Chapter 22

IONIZING RADIATION

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INTRODUCTION

It is unlikely Wilhelm Roentgen envisioned just how big of an impact his 1895 discovery of x-rays would have on society. Additional contributions such as Marie Curie's discovery of radium, the discovery and development of atomic fission and fusion, and other innovations described in this chapter led to numerous military and civilian applications of ionizing radiation (Exhibit 22-1). As the use of ionizing radiation began to flourish and develop, researchers gained a better understanding of the risks associated with its use. To minimize the risk while benefiting from its use, occupational health programs developed control measures for ionizing radiation. This chapter is an update to Chapter 16 in the previous edition of this book.[1]

Most military occupational exposures are minimal due to the administrative and engineering controls in place and the nature of the sources of the radiation. Many sources, however, have the potential to deliver significant levels of exposure, and a large number of military and civilian employees are routinely exposed to low-level radiation. Thus, occupational exposure to ionizing radiation demands strict adherence to all aspects of safety. Although exposure from a nuclear detonation poses the greatest ionizing radiation hazard to soldiers, *Medical Consequences of Radiological and Nuclear Weapons*[2] in the Textbooks of Military Medicine series thoroughly describes this hazard; therefore, this topic will not be discussed in detail here.

PROPERTIES OF IONIZING RADIATION

In general, radiation is the emission of waves or particles. These waves or particles travel through space and can deposit energy in matter with which they interact. Some common forms of radiation include visible light, radio waves, microwaves, x-rays, gamma rays, alpha particles, beta particles, and neutrons. Radiation is categorized by the amount of energy transferred to the atoms or molecules it interacts with. If the radiation has sufficient energy to strip an electron from its orbit around an atom, it is called *ionizing* radiation; otherwise, it is referred to as *nonionizing* radiation.

Ionizing radiation is a natural part of the environment. Ionizing radiation comes from many sources, including the sun and radioactive materials naturally present in soil, water, air, and food. On average, members of the US population receive a radiation dose of about 3.1 mSv from natural sources and another 3.1 mSv from manmade sources per year. Actual exposure levels of individuals vary depending on medical procedures, which create most manmade sources of ionizing radiation.

Particulate Radiation

Energetic particles emitted from radioactive material are referred to as *particulate* radiation. The most common examples are alpha particles, beta particles, and neutrons. The emission of alpha particles occurs primarily from heavy radioactive elements. Alpha particles contain two protons and two neutrons (a helium nucleus). Alpha particles are more massive in size compared to other common particulate radiation and have a double positive charge. When alpha particles interact with matter, they create a large number of ionizations, but these particles do not travel far. Most alpha particles travel less than 5 cm in air, but very energetic alpha particles may travel up to 10 cm. The most energetic alpha particles can travel up to 0.1 mm in soft tissue. A few centimeters of air or a sheet of paper readily shields alpha particles. Alpha particles, with energies less than 7.5 MeV, are not able to penetrate the dead layer of skin; therefore, alpha particles pose little to no hazard if the source is external to the body. However, alpha particles can be a radiation hazard if the alpha-emitting radioactive material is ingested.

Beta particles are electrons produced in the nucleus during the radioactive decay of many radioactive materials. Electrons do not normally exist in the nucleus; therefore, after the production of electrons, these particles are immediately ejected from the atom. Beta particles are smaller than alpha particles and have only a single negative charge; for this reason, they do not interact as strongly with matter. As with alpha particles, the range of a beta particle depends on its energy. Beta particles may travel several meters in air and a few millimeters in soft tissue. Therefore, beta particles from sources external to the body are a superficial skin hazard. Additionally, beta-emitting radioactive materials taken into the body can be an internal radiation hazard. Low-atomic-number materials, such as plastic or aluminum, readily shield beta particles and are preferred over higher atomic number materials. Using lead or other high-atomic-number materials to shield betas will result in the production of x-rays.

Neutrons are electrically neutral particles released during nuclear fission and some nuclear reactions. Unlike alpha and beta particles (which have a finite range in matter), there is no theoretical limit on the distance a neutron can travel. Thus, neutrons can penetrate deep into body tissues. In fact, many of the

EXHIBIT 22-1

KEY DEVELOPMENTS IN ATOMIC FISSION

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 accepted 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 realized that large amounts of energy were released in this process.

