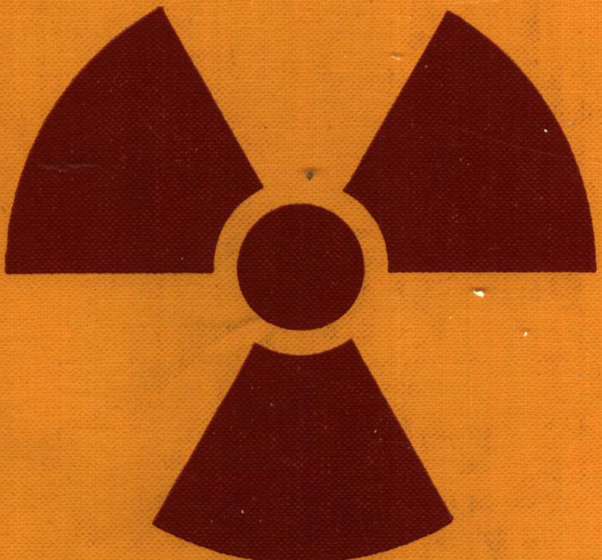
RADIOLOGIC SCIENCE FOR TECHNOLOGISTS



physics,
biology,
and
protection

Stewart C. Bushong

RADIOLOGIC SCIENCE FOR TECHNOLOGISTS

physics, biology, and protection

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Preface

This textbook is the outgrowth of a series of annual lectures incorporated into a radiologic science course for radiologic technologists in the Houston Community College program. These students receive their clinical training in one of several hospitals and assemble together for much of their didactic instruction. This textbook, therefore, is designed to meet the needs of students who may be receiving clinical training in a wide spectrum of environments.

This is not simply a physics textbook, but rather a text in radiologic science. Its purpose is to guide the student technologist through material that need not be as difficult as some portray it and to prepare the student as painlessly as possible for ultimate certification as a Registered Technologist. Throughout the book emphasis is placed on the radiation protection aspects of medical x-ray use. A chapter on radiobiology is included so that the student will have a basic understanding of the principal effects of radiation on humans. The radiobiology section identifies the basis for the establishment of radiation protection guides and in particular the maximum permissible dose. Attention is given to the basic atomic and nuclear physics underlying the production and application of x rays in diagnosis. This information is presented to establish a foundation for ease of understanding of the latter chapters of the book dealing with special aspects of diagnostic radiology.

The fundamentals of radiologic science cannot be totally divorced from mathematics, but for the purposes of this textbook little prior mathematical background is required of the students. Mathematical equations are presented in selected segments, but they are always followed by sample problems, which usually have a direct clinical application. Additional problems presented at the end of each chapter are intended for either homework assignments or review sessions. Answers to numerical problems can be found at the end of the book in Appendix F.

The book contains seventeen chapters of approximately equal content. It is designed for use in a two-semester course requiring two to three hours of lecture per week. Alternatively, the text can be adapted for a course that requires three quarters lasting approximately 12 weeks each with two to three hours of class time per week. The instructor should find that most chapters can be covered within two weeks, depending upon the extent to which additional teaching materials are employed. More time may be desired for the chapters that deal with x-ray production and interaction and with radiographic quality.

It is suggested that this text be supplemented by instructional material available from the various government agencies and commercial organizations serving the radiology field. A list of some of these organizations is included in Appendix A, along with the address for requesting educational material. These companies are a vast source of supplementary educational material, which they readily make available to x-ray technology training programs, usually at no charge. Specific pamphlets are not identified since they change from time to time. Appendixes B, C, and D contain some helpful common physical constants, units, and conversion factors that may occasionally be required for reference. Appendix E is a very brief and topical review of basic physics.

"Physics Is Fun" is the motto of my radiologic science courses and I believe this text will help make it enjoyable for the student technologist. Then we can all join together to *legalize physics*.

