Chapter 16

IONIZING RADIATION

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INTRODUCTION

Wilhelm Roentgen could not have envisioned the impact that his 1895 discovery of X rays would have. That discovery, Marie Curie's discovery of radium, the discovery and development of atomic fission and fusion, and other discoveries described in this chapter led to military and civilian applications of ionizing radiation (Exhibit 16-1). With these uses came the need for occupational health programs to control exposures.

Most military occupational exposures are minimal due to the safety procedures and engineering controls in place and the nature of the sources of the radiation. However, many sources do have the potential to deliver significant exposures and a large number of military and civilian employees are routinely exposed to low-level radiation. Thus, occupational exposure to ionizing radiation in the military demands recognition and attention, through strict adherence to all aspects of safety requirements. Clearly, exposures from a nuclear detonation pose the greatest ionizing radiation hazard to the soldier. However, because these effects are described in *Medical Consequences of Nuclear Warfare,* Part I, Volume 2 in the Textbook of Military Medicine series, they will not be discussed in detail here.

PROPERTIES OF IONIZING RADIATION

Radiation is categorized according to its origins and its properties. For radiation to be considered *ionizing*, it must have sufficient energy to strip electrons from the outer shell of neutral atoms or molecules. This stripping of electrons liberates free electrons and positive ions, which can cause a biological effect. Ionizing radiation can be characterized as either *particulate* or *electromagnetic* (EM).

Particulate Radiation

Particulate radiation is composed of alpha particles, beta particles, and neutrons. Alpha particles, which are equivalent to helium nuclei, are heavy and have a double positive charge. They are emitted from nuclei of heavy radioisotopes and can travel up to 10 cm through air, and up to 0.1 mm through tissue. Because alpha particles are easy to shield against and cannot penetrate the outer layers of skin, exposure from external sources causes little biological damage. However, alpha particles that are deposited internally can cause considerable biological damage.

Beta particles are equivalent to electrons: they weigh far less than alpha particles and have a single negative charge (or, in the case of positrons, a single positive charge). They are emitted from the nuclei of radioisotopes, and can travel up to 10 m through air and up to 8 mm through tissue. Beta particles can cause biological damage if they remain on exposed skin and if they are deposited internally. The best shields against beta particles are plastics, or metals with low atomic numbers.

Neutrons have no charge. They are produced in nuclear reactions or are emitted by certain heavy, artificial radioisotopes and can travel up to 3,000 m through air. Because neutrons can penetrate tissue easily, exposure to external sources can cause biological damage to deeper tissues. The best substances to shield against neutrons are hydrogenous materials such as water, paraffin, and concrete.

Electromagnetic Radiation

Gamma rays and X rays are types of EM ionizing radiation, but they differ in their origins: the nuclei of most radioisotopes emit gamma rays, whereas the orbital shells of virtually all radioisotopes emit X rays. X rays can also be machine produced. Both gamma and X rays can travel up to 3,000 m through air. Typically, gamma and X rays can penetrate tissue easily, but their range through tissue depends on their energy. Gamma and X rays can cause biological damage from external exposure or internal deposition of emitting radioisotopes. The best shields against these radioisotopes are heavy, dense metals such as lead, steel, and depleted uranium.

DISCOVERY AND APPLICATIONS OF X RAYS

Roentgen's discovery of X rays was a culmination of the research of scientists such as Wilhelm Hittorf, William Crookes, Heinrich Hertz, and Philipp Lenard. Roentgen's discovery was sparked on 8 November 1895 when he saw the barium platino-cyanide screen fluorescing on a table some distance from the cathode ray tube with which he was working.[1,2] This occurrence stimulated his interest, and he worked feverishly over the next few days to comprehend and document the observed phenomenon. By turning the

EXHIBIT 16-1

KEY DEVELOPMENTS IN ATOMIC FISSION

Year	Development
1897	J. J. Thomson identified the electron. Ernest Rutherford identified alpha and beta rays emanating from uranium and later correctly identified them as helium nuclei and electrons, respectively.
1898	Villard recognized gamma rays and observed their similarities to the roentgen ray.
1905	Albert Einstein proposed his famous equation, $E=mc^2$, stating the relationship of energy to mass.
1910	F. Soddy suggested an explanation for atoms with slightly different weights, but identical chemical properties, and called them *isotopes*.
1911	Rutherford proposed the atomic theory with a distribution of mass and charge that is essentially the one that we accept today.
1913	Niels Bohr suggested an atomic structure involving a central nucleus with orbital electrons in layers around it.
1919	Rutherford bombarded nitrogen atoms with alpha particles and observed the production of hydrogen and oxygen. This milestone was the first controlled experiment in which one element was artificially transformed into another.
1931	Ernest Lawrence invented the cyclotron, a chamber in which it is possible to accelerate particles to immense speeds for use as projectiles.
1932	James Chadwick of Cambridge University recognized the neutron.
1934	Enrico Fermi first split an atom of uranium by neutron bombardment. Lise Meitner, a German physicist, explained the process and termed it *fission*; it was quickly realized that large amounts of energy were released in this process.
1939	Fermi approached the U.S. Navy Department about the prospects for an atomic weapon, and expressed his fear that Germany would produce and use such a weapon. The importance and power of atomic fission was clear to many scientists. Some also foresaw and were frightened by the implications of its use as a weapon. A letter, drafted by Leo Szilard and signed by Einstein, was forwarded to President Franklin D. Roosevelt, and Roosevelt started the process that would result in the development of the atomic bomb.
1940	D. W. Kerst constructed a betatron, in which electrons were accelerated to energies of 20 million electron volts (MeV), and later to 300 MeV, by magnetic induction.
1941	The Manhattan Project began, consolidating the fragmented efforts at atomic weapons development. Brigadier General Leslie Groves (a civil engineer) was appointed as the project's director, and J. Robert Oppenheimer (a physics professor at the University of California, Berkeley) was selected as the scientific director.
1942	On 2 December Fermi successfully initiated the first self-sustaining nuclear chain reaction in a uranium pile at the University of Chicago.
1945	On 16 July the first atomic bomb (a plutonium-fueled implosion device) was detonated in New Mexico. On 6 August an atomic bomb (a gun-assembly, uranium-fueled device code-named Little Boy) was dropped on Hiroshima, Japan. On 11 August a second atomic bomb (a plutonium-fueled implosion device code-named Fat Man) was dropped on Nagasaki, Japan.

Source: Dewing SB. *Modern Radiology in Historical Perspective*. Springfield, Ill: Charles C Thomas; 1962.

current on and off, Roentgen observed that the fluorescence was related to discharge within the tube. Roentgen concluded that he had found a new phenomenon, which emanated from the tube.

In testing this phenomenon's ability to penetrate various materials, Roentgen was startled to see the image of the bones of his own hand on a photographic plate. After this discovery, Roentgen observed and recorded the differential development of photographic plates using materials of various densities. He even produced an image of his wife's hand with a 15-minute exposure.[2] To document the findings of these experiments, Roentgen wrote a paper describing the rays' means of production and their important properties. In December 1895, he submitted it, entitled *A New Kind of Rays,* to the Wurzburg Physical-Medical Society. On 6 January 1896 Roentgen's discovery was announced to the world, creating an immediate stir in the scientific community.[2] Others apparently had observed the photographic effects of X rays but had failed to recognize the significance of the phenomenon.

Medical Uses

The medical community in general, and the U.S. Army in particular, were quick to embrace the new technology that followed the discovery of X rays. Within a year, several examples of the use of X rays for diagnoses were available.

The army attempted to experiment with X rays within 3 months of Roentgen's discovery when the curator of the Army Medical Museum, Major Walter Reed, applied to The U.S. Army Surgeon General for authority to obtain a roentgen-ray apparatus. Although Surgeon General George Sternberg initially denied Reed's request, there is evidence that the museum possessed a roentgen-ray apparatus by June 1896. Admission records of Garfield Hospital in Washington, D.C., show that a 17-year-old female patient was admitted with a penetrating gunshot wound to the hip, which had been inflicted when her brother accidentally discharged a .22-caliber weapon. Dr. Joseph S. Wall accompanied the patient in a horse-drawn ambulance to the Army Medical Museum, where Dr. William Gray could assist in identifying the bullet's exact location with a Roentgen tube (Figure 16-1). The patient was exposed to X rays for 1 hour before a roentgenogram showing the bullet's location could be obtained. After this examination, the patient was returned to Garfield Hospital, where the bullet was successfully removed.[3]

Although the army began experimenting with X rays soon after their discovery, other countries had actually employed them in treating military casualties

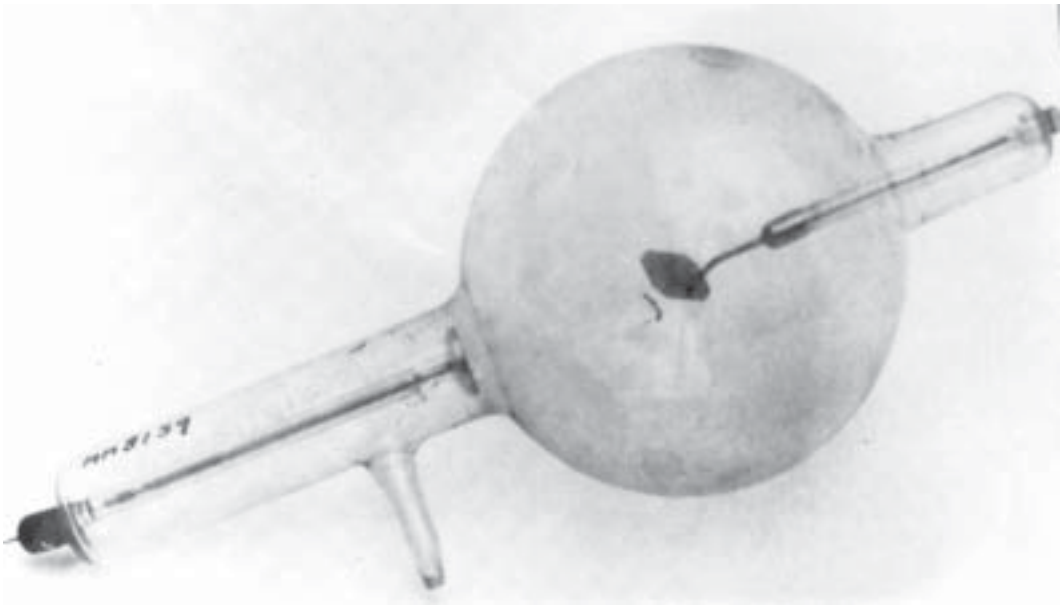

Fig. 16-1. A roentgen-ray tube similar to the one possessed by the U.S. Army Medical Museum that was used to locate a bullet lodged in a patient in 1896. Crude tubes of this type were the first X-ray machines used by the U.S. Army. Source: Henry RS. *The Armed Forces Institute of Pathology, Its First Century 1862–1962*. Washington, DC: Office of The Surgeon General, DA, 1964.

in early 1896. Lieutenant Colonel Giuseppe Avaro, an Italian physician, used an apparatus to examine wounded soldiers near the end of Italy's campaign in Ethiopia. At approximately this same time, British military physicians used diagnostic X rays during the Nile Expedition.[1] The British were the first to employ X rays in battlefield treatment facilities, during the Tirah Campaign (on the Indian-Afghanistan border) in October 1897.[4] Surgeon Major W. C. Beevor operated the X-ray apparatus and used the roentgenograms to locate bullets and bullet fragments. He advocated that X-ray apparatuses be easily accessible to examine soldiers wounded in the line of duty.[4]

The U.S. Army Surgeon General had supplied roentgen-ray apparatuses to the larger post hospitals soon after Roentgen's discovery, but the outbreak of war with Spain in 1898 prompted an increase in supply. The most important general hospitals and three hospital ships (*Relief*, *Missouri*, and *Bay State*) received systems similar to the original roentgen-ray apparatus. Seventeen apparatuses were available during the Spanish-American War.[5] Their availability and utility proved invaluable, according to Captain William C. Borden, who was in charge of their use. He claimed that the roentgen-ray apparatus made exploring bullet wounds—with probes or by other means—unnecessary, thus obviating the dangers of infection and iatrogenic traumas (Figure 16-2). Borden also extolled the benefits of roentgen rays in the diagnosis and treatment of fractures.[5] Although the quality of the

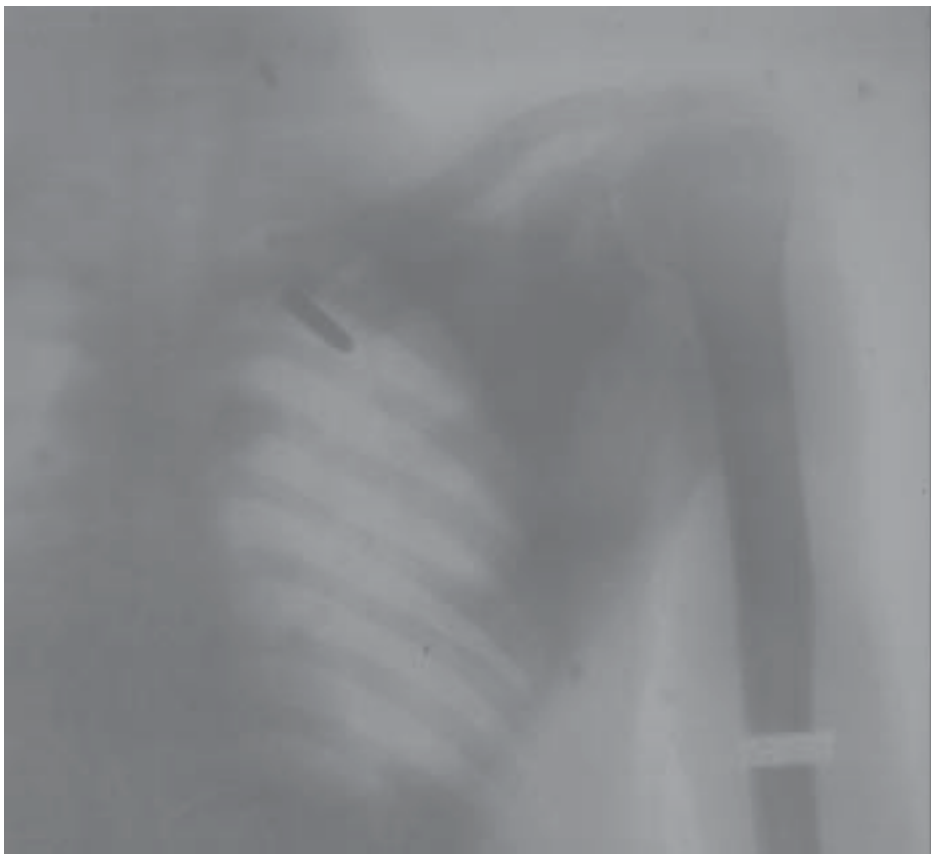

Fig. 16-2. Captain William C. Borden, M.D., wrote in his 1900 history of the use of roentgenography in the Spanish-American War: " [This soldier was] wounded at Malate, Philippine Islands, July 31, 1898. . . . He was transferred to the division hospital, Presidio, San Francisco, Cal., October 22, 1898." This radiograph, *viewed from the patient's back*, shows the Mauser bullet, which had passed through the spine, lying 2 in. to the right of the spine over the third intercostal space. First published in Dr. Borden's 1900 book, the chest film "demonstrated that the [patient's] symptoms were due to the original traumatism and not to the presence of the bullet." Reprinted from Borden WC. *The Use of the Röntgen Ray by the Medical Department of the United States Army in the War with Spain* (*1898*). Washington, DC: Office of The Surgeon General (George M. Sternberg, US Army), DA; 1900: 40.

early roentgenograms may leave much to be desired by today's standards, they were, in fact, remarkable for their clarity and utility (Figure 16-3).

By the time the United States entered World War I, radiology was becoming established as a medical discipline. However, the use of X rays was limited because the equipment and supplies were unsuited to mass use and too few radiologists were available. In fact, in April 1917 the U.S. Army had only one radiologist: Colonel Philip Huntington.[4]

While no real distinction existed between military and civilian medical applications of roentgenology, the military's differing circumstances required specialized apparatus. For example, portable and bedside X-ray units, not used in the civilian sector, were tailored to military needs (Figure 16-4). The army also recognized that X-ray capabilities were necessary in mobile hospitals and surgical units, and therefore modified a standard army ambulance to house a field-portable X-ray apparatus and one bedside unit. In May 1918 the first X-ray ambulance was tested and found to be successful.

