PRACTICAL RADIOGRAPHIC IMAGING

Frontispiece. X-ray film has been prepared in many sizes for medical work. The largest film (32 by 72 inches) used was for the entire body radiography of a woman, aged 33, exhibiting hip pathology. The radiograph was made with a one-second exposure, 75 kVp, 150 mA, 12 feet target-film distance, fast screens, and tissue-compensating filtration.

Eighth Edition

PRACTICAL RADIOGRAPHIC IMAGING

By

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To

WOLFRAM CONRAD FUCHS

Roentgen Pioneer

1865-1907

and

ARTHUR WOLFRAM FUCHS

1895-1962

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PREFACE TO THE EIGHTH EDITION

ARTHUR W. FUCHS was a man who understood and believed in experiential learning. The philosophy is that learning obtained through hands-on experience is more likely to be understood, retained, and applied than are notes from lectures. His first edition of this textbook, published in 1955, had a format of illustrated experimentation. He used exemplary scientific method, yet remained focused upon the daily practice of medical radiography. This book has always emphasized the application of radiographic *technique* rather than mere theory. It is intended to complement and build upon the typical radiographic physics textbook. Many educators recognize that the need for this kind of practical instruction has continued into the twenty-first century. It is for this reason that I feel honored to dedicate this book to Arthur Wolfram Fuchs and to his father.

There are well over 20 fundamental variables that affect radiographic image quality. There are only six essential image qualities to an image (density, contrast, noise, sharpness, magnification, and shape distortion). By organizing this textbook by variables, the material is broken down into smaller chapters and allows easier assimilation by the student. In the early chapters, each variable under discussion is systematically examined for its effects upon each of the six image qualities. This provides a logically progressive and consistent approach to learning for the student.

Chapters and material have been added over the years in response to input from educators, and contributing authors have been instrumental in making improvements and adding depth. *Review exercises* are generously distributed throughout each chapter that deals with the mathematics of technique, and serve as drills with answers provided in the appendix. Other unique aspects of the book include very thorough summaries at the end of each chapter with highlighted key words, lots of chapter review questions, and an extensive index. Great effort has been invested in making the book "user-friendly" for students, with clear, concise explanations, crisp illustrations and plentiful examples, experimental proofs, and analogies to everyday life.

The accompanying Instructors' Manual provides extensive additional tools for the educator, including additional *calculation banks* that can be assigned to students, over 1,000 multiple-choice questions organized by chapter, suggested laboratory exercises, and, of course, answers to all chapter review questions, multiple-choice questions, and calculation banks.

This Eighth Edition presents four extensive chapters on digital imaging, with a steady progression from computer fundamentals to the detailed clinical applications of computerized radiography (CR) and direct digital radiography (DR). Also of particular value are the thorough treatment of technique skills including the proper application of automatic exposure controls (AEC), the "how-to" of quality control, and repeat analysis.

I am grateful for the professional association of my colleagues in education over the years and of those practicing radiographers on the "front line." Their continued feedback for improvements in future editions of this valuable textbook will be greatly appreciated. It is sincerely hoped that this text will contribute to the competency and fulfillment of radiographers in their career, to the professionalism and cost-effectiveness of medical imaging departments, and ultimately to the enhancement of patient care.

Q.B.C.

ACKNOWLEDGMENTS

I WISH TO EXPRESS my thanks to the professional staff of Charles C Thomas, Publisher for their valuable help in developing, illustrating, and producing the text.

Special thanks to Euclid Seeram, Robert DeAngelis, and Robert Parelli for their valuable contributions to a text which remains a classic in the field, and to all of my professional colleagues who have offered suggestions for improvements, assisted with corrections, and shared their expertise and association over the years.

I am grateful to Jason, Melissa, Chad, Tiffani, Brandon, and Tyson for their patience when I am writing.

Above all, I wish to express my gratitude to my wife Margaret for her unwavering support and confidence in all that I do and for her belief in what each human being can do.