No scientific textbook is ever written without considerable assistance and support from large numbers of people. This one is no exception. To all of my former radiologic technology students who tested most of this material, suggesting revisions and additions, I am deeply thankful. It is only because of them that this text was written.

I am grateful to Dr. Robert S. MacIntyre and Robert Phillips of the Methodist Hospital, Houston, Texas, for their suggestions, encouragement, and continued support during the preparation of this text. The preparation of this manuscript was possible only because of the tireless efforts of Sharon Glaze, who so efficiently attended to the many details necessary for the successful production of a textbook. The entire manuscript was typed and retyped by Junille Taylor; her conscientious and efficient approach to each page of the manuscript is gratefully appreciated.

Ross Carnes of the Van Doren Company and Paulette Stone of the Medical Illustrations Department, Baylor College of Medicine, are responsible for most of the graphs and illustrations contained herein. The radiographs used for illustrations were taken by Gloria Bowser, Baylor College of Medicine, and were photographed for illustration by Lucille Thomas. Many photographic figures were supplied by various commercial radiology firms.

The following persons reviewed the manuscript and provided helpful suggestions for improvement and I wish to thank each of them for their time and assistance: Edna B. Stephens of East Texas State University; Marilyn Chitwood of Lamar University; Mary Lou Phillips and Evelyn Frank of Houston Community College; and Eloise Jeter of St. Luke's Episcopal Hospital, Houston, Texas.

I am also grateful for the profound patience and understanding of my family, to whom this book is dedicated.

Stewart C. Bushong

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chapter 1

Concepts of radiation

NATURE OF OUR SURROUNDINGS

In a physical analysis, all things visible and invisible can be classified as matter or energy.

Matter is anything that occupies space and has form or shape. It is the material substance of which physical objects are composed. All matter, basically, is composed of fundamental building blocks called atoms, arranged in various complex ways. These atomic arrangements will be considered at greater length in Chapter 2.

A primary, distinguishing characteristic of matter is **mass**, the quantity of matter contained in any physical object. We generally use the term "weight" when describing the mass of an object, and for our purposes we may consider mass and weight to be the same, although they are not in the strictest sense. Mass is actually described by its energy equivalence, while weight is the force exerted by a body under the influence of gravity.

For example, we know that a 200 lb man will "tip the scales" more easily than a 150 lb man. This occurs because of the mutual attraction, called the force of gravity, between the earth's mass and the masses of the men. On the moon these same men would weigh only about one-fourth what they weigh on earth because the mass of the moon is much less than that of the earth. The masses of the men remain unchanged at 91 kg and 68 kg, respectively. The gram (g) is the scientific unit of mass and is unrelated to gravitational effects. The prefix kilo stands for 1000; a kilogram (kg) is equal to 1000 g.

Although mass, the quantity of matter, remains unchanged regardless of its surroundings, it can be transformed from one size, shape, and form to another. Consider a 1 kg block of ice. Its shape changes as the block of ice melts into a puddle of water. If the puddle is allowed to dry, the water apparently disappears entirely. We know, however, that the ice is transformed from a solid state to a liquid state, and that the liquid water becomes water vapor suspended in the air. If we could gather all the molecules making up the ice, the water, and the water vapor and measure their masses, we would find that each form has the same mass.

Energy is the ability to do work. Like matter, energy can exist in several forms:

Potential energy is the ability to do work by virtue of position. A heavy guillotine blade held 20 feet in the air by a rope and pulley is an example of an object that possesses potential energy (Fig. 1–1). If the rope is cut, the blade will descend and do its ghastly task. Work was required to get the blade to its high position, and because of this position, the blade is said to possess potential energy. Other examples of objects that possess potential energy include a roller coaster on top of a hill and the stretched spring of an open screen door.

Kinetic energy is the energy of motion. It is possessed by all matter in motion—a moving automobile, a turning windmill wheel, a falling guillotine blade. These systems can all do work because of their motion.