On 25 November of that same year, the army refined its methods for using X rays and published the *United States Army X-ray Manual* under the direction of the Division of Roentgenology of the Office of The Surgeon General.[6] This manual served as a guide and textbook for military roentgenologists. By the end of World War I, the United States had shipped 150 complete base hospital X-ray units, 250 bedside X-ray units, 264 portable X-ray units, and 55 X-ray–equipped ambulances overseas.[7]

Radiology as a specialty made tremendous strides during the interval between World War I and World War II: equipment was improved, radiologists were formally trained, and radiological technologies were developed and clinically applied. By the onset of World War II, the use of X-ray technology was well

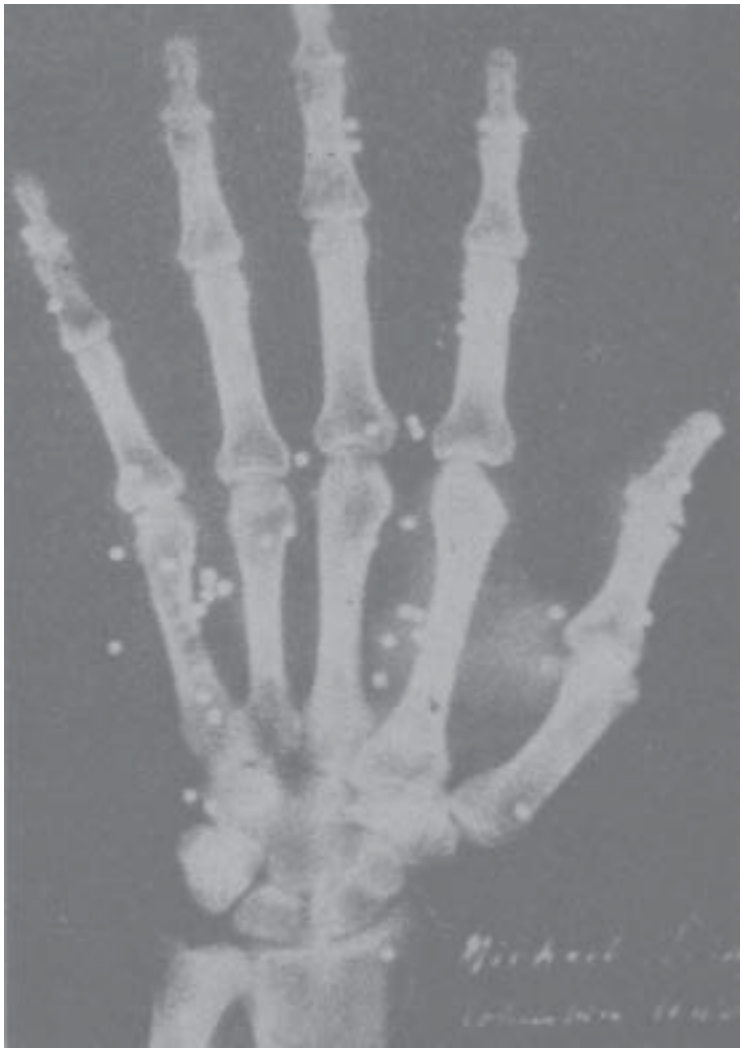

Fig. 16-3. This famous radiograph of the hand of Prescott Hall Butler showing multiple, retained shot was made by Michael I. Pupin in New York City, probably on 14 February 1896. It was "the first roentgen plate to guide a surgical operation in New York...[and] is the best of all early roentgen prints as far as technical quality (and bone detail) is concerned which is quite unusual when one considers the fact that the x rays were produced in the glass of the tube, and were in no way focused." Reprinted from Grigg ERN. *The Trail of the Invisible Light: From X-Strahlen to Radio(bio)logy*. Springfield, Ill: Charles C Thomas; 1965: 312.

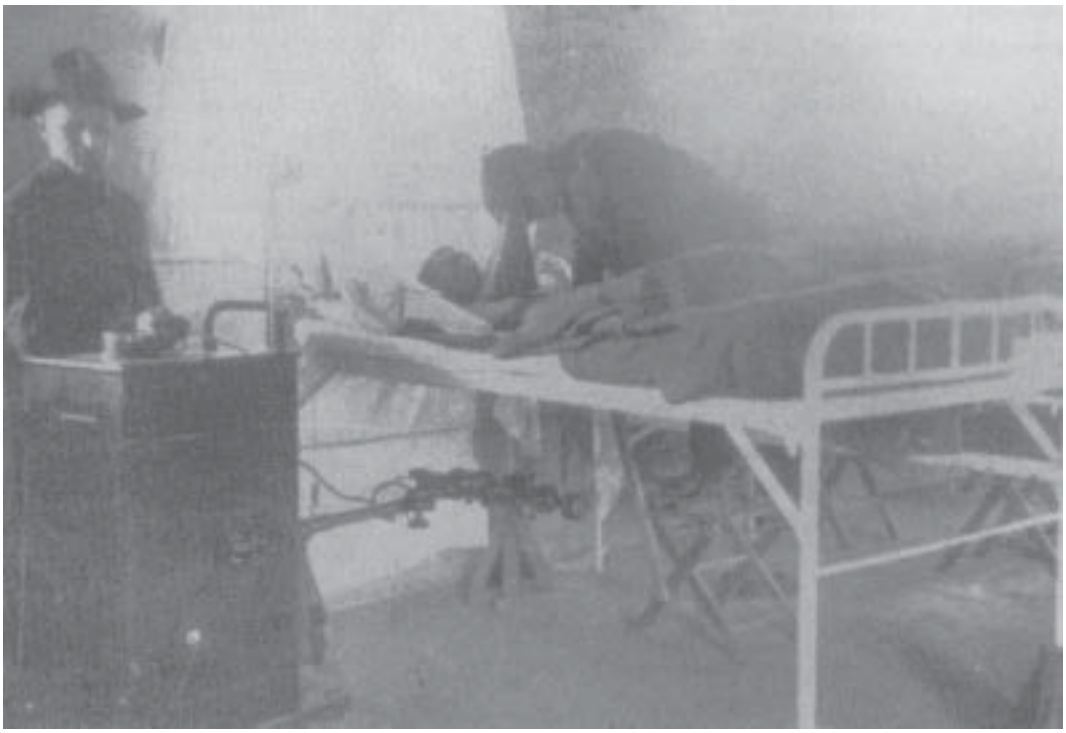

Fig. 16-4. The Waite and Bartlett Army bedside unit, shown at the base hospital in Grand Blottereaux in 1915, was the first stock X-ray equipment that used a Coolidge hot-cathode tube. The examiner looked into a *cryptoscope*, the hand-held fluoroscope. Source: Feldman A. A sketch of the technical history of radiology from 1896 to 1920. *RadioGraphics.* 1989;9(6):1113–1128. Photograph: Courtesy of Arnold Feldman, Methodist Medical Center, Peoria, Ill.

established as a diagnostic and therapeutic tool. Radiology as a recognized medical specialty was an integral part of every hospital, and radiology teams were part of auxiliary surgical groups that performed front-line surgery.

Providing radiological services was not effortless, however. Once basic equipment was supplied, radiologists and technicians had to maintain it, often with great difficulty and improvisation. Battlefield needs sparked further developments in mobile and portable X-ray systems such as the U.S. Army Field X-ray unit, which was widely used both at front- and rear-echelon military medical facilities (Figure 16-5).[8] Despite the advances in radiology and training techniques, radiologists were constantly in short supply during World War II. In an effort to meet radiological needs, training courses were provided for medical officers and technicians at institutions such as the U.S. Army School of Roentgenology.[4]

The importance of radiology during World War II was also reflected in the structure of the U.S. Army Surgeon General's Office. The Radiation Branch, later renamed Radiology, was established on 12 July 1942 under the direction of Major Michael E. DeBakey. This branch, a part of the Surgery Division, later became the Surgical Consultants Division.[4]

Great advances in radiological technology were made beginning in the 1950s, partly resulting from the military uses of radiology during World War II. During the Korean and Vietnam Wars, X rays were used extensively in the diagnosis and treatment of casualties (Figure 16-6).

Also during the 1950s and 1960s, A. M. Cormack, a South African, did the original work on projection imaging that set the stage for computed tomography (CT). However, the evolution of that technology from experimental curiosity to clinical reality was largely due to the efforts of English engineer Godfrey Hounsfield.[9]

CT was introduced into medical practice in the early 1970s. This technology made cross-sectional imaging with X rays possible, which greatly enhanced the physician's ability to see abnormalities in a variety of anatomical structures. Vast technological improvements have been made in CT technology since the Hounsfield scanners were introduced. Within only 4 years, major improvements (four generations) of the CT scanner decreased minimum scanning times from

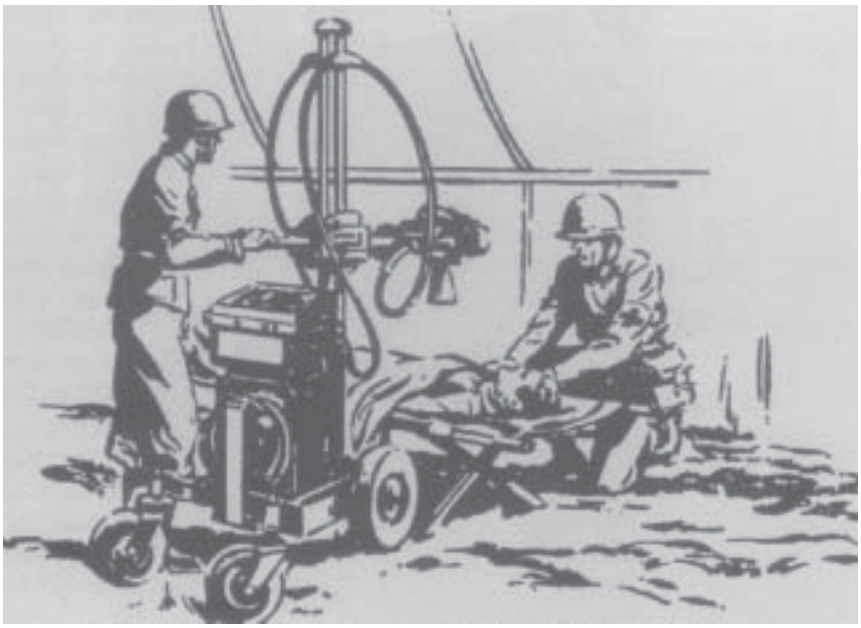

Fig. 16-5. A portable field X-ray unit in action in World War II. The unit shown was developed by the Picker Corporation, which became the sole supplier of the U.S. Army Field X-Ray unit during World War II. Source: Krohmer JS. Radiography and fluoroscopy 1920–1989. *RadioGraphics* 1989;9(6): 1129–1153. Photograph: Courtesy of Jack S Krohmer, PhD, Georgetown, Tex.

Fig. 16-6. The X-ray section of a forward surgical hospital during the Korean War. The advances in X-ray technology and techniques that had been developed since World War II permitted field hospitals to practice quality imaging in their treatment of battlefield casualties. Source: Howard JM, ed. The battle wound: Clinical experiences. In: *Battle Casualties in Korea, Studies of the Surgical Research Team.* Vol 3. Washington, DC: Army Medical Service Graduate School, Walter Reed Army Medical Center; 1955.

5 minutes to 5 seconds; during the next 2 years, the minimum scanning times were reduced to 2 seconds.[9] Advances and refinements continue to achieve enhanced imaging and resolution and to further reduce scan times to milliseconds. Clinical medicine has benefited from cross-sectional imaging, and the field of radiology continues to evolve as medicine advances with the computer era. Current approaches being explored employ radiation sources at wavelengths not now used for imaging.

Parallel to their diagnostic uses, the therapeutic uses of X rays date back to 29 January 1896, when Emil H. Grubbe reported that he, in collaboration with Dr. R. Ludlum in Chicago, had treated a carcinoma of the breast with 18 X-ray treatments.[10] During the next few years, therapeutic X rays were tried on conditions ranging from malignancies to excess facial hair. This experimentation resulted in many disappointing outcomes as well as radiation injuries. However, the number of successes was sufficient to maintain the interest of scientists and physicians in the therapeutic value of X rays, particularly with respect to tumors.

In the early years, the efficacy of therapeutic X rays was limited by the low kilovoltage that the equipment could achieve, which enabled the X-ray beam to penetrate only shallowly.[10] Thus, *brachytherapy* (ie, the application of an encapsulated radioactive source or sources to deliver a radiation dose at a distance not greater than a few centimeters) using radium was more useful than external-beam therapy (teletherapy) until approximately 1921, when higher-energy external-beam systems became available.[10] In 1937, the

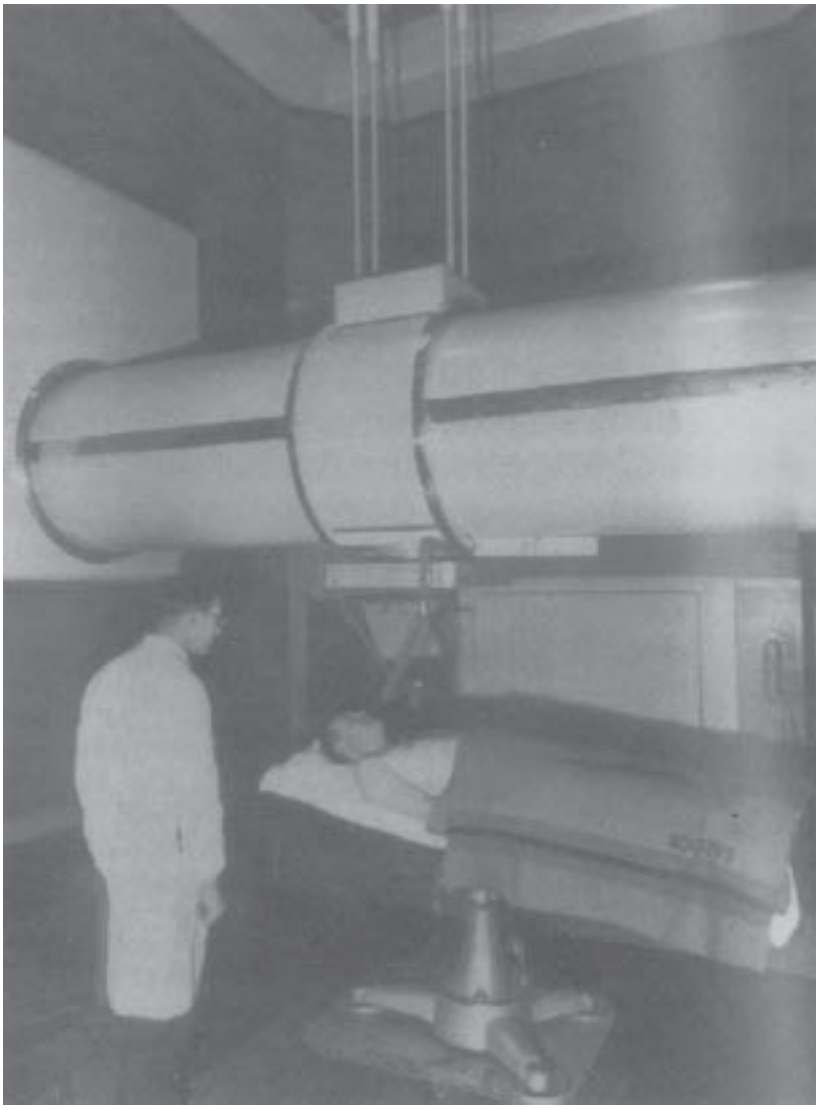

Fig. 16-7. Dr. Ralph Phillips and a patient to be treated using the 1-million-electron-volt (MeV) therapy installation at St. Bar-tholomew's Hospital, London. The unit created high-energy, penetrating X rays that could be used for treating cancers and other tumors. The immediate benefit to the patient of the eradication or reduction of the tumor generally was thought to outweigh the risk of developing future cancers from the high radiation dose delivered by such a therapy device. Source: Laughlin JS. Radiation therapy. *RadioGraphics*. 1989;9(6):1252. Photograph: Reprinted with permission from *Brit J Radiology*. British Institute of Radiology, London, England.

earliest type of supervoltage teletherapy unit (Figure 16-7) was used on patients.[11] This 1-million-electron-volt (MeV) unit was used at St. Bartholomew's Hospital in London, England, under the supervision of Dr. Ralph Phillips and George Innes.