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PRODUCING THE RADIOGRAPHIC IMAGE

Chapter 1

X-RAYS AND RADIOGRAPHIC VARIABLES

A SATISFACTORY UNDERSTANDING of exposure and processing terms requires at least a limited knowledge of x-rays and their characteristics. X-rays are a form of invisible radiant energy and were discovered by Wilhelm Conrad Roentgen on November 8, 1895. They are quite similar to light in their general properties since they travel at the same speed and obey many of the same laws. A distinguishing feature of x-rays, however, is their extremely short wavelength–only about one ten-thousandth the wavelength of *visible* light. It is this property that is responsible for x-rays' ability to penetrate materials that ordinarily would absorb or reflect light.

GENERATION OF X-RAYS

The generation of x-rays is a complex process. Fortunately, a knowledge of only a few of the principles is necessary. The essential feature of x-ray production is the striking of matter by high-speed electrons; this may occur within or outside a vacuum but is much more efficient within a vacuum where there are no air molecules impeding the path of these electrons on their way to their target. The device in which x-rays are generated is the x-ray tube. The modern x-ray tube is a sealed glass tube with all remnants of air vacuumed out of it.

X-rays are produced in an x-ray tube when electrons, traveling at great speed, under stress of high voltage, collide with a metallic target of high molecular weight such as tungsten. The efficiency of x-ray production is very small, for only about one part in a thousand of the energy from these electrons is converted into x-rays that are penetrating enough to make a radiograph; the balance is dissipated into heat.

The x-ray tubes employed by early workers contained gas under low pressure. These tubes were known as Crookes or Hittorf tubes. Roentgen's early tubes (Fig. 1-1) were of the Crookes type which consisted of a pear-shaped glass tube filled with air under low pressure. An aluminum cathode was installed in the small end of the tube and, through a stem of glass on the side of the tube was inserted an aluminum anode.

When a high-voltage electrical current was passed between the cathode and anode, the residual gas in the tube became ionized and a stream of electrons was repelled by the cathode. Many of these electrons were attracted to the anode because of its positive charge and location in the tube, but the majority of the electrons were bombarded against the glass at the end of the tube. The sudden stoppage of the electrons against the glass produced x-rays.