Chemical energy is the energy released by way of a chemical reaction. An important example of this type of energy is the energy provided to our bodies through chemical reactions involving the food we eat. At the molecular level this area of science is called biochemistry. The energy released when a stick of dynamite explodes is a more dramatic example of chemical energy.

Electrical energy represents the work that can be done when an electron or an electronic charge moves through an electric potential. The most familiar form of electrical energy is normal household electricity which involves the movement of electrons through a copper wire under an electric potential of

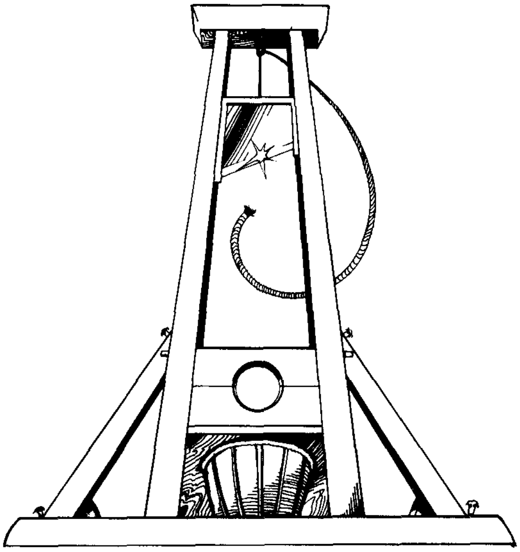

Fig. 1–1. The blade of a guillotine is a dramatic example of both potential and kinetic energy. When the blade has been pulled to its maximum height and locked in place, its position gives it the potential, or ability, to do work when the blade lock is removed. This situation represents potential energy. During the short time that the blade falls, energy is released in the form of kinetic energy.

about 110 volts. All electric apparatus, such as motors, heater, and blowers, function through the use of electrical energy.

Thermal (heat) energy is the energy of motion at the atomic or molecular level and in this regard may be viewed as the kinetic energy of atoms. Thermal energy is measured by temperature. The faster the atoms and molecules of a substance are moving, the more heat energy the substance contains, and the higher its temperature.

Nuclear energy is the energy contained in the nucleus of an atom. We control the release and use of this type of energy in nuclear electric-power-generating plants. An example of the uncontrolled release of nuclear energy is the atomic bomb.

Electromagnetic energy, perhaps the least familiar of these forms, is the most important for our purposes because it is the type of energy in an x ray. For the time being electromagnetic energy will be described as an electric and magnetic (electromagnetic) disturbance traveling through space at the speed of light. In addition to x rays, electromagnetic energy includes radio waves, microwaves, and visible light.

Just as matter can be transformed from one size, shape, and form to another, so energy can be transformed from one type to another. In radiology, for example, electrical energy in the x-ray machine is used to produce electromagnetic energy (the x ray), which then is converted to chemical energy in the radiographic film.

Reconsider now the statement that all things can be classified as matter or energy. Look around you and think of absolutely anything, and you should be convinced of this statement. You should be able to classify anything as matter, energy, or both. Frequently matter and energy exist side by side. A moving automobile has mass and kinetic energy. Boiling water has mass and thermal energy. The leaning tower of Pisa has mass and potential energy.

Perhaps the strangest property associated with matter and energy is their interchangeability of form, a characteristic first predicted by Albert Einstein in his famous theory of relativity. Einstein's **mass-energy equivalence** equation is a cornerstone of that theory:

$$E = mc^2 \tag{1-1}$$

where E is energy; m, mass; and c, the speed of light.

This mass-energy equivalence is the basis for the atomic bomb, nuclear power plants, and nuclear medicine. As we shall see later, it also has some relevance to radiology.