The therapeutic use of X rays progressed when high-energy sources became available. In 1940, Donald W. Kerst of the University of Illinois developed the betatron (Figure 16-8), which functioned as an electron accelerator. This first betatron operated at 2.3 MeV, the second at 20 MeV, and the third at 300 MeV. In 1948, Kerst collaborated with Dr. Henry Quastler at the University of Illinois in the first treatment of a tumor using these high-energy rays. Localized irradiation from the betatron was administered to a graduate student at the university whose brain tumor had been partially excised. The patient eventually succumbed to cancer, but the autopsy revealed no viable neoplastic cells in the irradiated region.[11] The Allis-Chalmers Manufacturing Company developed a commercial version of the betatron in 1948 with improvements for medical use.

The development of the linear accelerator further advanced the therapeutic use of X rays. Before and during World War II, oscillator tubes capable of relatively high-power output at microwave frequencies were developed and applied to radar.[11] At the end of World War II, the technology was refined and applied to the advancement of the linear accelerator, which has become the predominant modality for delivering modern radiation teletherapy treatment.

Industrial Uses

Industrial radiography sprang from Roentgen's mention of the radiograph of a piece of metal in his 1895 paper. Metallurgists seized this concept as a nondestructive method of examining metals. As early as 1896, the war departments of Germany, Austria, and the United States were using X rays to examine cannons. In 1922, a 200-kV, 5-mA industrial X-ray unit was assembled at the U.S. Army Arsenal at Watertown, Massachusetts.[2] During the 1940s, betatrons were also used extensively in industrial radiography. New

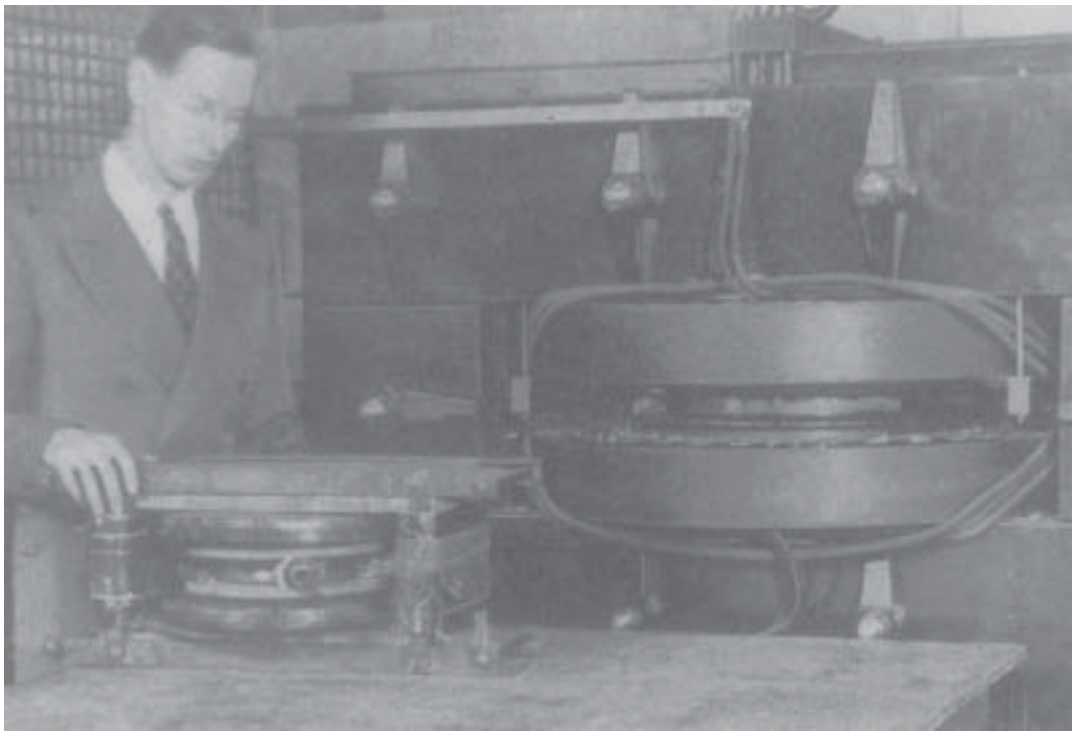

Fig. 16-8. Professor Donald Kerst with two of his betatrons (1940). A betatron is an electron accelerator. These betatrons were compact and able to accelerate electrons to high energies. Electrons that reach sufficiently high energies are able to penetrate deeply into tissue; therefore, accelerated electrons can be used therapeutically. Additionally, the betatron-accelerated electrons were relatively monoenergetic and their energy was easy to control. Source: Laughlin JS. Radiation therapy. *RadioGraphics.* 1989;9(6):1254. Photograph: Courtesy of John S. Laughlin. Medical Physics Department, New York, NY.

technology and increased and diversified uses of conventional applications, such as radiography, have proliferated the industrial uses of machine-produced ionizing radiation.

During World War II, General Electric Company physicist E. Dale Trout was assigned to work with the military on industrial radiography. Trout assured the quality of all aircraft templates for the B-17s, B-24s, B-29s, and B-50s with X rays. He claimed that during his work with the military, every shell of 155 mm or larger, all aircraft bearings, and all rocket propellant grains were X rayed, on continuously operating equipment. Trout and the military also assembled a 1-MeV unit at Hayward, California, to radiograph the outboard struts on ships built at Mare Island and at Hunter's Point.[12]

As part of its production-line quality control, the U.S. Army inspects materiel by means of radiographic, fluoroscopic, and continuous automatic inspection. Radiographic inspection to detect a defective weld was attempted within 1 year after the discovery of X rays. However, industrial radiography was used very little until 1920 because neither the equipment nor the film available were suited for that purpose. Today, the army has several industrial radiographic units, which range in size from the small portable unit used to inspect pipeline welds to the 25 MeV betatron used to inspect armor plate and missiles.

Fluoroscopy, which produces X-ray images in real time, lends itself to use on conveyor production lines or assembly lines, and is also used for nondestructive, noninvasive inspection of packages and luggage. In the past, fluoroscopic inspection on production lines was limited to thin, lightweight metals and nonmetallic goods, but the development of state-of-the-art image intensifiers permits inspection of heavier materials. Continuous automatic inspection uses devices such as thickness and height-of-fill gauges. Thickness gauges, which automatically control the production machinery, are used to continuously measure the thickness of sheet metal, glass, and rubber. These measurements are made by passing the product between an X-ray–emitting tube and the detector. Height-of-fill gauges also operate by passing filled containers between the X-ray tube and the detecting element. Containers not filled to the predetermined level permit more X rays to pass through, which activates a device that automatically removes the underfilled containers from the conveyor.

The military and private industry also employ ionizing radiation to analyze materials by means of X-ray diffraction and X-ray absorption photometry. Because crystals diffract X rays in a specific diffraction pattern, X rays permit qualitative and quantitative analyses of crystalline materials. X-ray absorption photometry is also an analyzing technique, but this method utilizes the differences in absorption of the various elements.

The military, like private industry, uses electron-beam generators to deliver massive doses of radiation. One device for electron-beam processing is the Van de Graaff apparatus, which is an electron accelerator. Another is the 1- or 2-MV resonant transformer X-ray apparatus. Some applications of electron-beam processing include sterilizing foods and drugs, exterminating insects in seeds, toughening polyethylene containers (which induces cross-linkage of polyethylene molecules), and activating chemical reactions in petroleum processing.

DISCOVERY AND USES OF RADIOISOTOPES

In 1896, Henri Becquerel followed Wilhelm Roentgen in exploring the idea that naturally fluorescent minerals might emit rays similar to roentgen rays. On 1 March 1896, while studying the influence of light on the fluorescence of uranium salts, Becquerel placed a sample of uranium in direct sunlight to study the degree of development of a shielded photographic plate he had placed under the sample. When the sky became cloudy, Becquerel interrupted the test and set the cassette aside. He processed this cassette a few days later and found that its emulsion had developed identically to that from cassettes that had been exposed to bright sunlight. Recognizing the importance of his finding, Becquerel announced to the Paris Academy of Science in November 1896 that he had detected the spontaneous emission of rays.[2] The emanations of uranium were initially named Becquerel rays; however, this discovery received surprisingly little attention until consequent work was done by Marie and Pierre Curie. In fact, the Curies coined the term *radioactivity* to describe the phenomenon.

Becquerel conducted much work on radioactivity with the Curies after Marie Curie took an avid interest in Becquerel's report in 1897. In July of 1898, the Curies and Becquerel positively identified a new element and named it *polonium*. In December they identified another and dubbed it *radium*. However, it was not until 1902 that they refined a pure sample, which allowed them to establish the atomic weight of radium as 226. In 1910, Marie Curie purified radium metal in

her own laboratory and prepared the official radium standard, which is still deposited in the Bureau of Weights and Measures at Sevres, France.[2]

Development of Medical Uses

Georg Charles de Hevesy of England published the first paper (with Fritz Paneth) on the radioactive-tracer concept in 1913, which introduced radioisotopes to medicine and evolved into modern nuclear medicine. His discovery occurred when he attempted to separate lead 210 from nonradioactive lead and realized that small amounts of lead 210 could represent nonradio-active lead atoms in qualitative and quantitative processes. His first experiment using the tracer concept outside the laboratory resulted from a personal concern: convinced that his landlady was using food scraps from the plates of her boarders to make hash, de Hevesy spiked the leftover food on his plate with a radioactive tracer. His detection of the tracer in the hash verified his suspicions, but got him evicted for his efforts.[13]

In 1924, the tracer concept advanced to clinical medicine and paved the way for the use of radioisotopes as diagnostic tools. Blumgart and Weiss injected bismuth 214 solutions into one arm of a subject and detected the solution's arrival in the other arm, measuring arm-to-arm circulation time. In 1934, Frederick Joliot and Irene Curie discovered artificially produced radioactivity, which, coupled with the Geiger counter's detection capabilities, markedly expanded the range of possible radionuclides for clinical tracer studies. Within a few months, Enrico Fermi produced a large number of radionuclides, including phosphorus 32. Also during this time, molybdenum 99, the parent of technetium 99m, was produced in the cyclotron (Figure 16-9). Unfortunately, another 20 years elapsed before Richards's introduction of the molybdenum 99-technetium 99m generator made technetium 99m the radionuclide most widely used for diagnostic imaging.[13]

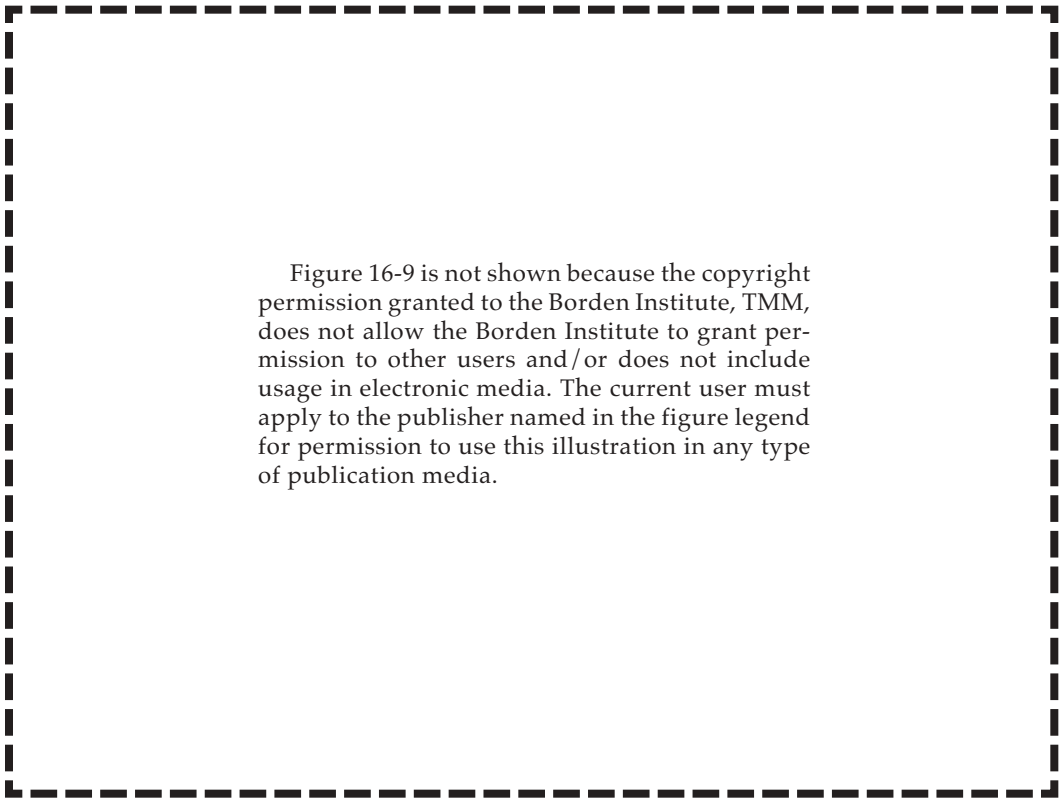

Fig. 16-9. Ernest Lawrence's invention of the cyclotron greatly expanded the number of radionuclides that could be used as tracers. The cyclotron accelerates charged particles to a very high velocity and slams the particles into a target, creating radioactive material in the process. The cyclotron (and other particle accelerators) are still used today in radionuclide production. Reprinted with permission from Myers WG, Wagner HN Jr. Nuclear medicine: How it began. *Hosp Prac*. 9(3):1974;103–113.

The demand for radioactive materials soon exceeded the capacity of the few cyclotrons then operating, but the construction of the Oak Ridge reactor during World War II partially resolved this imbalance. However, the reactor was constructed under the secrecy of the Manhattan Project. To protect this secrecy, the phosphorus 32 produced by the reactor had to appear as if it had been produced by a cyclotron. Thus, the phosphorus 32 was sent from Oak Ridge to the cyclotron group at the University of California at Berkeley, and was distributed from there to the medical centers that had ordered it. The shortage of radioisotopes ended in 1945, when isotopes became widely available for research and medical use, including reactor-produced iodine 131 from Oak Ridge.[13] The work inherent in the development of the atomic bomb created this availability, and thus contributed substantially to the medical applications of radionuclides.

The medical use of radionuclides now available was enhanced by improvements in radiation-detection instruments. H. Kallmann devised the scintillation detector in 1947, using organic crystals of naphthalene attached to the face of a multiplier tube. This device utilizes the physical phenomenon whereby a phosphor absorbs X- or gamma-ray energy, which is then converted to light. The light that the phosphor emits is then absorbed by the photocathode, which emits electrons. The number of electrons is multiplied in the photomultiplier tube and a pulse, proportional to the initial radiation energy, is finally generated. Although crude, the scintillation detector was more sensitive than a Geiger-Muller tube. R. Hofstadter modified the basic design to enhance the sensitivity by adding small amounts of thallium to a sodium iodide crystal. In 1958, H. Anger constructed the prototype scintillation camera at the Lawrence Berkeley Laboratory, but scintillation cameras did not become commercially available until 1964.[13]

Diagnostic Uses

As part of their diagnostic armamentarium, hundreds of hospitals use radioisotope techniques, including dilution techniques, flow or diffusion measurements, and biochemical concentrations. Dilution techniques can be used to measure blood volume by injecting human serum albumin that is labeled with iodine 125 into the bloodstream. After the iodine 125 has been uniformly distributed in the bloodstream (the time required is patient dependent), an aliquot of blood is removed and the amount of activity in the sample is compared with the amount injected. Dilution techniques may also be employed to measure total body water content, and similarly, extracellular body water using sodium 24 or bromine 82 as a tracer. Red-cell mass can be determined by using erythrocytes labeled with chromium 51 in dilution techniques.

Flow or diffusion measurements are used to assess cardiac output and peripheral vascular disorders. Regardless of the condition under assessment, this technique requires that a known amount of radioactive material be injected into the patient's arm or another site. The circulation time is then determined by measuring the time elapsed for the radioactive material to return to the heart after its first pass.

Biochemical concentration techniques are used to diagnose liver function and thyroid disorders, and to locate and examine the extent of malignancy. For example, if thyroid cancer is suspected to have metastasized, a diagnostic dose of iodine 131, followed by whole-body imaging, can frequently locate the metastatic tumors.