1939 Fermi approached the US Navy 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 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 December 2, Fermi successfully initiated the first self-sustaining nuclear chain reaction in a uranium pile at the University of Chicago.

1945 On July 16, the first atomic bomb detonation (a plutonium-fueled implosion device) occurred in New Mexico. On August 6, an atomic bomb (a gun-assembly, uranium-fueled device code-named Little Boy) was dropped on Hiroshima, Japan. On August 11, a second atomic bomb (a plutonium-fueled implosion device code-named Fat Man) was dropped on Nagasaki, Japan.

1986 Chernobyl Accident. On April 27, 1986 the Number 4 reactor at the Chernobyl Nuclear Power Plant in Pripyat, Northern Ukraine, was undergoing testing that resulted in a series of uncontrolled reactions. These reactions caused a non-nuclear explosion and fire that blew the roof off the top of the building. The resulting plume spread radioactive materials across Europe, and radionuclides from the damaged reactor were detected around the world. Currently, some areas near the damaged reactor are off limits to people.

1999 Tokaimura Criticality Accident. Three workers at the Japan Nuclear Fuel Conversion Company brought too much enriched uranium together and created a limited, uncontrolled nuclear chain reaction, which lasted several hours. The three workers were taken to the hospital, where one worker died after 12 weeks, and a second worker died 7 months later.

2011 Fukushima Daiichi Nuclear Power Plant Accident. On March 11, 2011, a 9.0-magnitude earthquake, the largest ever recorded in Japan, occurred northeast of Tokyo off the coast of Honshu Island. This earthquake caused the automatic shutdown of 11 nuclear power plants at four sites along the northeast coast of Japan. About 40 minutes after the earthquake and shutdown of the operating units, the first large tsunami wave inundated the Fukushima Daiichi Nuclear Power Plant. As a result of the tsunami, electrical power was lost at reactors 1 through 4. The station blackout led to a loss of cooling and a major release of radioactive material.

Data sources: (1) Dewing SB. Modern Radiology in Historical Perspective. Springfield, IL: Charles C Thomas; 1962. (2) Pizzo PP. Non-destructive inspection. San Jose State University website. http:// http://www.engr.sjsu.edu/WofMatE/Mat'sChar3.htm. Accessed November 20, 2017. (3) Kathren RL, Ziemer PL. Health Physics: A Backward Glance. New York, NY: Pergamon Press; 1980. (4) Department of the Air Force. Nondestructive Inspection Methods, Basic Theory. Washington, DC: USAF; 2016. TO 33B-1-1/NAVAIR 01-1A-16-1/TM 1-1500-335-23. (5) Graham LS, Kereiakes JG, Harris CC, Cohen MB. Nuclear medicine from Becquerel to the present. RadioGraphics. 1989;9(6):1189–1202.

neutrons may pass completely through barriers and interact with hydrogen atoms within the human body; therefore, neutron sources are an external radiation hazard. Neutrons interact most strongly with light elements such as hydrogen. For this reason, neutron-shielding materials are generally hydrogenous (eg, water, paraffin, or plastic).

Electromagnetic Radiation

Electromagnetic radiation is composed of oscillating electric and magnetic fields such as visible light, radio waves, microwaves, x-rays, and gamma rays. Of these, x-rays and gamma rays are ionizing radiation. X-rays and gamma rays differ only in their source. Gamma rays are electromagnetic radiation released from inside the nucleus of atoms that have excess energy, usually following alpha particle or beta particle emission. Electron transitions within the electron cloud of an atom produce x-rays. In many elements, the difference in energy between electron orbits is high enough that when an electron drops to a lower energy orbit, ionizing radiation is emitted. This radiation is called *characteristic* x-rays because it is emitted only at specific energies that are characteristic of the particular element. Another example of an electron transition producing x-rays is when a high-atomic-number material is bombarded with fast-moving electrons. This process, in which some of the kinetic energy of the electrons is converted into x-rays, is called *bremsstrahlung* (German for braking radiation). This is the process used to produce x-rays in medical and industrial x-ray systems. For this reason, high-atomic-number materials such as lead are not used as shielding for beta-emitting radionuclides.