Energy emitted and transferred through matter is called **radiation.** When a piano string vibrates, it is said to radiate sound; the sound is a form of radiation. Ripples, or waves, radiate from the point where a pebble is dropped into a still pond. Visible light, a form of electromagnetic energy, is radiated by the sun and often is called **electromagnetic radiation.** In fact, electromagnetic energy usually is referred to as electromagnetic radiation or simply, radiation.

Matter that intercepts radiation and absorbs part or all of it is said to be **exposed** or **irradiated.** When one spends a day at the beach, one is exposed to ultraviolet light and that exposure may result in a sunburn. During a radiographic

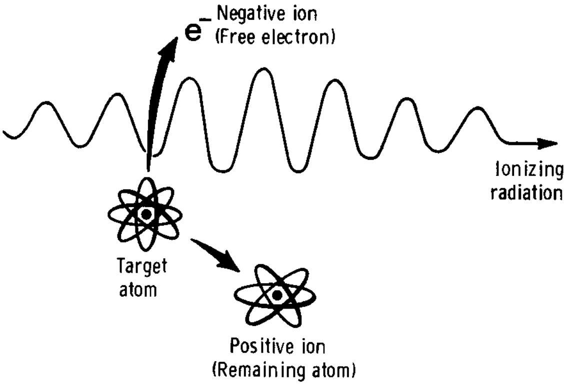

Fig. 1–2. Ionization is the process whereby an electron is removed from a target atom. Ionizing radiation interacts with the orbital electrons of the target atom, ejecting one from the atom. The ejected electron and the resulting positively charged atom are called an ion pair.

examination, the patient is exposed to x rays, or as some would say, the patient is irradiated.

Ionizing radiation is a special type of radiation that includes x rays. Ionizing radiation is any kind of radiation capable of removing an orbital electron from an atom with which it interacts. Fig. 1–2 depicts this type of interaction between radiation and matter, called **ionization.** Ionization occurs when incident ionizing radiation, upon passing through matter, passes close enough to an orbital electron of a target atom to transfer enough energy to the electron to remove it from the atom. The ionizing radiation may interact with and ionize additional atoms. The orbital electron and the atom from which it was separated are called an **ion pair**; the electron is a negative ion, and the remaining atom is a positive ion.

Thus, any type of energy or matter-energy combination capable of ionizing matter is known as ionizing radiation. X rays and gamma rays are the only electromagnetic radiation with sufficient energy to ionize matter. Some fast moving particles (particles with high kinetic energy) are also capable of ionization. Examples of particle-type ionizing radiation are alpha and beta particles and some types of cosmic radiation. Although alpha, beta, and cosmic radiations are sometimes called rays, such designation is a misnomer, for they are particles.

SOURCES OF IONIZING RADIATION

Many types of radiation are harmless, but ionizing radiation can severely injure humans. We are exposed to many sources of ionizing radiation (Table 1–1). The most intense source is **natural environmental radiation,** which results in an annual dose of approximately 100 mrads. A mrad (millirad) is $^1/_{1000}$ of a **rad.** The rad is the unit of radiation absorbed dose; it is used to express the quantity of radiation absorbed by man. The approximate annual dose resulting from medical applications of ionizing radiation is 73 mrads. Unlike the natural radiation dose, this level takes into account those persons not receiving an x-ray exam and those receiving several within the period of a year. The medical radiation exposure for some segments of our population will be zero, but for others, such as fetuses carried by women undergoing x-ray pelvimetry, it may

Table 1–1. Estimated average annual whole-body radiation doses (mrad) in the United States from natural and man-made sources

Radiation source	Annual dose	
Natural		
Cosmic rays	44	
External terrestrial, principally from ^{40}K, ^{226,228}Ra, ^{220,222}Rn, ^{14}C	40	
Internal terrestrial, principally from ^{238}U and ^{232}Th series and ^{40}K	18	
Subtotal		102
Man-made		
Fallout	1	
Diagnostic x rays	72	
Radiopharmaceuticals	1	
Miscellaneous	3	
Subtotal		77
Total		179

be quite high. Although this average level is comparable to natural radiation levels, it is actually a rather small amount of radiation. One could question, therefore, why it is necessary to be concerned with radiation control and radiation safety in radiology.