When the Jackson *focus* tube was made, the electron stream was focused onto a

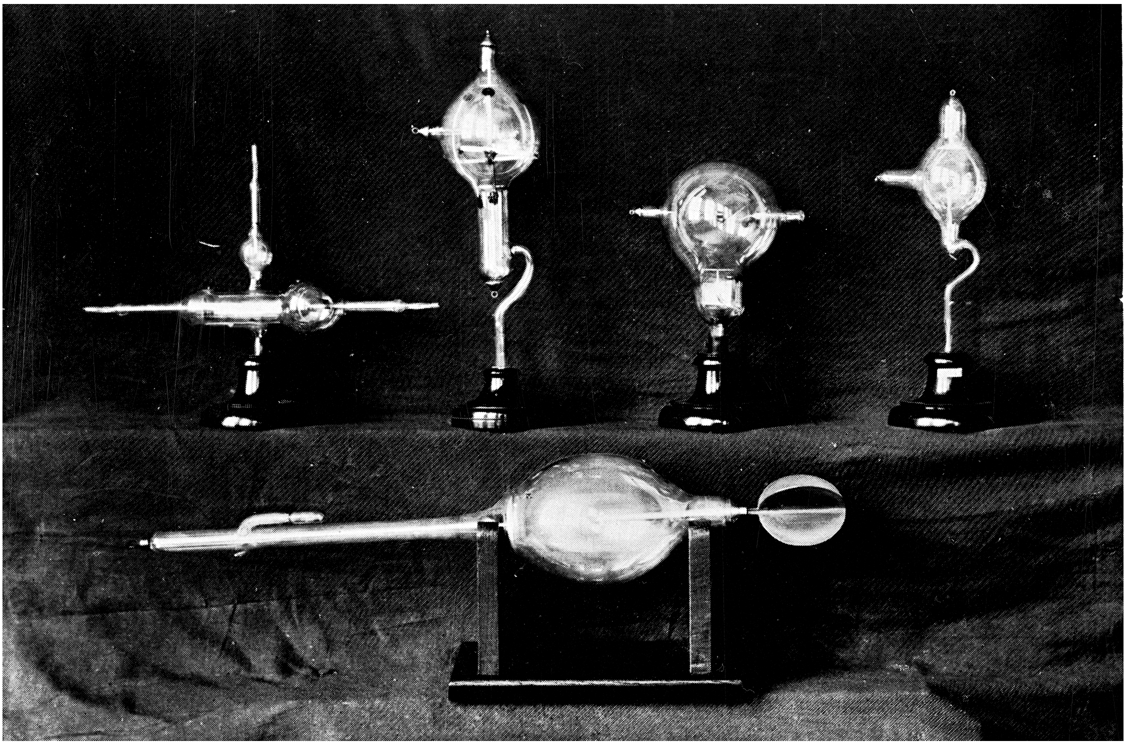

Figure 1-1. Photograph of the gas discharge tubes employed by Roentgen in his experiments that led to his discovery of the x-rays.

metal anode at the end of the tube and inclined at an angle so that a larger amount of radiation could be concentrated on a particular area.

Maintenance of a constant pressure in the early glass tubes was almost impossible for the pressure would vary with each use of the tube. These early tubes were quite erratic. The advent of the Coolidge hot cathode x-ray tube made possible the generation of a constant source of x-rays that could be easily duplicated at will. This tube was invented by Dr. W. D. Coolidge of the General Electric Company in 1913 (Fig. 1-2).

X-RAY TUBE

The modern x-ray tube consists of a highly evacuated glass bulb into which are sealed two electrodes–the *cathode*, or negative electrode (the source of electrons), and the *anode*, or positive electrode (the source of x-rays). Due to the vacuum and the arrangement of the electrodes, no discharge of electrons between the cathode and the anode is possible until the filament in the cathode is heated (Figs. 1-3 & 1-4).

Thermionic Electron Emission

Employing the principle that all *hot* bodies emit electrons, a spiral, incandescent filament of tungsten wire is incorporated in the cathode of the x-ray tube. This filament is heated by an electrical current of low amperage from a step-down transformer. The temperature of the filament, as governed by the amount of current that passes through it, controls the number of electrons emitted–the higher the filament tempera-

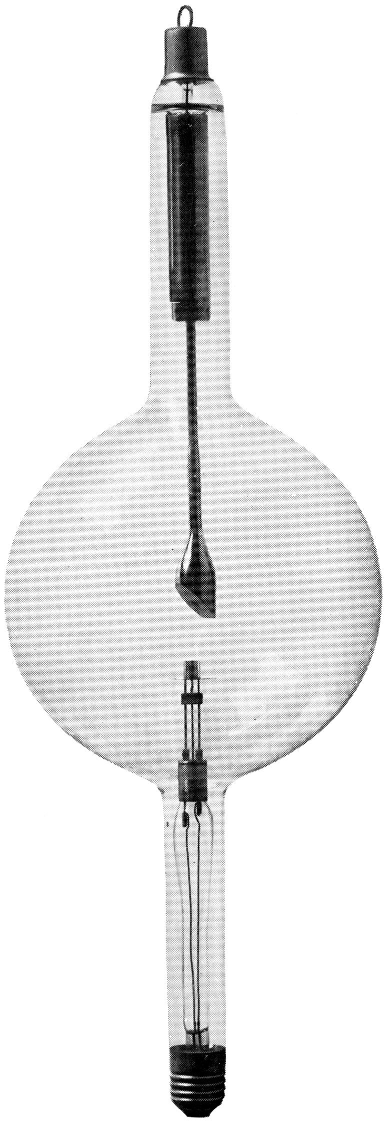

Figure 1-2. Photograph of an early Coolidge stationary anode tube in which the electrons originate in heated tungsten filament.

ture, the greater the electron emission. Because of its small mass, an electron rapidly accelerates to a high speed in an electric field. Surrounding the filament is a shield that serves to focus the electron stream from the heated filament to the *focal spot* on the tungsten target located at the end of the anode. The stream of electrons from cathode to anode constitutes the tube current and is measured in milliamperes. The electron stream is propelled by high-voltage electricity impressed on the tube electrodes by a high-voltage transformer. This voltage, which may be varied at will, regulates the *speed* with which the electrons cross the gap between the cathode and the anode. Thousands of volts (kilovolts) are normally used for this purpose. The stream of electrons forms a conducting path for the high-voltage current to reach the anode. Upon impact with the focal spot of the tube, the electrons produce a stream of x-rays which are emitted over a 180° angle from the focal spot of the target.