As with neutrons, there is no theoretical limit on the travel range of x-rays and gamma rays. Increasing the thickness of shielding material helps to reduce the amount of radiation passing through the shield, but in theory, no amount of shielding will stop all the radiation. As the energy of the x-rays or gamma rays increases, more shielding material is needed to achieve the same level of radiation attenuation. Dense, heavy materials such as lead, steel, or even depleted uranium (DU) are the best shields for gamma rays or x-rays. Building materials such as concrete are utilized frequently for structural shielding because they are less expensive than heavy materials and are self-supporting.

Gamma rays and x-rays are both external radiation hazards. They can be internal hazards if the emitting radionuclides are in the body.[3]

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 on November 8, 1895, occurred when he saw a barium platino-cyanide screen fluorescing on a table some distance from the cathode ray tube with which he was working.[3,4] This occurrence stimulated his interest, and he worked feverishly over the next few days to comprehend and document the observed phenomenon. By turning the current on and off, Roentgen observed the relation of fluorescence to discharge within the tube. Roentgen concluded that he had found a new phenomenon emanating 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.[5] 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 "A New Kind of Ray" to the Würzburg Physical-Medical Society. On January 6, 1896, Roentgen's discovery was announced to the world, creating an immediate stir in the scientific community.[5] Although other scientists observed the photographic effects of x-rays, they failed to recognize the significance of the phenomenon.

Medical Uses

In general, the medical community, and the US Army in particular, was quick to embrace the new technology that followed the discovery of x-rays; several examples of the use of x-rays for diagnoses were available within a year. Within 3 months of Roentgen's discovery, the curator of the Army Medical Museum, Major Walter Reed, applied to the 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, DC, 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 ac-

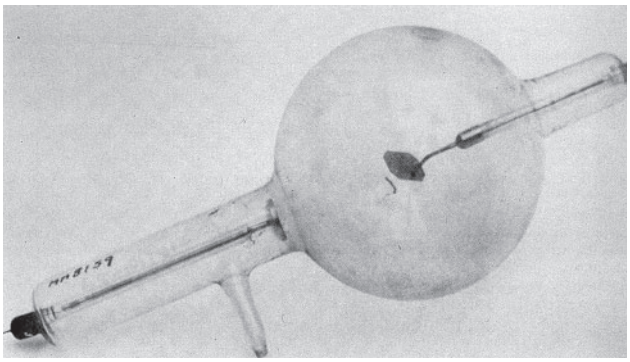

Figure 22-1. A roentgen-ray tube similar to the one possessed by the US Army Medical Museum and used to locate a bullet lodged in a patient in 1896. Simple tubes of this type were the first x-ray machines used by the Army.
Reproduced from: Henry RS. *The Armed Force Institute of Pathology: Its First Century, 1862-1962*. Washington DC: Office of the Surgeon General, DA; 1964: 102.

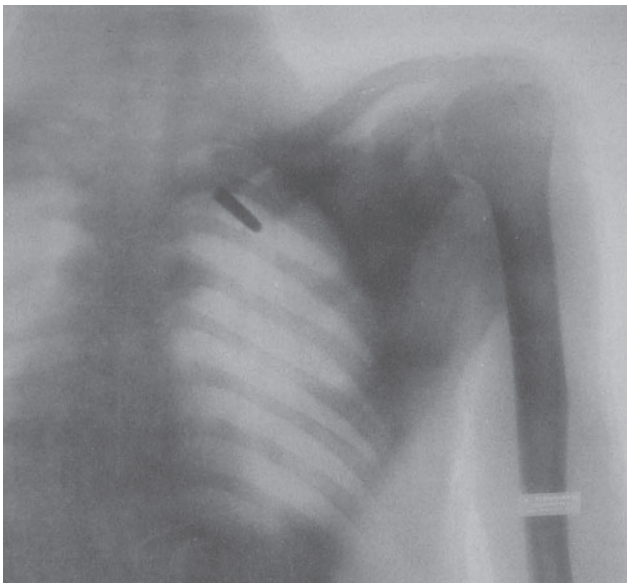

Figure 22-2. Captain William C. Borden, MD, wrote in his 1900 history of the use of roentgenography in the Spanish-American War, "[This soldier was] wounded at Malate, Philippine Islands, July 31, 1898. He was transferred to the division hospital, Presidio, San Francisco, Cal., October 22, 1898." This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

companied the patient in a horse-drawn ambulance to the Army Medical Museum, where Dr William Gray assisted in identifying the bullet's exact location with a Roentgen tube (Figure 22-1). The patient was exposed to x-rays for 1 hour before a roentgenogram showing the location of the bullet could be obtained. After this examination, the patient returned to Garfield Hospital, where the bullet was successfully removed.[6]

