaging equipment has become the very symbol of high technology. There are several textbooks dedicated to one or two of the disciplines that comprise the science of medical imaging. We felt there was a need to develop a comprehensive text that focused on the essential elements of all of the relevant disciplines in medical imaging. Our goal was to approach this material in a straightforward manner with an emphasis on the practical aspects. Because medical imaging is a "visual" science, we have chosen to illustrate this text heavily in an attempt to bring to life some of the physical concepts that are often difficult to understand from text alone. In addition many of the topics are summarized in tables to provide the reader with an easy reference to the material or to draw comparisons between various elements of a particular technology.

This text evolved over the last several years as we continued to improve the syllabus used for our national annual radiology residents' review course. The review course presented the challenge of distilling all of the essential elements of the basic sciences of diagnostic imaging in a three and one-half day course. Students often complained that while there were several texts that covered various elements of diagnostic imaging, none covered all of the topics for which they were responsible in the physics section of the written portion of the American Board of Radiology (ABR) exam.

Using the ABR exam topics outline for the physics section as a general guide, we constructed a review course, and now a text, that covers these essential elements. This text is organized into four sections: 1) Basic Concepts, which sets the foundation of radiation physics and computers in medical imaging; 2) Diagnostic Radiology, that includes all of the major imaging modalities along with image quality assurance; 3) Nuclear Medicine, including radionuclide decay, production, radiopharmaceuticals, radiation detection and imaging; and 4) Radiation Protection, Dosimetry (x-ray and nuclear) and Biology. The appendix reviews the principles of basic physics applicable to diagnostic imaging.

It is our hope that this text will provide the reader with a comprehensive understanding of the basic sciences of medical imaging. By combining the physics of all of the diagnostic imaging modalities and related disciplines into a single volume, we have attempted not only to unify many to the concepts that are similar between various imaging disciplines but also note important differences. Our goal was to capture the essential elements of medical imaging while realizing that detailed information for each one of the subject areas covered is available in other texts and references—some of which have been listed at the end of each chapter as "suggested reading."

The rapidly expanding field of diagnostic imaging continues to present a challenge to teach its essential basic sciences in a way that is clinically relevant and easy to understand. Suggestions from our students and colleagues have been an invaluable resource. We hope that the readers of this text will provide us with feedback that will continue to enhance our teaching efforts.

ACKNOWLEDGMENTS

It is with great pleasure that we acknowledge our department chair, Dr. Rick Katzberg, whose support and encouragement of our efforts on this project are greatly appreciated.

During the production of this work there have been several individuals who have generously given of their time and expertise. First, we would like to acknowledge Drs. L. Stephen Graham and Fred Mettler who reviewed several of the chapters and provided valuable insight and refinements to the text. We are also grateful to Dr. Mark Anderson for providing CT images.

The assistance of Mr. Fernando Herrera from UCD Illustration Services was of great help in bringing to life some of the illustrations used in several chapters. The undaunted efforts and patience of Ms. Joanne Waterman who typed several of the chapters (along with countless revisions) and dealt with some of the administrative details of various portions of this book are gratefully acknowledged.

Finally, we would like to thank Mr. Tim Grayson, Mr. Will Passano, and especially Ms. Victoria Vaughn from Williams & Wilkins for their support, encouragement, attention to detail, and sense of humor, all of which were *Essential* elements in bringing this work to fruition.

There has been an
Alarming Increase

in the Number
of Things
I Know
Nothing About

CONTENTS

BASIC CONCEPTS

I

RADIATION AND THE ATOM

1

RADIATION AND THE ATOM

Radiation is energy that travels through space or matter. Two types of radiation used in diagnostic imaging are electromagnetic (EM) and particulate.

Electromagnetic Radiation

EM radiation has no mass, is unaffected by either electrical or magnetic fields, and has a constant speed in a given medium. Although electromagnetic radiation propagates through matter, it does not require matter for its propagation. Its maximal speed (2.998×10^8 m/s) occurs in a vacuum. In other media, its speed is a function of the transport characteristics of the medium. EM radiation travels in straight lines; however, its trajectory can be altered by interaction with matter. This interaction can occur either by *absorption* (removal of the radiation) or *scattering* (change in trajectory).

EM radiation is characterized by wavelength λ, frequency ν, and energy per photon E. Categories of EM radiation (including radiant heat; radio, TV, and microwaves; infrared, visible, and ultraviolet light; and x and gamma rays) comprise the electromagnetic spectrum (Fig. 1.1).

Categories used in diagnostic imaging include: (1) *gamma rays* (resulting from changes in the energy of the nuclei of radioactive atoms) are used to image the distribution of radiopharmaceuticals; (2) *x-rays,* which are extranuclear in origin, are currently the primary tool in diagnostic imaging; (3) *visible light* is produced in detecting x and gamma rays and is used for the observation and interpretation of images; and (4) *radiofrequency* EM radiation in the FM region is used as the transmission and reception signal for magnetic resonance imaging (MRI).