Rotating Anode Tube

The Coolidge tube was still limited in the quantity of x-rays it could produce.

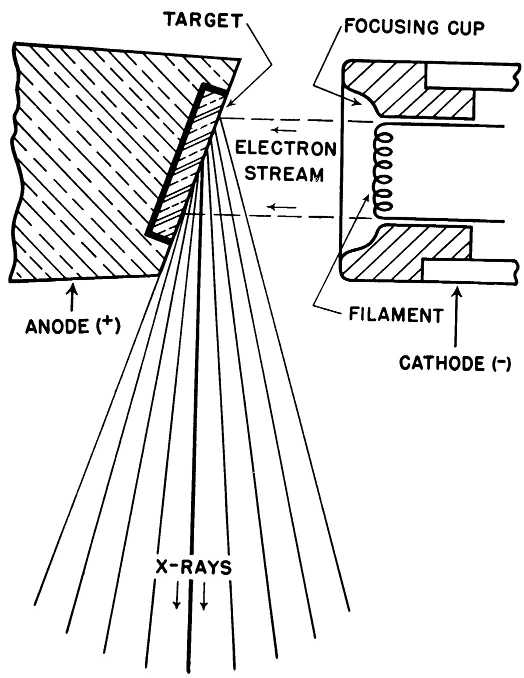

Figure 1-3. Diagram of the essential elements of an x-ray tube wherein electrons generated by a heated filament in the cathode are bombarded against a tungsten-rhenium target in the anode, resulting in x-ray production.

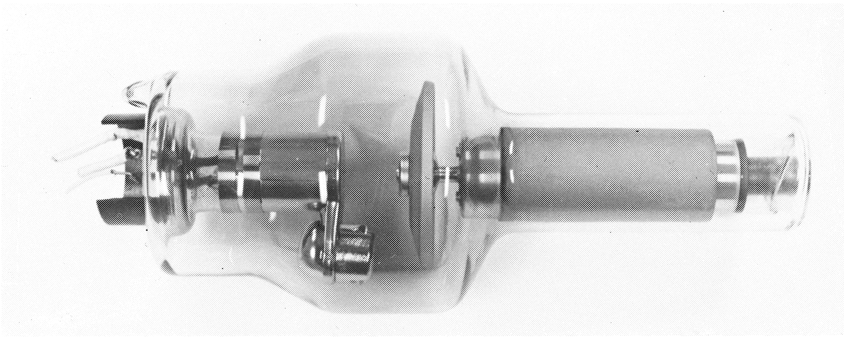

Figure 1-4. Photograph of a modern x-ray tube with the cathode visible to the lower left, the rotating anode disc in the middle, and the rotor which rotates the anode disc on the right half.

With the enhanced electron emission of a hot cathode, the stationary anode plate could be melted from the intense bombardment of electrons. To prevent this destruction of the anode surface, a better way of dissipating the heat had to be devised. In 1936, the *rotating anode tube* was developed (Fig. 1-4).

The rotating anode is shaped like a disc and composed of a metal with good heat-conducting and electron-conducting characteristics, usually molybdenum. The front surface of the disc is coated with an alloy of tungsten and rhenium. These two elements are made of "large" atoms with many orbital electrons, and are very effective at stopping the electron beam emitted from the cathode. With their high melting points, tungsten and rhenium are ideal metals for the "target" surface of the anode.