Remember, however, that man has existed on this planet for approximately 50,000 years in the presence of this natural background radiation level. Man's evolution and the development of his environment have undoubtedly been influenced by this natural radiation. Some geneticists contend that evolution is influenced primarily by ionizing radiation. If this is so, then we must indeed be concerned with control of unnecessary radiation exposure because over the last 70 years, with the increasing medical applications of radiation, the average annual exposure of our population to radiation has nearly doubled. It is necessary to institute proper radiation-control measures now, for later it may be too late to do so.

Medically employed x rays constitute the largest source of man-made ionizing radiation. The benefits derived from the application of x rays in medicine are indisputable; however, such applications must be made with prudence and with regard to reducing unnecessary exposure to patients and personnel. This responsibility falls primarily on the x-ray technologist, since the technologist usually controls the operation of the x-ray machine during radiologic examination.

DISCOVERY OF X RAYS

X rays were not developed; they were discovered, quite by accident. During the 1870's and 1880's, many university physics laboratories were involved in the investigation of the conduction of cathode rays, or electrons, through a large, partially evacuated glass tube known as a Crookes tube. Sir William Crookes was an Englishman from a rather humble background who was a self-taught genius. The tube that bears his name was the forerunner of modern fluorescent lamps and neon-sign type lamps. Fig. 1–3 is a rendering of the type of Crookes tube with which Roentgen was experimenting when he discovered x rays. There were many different types of Crookes tubes; a majority of them were capable of producing x rays.

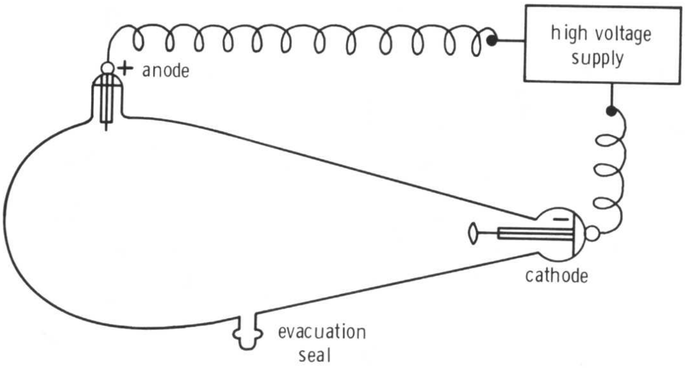

Fig. 1–3. Schematic representation of type of Crookes tube Roentgen was using when he discovered x rays. Cathode rays (electrons) leaving the cathode are attracted to the anode by the high voltage. Many of the cathode rays travel directly to the opposite end of the tube, however, and there x rays and fluorescent light are produced.

Fig. 1–4. The hand shown in this x ray is Mrs. Roentgen's. This was the first indication of the possible future medical applications of x rays and was made within a few days of their discovery. (Courtesy Deutsches Roentgen-Museum.)

On November 8, 1895, Roentgen was working in his laboratory at Würzburg University in Germany. He had darkened his laboratory and completely enclosed his Crookes tube with black photographic paper so that he could better visualize the effects of the cathode rays in the tube. A plate coated with the barium platinocyanide, a fluorescent material, happened to be lying on a bench top several feet from the Crookes tube. No visible light escaped from the Crookes tube because of the black paper enclosing it, but Roentgen noted that the barium platinocyanide fluoresced regardless of its distance from the Crookes tube. The intensity of fluorescence increased as the plate was brought closer to the tube; consequently, there was little doubt about the origin of the stimulus for fluorescence. Roentgen's immediate approach to investigating this "X-light," as he called it, was to interpose various materials—wood, aluminum, his hand—between the Crookes tube and the fluorescing plate. He feverishly continued these investigations for several weeks.

