An Introduction to the Physics of Diagnostic Radiology

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SECOND EDITION

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An Introduction to the Physics of Diagnostic Radiology

DEDICATED TO:

Dolly
Miss Winn
Vauda

Preface

In the preface to the first edition of this text we spoke of the understandable apprehension with which the radiology resident approached the study of physics. We must now acknowledge the terrible apprehension with which two of us (E.E.C. and T.S.C.) approached the preparation of the second edition. Advances in technology threaten to overwhelm the clinical radiologist. Understanding how to apply this technology in rendering improved patient care is difficult, but also understanding the complex physics that provides these techniques is just about impossible. In this edition, we attempt to introduce the important equipment advances and changes which confront radiology. Ultrasound requires us to explore the physics involved in the generation, propagation and detection of sonic waves. Computerized tomography uses many physical principles familiar to radiologists, but adds the complex mathematics of image reconstruction with strange new words like pixel and voxel. And then there is xeroradiography which detours us into the exotic realm of solid state physics. Even our old friends, intensifying and fluoroscopic screens and x-ray film, now emerge with new colors and compositions that include rare earths and other elements that most of us had rarely, if ever, even been aware of. Radiation protection has been accorded the chapter it deserves; the absence of this chapter from the first edition was our most frequent criticism. The topics of cineradiography, television and magnification have been considerably amplified.

Our purpose remains to present this material in an understandable format not only to radiology residents, but also to students of radiologic technology. Unfortunately, some of the new topics demand a little more arithmetic, but we have insisted on keeping things as simple as possible. That we have succeeded for only a few readers will make the effort amply rewarding. The following comment which we received from two young radiologists in New York describes our wish for all our students.

". . . your book actually made the subject understandable and almost believable. It was the most readable book since *The Joy of Sex,* although the illustrations were not quite as interesting."

Thank you. And good luck.

Dallas, Texas

E. E. CHRISTENSEN, M.D.
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Preface to the First Edition

The resident in Radiology, in seeking to attain proficiency in his chosen specialty, finds himself confronted with the need to assimilate knowledge from a number of different disciplines. Having completed medical school, he is well prepared to deal with the biological aspects of the subject, but the realization that physics is also included in the curriculum of diagnostic radiology often comes as an unpleasant surprise. The facts learned in the physics course taken in undergraduate school have usually been dimmed by the passing years or lost in the confusion produced by the massive onslaught of the medical school curriculum. Therefore, most residents in diagnostic radiology, when they reencounter the study of physics, enter the field with understandable apprehension. For several years we sympathized with our residents as they mounted an inefficient, time consuming offensive against this traditionally formidable subject. It soon became apparent that physics, by demanding a disproportionate share of their time, had distracted them from their other academic pursuits.

In an effort to provide assistance, in addition to sympathy, we prepared a series of lectures dealing primarily with some of the applications of physics to the clinical practice of diagnostic radiology. These were well received, and it is upon these lectures that the text of this book is based. The book is intended to be used by radiology residents beginning their study of the physics of diagnostic radiology. Two of us (E.E.C. and T.S.C.) are diagnostic radiologists, singularly unschooled in higher mathematics or advanced physics. Thus, our understanding and presentation are based on the experience of a clinician.

Our purpose is to introduce the student of radiology to the tools of his trade and to describe some of the physical and chemical phenomena which make those tools work for him. The subjects of electricity, magnetism, atomic structure, circuitry, and x-ray protection are not discussed, except where such subjects are necessary for the understanding of a specific point. We have attempted to introduce those topics that are truly important and must be mastered if the maximum amount of diagnostic information is to be obtained from the radiographic examination, whether this information be recorded on film, a fluoroscopic screen, or a television monitor. We begin with the production of x-rays and the interactions between the patient and the x-ray beam. Such considerations lead to a discussion of collimators, grids, x-ray film and its proper exposure and processing, magnification, subtraction techniques, stereoscopy, and tomography. We feel that it is equally important to examine the use of devices which decrease the radiation dose to the patient, such as the x-ray image intensifier and intensifying screens, and to determine how the use of these devices affects the final radiographic image.