Although the Army began experimenting with x-rays soon after their discovery, other countries had actually employed them in treating military casualties 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 the same time, British military physicians used diagnostic x-rays during the Nile Expedition.[3] The British were the first to employ an x-ray apparatus in battlefield treatment facilities, during the Tirah Campaign (on the Indian-Afghanistan border) in October 1897.[7] Surgeon Major W.C. Beevor operated the x-ray apparatus and used the roentgenograms to locate bullets and bullet fragments. He advocated for x-ray apparatuses to be easily accessible for examining soldiers wounded in the line of duty.[7]

The US 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.[8]

The availability and utility of the roentgen-ray apparatus proved invaluable, according to Captain William C. Borden, who was in charge of their use.[8] Borden 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 22-2). Borden also extolled the benefits of roentgen rays in the diagnosis and treatment of fractures.[8] Although the quality of the early roentgenograms may leave much to be desired by today's standards, they were, in fact, remarkable for their clarity and utility (Figure 22-3).

By the time the United States entered World War I, radiology was becoming an established 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 US Army had only one radiologist, Colonel Philip Huntington.[7] While

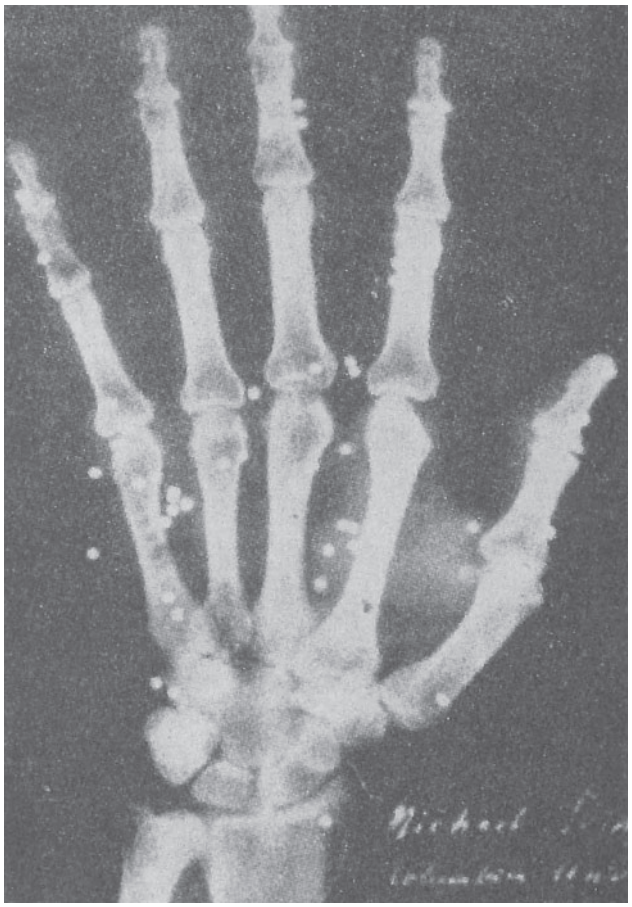

Figure 22-3. This famous radiograph of the hand of Prescott Hall Butler showing multiple retained shot was made by Michael I. Pupin in New York City, probably on February 14, 1896. It was "the first roentgen plate to guide a surgical operation in New York [and] is the best of all early roentgen prints 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."
Reproduced from: Grigg ERN. *The Trail of the Invisible Light: From X-Strahlen to Radio(bio)logy.* Springfield, IL: Charles C. Thomas; 1965: 312.

no real distinction existed between military and civilian medical applications of roentgenology, the military's differing circumstances required a specialized apparatus. For example, portable and bedside x-ray units, not used in the civilian sector, were tailored to military needs (Figure 22-4). 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.