The anode disc is connected to a rotor shank (Fig. 1-4) which is actually part of a motor. Whenever the "rotor" switch is depressed on an x-ray machine, this shank spins at the same time that the filament is being heated. By spinning the anode disc, the target surface struck by the electron beam is constantly changing. The heat is distributed across a greater surface area and the anode is less likely to melt.

Thus, the three most essential components to the modern x-ray tube can be described as (1) the vacuum tube, (2) the heated cathode, and (3) the rotating anode.

X-Ray Wavelength

Despite the enormous energy in the electron stream, only a small portion is converted into x-rays; the bulk is dissipated as heat at the anode. The greater the force of impact of the electrons on the anode, the shorter is the wavelength of the x-rays produced and the more readily do they penetrate the object being examined. In other words, the higher the voltage, the greater is the speed of the electrons striking the anode. The result is an increase in both the intensity and the penetrating power of the x-rays produced, and a shortening of their wavelength. The wavelengths of x-rays (much shorter than those of visible light) are measured in *Angstrom (A) units.* An angstrom unit is equal to 10^{-6} millimeter, about one-millionth the size of a pinhead. The useful range of wavelengths for medical radiography is approximately *0.1 to 0.5 angstroms.*

INTERACTIONS IN THE ANODE

The wavelengths and the energy levels of x-rays in the beam are determined by the specific interactions of the electrons with the atoms in the anode. Atoms with a high atomic number will have much larger nuclei as well as many more orbital electrons with which the high-speed electrons from the cathode may interact. This means that more interactions will occur, and that those which do occur will result in higher-energy x-rays being produced. This is the reason why tungsten and rhenium (atomic numbers 74 and 75 respectively) are used as target material on the anode.

When a high-speed electron strikes an atom in the anode, it must interact with either the nucleus of the atom or with an orbital electron in one of the electron shells.

BREMSSTRAHLUNG

If the electron passes near the atomic nucleus, the positive attraction of the nucleus will cause it to *brake* or slow down. This deceleration in the speed of the electron represents a loss of kinetic energy, and that energy which is lost is emitted as an x-ray *photon* (Fig. 1-5). The word "photon" is often used to denote a single x-ray. X-rays produced by this interaction are called *bremsstrahlung* (braking radiation) and they account for the vast majority of the total x-ray beam.

High-speed electrons may pass by the nucleus at various distances from it. The closer an electron approaches to the nucleus, the greater will be its deceleration, due to the stronger pull of the nucleus–thus, the more energy will be lost and the higher will be the energy (keV) of the emitted x-ray. Bremsstrahlung, occurring at various distances from the nucleus, produces a wide range of x-ray energies and is thus responsible for the *heterogeneous* or poly-energetic nature of the x-ray beam. Heterogeneity contributes to the differential absorption of

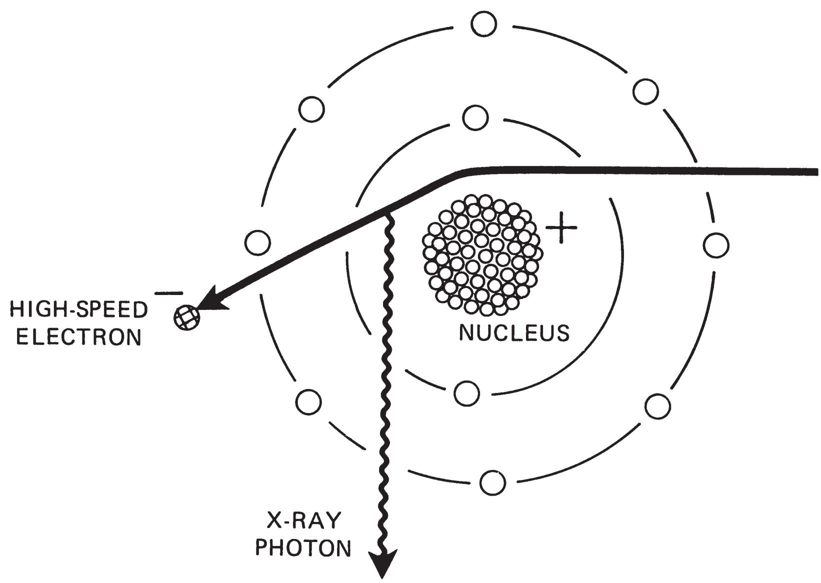

Figure 1-5. The bremsstrahlung interaction in the x-ray tube anode. When a high-speed electron is attracted to a nearby atomic nucleus, it decelerates and changes direction, losing energy. The lost energy is emitted as an x-ray.