Therapeutic Uses

Pierre Curie's observations in 1904 that diseased tissue is sensitive to radiation prompted new attempts to treat malignancies with radiation:

> By 1905, radium plaques and implants were used in New York and London, and intracavitary radium for carcinoma of the uterus was employed at Paris.[2]

In the early years of such procedures, glass seeds containing radon were used for implantation. Marie Curie personally supervised, worldwide, not only the systematic production of radon from her own radium source but also the construction of radon-generation systems. Only a small quantity of radium was needed to produce enough radon seeds to supply a large area. In New York in 1926, Gioacchino Failla developed gold radon seeds for permanent implantation.[2]

Brachytherapy. In 1939, Ralston Paterson and Herbert Parker of the Christie Hospital in Manchester, England, published a system for using radium implants in brachytherapy.[11] This system was based on tables that ensured a relatively uniform dose distribution through prescribed placement of sources. In time, physicians used computers to design brachytherapy systems for artificial radionuclide sources. Today, primarily iridium 192 and cesium 137 have replaced radon seeds and radium sources in brachytherapy.

Modern brachytherapy is performed using sealed radioactive sources for surface, interstitial, or intracavitary application. Encapsulated sources such as cesium 137 can be inserted into body cavities using the same devices as those in existence since the initiation of radium therapy. The use of iodine 125, iridium 192,

or gold 198 encapsulated in seeds, wires, or needles allows the radioactive source to be inserted directly into the tumor to be irradiated.

Radiopharmaceutical Therapy. Two principles of radiopharmaceutical therapy can be used to concentrate unsealed radioactive material in the target organ: *selective absorption* or *differential turnover*. Selective absorption is used if a tissue preferentially absorbs a particular material in order to accomplish its function (eg, the thyroid's selective absorption of iodine). Differential turnover is used if the more-rapid metabolism of a particular tissue (eg, the metabolism of phosphorus by the bone- and blood-forming elements) can be monitored. After World War II, the availability of reactor-produced iodine 131 allowed its wide use as a therapeutic agent, particularly for procedures such as thyroid ablations.

Teletherapy. Cobalt 60 teletherapy, introduced in 1951, employs a penetrating beam that is clinically equivalent to the beam from a 2-MeV linear accelerator. The encapsulated radioactive source is usually located at least 80 cm away from the patient. Teletherapeutic doses are typically divided into daily treatment fractions (over 5–40 d), which allows high doses to be delivered to the tumor while minimizing unwanted side effects. Cobalt units require no associated high-voltage power supply or complicated acceleration apparatus, and the head, which contains the radioactive source and the collimator, is relatively compact. These units can be installed almost anywhere, but they also have some significant disadvantages: compared with linear accelerators, they contain a substantial radioactive source, with the associated potential exposure hazards to both patients and medical personnel; they give poorer depth-dose characteristics; and the penumbra from the radiation source is much larger.

Currently, the search for therapeutic uses of radioisotopes includes investigating californium 252 for use in patient treatment, and studying the use of energetic heavy particles such as neutrons, protons, and alpha particles.[11,12]

The Accident at Goiânia, Brazil

When devices that are intended for sophisticated medical diagnostic or therapeutic uses are mishandled, the consequences can be disastrous. One of the worst incidents of this kind occurred at Goiânia, Brazil, in September 1987:

> [A]n irresponsibly abandoned radioactive source [that] was found by innocent, unsuspecting, and uninformed persons seeking potential gain … led to this tragedy.[14(p1)]
>
> On Sunday, 13 September 1987 … a source assembly containing a 50.9-TBq (1375-Ci) ^{137}Cs source was removed from a radiotherapy unit by two scavengers and left behind in an abandoned clinic. The assembly, weighing about 100 kg, was removed from its shield, loaded onto a wheelbarrow, and taken to the home of one of the men. Neither of them had any idea of its significance. A preliminary attempt was made to dismantle the assembly with the use of a maul and punch. The men managed to break the shutter of the collimator orifice, exposing and rupturing the source in such a manner that fragments of it were spread over the adjacent areas. Small bits of the source were also withdrawn with the aid of a screwdriver. This operation took place on a plot of land shared by several families living in a housing development. The attempted dismantling, which lasted 2–3 h, could not be completed because of the strong resistance of the device.
>
> . . . .
>
> About 3 h after the attempt to break open the apparatus, both men developed nausea followed by vomiting; one of them had diarrhea. The gastrointestinal disturbances persisted for 4–5 d.
>
> . . . .
>
> On 14 September, … the assembly was apparently offered to a junkman, according to one of the scavengers. According to the junkman's version, however, it came into his hands on 18 September, … around 4:00 PM, and was placed in a dump in his backyard. At 9:00 PM, when he went back to the dump, he noticed that the object he had purchased earlier emitted some sort of luminescence, which intrigued him sufficiently to cause him to bring it into his house. It remained in the living room until 21 September, … accessible to family, friends, and curious neighbors. Later, it was taken back to the dump, broken into pieces, and distributed among various individuals, mostly relatives and friends.[15(pp17–18)]
>
> [Brazil's National Nuclear Energy Commission was informed on 29 September 1987.] During this time [between the removal of the device and the discovery of the emergency by the authorities], many individuals were exposed to various mixes of external irradiation, skin contamination, and internal contamination, mainly due to ingestion.[16(p57)]
>
> Approximately 112,000 people were monitored, of whom 249 were contaminated either internally or externally. One-hundred twenty had light surface or clothing contamination and were rapidly decontaminated. One-hundred twenty-nine had moderate to severe internal or external contamination, and 50 required close medical surveillance; 79 persons with low-dose total-body irradiation were managed as out-patients. Twenty persons out of these 50 were hospitalized at the Goiânia General Hospital … and 14 [who] required intensive medical care were transferred to a specialized unit … in Rio de Janeiro. Thirty

> remained under medical observation at a primary care level unit and other dispensaries.
>
> Fourteen persons developed bone marrow failure and eight of them experienced the prodromal phase of the acute radiation syndrome (ARS).[17(p31)]
>
> . . . .
>
> Four … died during the first month after the accident from complications of ARS, including bleeding diathesis and infection.[17(p34)] [No information regarding the total number of deaths was given.—*Eds.*]
>
> . . . .
>
> Because so much of the public and the city environs were involved, this accident is one of the largest that has occurred, probably exceeded only by the nuclear-reactor accident at Chernobyl, [USSR], in 1986.[14(p1)]

Industrial Uses

Radioisotopes are useful in industry because they are portable, easily applied in physically awkward areas—such as the gooseneck in plumbing—and do not depend on an external power source. They are used in a range of military and industrial applications including weapons, gauges for thickness or density, tracer techniques, research, neutron activation analysis, sterilization of biological and food products, smoke detection, and illumination. The military also has used nuclear reactors to produce materials for atomic weapons, to produce electrical power, and for research.

The radioisotopes most commonly used in industrial radiography are cobalt 60, iridium 192, and cesium 137. The potential hazards from these sources depend on whether they are used as stationary or portable units. Personnel exposure from stationary irradiation facilities can be controlled by shielding, interlocks, warning lights or buzzers, and established operating procedures. Exposures from portable sources are much more difficult to control. Portable units are often transported to construction sites to check welds on metal structures and pipes; they can be very small and are easy to misplace. An essential part of the operating procedures for portable radiography is to survey the area with a radiation detector before leaving the work area to ensure that no radioactive sources remain. Numerous cases of injury and some deaths have resulted from exposure to misplaced industrial radiography sources.

Radioactive commodities that are government property, composed in whole or in part of radioactive materials, are assigned a National Stock Number or part number. Approximately 3,000 different commodities currently meet this definition, including depleted uranium munitions, luminous light sources on fire-control devices, engine components, muzzle reference sensors, and compasses and watches. The complete list is found in U.S. Army Technical Bulletin 43-0116.[18]

Many of these commodities use radioactive materials applied in paints to achieve luminosity. The radioactive material itself is not luminous, but when its energy is absorbed by phosphors (eg, zinc sulfide activated with copper), visible light is produced. For many years, radium had been used in luminous paints for such items as watch dials and the instruments in military vehicles. However, radium is not only an external hazard but can also be a significant internal hazard if inhaled or ingested. For this reason, radium has been phased out as a source for luminous devices and replaced by other less-hazardous radioisotopes such as tritium (heavy hydrogen, ^{3}H).

Radioisotopes have various applications in materials analysis, materials processing, and process control. The response of radiation sensors to radiation that has interacted with the material being measured can be connected to a feedback loop to control the manufacturing process. The unique radiation scattering and absorption characteristics of individual elements and compounds can be used to measure the thickness, density, and moisture content of materials in industrial processes. Testers that are used to measure the density and moisture content of soils and asphalt usually contain two radioactive sources: cesium 137 (the gamma source) and a mixture of americium 241 and beryllium (the neutron source). Several models of density and moisture testers are available commercially, and the standard military model is similar to those used in civilian operations.

In many industrial processes, the rapid movement of nonconducting material through machinery will generate static electricity, which may constitute a fire or explosive hazard, or which may adversely affect the quality of the product. This static charge can be eliminated by producing ionized air near the charged surface. Polonium, radium, and some beta emitters are used in radioactive static eliminators, which are used most commonly in ammunition plants. Radioisotopes can also be used for quality control in materials processing in much the same way that machine-produced radiation is used.

Elements with varied levels of radioactivity are used to calibrate radiation-measuring instruments. Depending on the range and sensitivity of the instrument being calibrated, radionuclides with activities that range from a few microcuries to hundreds of curies—such as plutonium and cesium—are used. Gamma-radiation instruments are frequently calibrated with cobalt 60 and cesium 137. The most common radioactive source used to calibrate neutron

instruments is a plutonium-beryllium mixture, which produces neutrons when the beryllium absorbs alpha particles from the decaying plutonium. Plutonium sources are usually used to calibrate instruments used to detect alpha particles. Due to the energy-response characteristics of these instruments, they should only be used for quantitative measurements if they have been calibrated with the same type of radioactive source as that being monitored.

Radiation Produced by Nuclear Weapons

The U.S. Army currently maintains two nuclear reactors that are designed to simulate the neutron and gamma radiation that would be encountered in tactical and strategic nuclear environments. Each fast-burst reactor system operates in either pulse or steady-state modes (to simulate battlefield conditions) and produces neutron and delayed gamma radiation. Each reactor system can also be operated in conjunction with other radiation-producing systems; thus, materiel can be tested in a complete nuclear radiation environment. For example, a tank might be tested in a nuclear battlefield simulator to see if its electronic components would be adversely affected by the radiation.

Nuclear weapons are militarily unique sources of ionizing radiation. In fission—the process used in atomic bombs—neutrons bombard the nucleus of a heavy element, causing it simultaneously to split into nuclei of lighter elements and to release energy. The most commonly used fissionable radioisotopes are uranium 235 and plutonium 239. In contrast, in fusion—the process used in hydrogen bombs—lightweight nuclei join to form a heavier nucleus. The impetus for this reaction is provided by kinetic energy derived from the violent thermal agitation of particles at very high temperatures. The amount of energy released depends on the types of particles colliding and the amount of agitation.

Nuclear explosions are accompanied by gamma and neutron radiation, which are highly penetrating (the *initial* nuclear radiation). In addition, radioactive material from fallout and neutron-activation products remain after a nuclear explosion (the *residual* nuclear radiation), emitting alpha, beta, and gamma radiation. Exposure to both initial and residual radiation presents biological hazards.

BIOLOGICAL EFFECTS OF RADIATION

The biological effects that result from radiation exposure depend on the type, dose rate, and total dose that an individual receives. The term *exposure* is usually used qualitatively to mean the circumstance in which a person walks into, or is irradiated by, radiation emanating from an X-ray machine, a particle accelerator, or a source of radioactive material. The quantitative term *dose* or *absorbed dose* characterizes the amount of radiation energy that the individual, or the individual's organs or tissues, actually absorbs. Dose is measured in units of grays (Gy) or *rads*, where 1 Gy is equivalent to 1 joule (J) per kg of body weight and 1 Gy is equivalent to 100 rads. To put these amounts in perspective, a posteroanterior-lateral (PA-LAT) chest radiograph delivers a whole-body dose of approximately 0.0001 Gy, and a CT scan delivers approximately 0.03 Gy to the irradiated area.

Health physicists use the term *dose equivalent* to account for the fact that certain types of radiation, such as neutrons, are more dangerous than other types. The dose equivalent is measured in units of sieverts (Sv) or *rems*, where 1 Sv is equivalent to 1 J/kg of body weight and 1 Sv is equivalent to 100 rems. The dose-equivalent limit for an occupational radiation worker is 0.05 Sv, or 5 rems/year.

The amount of radioactive material is described by the term *activity*, which is the rate at which the radioactive atoms are decaying. Activity is measured in units of becquerels (Bq) or curies (Ci), where 1 Bq is equivalent to 1 disintegration per second (dps) and 1 Ci is equivalent to 37,000,000 Bq. Typical radiopharmaceutical activities used in nuclear medicine, for example, are 0.4 to 4,000 megabecquerels (MBq), or approximately 0.01 to 100 millicuries (mCi).

Recognition of Effects

Almost immediately after the discovery of X rays came the first reports of their apparent effects on health. Reports of skin reactions such as erythema and loss of hair from prolonged X-ray exposure increased during 1896.[2] These effects were initially considered trivial, and only years later were the cumulative damage and late complications from radiation exposure recognized. Borden noted that during the Spanish-American War (1898), serious burns to some patients had been induced:

> It appears that the factors which influence the production of Roentgen ray burns are (*a*) the length of exposure; (*b*) the nearness of the tube to the surface of the body; (*c*) the physical condition of the patient; and (*d*)

> individual idiosyncrasy. Relative to the length of exposure: it should not exceed thirty minutes, for with this length of exposure any part of the body may be radiographed, provided the apparatus is working properly and good technic is used. If photographic results are not obtained with a thirty-minute exposure, the operator should look to improving his apparatus or technic rather than to lengthening the time which he exposes the patient to the action of the rays.[5(p96)]

He reported two incidents of roentgen-ray burns that had been induced by prolonged and frequently repeated exposures, one of which is shown in Figure 16-10:

> Six days after the last exposure, slight redness of the skin appeared on the front of the chest and shoulder. This erythematous condition increased and, two days later, small blebs appeared. These broke and small ulcers formed, which gradually spread and coalesced. The tissue necrosis deepened and extended and was accompanied by marked pain and hyperaesthesia. The inflammatory action continued until the burn nearly covered the whole right breast.
>
> Treatment of various kinds was tried, but the greatest benefit was derived from continuous application of lead and opium lotion. The burn showed no sign of healing for four months. After that time it gradually grew better, but the healing process was very slow and the burn was not entirely healed until eleven months after its first appearance.[5(p94)]

During the early years of X-ray use, the fluoroscopic hand test (Figure 16-11) was taught routinely.[2] This procedure, in which the radiologist or an assis-