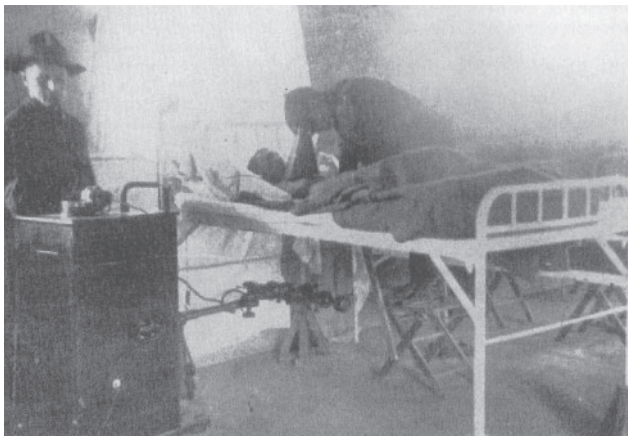

Figure 22-4. The Waite and Bartlett Army bedside unit, shown at the base hospital in Grand Blottereaux in 1915, was the first stock x-ray equipment that used a Coolidge hot-cathode tube. The examiner looked into a cryptoscope, the hand-held fluoroscope.
Reproduced from: Feldman A. A sketch of the technical history of radiology from 1896 to 1920. *RadioGraphics.* 1989;9(6):1113–1128. Copyright: The Radiological Society of North America (used with permission).

The Army worked on refining its methods for using x-rays, and on November 25 that year published the *United States Army X-Ray Manual* under the direction of the Office of The Surgeon General's Division of Roentgenology.[9] 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.[10]

Radiology as a specialty made tremendous strides during the interval between World War I and World War II: equipment was improved, radiologists received formal training, and radiological technologies were developed and clinically applied. By the onset of World War II, the use of x-ray technology was well established as a diagnostic and therapeutic tool. Radiology as a recognized medical specialty became an integral part of every hospital, and radiology teams were part of auxiliary surgical groups that performed frontline surgery.

Providing radiological services was still complicated, 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 US Army field x-ray unit, which was widely used in both front- and rear-echelon military medical facilities (Figure 22-5).[11]

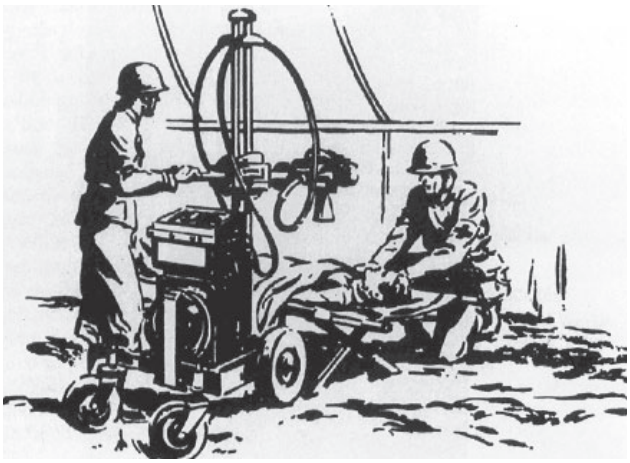

Figure 22-5. A portable field x-ray unit in action in World War II. The unit shown was developed by the Picker Corporation, which became the sole supplier of the US Army field x-ray unit during World War II.
Reproduced from: Krohmer JS. Radiography and fluoroscopy 1920-1989. *RadioGraphics*. 1989;9(6):1129–1153; Figure 15. Copyright: The Radiological Society of North America (used with permission).

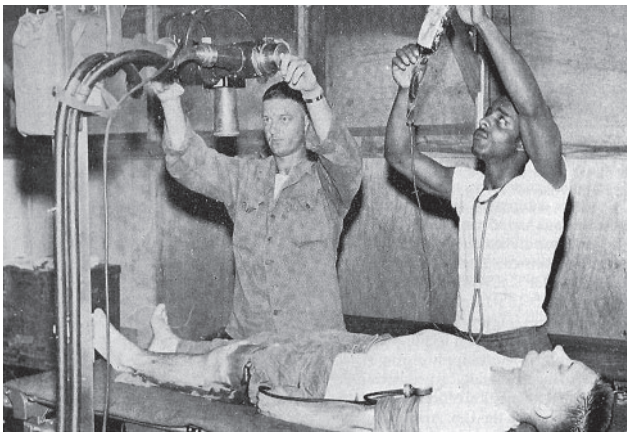

Figure 22-6. The x-ray section of a forward surgical hospital during the Korean War. The advances in x-ray technology and techniques that had been developed since World War II permitted field hospitals to practice quality imaging in their treatment of battlefield casualties.
Reproduced from: Howard JM, 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.