There are two equally correct ways of describing EM radiation—as waves and as particle-like units of energy called *photons* or *quanta.* In some situations, EM radiation behaves as waves and, in other situations, like particles.

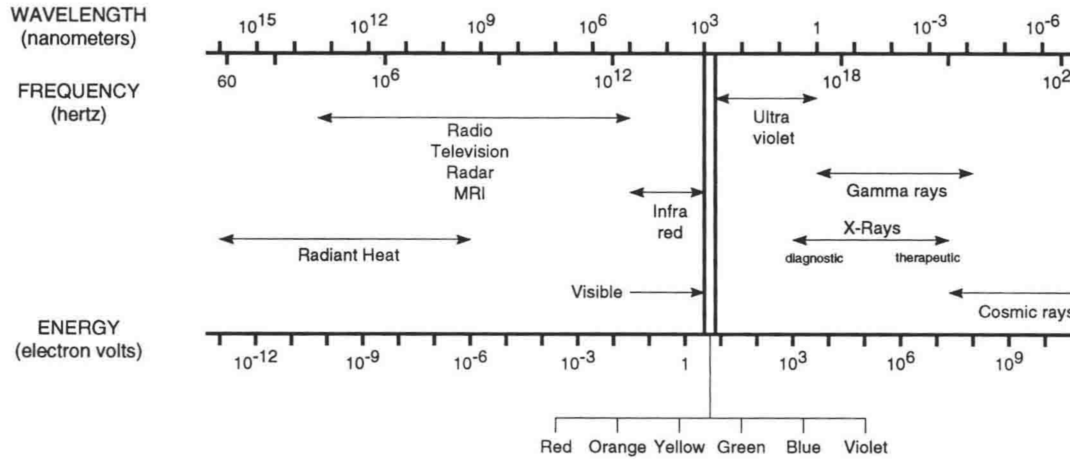

Figure 1.1. The electromagnetic spectrum.

Wave Characteristics

All waves (mechanical or electromagnetic) are characterized by their *amplitude* (maximal height), *wavelength* (λ, lambda), *frequency* (ν, nu), and *period*. The amplitude is the intensity of the wave. The wavelength is the distance between any two identical points on adjacent cycles. The time required to complete one cycle of a wave (i.e., one λ) is the period. The number of cycles accomplished per second is the frequency (1/period). Two waves of the same frequency are related to each other by phase; phase is the temporal shift of one wave with respect to the other. Some of these quantities are depicted in Fig. 1.2. The speed, wavelength, and frequency of all waves are related by:

$$c = \lambda\nu \qquad (1.1)$$

where c is the speed, λ is the wavelength, and ν is the frequency.

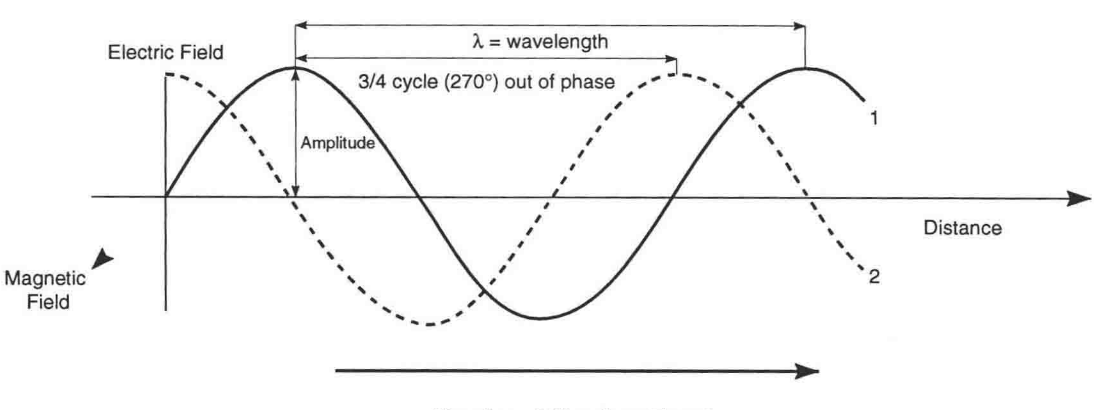

Figure 1.2. Characterization or waves.

Because the speed of EM radiation is essentially constant, its frequency and wavelength are inversely proportional. Wavelengths of x-rays and gamma rays are typically measured in *nanometers* (nm), where 1 nm = 10^{-9} m. Frequency is expressed in *hertz* (Hz), where 1 Hz = 1 cycle/s = 1 s^{-1}.

EM radiation can be described as mutually dependent perpendicular electric and magnetic fields, as shown in Fig. 1.3, which travel through space with the same frequency, velocity, and phase.

Problem: Find the frequency of blue light with a wavelength of 400 nm.