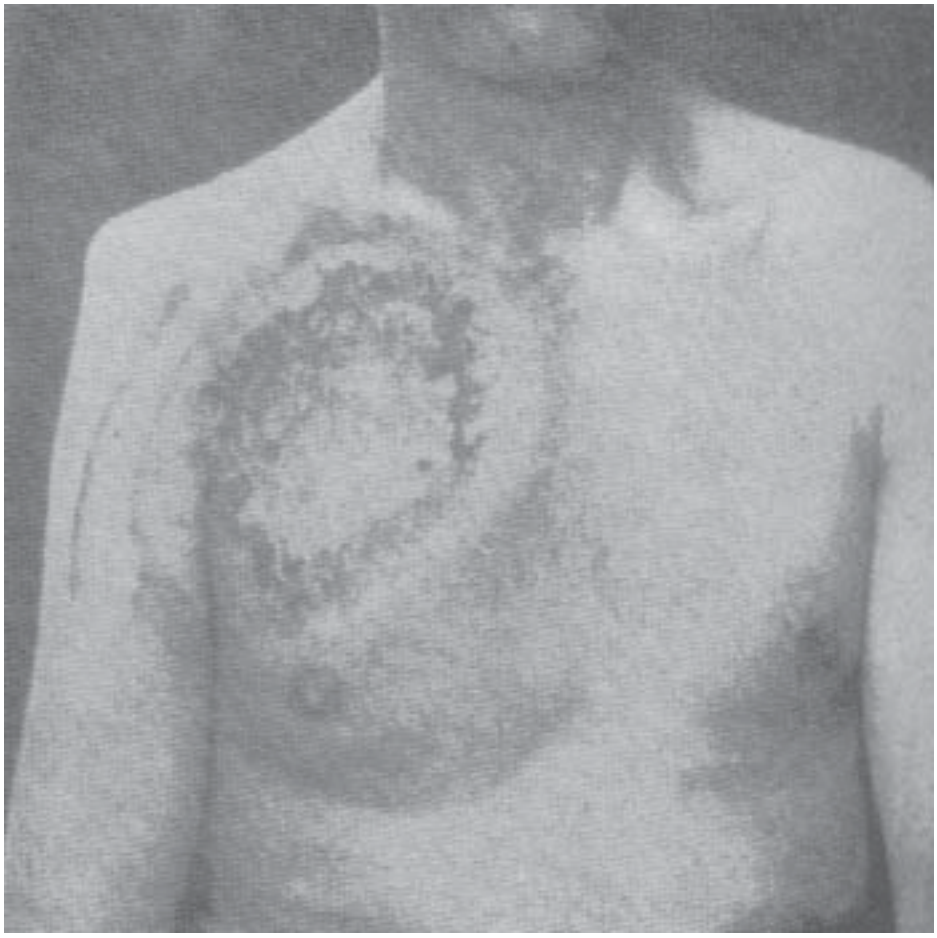

Fig. 16-10. Radiation injury to the skin of a Spanish-American War soldier as a result of an X-ray examination (1898). The radiation exposure necessary to cause this type of burn is greater than 600 roentgens (R). Current technology allows the radiologist to obtain better diagnostic information at exposures that are 1,000-fold lower than the exposure this patient received. Reprinted from Borden WC. *The Use of the Röntgen Ray by the Medical Department of the United States Army in War with Spain* (*1898*). Washington, DC: Office of The Surgeon General (George M. Sternberg, US Army), DA; 1900.

tant placed his or her hand in the beam, was used to gauge the beam's hardness or softness. The hardness of an X-ray beam is a relative measure of the beam's average energy. The hardness test, using an individual's hand to absorb the beam, was used to determine contrast while adjusting the energy output of the X-ray system. A large number of hand injuries, many of which progressed to malignancy, resulted from this procedure. Clarence Dally, Thomas Edison's assistant, was an early casualty in 1904 (Figure 16-12).[2]

With the recognition that health effects were associated with radiation exposure, physicians and other scientists began to investigate. In 1901, Becquerel realized that the 200 mg of uranium that he carried in his vest pocket had burned his skin. The burn ulcerated and healed very slowly. That same year, Pierre Curie tested the effect of radium on his own arm and developed a significant lesion. In 1904, Curie and two other physicians conducted experiments with radium on animals and noted that radium killed diseased cells preferentially.[2]

Most of the general public and the industrial community were heedless of radiation's apparent health effects, and many projects before, during, and after World War I utilized radium. For example, just before World War I, radium was used to create a self-luminous effect on expensive watches and other instruments, achieved by painting the items with a mixture of zinc sulfide and a minute amount of radium. An entire industry arose to supply the demand for these glow-in-the-dark novelties. The industry, centered in northern New Jersey, employed as many as 2,000 workers, most of them young women. The entry of the United States into World War I created a massive demand for luminous dials. After World War I, the industry sought new markets, including luminous doorknobs and light switches.[19]

The health effects of radium exposure accompanied

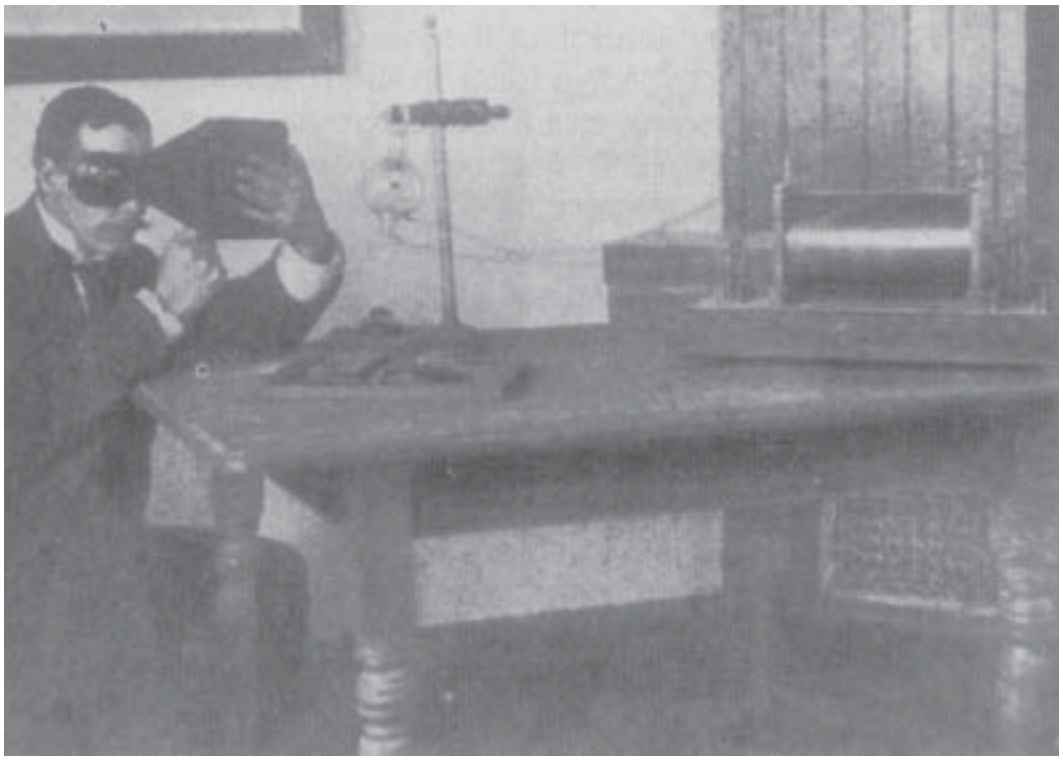

Fig. 16-11. The classical posture of the radiation pioneer, shown in 1896 using his hand to test the *hardness* of the X-ray beam. The term hardness was used to describe the energy of the X-ray beam: the more penetrating the X ray, the harder the beam. An X-ray beam that was too soft would not pass through the tissue of the hand onto the film. An X-ray beam that was too hard would not be stopped by dense material such as bone, and contrast on the film would be lost. Therefore, the operator would often use his own hand as the imaging object, and adjust the unit to balance penetrability with contrast. Repeated exposures of this type over several years cost many their fingers and hands. Reprinted from Feldman A. A sketch of the technical history of radiology from 1896 to 1920. *RadioGraphics* 1989;9(6):1113–1128. Photograph: Courtesy of Arnold Feldman; Department of Radiation Oncology; Methodist Medical Center; Peoria, Ill.

the manufacturing of these luminous items. The radium-containing paint was applied using fine brushes, which the workers "tipped" with their lips. Thus, each worker ingested radium daily. By late 1923, the industry warned its workers against tipping their brushes, but much damage had already occurred. In 1924, the first report of human radium poisoning was recorded. A young woman employed in the industry was referred to Theodore Blum, a New York dentist and oral surgeon, when her jaw failed to heal after dental work. The inflammation and signs of necrosis indicated to Blum that the bone was dying. Aware that the woman had been employed painting figures on dials with radium-containing paint, Blum correctly attributed the condition to radium ingestion. Because radium is chemically similar to calcium, the radium that she (and other dial painters) absorbed became incorporated into bone, where it constantly

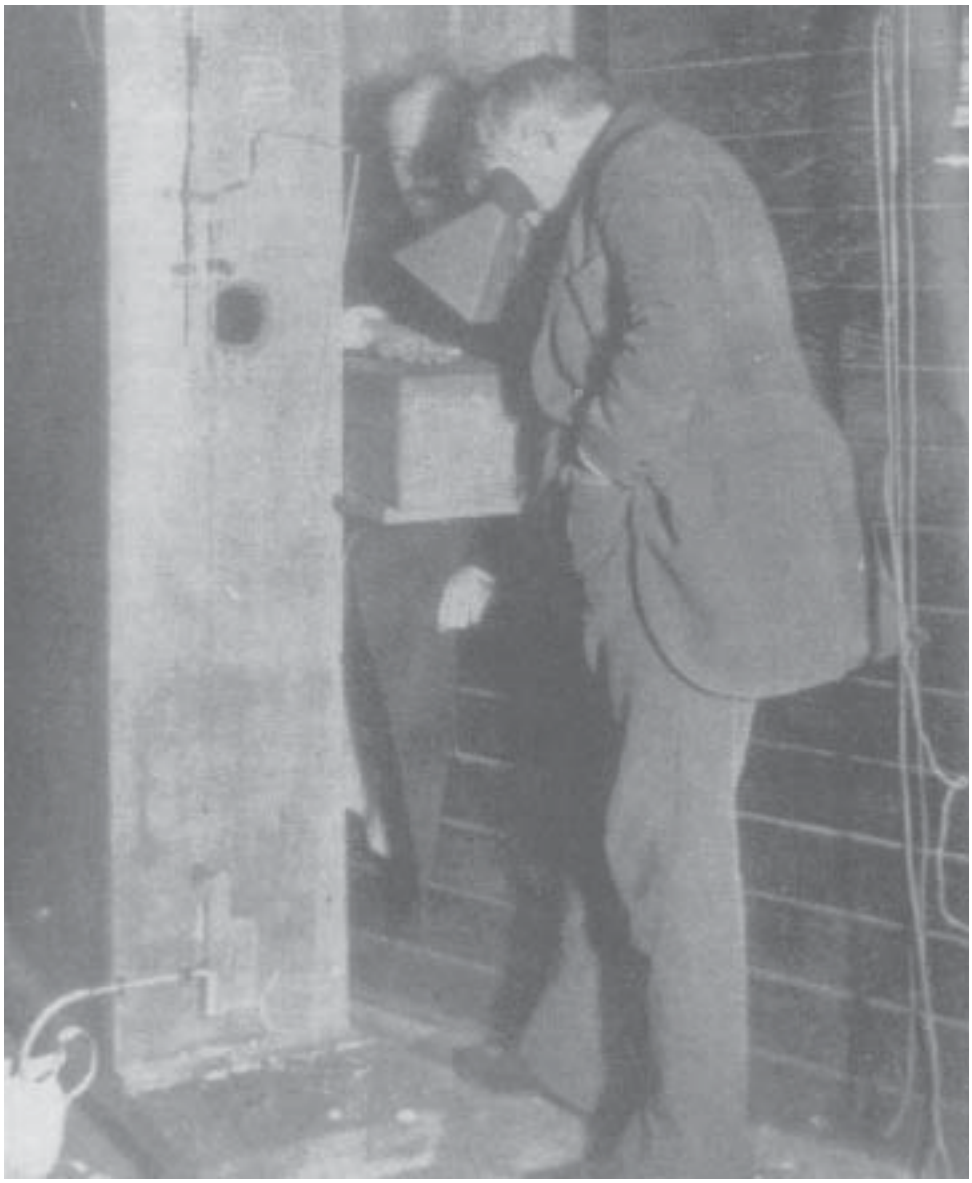

Fig. 16-12. Thomas Edison looks through the fluoroscope; his subject is his assistant Clarence Dally, who died in 1904 as a result of his frequent exposure to X rays. Reprinted from Feldman A. A sketch of the technical history of radiology from 1896 to 1920. *RadioGraphics.* 1989;9(6):1113–1128. Photograph: Courtesy of Arnold Feldman; Department of Radiation Oncology; Methodist Medical Center; Peoria, Ill.

bombarded the bone and its marrow with alpha particles and gamma rays.[19]

Dial painters were not radium's only victims. Chemists and workers who extracted radium from its ores or prepared its compounds in the laboratory were also affected. However, perhaps the largest group of victims consisted of people who deliberately ingested radium for quasi-medicinal purposes. Radium ingestion was almost a fad at that time and it could be purchased over the counter. A prominent Pittsburgh industrialist, Eben M. Byers, was a faithful user of an elixir containing 1 microcurie (μCi) of radium 226 and 1 μCi of radium 228 in one-half ounce of water.[12] His avid consumption of the elixir led to his death in 1932, which was reported nationally.[19]

Eventually, scientists involved in radiation research also became victims of its effects. Marie Curie's death from aplastic anemia was attributed to her significant and prolonged exposures to radiation. Before she died in 1934, she had also developed cataracts, and her hands had sustained radiation damage.[20]

Medical professionals were able to observe and document one of the first cases of acute, fatal radiation injury in May 1946. Louis Slotin, a young physicist working at Los Alamos, New Mexico, noted that a nuclear chain reaction was developing criticality too rapidly. Realizing that the impending powerful explosion must be averted, he broke up the reactor pile with his bare hands, thereby exposing himself to massive levels of radiation. He died within a few weeks.[2]

Categories and Mechanisms of Effects

As early as 1896, it was recognized that ionizing radiation exposure could harm a worker's health. These early effects were associated with doses at least 10-fold higher than the current occupational limit for radiation workers (5 rem/y). By consensus within the radiological community, these effects are categorized as *somatic* (to nongerm cells), *genetic* (to germ cells), and *teratogenic* (to fetal cells). Somatic effects are sustained by the exposed individual. These may be further divided into *prompt effects* (such as the skin reddening experienced by the early pioneers of radiation use), and *delayed effects* (such as cancer), which become manifest years after the exposure. Genetic effects include abnormalities that can occur not only in the offspring of exposed individuals but also in their succeeding generations. Teratogenic effects are observed in offspring who were exposed during their embryonic or fetal stages of development. Fetal exposure to even low doses of radiation can cause central nervous system (CNS) malformations, decreased birth weight and head size, and childhood cancer, and no medical interventions are available to alter the course after exposure. If a fetal exposure occurs, a qualified radiation physicist should calculate the estimated dose and assist in counseling the mother on the risks.

As far as medical treatment is concerned, exposure to ionizing radiation causes two types of biological damage: cell death and cancer induction. Cell death, which usually occurs at intermediate to high doses of radiation, is defined as the cessation of the cell's aerobic metabolism or the loss of its ability to divide. Obviously, a casualty's health is threatened if a large number of critical cells die. The effects of intermediate doses can range from subclinical, to protracted severe illness, to death. In general, high doses are fatal. Factors specific to the exposure, such as whole- or partial-body exposure, external irradiation or internal deposition, and a chronic or acute exposure period, will determine the casualty's response.

Unlike cell death, the mechanisms by which radiation induces cancer and leukemia are not well understood. One theory is that radiation injury to a cell allows the expression of a normally suppressed oncogene. Perhaps this process is initiated by the disruption of chemical bonds, which are weak compared to the energy of a single X ray, gamma ray, or electron. Thus, small amounts of radiation may be carcinogenic. A latency of 10 to 20 years or longer exists before cancer is expressed, and a latency of 2 to 4 years is characteristic of leukemia. This long latency and the fact that radiation-induced cancers are indistinguishable from other cancers combine to make low-dose exposures difficult to follow up.

Occupational Radiation Risks

The term *stochastic* is defined to mean that, for the effect in question, a statistical distribution exists over time, and therefore includes the element of chance for all individuals. Stochastic effects occur with a certain frequency in any irradiated population, but predictions cannot be made for any specific irradiated individual. The frequency of the effect may increase with increasing dose, but the severity of late stochastic effects is not related to the exposure level. Thus, the likelihood of developing a cancer as a result of radiation exposure increases with increasing dose, but the cancer or hereditary defect remains an all-or-none phenomenon: an individual either develops, or does not develop, the defect. *Nonstochastic* effects are not statistical: every exposed individual will experience the effect at a certain dose level. For example, every individual exposed to an acute dose of 100 to 200 rem will experience leukopenia (an abnormally low number of circulating leukocytes). The exact dose level

that will cause this effect in a particular individual varies, but all individuals exposed will be affected. Nonstochastic effects can be avoided in all normal circumstances simply by restricting exposures to below the threshold. Skin reddening, cataracts, and prompt death are examples of nonstochastic effects; below their thresholds, these effects do not occur.