There are several amazing features about the discovery of x rays that cause it to rank high in the events of human history. First, the discovery was quite by accident. Second, probably no fewer than a dozen contemporaries of Roentgen had previously observed x-radiation, but none of these other physicists had recognized its significance nor investigated it. Third, Roentgen followed his discov-

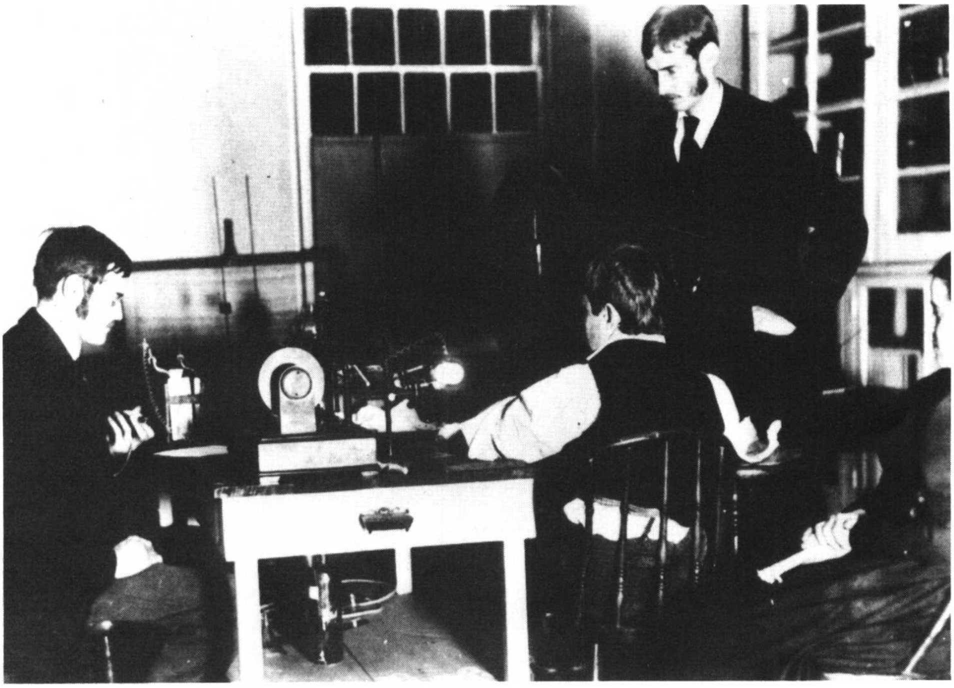

Fig. 1–5. This photograph records the first medical x ray in the United States. A young patient, Eddie McCarthy of Hanover, New Hampshire, broke his wrist while skating on the Connecticut River and submitted to having it photographed by the "X-light." With him are (left to right) Professor E. B. Frost, Dartmouth College; his brother, Dr. G. D. Frost, Medical Director, Mary Hitchcock Hospital; and Mrs. G. D. Frost, the hospital's first head nurse. The apparatus was assembled by Professor F. G. Austin in his physics laboratory in Reed Hall, Dartmouth College, February 3, 1896. (Courtesy Mary Hitchcock Hospital.)

ery with such scientific vigor that within little more than a month he had ascribed to x-radiation nearly all the properties recognized today. His initial investigation was extremely thorough, and he was able to report his experimental results to the scientific community before the end of 1895. For this work he received in 1901 the first Nobel prize in physics. Finally, Roentgen immediately recognized the value of his discovery to medicine. He produced and published the first medical x ray, an x ray of his wife's hand (Fig. 1–4).

Fig. 1–5 is a reproduction of a photograph of what is reported to be the first x-ray examination in the United States, conducted in early February, 1896, in the physics laboratory at Dartmouth College.