Solution: From Equation 1.1:

$$\nu = c/\lambda = [(3 \times 10^{8}\ \text{m/s})/400\ \text{nm}](10^{-9}\ \text{m/nm}) = 7.5 \times 10^{14}\ \text{s}^{-1} = 7.5 \times 10^{14}\ \text{Hz}$$

Particle Characteristics

When interacting with matter, EM radiation can exhibit particle-like behavior. These particle-like bundles of energy are called *quanta* or *photons*. The amount of energy in a quantum is equal to its frequency times Planck's constant h:

$$E = h\nu = hc/\lambda \qquad (1.2)$$

where h = 6.62×10^{-34} J-s = 4.13×10^{-18} keV-s. When E is expressed in keV and λ in nanometers (nm), the following relationship that relates energy to wavelength is obtained:

$$E\ (\text{keV}) = \frac{1.24}{\lambda\ (\text{nm})} \qquad (1.3)$$

EM radiation of higher frequency than the near ultraviolet region of the spectrum carries sufficient energy per photon to remove bound electrons from atomic shells, thus producing ionized atoms and molecules. Radiation in this portion of the spectrum (ultraviolet, x-rays, and gamma rays) is called *ionizing radiation*. The threshold energy for ionization is

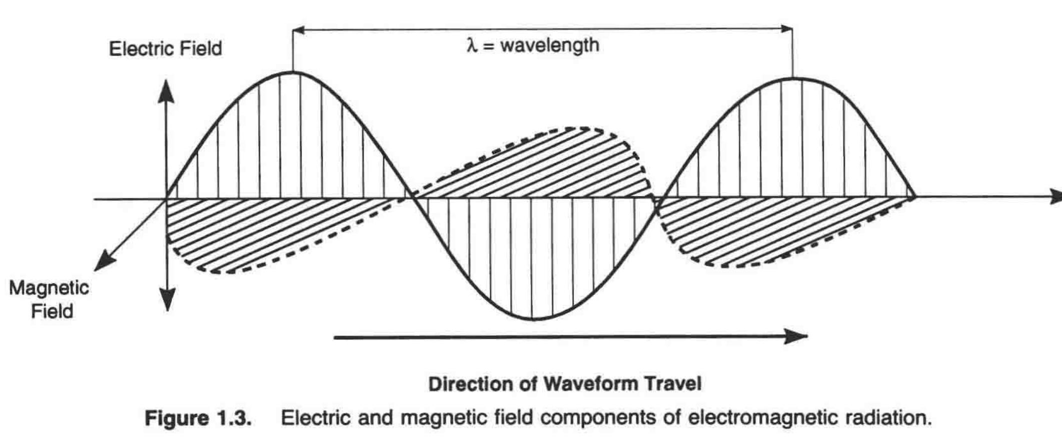

Figure 1.3. Electric and magnetic field components of electromagnetic radiation.

approximately 10 eV. EM radiation can also be absorbed by atoms or molecules, temporarily promoting the electrons to higher energy states without actually ejecting the electrons and ionizing the atoms or molecules. This energy transfer process is called *excitation.*

Particulate Radiation

The physical properties of the most important particulate radiations associated with medical imaging are listed in Table 1.1. Protons are found in the nuclei of all atoms. Each proton has a single positive charge and are identical to the nuclei of hydrogen-1 atoms. Electrons exist in atomic orbits and, when emitted by the nuclei of radioactive atoms, are called *beta minus particles.* Beta minus particles are also referred to as *negatrons* or simply "beta particles." Positrons, emitted from nuclei during a certain type of radioactive decay, are identical to electrons in every way except that their charges are positive. A neutron is an uncharged nuclear particle that has a mass slightly larger than that of a proton. Neutrons are released by nuclear fission and are used for radionuclide production. An alpha particle consists of two protons and two neutrons; it thus has a +2 charge and is identical to the nucleus of a helium atom ($^4He^{++}$). Alpha particles are emitted by certain naturally occurring radioactive materials, such as uranium, thorium, and radium.

Mass Energy Equivalence

Einstein's theory of relativity states that mass and energy are equivalent and interchangeable. In any reaction, the sum of the mass and energy must be conserved. In classical physics, there are two separate conservation laws, one for mass and one for energy. Einstein showed that these conservation laws are valid only for objects moving at low speeds. The speeds associated with some nuclear processes approach the speed of light. At these speeds, mass and energy are equivalent according to the expression

$$E = mc^2 \qquad (1.4)$$

where E represents the energy equivalent to mass m at rest and c is the speed of light in a vacuum (2.998×10^8 m/s). For example, the energy equivalent of an electron ($m = 9.109 \times 10^{-31}$ kg) is:

Table 1.1
Fundamental Properties of Particulate Radiation

Particle	Symbol	Relative Charge	Mass (amu)	Approximate Energy Equivalent (MeV)
Alpha	α, $^4He^{++}$	+2	4.0028	3727
Proton	p, $^1H^+$	+1	1.007593	938
Electron (Beta minus)	e^-, β^-	−1	0.000548	0.511
Positron (Beta plus)	e^+, β^+	+1	0.000548	0.511
Neutron	n^0	0	1.008982	940