x-rays within the patient's body by different tissues. It is just this differential absorption which provides *subject contrast* to the image and makes the radiographic image possible. If all of the x-rays were of the same energy, the image would be extremely poor, essentially a silhouette. Subtle differences between tissues only show up on the radiograph when a variety of x-ray energies result in a wide range of densities (gray shades) in the image.

The distance at which an electron will pass a nucleus is a function of statistical probability. It is more likely that the electron will pass farther away from the nucleus, where greater areas are involved, than that it will pass very near the nucleus. Hence, more x-rays are produced at lower energies than at higher energies. A plot of this relationship between energy levels and the numbers of x-rays produced would look like Figure 1-6. However, because inherent filtration in the x-ray tube (including the glass around the tube) stops the x-rays with the lowest energies, the remaining bremsstrahlung portion of the beam is graphed like Figure 1-7.

Reviewing Figure 1-7, note that there are

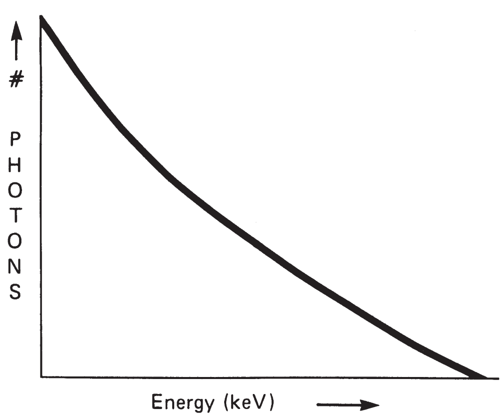

Figure 1-6. Graph of the bremsstrahlung x-ray beam spectrum as it would appear with no filtration. Most x-rays are generated at lower energy (keV) levels. Very few are produced at the highest energies.

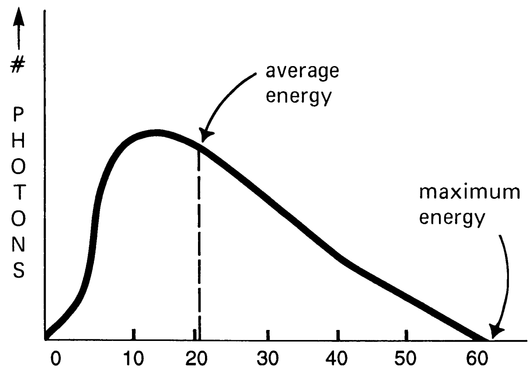

Figure 1-7. Graph of the actual bremsstrahlung x-ray beam spectrum with filtration present and the kVp set to 60. X-rays with the lowest energies are absorbed by the glass, oil, and filters through which they pass. The average energy is about 20 keV, one-third of the kV peak.

very few x-rays emitted from the x-ray tube at very low energies, because of filtration. There are also very few x-rays emitted at high energies: this is because of the statistical distribution of the bremsstrahlung interaction, that is, only a few of the electrons passed very close to the nucleus to produce these high energies. The *total* number of x-rays produced by bremsstrahlung is represented by the *total area* under the beam spectrum curve of the graph. Bremsstrahlung x-rays are produced at many different energies, making the beam *heterogeneous. Note that the average energy of these x-rays is about one-third of the maximum energy.*

CHARACTERISTIC RADIATION

The second possibility for the high-speed electron in the x-ray tube is that, instead of interacting with the nucleus of an atom in the anode, it might interact with one of the atom's orbital electrons. When it passes near an orbital electron, its repulsive negative charge will eject the orbital electron out of its orbit, leaving a vacancy in the electron shell of the atom. The atom, left with a net positive charge, will pull in another