We have endeavored to present this material in such a way that it can be understood by a student with no mathematical training other than arithmetic and basic algebra. Therefore, presentations are necessarily simple, often superficial, and sometimes incomplete. We propose that it is better to understand a few fundamental principles than to be thoroughly confused by a plethora of data. This text is intended to be used in preparation for the study of the more complete textbooks of the physics of diagnostic radiology.

At some time during his period of intensive study the student of diagnostic radiology must decide to cross the Rubicon and learn physics. We hope that the following pages will make the journey a little easier.

Dallas, Texas

E.E. CHRISTENSEN, M.D.
T.S. CURRY, M.D.
J.E. NUNNALLY, M.A.

Acknowledgments

With the publication of the second edition, we acknowledge the absence of one of the original authors. Geographic separation from James Nunnally required that we acquire a new physicist who could share our offices and thoughts on a daily, and usually hourly, basis, so we welcome James E. Dowdey, Ph.D. as a co-author.

We must expand our indebtedness to many more people who helped in the preparation of this new edition.

We received valuable assistance from the E. I. duPont de Nemours and Company and the Eastman Kodak Company. We must especially thank R. E. Warynen of duPont for his continued help, and Al Allard of Kodak for joining our long list of helpers.

Nancy Sciscenti and Jan Dolph prepared all the new illustrations. Their suggestions and beautiful handiwork are much appreciated.

Three photographers, Dorothy Gutekunst, Katie Belle Wolf and Nancy Schreiber, shared the responsibility of preparing reproductions of the illustrations.

John Moore again assumed the role of coordinator and critic. In our department, John is known as "the man who built the book."

For typing the manuscript we are fortunate to have had Glenda Parkinson, Carolyn Tunnell and Linda Wooldridge.

The continued support we received from our friends and colleagues in the Radiology and Physics Departments remains one of the most rewarding aspects of this effort. Drs. Mike Landay and Harold Smitson assumed many of our clinical responsibilities, and Bob Murry and Mike Tipton occupied similar positions in the Physics Department. Other radiologists sharing the burden of our repeated absence from work include Drs. George Curry, Jan Diehl, Geral Dietz, Bob Epstein, Bill Kilman, Ken Maravilla and Bob Parkey. And our reliable and extraordinary friend, Dr. Jack Reynolds remained available to review and edit many pages of the manuscript.

Finally, we must confess that the entire project was undertaken only after we received permission from our patient wives. We are not sure why they let us do it, but we guess we are glad they did.

E.E.C.
T.S.C.
J.E.D.

Contents

CHAPTER 1

Radiation

Wilhelm Conrad Roentgen, a German physicist, discovered x rays on November 8, 1895. Several fortunate coincidences set the stage for the discovery. Roentgen was investigating the behavior of cathode rays (electrons) in high-energy cathode ray tubes. The tube consisted of a glass envelope from which as much air as possible had been evacuated. A short platinum electrode was fitted into each end, and when a high voltage discharge was passed through this tube, ionization of the remaining gas produced a faint light. Roentgen had enclosed his cathode ray tube in black cardboard to prevent this light from escaping in order to block any effect the light might have on experiments he was conducting. He then darkened his laboratory room to be sure there were no light leaks in the cardboard cover. Upon passing a high tension discharge through the tube, he noticed a faint light glowing on a work bench about 3 feet away. He discovered that the source of the light was the fluorescence of a small piece of paper coated with barium platinocyanide. Since electrons could not escape the glass envelope of the tube to produce fluorescence, and the cardboard permitted no light to escape from the tube, he concluded that some unknown type of ray was produced when the tube was energized. We can imagine his excitement as he investigated the mysterious new ray. He began placing objects between the tube and the fluorescent screen: a book, a block of wood, and a sheet of aluminum. The brightness of the fluorescence differed with each, indicating that the ray penetrated some objects more easily than others. Then he held his hand between the tube and the screen, and to his surprise, the outline of his skeleton appeared on the screen. By December 28, 1895, he had thoroughly investigated the properties of the rays and had prepared a manuscript describing his experiments. In recognition of his outstanding contribution to science, Wilhelm Conrad Roentgen was awarded the first Nobel Prize for Physics in 1901.