At the relatively low levels of occupational exposure to radiation that have been achieved in the United States, it is difficult, if not impossible, to show a relationship between exposure and effect. Thus, uncertainty and controversy surround risk estimates. A common assumption in radiation protection is that the probability of the occurrence of stochastic effects is proportional to the radiation exposure, and that no threshold exists. Using this linear, no-threshold hypothesis, it is impossible to eliminate stochastic effects other than by eliminating exposure. In addition to this hypothesis, a large human biological database of radiation effects exists, including Japanese survivors of the 1945 atomic bombing, dial painters occupationally exposed to radium, humans who have received therapeutic radiation or doses of radioactive material, and the rates of lung cancer among uranium-mine workers. Several complications limit the application of these data to radiation-risk assessments, however. All the observed effects occurred in populations who received doses much higher than those currently allowed for occupational exposures.

In its 1990 report, the National Academy of Sciences estimates the lifetime excess risk of death from cancer after an acute, whole-body dose of 0.1 Sv to be 0.8%.[21] A radiation worker whose annual exposure did not exceed 10% of the maximum permissible dose would require at least 20 years to accumulate a 0.1 Sv total dose. The report further states that the individual lifetime risk of acquiring cancer in the absence of radiation exposure is 20%. Therefore, exposure to 0.1 Sv of ionizing radiation raises the total risk to 20.8%. But these risk estimates have limitations: extrapolation to lower doses, for which actual data are not available, requires the assumption that the risk is a linear function of the dose. This is not an unreasonable assumption, but it cannot be validated. Departure from linearity could cause either an underestimate or an overestimate of the risk from lower doses. Also, because the confidence limits on the risk at low doses include zero, the available epidemiological data do not exclude the possibility of a threshold dose below which there is no increased risk.

PROTECTION AGAINST RADIATION

As adverse radiation effects became better documented and understood, the field of radiation protection also began to develop. The radiation protection that existed before World War II focused primarily on the practitioner, without considering protection for the patient. Even so, the operator dose deemed acceptable at that time would be excessive by today's standards. While the scientific community was aware of the adverse effects of high radiation doses, they were unaware of the delayed, cumulative, long-term effects of smaller, fractionated doses received over time.

The scientific community began to formulate its conclusions after studying many cases of radiation-induced effects. By 1948, the consensus was that a threshold for radiation effects might not exist; therefore, an element of risk might be incurred with any exposure. The acceptance of this philosophy radically changed the approach to radiation protection. Prompted by the global fallout from above-ground nuclear weapons testing, public concern about the delayed, long-term effects of low-dose radiation mounted in the 1950s and 1960s. At the same time, data gathered from atomic-bomb survivors in Japan provided evidence of the carcinogenic effects of radiation. Federal funds were allocated for research, the results of which indicated that some radiation effects may have no threshold.[22]

The combination of the dose from global fallout and the possibility that some effects have no threshold prompted the expansion of radiation protection initiatives to include the general public as well as the occupationally exposed. For example, the U.S. Public Health Service (USPHS) initiated a nationwide program to monitor air, water, and food for radioactivity. Responding to public concern, the scientific community soon focused on limiting exposures from diagnostic X rays. In the early 1960s, the USPHS initiated a program to reduce radiation exposures from medical X rays. Equipment was evaluated, restrictions were implemented, and X-ray operator techniques were reviewed to help ensure that quality images were produced with minimum radiation exposure to the patient as well as to the medical personnel. Information that was disseminated to the medical profession emphasized that medical professionals should exercise sound judgment concerning the clinical necessity for any X-ray examination they order.[22] Today, although the long-term effects of small radiation doses are understood in general, scientists are still struggling to precisely define and quantify small exposure levels and their effects.

Emergence of Radiation Protection

Only after 1900 was an effort made to build protection into X-ray tubes. H. Albers-Schonberg, who had experienced chronic X-ray–induced dermatitis, proposed restrictions on exposure frequency, a 30-cm distance between the tube and the patient, a leaded tube housing, additional lead shielding for the operator, and abandoning the hand test for the hardness of the beam.[20]

William Rollins, a Boston-area dentist, pioneered many advances in radiation protection. In 1896, he advocated using X-ray machines in rooms with lead-shielded walls, and in 1902, suggested that fluoroscopists be provided with leaded-glass goggles and X-ray systems outfitted with shielded tube housings.[20]

World War I spawned increased X-ray hazards, as more people used and were exposed to X-ray equipment, but it also engendered huge advances in X-ray development and radiation protection. The massive scale of war-related injuries placed immense demands on X-ray capabilities. In addition, wartime pressures produced hasty training, makeshift equipment, and carelessness. At the war's conclusion, many technologists, radiologists, and physicists, whose interest was heightened because of their wartime experiences, and whose professional field of interest was radiation, were reinjected into the civilian community. Also at this time, the death rate among radiologists from radiation exposure was noted to be rather high.[19] These concerns led to more research and a sharpened focus on radiation safety. Until this time, safety practices had concentrated on protecting workers from acute exposure that would cause severe erythema but had not been stringent enough to protect against the cumulative exposures that could lead to cancer.

Dr. George Pfahler, a Philadelphia radiologist, and Dr. J. S. Shearer, a Cornell University physicist, contributed much to the understanding of the hazards that medical radiation poses both to the patient and to medical personnel. Shearer, who also served in the U.S. Army during World War I, developed a bedside portable X-ray unit for field use. He was also involved in initiating and conducting an X-ray training school in New York for U.S. Army personnel.[12]

The formation of various interest groups demonstrated that the subject of radiation protection had reached the international level. In 1925, the first International Congress of Radiology convened in London and discussed the possibility of a universal unit for radiation exposure. The radiologists were generally content with the *unit skin dose* (ie, the erythema dose, or the amount of radiation necessary to cause the skin to redden) as the standard, but the physicists campaigned for an ionization-based unit. The physicists' triumph at the 1928 meeting in Stockholm led to the adoption of the roentgen (R), measured by the ionization in air, as the international X-ray unit. The International Committee on X-ray and Radium Protection, which was later renamed the International Commission on Radiation Protection, also was founded at this meeting.[20] Since 1928, the Commission has established the basic pattern for radiation protection recommendations throughout the world. Lauriston S. Taylor of the National Bureau of Standards was the American member of the original International Committee on X-ray and Radium Protection. On his return to the United States, Taylor immediately established the Advisory Committee on X-ray and Radium Protection, which later became the National Council on Radiation Protection and Measurements, to promote radiation protection in the United States.[19] This organization met for the first time in 1929.

Advances in radiation protection continued in 1929 with the production of an electrically insulated, radiation-shielded, X-ray tube. This unit contained radiation within a glass-lined, chromium-iron cylinder that was surrounded by lead; radiation was allowed to emerge only from a small aperture in the lead protective shield. This design provided both operator and patient with a significant degree of radiation protection; it also eliminated the hazard of severe electric shock that had been associated with uninsulated tubes.[23]

The Manhattan Project prompted the next surge of radiation-protection activity. Physicists recognized that a new and intense source of radiation and radioactivity would be created, and Ernest O. Wollan, a cosmic-ray physicist at the University of Chicago, was asked to form a group to study and control the radiation hazards.[12] The quantities and varied characteristics of the new radionuclides created by nuclear fission required the full-time attention of a new group of specially trained professionals: health physicists.[20]

The radiation-exposure safeguards developed and used during the Manhattan Project—remote handling of radioactive material, special clothing, laundry and decontamination procedures, controlling access to "hot" areas, monitoring workers and workplaces, reviewing exposure records, investigating exposures, training workers, and keeping exposures as low as possible—form the basis of radiation protection today.[19]

Measurement Instrumentation

During the first decade after X rays and radioactivity were discovered, most of the instruments used to measure radiation relied on chemicals that demonstrated colorimetric changes, and, to a lesser extent, on

gross observations of the fluorescence of photographic effects. The Curies used the rate of deflection of a simple gold-leaf electroscope in many of their early measurements. In 1907, E. Rutherford introduced the use of gas-filled tubes for detecting radiation. In 1928, Hans Geiger and Walter Muller constructed counters with large sensitive areas and various fill gases such as argon or ethyl alcohol, similar to the modern Geiger-Muller tubes. During the 1920s, efforts centered on the development of better instruments to measure ionization, and in 1927, John Victoreen introduced the first ionization chamber produced commercially in the United States. In 1929, Lauriston S. Taylor developed the first portable survey meter. By the 1930s, commercially manufactured radiation instruments were standard equipment in most hospitals.[12] The Manhattan Project, initiated in 1942, had an enormous impact on radiation-protection instrumentation, including

- development of a very reliable pocket ion chamber;
- advances in radiation-detection instrumentation, including improved ion-chamber survey meters that were capable of accurately monitoring both the output and the stray radiation from diagnostic X-ray apparatuses; and
- prolific development of portable instruments to monitor all types of radiation, including neutrons.

To this day, we see continual improvements in instrumentation to detect and measure radiation. These advances in our ability to detect and measure radiation contribute significantly to radiation protection.

Development of Dosimetry

Rome Vernon Wagner, an X-ray tube manufacturer, introduced an early form of dosimetry at the American Roentgen Ray Society meeting in October 1907. Wagner reported his practice of daily carrying an unexposed photographic plate in his pocket and then developing it to determine if he had been exposed to X rays.[12] This practice led to the use of film-badge dosimeters to monitor radiation exposure.

The use of film-badge dosimeters became a recommended practice in the 1920s and developments in dosimetry continued. Based largely on the work of New York radiological physicist Edith Quimby, by the end of the decade radiologists recognized that the film should be housed in a holder equipped with filters to determine the energy of the radiation exposure. Health physicists with the Manhattan Project refined this technique of using filters and correlating optical density with dose.[12] The U.S. Army used film badges to monitor radiation exposure, and replacement of the film badges with thermoluminescent dosimeters was phased in between 1985 and 1989.

Development of Standards

Various national radiological societies began to issue rules for radiation protection during World War I. One of the early recommendations was to limit exposures to approximately 10% of the erythema dose. As German physicist Hans Kustner had demonstrated, the erythema dose is approximately 600 R (600 centigrays [cGy] in modern units).[12,20] In June 1915, the British organized a radiation-protection interest group charged with preparing a brief outline of important protection requirements for the safe operation of X-ray equipment.[12] World War I interrupted the work of this British group, but its members regrouped after the war and drafted extensive recommendations for radiation workers, encompassing both diagnostic and therapeutic protection.[12]

After World War I, scientists focused on the concept of *tolerance dose*. The application of toxicological experience to radiation exposure led practitioners to believe that a safe dose existed. The concept of a tolerance dose arose from the belief that below this radiation threshold level damage would not be permanent, due to biological repair. This concept endured for some time, even though Herman J. Muller demonstrated in 1927 that a threshold probably did not exist for radiation-induced mutations.[20] When the quantitative means to measure radiation exposure were developed, tolerance doses were expressed in quantitative form. Arthur Mutscheller made the first real attempt to define the tolerance dose in 1924, and his work served as the basis for radiation safety standards for nearly two decades.[19] Mutscheller concluded early that, while absolute safety was not feasible, improvements in safety were both achievable and essential. He proposed a tolerance dose of 6 R, which is 0.01 the erythema dose per month. Swedish physicist Rolf Sievert, working independently, proposed the same tolerance dose in 1925. By 1928, Mutscheller's proposed tolerance dose was accepted by most physicists in the health field. In 1931, the International Commission on Radiation Protection recommended shielding tables based on a tolerance dose of 0.00001 R/second.[19]

In 1934, the American Advisory Committee suggested a tolerance dose of 0.1 R/day to the whole body and 5 R/day to the fingers for radium exposure. The committee had actually calculated a dose of 0.24 R/day, but, concerned about the assumptions needed to arrive at that value, the committee decided to take a

conservative approach and proposed 0.1 R/day instead. In that same year, the International Commission on Radiation Protection set the daily dose at 0.2 R/day. The basis for this calculation was the same as the American Advisory Committee's; however, the International Commission on Radiation Protection was less conservative in its approach.[19] In 1941, the National Bureau of Standards published Handbook 27, S*afe Handling of Radioluminous Compounds*,[24] which continued the use of 0.1 R/day as the permissible level for external exposure to radiation workers. However, it also incorporated the concepts of *maximum permissible body burden* of an ingested radionuclide (0.1 mCi of radium, based on the work of Robley Evans), and a *maximum permissible concentration* of a radionuclide in the workplace (10 picocuries [pCi] of radon per L of ambient air). In 1941, limits were established by setting the *safe* level lower than the amount of radium retained in any of the radium-dial painters who developed bone cancer.[20] That same year, Taylor recommended that the permissible level for external exposure be reduced to 0.02 R/day, which is approximately 5 rem/year. The rem unit, which *accounted for the biological effectiveness* of the radiation, and the maximum permissible concentration for inhaled radioactivity were byproducts of the Manhattan Project.[12]

After World War II, the National Council on Radiation Protection and Measurement, the Atomic Energy Commission, and the USPHS actively promoted radiation protection, focusing their attention on refining exposure limits. The concept of tolerance dose was replaced by *maximum permissible dose,* which did not necessarily imply a threshold. The whole-body maximum permissible exposure previously established at 30 R/year in 1936 was reduced to 15 rem/year in 1948, and then to 5 rem/year in 1958.[20] In 1949, the National Council on Radiation Protection and Measurements introduced the concept of a lower radiation level for nonoccupational exposure and established this level at 10% of the allowable exposure for radiation workers.

A decade of federal involvement in radiation protection began in 1959. The Federal Radiation Council was created that year from among members of key agencies that were involved in nuclear work. This body was charged with providing regulatory guidance concerning radiation protection to federal agencies, and in turn, federal agencies were required to comply with the standards that the Federal Radiation Council set. In 1970, the Federal Radiation Council was abolished and the EPA assumed its responsibilities. Today, the regulatory structure includes OSHA as well as the EPA.

A milestone in radiation protection occurred in 1969 with the passage of the Radiation Control for Health and Safety Act.[22] The Act resulted in the USPHS's assuming responsibility for regulating the perform-ance of imaging equipment. The first standard for diagnostic X-ray equipment was promulgated under the Act in 1974.

Further regulatory control has been introduced during the modern era:

- mandatory licensing of radionuclides,
- certification of machine sources of radiation,
- requirements for improved education and training of radiation workers, and
- implementation of radiation protection programs based on the concept of keeping radiation levels as low as is reasonably achievable (ALARA).

Regulatory Agencies

The Atomic Energy Commission, which had been established in 1954,[25] was dissolved in 1975; its activities relating to the promotion of technology were assigned to the Energy Research and Development Administration (which was later incorporated into the Department of Energy), and its regulatory authority was assigned to the newly created U.S. Nuclear Regulatory Commission. Today, the Department of Energy actually owns the nuclear weapons in the custody of the armed forces, and it operates several research and development laboratories. The EPA is also concerned with radiation protection and regulation: it published *Radiation Protection Guidance to Federal Agencies for Occupational Exposure* in January 1987, and is currently writing another document titled *Guidance to Federal Agencies for Radiation Protection of the General Public*. OSHA sets standards for the protection of employees who use any type of ionizing radiation source in the workplace.

Occupational Dose Limits

Because the United States has various regulatory bodies and authorities, current limits vary. The Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), the Occupational Safety and Health Administration (OSHA), and the individual states all promulgate limits based on recommendations of international or national scientific advisory bodies. However, for U.S. Army personnel, allowable exposure limits in the workplace are prescribed by Army Regulation (AR) 40-14, which is in accordance with 10 Code of Federal Regulations (CFR), Part 20. Occupational exposure must not ex-

ceed 1.25 rem in any calendar quarter nor 5 rem in any calendar year, to the whole body, head and trunk, active blood-forming organs, or lens of the eye. In addition, the accumulated dose equivalent of radiation to the hands and wrists, or to the feet and ankles, cannot exceed 18.75 rem in any calendar quarter nor 75 rem in any calendar year. Excluding the dose to the hands, wrists, feet, and ankles, the accumulated dose equivalent of radiation to the skin of the whole body cannot exceed 7.5 rem in any calendar quarter nor 30 rem in any calendar year. The accumulated dose equivalent of radiation to the bone, thyroid, and other organs, tissues, and organ systems also cannot exceed 5 rem in any calendar quarter nor 15 rem in any calendar year. In the special situation where a radiation worker is pregnant, the cumulative dose equivalent of radiation to the fetus due to occupational exposure to the expectant mother must not exceed 0.5 rem during the gestational period.[26]

Radiation exposure standards less restrictive than those prescribed above may be used in special circumstances only when approved by The Surgeon General of the army or the Director, Defense Logistics Agency (DLA), as appropriate. Proposals for the use of alternate radiation exposure standards will contain complete justification. They will describe the procedures by which the alternate standards will be implemented. Less-restrictive radiation exposure standards will not be considered for the following:

- persons under 19 years of age,
- females known to be pregnant,
- occasionally exposed persons, and
- members of the general public for whom the exposure is considered to be a nonoccupational exposure to ionizing radiation.[26]

Most army personnel who work with radiation receive an occupational radiation dose (the total dose minus both the background dose and any additional dose from a prescribed medical procedure) that is lower than their background dose. The average background dose in the United States is 103 mrem/year (excluding that from radon).[27] Although the occupational dose is low, the resultant risk may still be noteworthy.