DEVELOPMENT OF MODERN RADIOLOGY

There are two general types of x-ray procedures: **radiographic** examinations and **fluoroscopic** examinations. Radiographic examinations employ x-ray film and usually an x-ray tube mounted from the ceiling on a track that allows the tube to be moved in any direction. Such examinations provide the radiologist with fixed photographic images. Fluoroscopic procedures are usually conducted with an x-ray tube located under the examining table. The radiologist is provided with moving, or dynamic, images portrayed on a fluoroscopic screen or television monitor. There are many variations of these two basic types of examinations, but in general the x-ray equipment is similar. Although the x-ray equipment used today is quite sophisticated, there have not been many basic changes since Roentgen's time.

To produce a satisfactory x ray, one must supply the x-ray tube with a high voltage and a sufficient electric current. X-ray voltages are measured in kilovolts peak (**kVp**). One kilovolt (**kV**) is equal to 1000 volts (**V**) of electric potential. X-ray currents are measured in milliamperes (**mA**), where the ampere (**A**) is a measure of electric current. Normal household current is a few amperes. The prefix **kilo** stands for 1000; the prefix **milli**, for $^1/_{1000}$, or 0.001. Today voltage and current are supplied to an x-ray tube through rather complicated electric circuits, but in Roentgen's time simple static generators were all that were available. These units could only provide currents of a few milliamperes and voltages to perhaps 50 kVp.

Radiographic procedures employing equipment with these limitations of electric current and potential often required exposure times of 30 or more minutes for a satisfactory examination. One development that helped reduce this exposure time was the use of a fluorescent **intensifying screen** in conjunction with the glass photographic plates. Michael Pupin is said to have demonstrated this technique in 1896, but only several years later did it receive adequate recognition and use. Radiographs during Roentgen's time were made by exposing a glass plate with a layer of photographic emulsion coated on one side. Charles L. Leonard found that by exposing two glass x-ray plates with the emulsion surfaces together, exposure time was reduced and the image was considerably enhanced. This demonstration of double emulsion radiography was conducted in 1904, but double emulsion film did not become commercially available until 1918.

During World War I radiologists began to make use of film rather than glass plates. Much of the high-quality glass used in radiography came from Belgium and other European countries. This supply was interrupted during World War I.

The demands of the army for increased radiologic services made a substitute for the glass plate necessary. The substitute base for the photographic emulsion was **cellulose nitrate.** It quickly became apparent that the substitute was better than the original.

The **fluoroscope** was developed in 1898 by the American inventor Thomas A. Edison. Edison's original fluorescent material was barium platinocyanide, a widely used laboratory material. He investigated the fluorescent properties of over 1800 other materials, including zinc cadmium sulfide and calcium tungstate, the primary materials in use today. There is no telling what further inventions Edison might have developed had he continued his x-ray research, but he abandoned it when his assistant and long-time friend, Clarence Dally, suffered a severe x-ray burn that eventually required amputation of both arms. Dally died in 1904 and is counted as the first x-ray fatality in the United States.

Two devices designed to reduce the exposure of patients to x rays and thereby minimize the possibility of x-ray burn were introduced before the turn of the century by a Boston dentist, Dr. William Rollins. Dr. Rollins used x rays to visualize teeth and found that restricting the x-ray beam by a diaphragm and inserting a leather or aluminum filter improved the diagnostic quality of his radiographs. This first application of **collimation** and **filtration** was followed very slowly by general adoption of these techniques. It was later recognized that these devices reduce the hazard associated with the application of x rays.

Two developments that occurred at approximately the same time transformed the use of x rays from a novelty in the hands of a few physicians and physicists into a valuable, large-scale medical specialty. In 1907 H. C. Snook introduced a substitute high-voltage power supply, an interrupterless transformer, for the static machine and induction coils then in use. Although the Snook transformer was far superior to these other devices, its capability greatly exceeded the capacity of the Crookes tube. It was not until the introduction of the Coolidge tube that the Snook transformer was widely adopted.