THE ELECTROMAGNETIC SPECTRUM

X rays belong to a group of radiations called electromagnetic radiation. **Electromagnetic radiation is the transport of energy through space as a combination of electric fields and magnetic fields** (hence the name electromagnetic). Familiar members of the family of electromagnetic radiation include radio waves, radiant heat, visible light, and gamma radiation.

The interactions of electromagnetic radiations are difficult to understand. Some interactions of electromagnetic radiations are explained only if they are assumed to be particles, while other interactions are explained only by theories of wave propagation. **It is necessary to discuss electromagnetic radiations as if they were both particles and waves.**

Wave Concept of Electromagnetic Radiation

Electromagnetic radiations are propagated through space in the form of waves. They may be compared to a wave traveling down a stretched rope when one end is moved up and down in a rhythmic motion. However, while the waves with which we are familiar must be propagated in a medium (such as the example of the rope, waves traveling in water, or sound waves traveling in air), electromagnetic waves need no such medium; i.e., they can be propagated through a vacuum. Waves of all kinds have an associated wavelength and a frequency. The distance between two successive crests, or troughs, is the wavelength of the wave, and is given the symbol λ (the Greek letter **lambda,** the initial for length). The number of waves passing a particular point in a unit of time is called the frequency, given the symbol ν (the Greek letter **nu,** the initial for number). If each wave has a length λ, and ν waves pass a given point in unit time, the velocity of the wave is given by:

$$V = \lambda \times \nu$$

For example, if the wavelength is 4 feet and the frequency is 60 waves per minute, then the velocity is:

Velocity = 4 ft. × 60/min
Velocity = 240 ft./min

Electromagnetic radiations always travel at the same velocity in a vacuum. This velocity is 186,000 miles per second (3×10^8 meters per second), which is usually referred to as the velocity of light and given the symbol c. Therefore, we may express the relationship between velocity, wavelength, and frequency as:

$$c = \lambda\nu$$

c = velocity of light (m/sec)
λ = wavelength (meters)
ν = frequency (per second)

Since all electromagnetic radiations have the same velocity, the frequency of the radiation must be inversely proportional to its wavelength. All the radiations in the electromagnetic spectrum differ basically only in wavelength. The wavelength of a radiowave may be 5 miles long, while a typical x ray is only 1 billionth of an inch. The wavelength of diagnostic x rays is extremely short and it is usually expressed in angstrom units (Å). An angstrom is 10^{-10} meters. The wavelength of most diagnostic x rays is between 1Å and 0.1Å. The wavelength of an electromagnetic wave determines how it interacts with matter. For example, an electromagnetic wave 7000 Å long can be seen by the human eye as red light, and a wavelength of 4000 Å is seen as blue light. The frequency of blue light may be calculated by knowing its wavelength (4000 Å = 4×10^{-7} meters):

$$c = \lambda\nu \text{ or } \nu = \frac{c}{\lambda}$$

$$\nu = \frac{3 \times 10^8 \text{ meters per sec}}{4 \times 10^{-7} \text{ meters}}$$

$$\nu = 7.5 \times 10^{14} \text{ per sec}$$

Blue light, with a wavelength of 4000 Å, has a frequency of 7.5×10^{14} vibrations per second. Similarly calculated, the frequency of an x ray of wavelength 0.1 Å is 3×10^{19} vibrations per second.

The complete spectrum of electromagnetic radiations covers a wide range of wavelengths and frequencies. The various parts of the spectrum are named according to the manner in which the radiations are generated or detected. Some of the members of the group, listed in order of decreasing wavelength, are:

Radio, television, radar:	3×10^5 cm to 1 cm
Infrared radiation:	0.01 cm to .00008 cm (8,000 Å)
Visible light:	7,500 Å (.000075 cm) to 3,900 Å
Ultraviolet radiation:	3,900 Å to 20 Å
Soft x rays:	100 Å to 1 Å
Diagnostic x rays:	1 Å to 0.1 Å
Therapy x ray & gamma rays:	0.1 Å to 10^{-4} Å

There is considerable overlap in the wavelengths of the various members of the electromagnetic spectrum; the numbers listed are rough guides. It is again stressed that the very great differences in properties of these radiations are attributable to their differences in wavelength (or frequency).