Occupational radiation doses below the background are not necessarily acceptable from a public-health-planning perspective, since the risk of developing a fatal cancer from radiation exposure increases with increased dose. Therefore, occupational health programs consider all occupational ionizing radiation exposure to be potentially harmful, and attempt to keep exposures ALARA.

Nonoccupational Dose Limits

In an attempt to limit radiation exposures from the use of sources of ionizing radiation, nonoccupational dose limits were developed both for individuals in the general public and for the population as a whole. The accumulated radiation dose equivalent to the whole body for a person in the general public *must not* exceed 0.5 rem in any calendar year. This limit excludes natural background radiation and prescribed medical and dental exposures. For a representative sample of the exposed population, or for the whole exposed population, the accumulated ionizing-radiation dose equivalent to the whole body *must not* exceed a yearly average of 0.170 rem per person from all ionizing radiation sources. This limit also excludes natural background radiation and prescribed medical and dental exposures.

MEDICAL RESPONSE TO A RADIATION INCIDENT

In today's geopolitical climate, injury from ionizing radiation is less likely to result from a wartime nuclear detonation than from an isolated terrorist incident or an accident at a facility that uses or stores radioactive material or uses high-energy X-ray systems. Casualties from such an event could be expected to number from one individual to several hundred, even to several thousand. It is probable that at least some medical personnel and facilities would be available, however, and while such an event would certainly be a catastrophe, it probably would not be unmanageable.[28]

Types of Exposures

Radiation exposures are classified as (*a*) internal deposition, (*b*) external irradiation, (*c*) combined external irradiation and internal deposition, (*d*) hot-particle trauma, and (*e*) mass casualties.

Internal Deposition

Most internal deposition involves gas, vapor, or dust inhalation; other possible routes of entry such as ingestion, needlesticks, and skin absorption are less

likely. Fortunately, the likelihood that acute effects will result from internal deposition is very small. However, medical intervention has little effect once the deposition has occurred. Thyroid-blocking agents are effective if they are administered within a few hours after radioiodine has been ingested. Dilution through the administration of large volumes of fluids can be effective for tritium, while chelating agents such as diethylenetriamine pentaacetic acid (DTPA) can be effective in enhancing the biological elimination of plutonium and certain other heavy metals. As soon as an internal deposition accident is suspected, medical personnel should seek advice from the U.S. Army Environmental Hygiene Agency (USAEHA).[29]

External Irradiation

External irradiation can cause partial- or whole-body exposures. The most typical partial-body exposure is an extremity exposure, which usually occurs when an arm or hand is inserted into a radiation beam emitted by a medical or industrial X-ray machine. Accelerator accidents are also common sources of external irradiation. In these instances, victims can incur partial-body exposure by incorrectly assuming that the system is not operating, or that shutters and other protective devices are properly positioned. The doses resulting from partial-body external exposure can be extremely high, but the acute effects will be limited to the irradiated tissue. Systemic effects are unlikely from partial-body exposures. In comparison, external irradiation of the whole body typically involves exposure to an unretracted industrial radiography source, or to exposures from distant, large devices such as a nuclear reactor, a critical assembly, or an animal irradiator.

Combined Internal and External Exposures

Casualties who sustain both external irradiation and internal deposition should receive medical treatment for each insult simultaneously, because the treatments are completely different and the insults are medically independent. Accidents of this type usually involve an explosion or fire in a facility that handles large amounts of radioactive materials, such as a nuclear reactor, weapons plant, or waste-processing plant.

Hot-Particle Trauma

Hot-particle trauma occurs when a small, radioactive fragment, usually metal, penetrates the skin of a victim. This local radiation dose is extremely high, and if the fragment is not removed promptly, it can cause severe local tissue damage. In almost every credible accident scenario, an accident victim will not become a high-level source of radiation, especially if any degree of decontamination has been performed. The exception is the victim of an explosion whose body contains large, highly radioactive, metal fragments. In this event, the wounds should be quickly debrided, using long forceps or tweezers if possible, and any recovered fragments should be placed immediately in a lead-shielded container. The debridement of penetrating injuries that are contaminated with radioactive debris is discussed in *Emergency War Surgery*.[30]

Mass Casualties

Mass casualties is a relative term. It depends on the ratio of casualties to the medical resources available. When medical resources are plentiful, mass casualties should be triaged according to the urgency of the victims' medical needs, as any casualties are triaged in civilian practice: medical care must be concentrated on those patients for whom intervention could *possibly* make the difference between life and death. Based on the resources that would be expended in a peacetime radiation accident that produces only one casualty, an accident that produces mass casualties would probably require the resources of several hospitals.

If mass casualties occur in a setting where medical resources are limited, however, then triage must be similar to that used by the military medical departments during wartime (whose missions then are *to conserve the fighting strength* and *to maintain the fighting power of the command*): medical care must be prioritized, with those who are *most likely* to survive receiving first priority, and those for whom medical care will *probably* make the difference between life and death receiving second priority. Patients who are unlikely to survive should receive supportive care.

Radiation Triage

Radiation injuries will rarely be so severe that their treatment takes priority in triage. Even with very high levels of contamination within the patient, or with high-level radiation exposure, physical trauma will probably be the greatest immediate threat to the patient's life or limb. Treat casualties with combined injuries in this sequence:

- Treat life-threatening physical trauma first, to the extent necessary to stabilize the patient, and to permit decontamination and attention to severe radiation injuries.

- Perform initial decontamination and wound debridement, but terminate this phase if the patient's condition deteriorates; begin again when the patient is medically stable.
- Finish decontaminating the patient.
- Complete the short-term trauma care.
- Estimate the dose sustained from external irradiation and attempt to estimate the extent of internal deposition.
- Implement appropriate therapy for the radiation injuries.
- Initiate definitive medical care for physical trauma.
- Initiate long-term follow-up care.

Procedures for Whole-Body Exposures

The treatment of patients with significant whole-body radiation exposures is a complex medical problem. Our knowledge of ionizing radiation and its pathophysiology and treatment is based on data from the accidents in Chernobyl, USSR (1986) and Goiânia, Brazil (1987); wartime detonations of atomic bombs in Hiroshima and Nagasaki, Japan (1945); and a vast amount of laboratory experimentation. The subject is discussed in detail in *Medical Consequences of Nuclear Warfare*.[28]

Low-Dose Exposures

Medical intervention is rarely necessary for patients who have sustained low doses (< 50 cGy) of radiation. Patients who are only minimally irradiated should be placed in a holding area or available hospital beds. The most important therapy is the assurance and reassurance of the nonthreatening nature of the overexposure. Most patients will be asymptomatic, although chromosomal aberrations can usually be found and many patients will have transitory, minor drops in their platelet and leukocyte concentrations. With low-dose exposures, the risk of fatal cancer increases 0.5% to 1.0% over the normal incidence (approximately 16%) to approximately 16.5% to 17%. Long-term follow-up, which must be continued throughout the patient's life, should focus on solid tumors and, less likely, leukemia.

Intermediate-Dose Exposures

Medical care usually is necessary if patients who have sustained intermediate doses (50–500 cGy) are to survive acute radiation injury syndrome. Those who have been exposed to the lower portion of this dose range will have moderate-to-severe depression of all of the formed blood elements, which can lead to death from overwhelming infection. Exposure to the upper portion of this range additionally causes denudation of the crypts of the small intestine, which leads first to an inability to absorb fluids and nutrients from the small intestine, and then to the consequent dehydration, electrolyte imbalance, and potential death.

Patients generally experience three distinct phases of response to intermediate doses: the prodromal phase, the latent phase, and manifest illness. In the prodromal phase, patients experience nausea, vomiting, anorexia, diarrhea, and malaise. In the latent phase, which follows the prodromal, the patient stabilizes or begins to feel better. The manifest illness phase is characterized by the appearance of the hematopoietic and gastrointestinal signs and symptoms that can lead to death.

Triage is usually based on the severity of the symptoms and the time of onset of the prodromal phase. The earlier and more severe the prodromata, the higher the dose received. Doses at the upper end of the intermediate range cause the onset of the prodromal phase within a few hours. The prodromal phase will continue for a few days and will be followed by a latent period of up to 3 weeks. Doses at the lower end of the range cause a later appearance of prodromata. The lower-dose prodromal phase is shorter in duration than that associated with the upper-dose range. The latency for the lower-range doses is longer than that of the upper range.

The immediate care for casualties who have received doses of approximately 50 to 300 cGy is primarily supportive. Medical efforts should be directed toward any physical trauma, with attention to possible infection due to the depression of leukocytes.

However, medical care for casualties who have received doses of approximately 300 to 500 cGy is intensive. These patients must be hospitalized and closely observed for any decreases in blood values, the onset of aplastic anemia, and gastrointestinal bleeding and other sequelae of small-bowel injury.

Statistically, a dose of approximately 450 cGy will kill 50% of irradiated individuals within 60 days, even if antibiotics and other supportive care are available. Although any specific individual may respond differently, the 450 cGy value is a reasonable lethal-dose estimate for an individual, if special factors affecting radiation sensitivity are not known to be present.

High-Dose Exposures

Gastrointestinal complaints from patients who have received high doses (> 500 cGy) of radiation will dominate the early (days to hours) clinical picture,

with hematopoietic complications arising if the patient survives the gastrointestinal onslaught. Patients have a slim but real chance of surviving doses on the order of 1,000 cGy if they receive intensive therapy including bone marrow transplantation. At doses exceeding approximately 2,000 cGy, the patient will die of cardiovascular or cerebral collapse within hours to a few days. Medical care in this instance should be palliative or symptomatic.

Protecting the Medical Team

Protection of the medical staff against external irradiation is afforded by minimizing the amount of time that an individual is near the radiation, maximizing the distance from the source, and placing a shield between the individual and the radiation source. Contamination is the more common potential hazard to the medical response team, whereby radioactive material on or in the casualty becomes deposited on or in the medical worker's body. Because 90% of all contamination is on the clothing, early preventive measures for the medical team include

- wearing surgical gowns, booties, caps, gloves, and masks;
- careful removal of the victim's clothing; and
- thorough decontamination of the victim.

The risk to the members of the medical team who treat a victim of a radiation accident depends on the victim's level and type of exposure. Thus, the medical team's risk levels can be classified as low, moderate, or high. Medical personnel receive annual refresher training to reinforce concepts for treating the various radiation injuries and to allay any fears that these risk levels may present.

Low Risk

Victims who have received an exposure to an X-ray beam pose no risk to the medical team. Likewise, those who have sustained internal deposition from an accidental needlestick present little or no risk to the medical team, because the contamination is not removable and radiation levels near the victim would almost certainly be very low.

Moderate Risk

In general, externally contaminated patients pose a moderate risk to the medical team. The primary hazard to medical personnel is that the victim's external contamination will be transferred to the medical personnel and be deposited internally via ingestion, inhalation, or accidental needlestick. Although the radiation levels near accident victims are usually low, measurable amounts of radioactive contamination can be found on clothing, skin, and hair. In treating radiation victims, follow these preventive measures:

- Remove the casualty's clothing and decontaminate the patient as thoroughly as possible at the accident site or en route to the hospital.
- Allow a trained radiation safety specialist (health physicist, medical physicist, or nuclear medicine specialist) to monitor the patient throughout the course of medical treatment.
- Designate *presumed-contaminated* and *clean* areas within the treatment area and keep the casualties confined to the presumed-contaminated areas.
- Wear hospital gowns, booties, disposable rubber or plastic gloves, surgical caps, and surgical masks while treating casualties.
- Monitor all medical personnel as they leave the presumed contaminated area and decontaminate them if necessary.

High Risk

Radiation casualties who pose the greatest risk to medical personnel include those who have severe physical trauma with high levels of external contamination or imbedded radioactive projectile fragments. *These casualties can, themselves, emit high levels of radiation*. They require significant medical attention, and their level of physical trauma may make the removal of the radiation prior to treatment difficult or impossible to achieve.

All the preventive measures taken with a moderate-risk casualty apply in high-risk situations, but additional measures are necessary to protect medical personnel from radiation emitting from a casualty's body. Because special shielding is unlikely to be available except in designated and prepared hospitals, protection must be achieved through distance and time. When *distance* is employed, none but essential personnel are allowed into the treatment area, and even they must step away from the patient when their presence is not mandatory. When *time* is employed, only essential procedures must be performed initially, and these quickly but carefully. Additionally, the radiation safety officer may restrict the amount of time that members of the medical team can remain in

the treatment room, based on survey meter measurements and readings from personal dosimeters.

Controlling Contamination in the Medical Treatment Facility

The guiding principle in controlling contamination in a medical treatment facility (MTF) is to confine the radioactive contamination to a small, known area. *Any contaminated area must be removed from routine use until it has been completely decontaminated.* This could have a severe impact if the contaminated area were to be a critical component such as an operating room. Thus, a small, noncritical room should be used to treat contaminated patients. Vigorous efforts must also be exerted to keep the contamination from spreading beyond the treatment area. Extensive decontamination is expensive and time consuming, and frequently is accompanied by public-relations problems with the hospital staff and the general public. Preventive measures used to avoid extensive complications include the following:

- a written, periodically rehearsed response plan for radiation accidents;
- maximal patient decontamination at the accident site, en route to the hospital, or within the ambulance after its arrival;
- prior designation of the receiving and treatment areas for radiation casualties;
- a prepared radiation emergency-response kit that contains protective paper, absorbent pads, radiation signs, anticontamination gear, and a brief standing operating procedure (SOP) on radiation injury treatment;
- preparation of the receiving and treatment areas before the casualties arrive at the MTF, to facilitate the containment of the contamination and the subsequent decontamination;
- tight control by police or security personnel over entry into and exit from the receiving and treatment areas; and
- prior designation of an area where hospital public-affairs personnel can meet the media and local government officials.

THE U.S. ARMY RADIATION PROTECTION PROGRAM

The primary goals of all radiation protection are (*a*) to maintain both individual and collective exposure ALARA, and (*b*) to minimize the release of radioactive effluents into the environment. Through these goals, the U.S. Army Radiation Protection Program seeks to protect all personnel from unnecessary ionizing radiation exposure in accordance with national and international scientific recommendations. These recommendations include the following[31,32]:

- No procedure shall be adopted unless its introduction produces a positive net benefit.
- All exposures shall be maintained ALARA.
- Dose equivalent limits for individuals shall not exceed the limits recommended for the appropriate circumstances by the NRC.

Program Responsibilities

Within the U.S. Army, installation and activity commanders are responsible for the Radiation Protection Program. At facilities that require NRC licenses, such as research laboratories and MTFs with nuclear medicine departments, the commander is the licensee and can be held personally liable for program deficiencies. In clinical settings, the physician, dentist, or veterinarian in charge is similarly held personally responsible for maintaining the equipment in safe operating condition, and for protecting patients, medical personnel, and workers from unnecessary exposure to radiation. The U.S. Army Radiation Protection Program is managed for the commander through the radiation control committee (RCC) and the radiation protection officer (RPO).

Radiation Control Committee

Organizations that use radioactive material under a specific NRC license or DA Radiation Authorization (DARA) must appoint an RCC, an advisory body that assists the commander in establishing local rules and procedures for the safe use of radiation sources. The committee accomplishes this task by reviewing any matter affecting radiation safety and making recommendations for senior management approval. While the membership of the RCC will vary with each organization, the core should include a top-management representative, the RPO, a representative from each unit that uses radiation sources, and a medical representative. The RCC is responsible for

- ensuring the safe use of radiation sources;
- ensuring that the sources are used in compliance with regulations;

- ensuring that the use of the sources is consistent with the ALARA program, including the establishment of investigational levels for individual occupational exposures; and
- identifying problems and their solutions within the program.