The type of Crookes tube that Roentgen used in 1895 had existed for a number of years. Although some modifications were made by x-ray workers, it remained essentially unchanged into the second decade of the twentieth century. After considerable clinical testing, William D. Coolidge unveiled his hot-cathode x-ray tube to the medical community in 1913. It was immediately recognized as far superior to the Crookes tube. X-ray tubes in use today are refinements of the **Coolidge tube.**

The era of modern radiography is dated from the matching of the Coolidge tube with the Snook transformer; only then did acceptable levels of kVp and mA become possible. Few developments since that time have had major influence on diagnostic radiology. In the middle 1920's the Potter-Bucky grid, which greatly increased image sharpness, was developed. In 1946, the light amplifier tube was demonstrated at the Bell Telephone Laboratories. This device was adapted for fluoroscopy in the early 1950's. Today, image-intensified fluoroscopy is commonplace. Table 1–2 chronologically summarizes some of the more important developments.

REPORTS OF RADIATION INJURY

The first x-ray fatality in the U.S. occurred in 1904. Unfortunately, radiation injuries occurred fairly frequently in the early years. These injuries usually

Table 1–2. Some important dates in the development of modern radiology

Date	Event
1895	Roentgen discovers x rays.
1896	First medical applications of x rays in diagnosis and therapy.
1900	The Roentgen Society of the U. S., the first American radiology organization, is founded. In 1902 it became the American Roentgen Ray Society.
1901	Roentgen receives the first Nobel Prize in physics.
1905	Einstein introduces his theory of relativity and the famous equation $E = mc^2$.
1907	Introduction of the Snook interrupterless transformer.
1913	Bohr theorizes his model of the atom featuring a nucleus and planetary electrons.
1913	The Coolidge hot-filament x-ray tube is developed.
1916–1918	Cellulose nitrate film base is widely adopted.
1919–1921	Several investigators demonstrate the use of soluble iodine compounds as contrast media.
1920	The American Society of Radiologic Technology is founded.
1921	The Potter-Bucky grid is introduced.
1922	Compton describes the scattering of x rays.
1925	The First International Congress of Radiology is convened in London.
1929	Forssmann demonstrates cardiac catheterization . . . on himself!
1930	Tomographic devices are shown by several independent investigators.
1937	The International Committee on X-ray and Radium Protection officially defines the roentgen as the unit of radiation intensity.
1942	Morgan exhibits an electronic phototiming device.
1948	Coltman develops the first fluoroscopic image intensifier.
1953	The rad is officially adopted as the unit of absorbed dose.
1956	Xeroradiography is demonstrated.

took the form of skin damage (sometimes severe), loss of hair, and anemia. Physicians and, more commonly, patients were afflicted, primarily because of the long exposure time required for an acceptable radiograph and the low energy of radiation that was available at the time.

By about 1910 these acute injuries began to be controlled as the biological effects of x-radiation were scientifically investigated and reported. With the introduction of the Coolidge tube and the Snook transformer, the frequency of reports of injuries to superficial tissues decreased. Years later it was discovered that radiologists were developing blood disorders such as aplastic anemia and leukemia at a much higher rate than other physicians. Because of these observations, protective devices and protective apparel, such as lead gloves and lead aprons, were developed for use by radiologists. X-ray workers were routinely observed for any effects of their occupational exposure and were routinely provided with personnel radiation-monitoring devices. This attention to radiation safety in radiology has resulted in the disappearance of reports of any type of radiation effect on x-ray workers. Radiology is now considered a completely safe occupation.

Today the emphasis on radiation control in diagnostic radiology has shifted back to protection of the patient. Current studies suggest that even the low doses of x-radiation employed in routine diagnostic procedures result in a small but significant incidence of latent harmful effects. It is also well established that the human fetus is highly sensitive to x-radiation early in pregnancy. This sensitivity decreases as the age of the fetus increases. There is growing concern