The wave concept of electromagnetic radiations explains why these radiations may be reflected, refracted, diffracted, and polarized. However, there are some phenomena that cannot be explained by the wave concept.

Particle Concept of Electromagnetic Radiation

Short electromagnetic waves, such as x rays, may react with matter as if they were particles, rather than waves. The particles of which we speak are actually discrete bundles of energy, and each of these bundles of energy is called a **quantum** or a **photon.** These photons travel at the speed of light. The amount of energy carried by each quantum, or photon, depends upon the frequency (ν) of the radiation. If the frequency (number of vibrations per sec) is doubled, the energy of the photon is doubled. The actual amount of energy of the photon may be calculated by multiplying its frequency times a constant. The constant has been determined experimentally to be 4.13×10^{-18} keV sec, and it is called Planck's constant. The mathematical expression is written as follows:

$$E = h\nu$$

E = photon energy
h = Planck's constant
ν = frequency

The ability to visualize the dual characteristics of electromagnetic radiation presents a true challenge. But we must unavoidably reach the conclusion that electromagnetic radiation behaves sometimes as a wave and at other times as a particle. The particle concept is used to describe the interactions between radiation and matter. Since we will be concerned principally with interactions, such as the photoelectric effect and Compton scatter, we will use the photon (or quantum) concept in this text.

The unit that is used to measure the energy of photons is the electron volt (eV). An electron volt is the amount of energy that an electron gains as it is accelerated by a potential difference of 1 volt. Since the electron volt is a small unit, x-ray energies are usually measured in terms of the kiloelectron volt (keV), which is 1000 electron volts. We will usually discuss x rays in terms of their energy rather than their wavelengths, but the two are related as follows:

$$c = \lambda\nu \text{ or } \nu = \frac{c}{\lambda}$$

$$\text{And: } E = h\nu$$

$$\text{Substituting } \frac{c}{\lambda} \text{ for } \nu$$

$$E = \frac{hc}{\lambda}$$

The product of the velocity of light (c) and Planck's constant (h) is 12.4, when the unit of energy is keV and the wavelength is in angstroms. The final equation showing the relationship between energy and wavelength is:

$$E = \frac{12.4}{\lambda}$$

E = energy in keV
λ = wavelengths in angstroms (Å)

Table 1–1 shows the relationship between energy and wavelength for various photons.

If a photon has 15, or more, electron volts of energy, it is capable of ionizing atoms and molecules, and it is called ionizing radiation. An atom is ionized when it loses an electron. Gamma rays, x rays, and some ultraviolet rays are all ionizing radiations.

Table 1–1. Correlation Between Wavelength and Energy

WAVELENGTH (Å)	ENERGY (keV)
.0005	24,800
.08	155
.1	124
1.24	10

SUMMARY

Wilhelm Conrad Roentgen discovered x rays on November 8, 1895. X rays are members of a group of radiations known as electromagnetic radiations, of which light is the best-known member. They have a dualistic nature, behaving in some circumstances as waves and under different conditions as particles. Therefore, two concepts have been postulated to explain their characteristics. A single particle of radiation is called a photon, and we will discuss x rays in terms of photons.

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CHAPTER 2

Production of X rays

DIAGNOSTIC X-RAY TUBES

X rays are produced by **energy conversion** when a fast-moving stream of electrons is suddenly decelerated in the "target" anode of an x-ray tube. The x-ray tube is made of Pyrex glass which encloses a vacuum containing two electrodes (this is a diode tube). The electrodes are designed so that electrons produced at the cathode (negative electrode or filament) can be accelerated by a high potential difference toward the anode (positive electrode or target electrode). The basic elements of an x-ray tube are shown in Figure 2–1, which is a diagram of a stationary anode x-ray tube. Electrons are produced by the heated tungsten filament and accelerated across the tube to hit the tungsten target, where x rays are produced. It will be the purpose of this section to describe the design of the x-ray tube and to review the way in which x rays are produced.