To meet these responsibilities, RCC members should possess some background and competence in radiation use and safety and be familiar with the institutional Radiation Protection Program and applicable regulations. In general, the RCC meets at least quarterly and keeps written records or minutes of the meeting.

Within the army system, an RCC must exist before an application for an NRC Specific license can be made. For medical programs that use radioactive material for human use, specific requirements for the composition of an RCC and its responsibilities are listed in 10 CFR, Part 35, *Energy;* Technical Bulletin, Medical (TB MED) 525, *The Control of Hazards to Health from Ionizing Radiation Used by the Army Medical Department;* and the NRC license application that is specific to the individual licensee.[33,34]

Radiation Protection Officer

Because the commander bears the ultimate responsibility for the radioactive materials used under his or her command, AR 40-5 specifies that the commander designate an RPO and alternate RPO to manage the Radiation Protection Program. The qualifications of the RPO depend on the complexity of the operations and the range of potential health hazards. These factors also determine the amount of training, equipment, and support staff necessary for the RPO. Because the RPO must make decisions that affect the current and future lives and well-being of personnel, the RPO should report directly to the commander and be granted the authority necessary to enact safety decisions.

The role of the RPO is to provide specialized assistance and guidance in developing the radiation safety aspects of the Radiation Protection Program.[35] The RPO determines if established programs are being maintained and are adequate for present needs. (However, this function of the RPO in no way diminishes the responsibility of the user or supervisor to conduct operations in a safe and legal manner.) Although the RPO usually takes charge of regulatory compliance actions (such as surveys and personnel dosimetry), it is the licensee (the commander), not the RPO or the radiation safety staff, whom the NRC holds personally responsible for assuring both the safe performance of licensed activities and the adherence to NRC requirements.

Program Elements

The U.S. Army Radiation Protection Program includes the following elements: (*a*) administrative controls, (*b*) engineering controls, (*c*) medical surveillance, (*d*) personnel monitoring, (*e*) respiratory protection, and (*f*) recordkeeping.

Administrative Controls

Administrative controls are procedures used to minimize the radiation exposure of personnel. These procedures require the cooperation of radiation protection and operations personnel and include measures such as (*a*) SOPs, (*b*) training, and (*c*) designation of restricted areas.

Standing Operating Procedures. An SOP is a model procedure for the administrative control of radiation exposure. This document must specify, in as many specific steps as possible, safety policies concerning operational limitations and requirements throughout the radiation area. For example, the fluoroscope, if not properly controlled, is potentially the most dangerous of the common X-ray applications to both the patient and the examiner because the X-ray tube is energized for a longer time to view dynamic processes. However, techniques and equipment are available that can reduce radiation exposure as much as 50% to 75%, and the SOP should specify the use of such techniques and equipment.

In general, an SOP for ionizing radiation control should include

- the type of protective apparel required,
- posting requirements,
- the radiation monitoring devices required,
- personnel dosimetry requirements,
- bioassay types and frequency,
- recordkeeping requirements,
- the reiteration of any other applicable administrative requirements, and
- any special procedures or equipment required.

In this manner, entire complex radiation protection programs can be reduced to a series of written procedures. In fact, the NRC has adopted a licensing approach similar to this for medical licenses. The SOP should be dated, signed, and reviewed at least annually (more often if changes are made). This review should include the radiation supervisor, RPO, and

RCC. In many instances, it is necessary to document the review with signatures. Reviewed and updated SOPs are useful tools that provide for

- program continuity regardless of personnel changes,
- uniform performance throughout large groups of people,
- the opportunity for personnel to become familiar with procedures and operations before actually using radiation sources, and
- response planning prior to an actual emergency.

Training. Training is the cornerstone of the administrative control of ionizing radiation, and strong management support is essential to an adequate radiation protection training program. Although the RPO is responsible for providing the policies and procedures relating to radiation safety to all staff members, staff members must be kept aware of management's commitment to radiation safety.

The scope of training varies greatly depending on the job requirements. For example, physicians who treat patients with radioisotopes are required to be either board certified in radiology, nuclear medicine, radiation therapy, or another appropriate discipline; or they must meet the experience requirements detailed in 10 CFR, Part 35.[33] All who work in radiation or controlled areas should receive extensive training. Other personnel such as firefighters, security forces, janitors, and medical-maintenance personnel should also receive training; even though they do not work with radiation directly, they might be required to enter radiation areas. All personnel should receive training before entering or beginning work in a radiation or controlled area. They should also receive training annually thereafter, more often if policies and procedures change.

Exhibit 16-2 lists some common safety subjects that radiation protection training may include, but this list is not exhaustive. The depth of these subjects should be tailored to the audience and their educational needs. In some instances, particularly if a serious, acute health hazard exists, training with mock sources or facilities will familiarize personnel with the actions necessary for them to take in an emergency.

One area of training that requires special consideration is the instruction of women of reproductive capacity. Because a fetus is highly sensitive to ionizing radiation, women of childbearing age should be advised of the risks and of the special need to limit their exposure. Additionally, pregnant women should be counseled on the options available to limit the fetus's exposure to radiation.

Designation of Restricted Areas. Another form of administrative control is the identification and labeling of areas to which entry is controlled or restricted. The designation of restricted areas not only heightens awareness of the hazard, but also ensures that personnel in the area are monitored and have obtained specialized training. The U.S. Army, the NRC, and OSHA have all established special controls, particularly training requirements, that apply whenever personnel enter a radiation-controlled area.

Engineering Controls

Engineering controls are safety systems such as warning devices, shields, interlocks, and ventilation that are built into the source itself or its holding facility. The *fail-safe* principle is employed whenever possible in the design and construction of safety sys-

EXHIBIT 16-2

ELEMENTS OF IONIZING RADIATION PROTECTION TRAINING

Radiation biology and the risk from occupational exposure

Specific training on risks to pregnant workers

Types of radiation and their characteristics

Differences in internal and external radiation exposure

Locations of radiation sources

Dosimetry requirements

Detection and control of contamination

Dose limits

Individual responsibilities

Signs and symbols

ALARA concept

Rules and procedures, including the SOP

Egress controls

Emergency preparedness including: plant safety and accident-control features, signals and alarms, evacuation routes and procedures, assembly points, communication resources, emergency equipment, general first aid, and the initial treatment of wounds

tems. A fail-safe system is designed such that any malfunction, including the malfunction of the fail-safe system itself, causes the device to shut down without exposing personnel to radiation.

The proper design of facilities is another important engineering control. Properly designed facilities provide a higher margin of safety than administrative rules and procedures. Although the design of facilities cannot eliminate the possibility of accidental exposure to radiation, it can minimize the probability and severity of accidents. Design considerations include, but are not limited to,

- general facility layout with traffic-flow patterns and work areas,
- specific equipment and system requirements,
- appropriate shielding for radiation workers and the general population,
- proper ventilation to control the movement of airborne contaminants, and
- nonporous, easily cleaned surface materials for radioactive material handling areas.

A qualified health physicist must be consulted in the planning, design, and construction phases of new or modified radiation facilities. During the design phase, the health physicist should implement the general principles of radiation control. The most common methods of controlling an internal radiation hazard (radioactive material) are to (*a*) confine and con-tain and (*b*) dilute and disperse. An example of the *confine and contain* method is a glove box inside a shielded room that is ventilated with filtered and recirculated air; an example of the *dilute and disperse* method is the mixing of radioactive gases with a large volume of clean make-up air, which is then discharged through an exhaust stack into the atmosphere at a height above any air intakes or occupied areas. Common engineering methods to control an external radiation hazard (and to maintain exposure ALARA) include increasing the absorptive shielding around the source, increasing the distance between the radioactive source and the employee (remote handling), and decreasing the amount of time that the employee is near the source (which is also subject to administrative control).

Medical Surveillance

Although significant overexposure to radiation is required before clinical signs or symptoms of overexposure appear, medical surveillance is an important tool that occupational health professionals use to protect workers from possible radiation damage. The U.S. Army Radiation Protection Program requires a preemployment physical examination before an individual begins occupational exposure as a radiation worker. This physical examination should include a medical and family history to determine predisposition to radiation-induced effects such as dermatitis, cataracts, or blood disorders including leukemia. The medical history should also include detecting possible indirect effects, such as a sensitivity or allergy that might preclude the use of protective devices like rubber gloves. The documentation of any previous radiation exposure, including exposure for therapeutic procedures, should also be included. In addition, AR 40-14 requires that baseline blood values be determined, including platelets, hemoglobin, and leukocyte differential. Employees with a potential for exposure to neutrons, high-energy beta particles, or heavy particles should have ophthalmic examinations with particular attention directed to any changes or abnormalities in the lens of the eye.

After the preemployment physical examination, the Radiation Protection Program requires that employees who are likely to be exposed to significant radiation undergo periodic medical examinations. These examinations ensure that individuals do not display signs that would contraindicate further occupational exposure. Medical examinations are also required on an employee's termination of employment in a radiation area. Termination examinations evaluate any recorded exposures for possible health effects in the worker.

In addition to the preemployment, periodic, and termination examinations, any person suspected of receiving an excessive exposure must be referred to a physician. These individuals will receive whatever examination is determined appropriate by the local medical authority, in consultation with the RPO. When appropriate, this examination should include tests to evaluate any potential health hazard or injury, and should include plans for medical care.

Personnel Monitoring

Personnel monitoring includes bioassay and monitoring devices such as photographic film, thermoluminescent dosimeters, and self-reading pocket dosimeters. *Dosimetry* measures exposure to radiation, and a *dosimeter* is a device used to provide a quantitative estimation of the dose received. Dosimeters should respond with accurate, reproducible readings; be capable of measuring all radiation exposures that personnel encounter; and be simple, convenient, small,

and inexpensive. Each person who might receive an accumulated dose equivalent in excess of 5% of the applicable dose limits listed in AR 40-14 must wear a dosimeter. In addition, any employee who enters a high-radiation area must wear a supplementary dosimeter, usually a self-reading pocket one. The dosimeter-wearing period is usually 1 month or one-quarter of a year for occupational doses, although other wearing periods can be arranged. The U.S. Army Materiel Command supplies dosimeters to all Department of the Army, U.S. Army National Guard, and Defense Logistics Agency personnel through the U.S. Army Ionizing Radiation Dosimetry Center.[36]

Bioassay. A bioassay determines the type, quantity, location, and retention of radionuclides in the body either directly, by in vivo measurement, or indirectly, by in vitro analysis of material excreted or removed from the body. Bioassays may be considered the final quality control used to assure adequate protection of workers against internal radiation exposure. Requirements for bioassays are usually components of occupational health programs dealing with metals and other industrial chemicals.[37] Although the requirements of a bioassay program are beyond the scope of this chapter, *International Commission on Radiation Protection Report No. 54* provides comprehensive information.[38]

Photographic Film. Photographic film consists of an emulsion of silver bromide crystals imbedded in a gelatin base and supported on polyester. When the film is exposed to ionizing radiation, electrons are produced in the emulsion. The electrons combine with silver ions to form elemental silver, which forms black deposits on the film during processing. The density of the black deposits is proportional to the initial radiation exposure. Additionally, filters of differing densities and thicknesses permit the type and energy of the incident radiation to be estimated.

Thermoluminescent Dosimeter. Thermoluminescent dosimeters are based on the energy-storage characteristics of certain crystals, lithium fluoride being the crystal most commonly used. Exposure to radiation causes the crystals' electrons to be raised to a higher energy state. Subsequent heating of the crystals causes the electrons to return to their normal energy state, with a corresponding release of energy in the form of light. The amount of light emitted is directly proportional to the amount of radiation exposure.

Pocket Dosimeter. Film and thermoluminescent dosimeters require processing to obtain dose information, but the pocket dosimeter is a small ion chamber approximately the size of a fat ballpoint pen, which the wearer can immediately read. The pocket dosimeter is simple to use but has some inherent disadvantages (eg, it can discharge if it is physically jarred, which can cause a false dose reading). Therefore, a pocket dosimeter should only be used with guidance from a qualified radiation protection professional.

Respiratory Protection

Respiratory protection is required wherever unsealed radioactive material is processed in such a manner that inhalable air concentrations pose a significant threat to the radiation worker. As a guideline, respiratory protection must be evaluated whenever an individual is potentially exposed for 40 hours/week for 13 weeks (one-quarter of a year) to air concentrations equal to or greater than those listed in 10 CFR, Part 20.[39] Whenever respiratory protection is required to protect the worker, a bioassay program is also required.

The careful design of an air-sampling program can alert the RPO to trends or situations that require intervention, such as the necessity for respiratory protection, or to provide assurance that processes are functioning as designed. When air sampling is conducted to assure that adequate personnel protection is in place, it is imperative that the sample be representative of the situation under investigation. For this purpose, a worker wears a personal air sampler near his respiratory zone to collect an air sample. In addi-

EXHIBIT 16-3

REQUIRED DOCUMENTATION FOR RADIATION PROTECTION PROGRAMS

Dose data for facility employees

Radioactive source inventories and disposal records

Ambient radiation-level surveys

Airborne radioactivity data

Bioassay results

Training program content and attendance

Radioactive effluent data

Environmental monitoring data

Audit or inspection results

Unusual occurrences or operational failures

Quality assurance data

tion, area sampling of ambient air should be conducted at the worker's height to approximate the air concentration of the contaminant in the worker's breathing zone. In addition to being properly placed, the sampler should be oriented to collect respirable-sized particles rather than the larger, heavier particles that settle out of the air onto the collector. A sample collected in this manner must be large enough to represent a reasonably accurate estimate of the mean concentration of airborne particles and to meet the sensitivity requirements of the radiation detector.

Recordkeeping

Keeping the evidence necessary to demonstrate the reliability and effectiveness of a radiation protection program is called *documentation*. Complete records should include information on radiation exposure patterns and working conditions (Exhibit 16-3). For medical or legal reasons, significant information from these records (such as those that establish personnel exposure history or characterize effluents and residual radiation) are retained indefinitely.

SUMMARY

Ionizing radiation—from both outer space and the earth itself—has always bombarded humans, and only during the past 100 years has man harnessed the power of this radiation for his own purposes. Military medicine can be particularly proud of its role in the technological development, clinical application, and safe utilization of this potent force. Soon after its discovery, radiation was recognized as both beneficial and dangerous. Some early radiologists and physicists developed cancers, some of which were fatal. As the deleterious affects of radiation became better known, researchers turned their attention to attempting to understand the mechanisms of radiation damage.

Medicine, industry, and the military have become heavily dependent on the applications of ionizing radiation. Radiographic and nuclear medicine examinations are now integral to the healthcare system. Inspection of critical welds, explosive ordnance disposal, production-line quality control, and materials analysis all employ sources of radiation. Self-luminous commodities containing radioactive material, such as compasses and indicator dials, are used throughout the armed forces. Each of these technologies can be used safely, but each also can pose health hazards if not handled properly.

Although radiation is not detectable by our physical senses, it is relatively easy to detect and quantitate with instrumentation. Physicists, physicians, and biologists have worked closely to attempt to establish quantitative estimates of risk and to derive safe dose levels, and the scientific community has provided guidance and made technological advances that have helped improve radiation protection. Federal, state, and local governments, with the help of scientific advisory groups, have also played significant roles in the control of radiation exposures. Progress in radiation protection during the recent past includes stricter reg-ulatory control, improved education and training, and implementation of programs aimed at maintaining exposures ALARA. As a result, current radiation-protection regulations and recommendations, civilian and military, provide a solid framework for the safe use of radiation sources.

However, despite regulations, safety equipment, and training, accidents do happen. These incidents have provided a rich case history for determining the optimal medical treatment of future radiation-accident victims. With proper training and planning, medical teams can treat accident victims with minimal risk to the treatment team and with excellent likelihood that the patient will have a successful outcome.

At high doses, radiation can cause severe injury and even death. However, such large doses are rarely encountered in the military (apart from nuclear weaponry); the levels of radiation doses received from military sources are more likely to be in the range where cancer induction and teratogenic effects are of statistical concern. The challenge of the U.S. Army Radiation Protection Program is to protect workers, the public, and the environment while enabling the benefits of radiation to be exploited.

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