The Glass Enclosure

It is necessary to seal the two electrodes of the x-ray tube in a vacuum. If gas were present inside the tube, the electrons which were being accelerated toward the anode (target) would collide with the gas molecules, lose energy, and cause secondary electrons to be ejected from the electron orbits of the gas molecules. By this

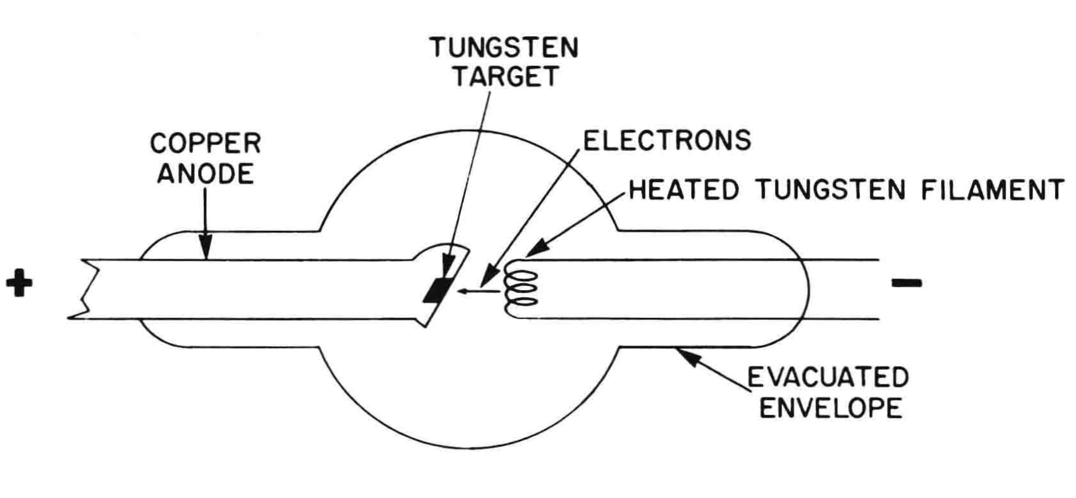

Figure 2–1 The major components of a stationary anode x-ray tube

process (ionization) additional electrons would be available for acceleration toward the anode. Obviously, this production of secondary electrons could not be satisfactorily controlled. Their presence would result in variation in the number and, more strikingly, the reduced speed of the electrons impinging on the target. This would result in a wide variation in tube current and in the energy of the x rays produced. Actually, this principle was used in the design of the early, so-called "gas" x-ray tubes, which contained small amounts of gas to serve as a source of secondary electrons. The purpose of the vacuum in the modern x-ray tube is to allow the number and speed of the accelerated electrons to be controlled independently. The shape and size of these x-ray tubes are specifically designed to prevent electric discharge between the electrodes.

It is necessary to seal the connecting wires into the glass wall of the x-ray tube. During operation of the x-ray tube, both the glass and the connecting wires are heated to high temperatures. Because of differences in their coefficients of expansion, most metals expand more than glass when heated. This difference in expansion would cause the glass-metal seal to break and destroy the vacuum in the tube if special precautions were not taken. Because of this problem, special alloys, having approximately the same coefficients of linear expansion as borosilicate glass, are usually used in x-ray tubes.

The Cathode

The negative terminal of the x-ray tube is called the cathode. In referring to an x-ray tube, the terms **cathode** and **filament** may be used interchangeably, a statement which is not true for other types of diode tubes. In addition to **the filament,** which **is the source of electrons** for the x-ray tube, the cathode has two other elements. These are: (1) the connecting wires which supply the source of voltage (average about 10 volts) and amperage (average about 3 to 5 amperes) which heat the filament, and (2) a metallic focusing cup. The number (quantity) of x rays produced depends entirely on the number of electrons which flow from the filament to the target (anode) of the tube. **The x-ray tube current, measured in milliamperes** (1 mA = 1/1000 ampere), **refers to the number of electrons flowing per second.** It is important to understand where these electrons come from and that the number of electrons determines x-ray tube current. For example, in a given unit of time, a tube current of 200 mA is produced by twice as many electrons as a current of 100 mA, and 200 mA produces twice as many x rays as 100 mA.

The filament is made of tungsten wire, about 0.2 mm in diameter, which is coiled to form a vertical spiral about 0.2 cm in diameter and 1 cm or less in length. When current flows through this fine tungsten wire, it becomes heated. When a metal is heated, its atoms absorb thermal energy, and some of the electrons in the metal acquire enough energy to allow them to move a small distance from the surface of the metal (normally, electrons can move within a metal, but cannot escape from the metal). Their escape is referred to as the process of **thermionic emission,** which may be defined as the emission of electrons resulting from the absorption of thermal energy. A pure tungsten filament must be heated to a temperature of at least 2200°C to emit a useful number of electrons (thermions). Tungsten is not as efficient an emitting material as other materials (alloys of tungsten) used in some electron tubes. However, it is chosen for use in x-ray tubes because it can be drawn into a thin wire that is quite strong, has a high melting point (3370°C), and has little tendency to vaporize; thus such a filament has a reasonably long life expectancy.

Electrons emitted from the tungsten filament form a small cloud in the immediate vicinity of the filament. This collection of negatively charged electrons forms what is called the **space charge.** This cloud of negative charges tends to prevent other electrons from being emitted from the filament until they have acquired sufficient thermal energy to overcome the force caused by the space charge. The tendency of the space charge to limit the emission of more electrons from the filament is called the **space charge effect.** When electrons leave the filament, the loss of negative charges causes the filament to acquire a positive charge. The filament then attracts some emitted electrons back to itself. When a filament is heated to its emission temperature, a state of equilibrium is reached quickly. In equilibrium the number of electrons returning to the filament equals the number of electrons being emitted. As a result the number of electrons in the space charge remains constant, the actual number depending on filament temperature.

The high currents which can be produced by the use of thermionic emission are possible because of the fact that large numbers of electrons can be accelerated from the cathode (negative electrode) to the anode (positive electrode) of the x-ray tube. The number of electrons involved is enormous. The unit of electric current is the ampere, which may be defined as the rate of "flow" when 1 coulomb of electricity flows through a conductor in 1 second. The coulomb may be defined as the amount of electric charge carried by 6.25×10^{18} electrons. Therefore, an x-ray tube current of 100 milliamperes (0.1 ampere) may be considered as the "flow" of 6.25×10^{17} electrons from the cathode to the anode in 1 second. **Electron current across an x-ray tube is in one direction only** (always cathode to anode). Because of the forces of mutual repulsion and the large number of electrons, this electron stream would tend to spread itself out and result in bombardment of an unacceptably large area on the anode of the x-ray tube. This is prevented by a structure called the cathode **focusing cup** which

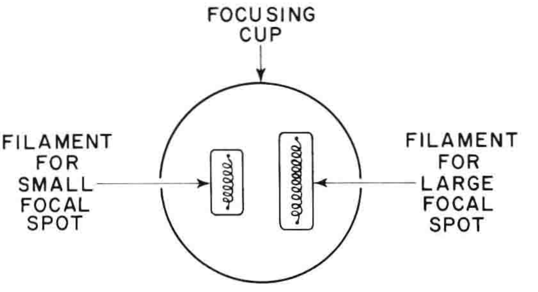

Figure 2–2 A double filament contained in the focusing cup

surrounds the filament (Figures 2–2 and 2–4). When the x-ray tube is conducting, the focusing cup is maintained at the same negative potential as the filament. The focusing cup is designed so that its electrical forces cause the electron stream to converge onto the target anode in the required size and shape. The focusing cup is usually made of molybdenum. Modern x-ray tubes may be supplied with a single or, more commonly, a double filament. Each filament consists of a spiral of wire, and they are mounted side by side or one above the other, one being longer than the other (Figure 2–2). It is important to understand that only one filament is used for any given x-ray exposure, the larger filament generally being used for larger exposures. The heated filament glows and can be easily observed by looking into the beam exit port of an x-ray tube housing (do not forget to remove the filter).

Vaporization of the filament when it is heated acts to shorten the life of an x-ray tube, because the filament will break if it becomes too thin. The filament should never be heated for longer periods than necessary. Many modern x-ray circuits contain an automatic filament-boosting circuit. When the x-ray circuit is turned on, but no exposure is being made, a "standby" current heats the filament to a value corresponding to low mA, commonly about 5 mA. This amount of filament heating is all that is required for fluoroscopy. When