Furthermore, 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 US Army School of Roentgenology.[7] The importance of radiology during World War II was also reflected in the structure of the Army Surgeon General's Office. The Radiation Branch, later renamed Radiology, was established on July 12, 1942, under the direction of Major Michael E. DeBakey. This branch, a part of the Surgery Division, later became the Surgical Consultants Division.[7]

Diagnostic Uses

Beginning in the 1950s, great advances in radiological technology were made, 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 22-6). 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 CT technology from experimental curiosity to clinical reality was largely due to the efforts of English engineer Godfrey Hounsfield.[12] Hounsfield CT scanners were introduced into medical practice in 1974.

CT makes 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 1970s. Within several years, scanning times decreased from 5 minutes to 5 seconds, and later to 2 seconds.[12] New generations of CT machines incorporated new software packages and hardware designs that enhanced the efficiency and quality of cross-sectional imaging while reducing the exposure to patients.

Advances and refinements continue to produce enhanced imaging and resolution and further reduce scan times. Current CT scanners typically have a scan time of about 1 second, and electron-beam CT systems have scan times of approximately 50 milliseconds. Another advance was the creation of the spiral CT (Figure 22-7), in which scans are in a continuous spiral movement (in contrast to the traditional CT scan, in which the x-ray tube head rotates 360°, then moves to the next position and continues with additional scans). In comparison to conventional CT, spiral CT reduces radiation exposure to patients undergoing the study while providing superior two- and three-dimensional imagery. Clinical medicine has benefited from cross-sectional imaging, and the field of radiology continues to evolve as medicine advances with the computer era. Approaches being explored employ radiation sources at wavelengths not currently used for imaging. There

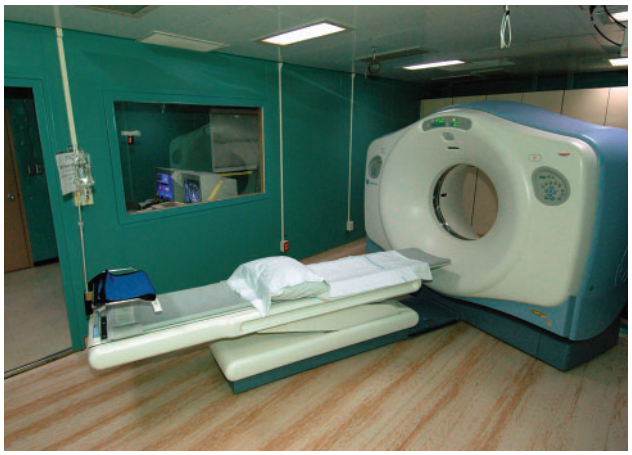

Figure 22-7. May 10, 2006. The computerized tomography (CT) scanner aboard the Military Sealift Command hospital ship USNS Mercy (T-AH 19) uses x-rays and computers to create cross-sections of bodily tissues. US Navy photograph by Journalist Seaman Joseph Caballero.
Reproduced from Wikimedia Commons.

are also new techniques being developed and implemented to combine CT, positron emission tomography (PET), and magnetic resonance.

Therapeutic Uses

Parallel to their diagnostic uses, the therapeutic uses of x-rays date to January 29, 1896, when Emil H. Grubbe reported that he, working in Chicago in collaboration with Dr R. Ludlum, treated a breast carcinoma with 18 x-ray treatments.[13] During the next few years, Grubbe and Ludlum continued to use therapeutic x-rays 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 for tumors.

In the early years, the efficacy of therapeutic x-rays was limited by the low kilovoltage the equipment could achieve, which only enabled the x-ray beam to penetrate shallowly.[13] Thus, brachytherapy (ie, the application of an encapsulated radioactive source or sources to deliver a radiation dose at a distance of not more than a few centimeters) using radium was more useful than external-beam therapy (teletherapy) until higher-energy external-beam systems became available.[13]

In 1937, the earliest type of super voltage teletherapy unit (Figure 22-8) was used on patients.[14] This 1-MeV unit was used at St Bartholomew's Hospital in London,

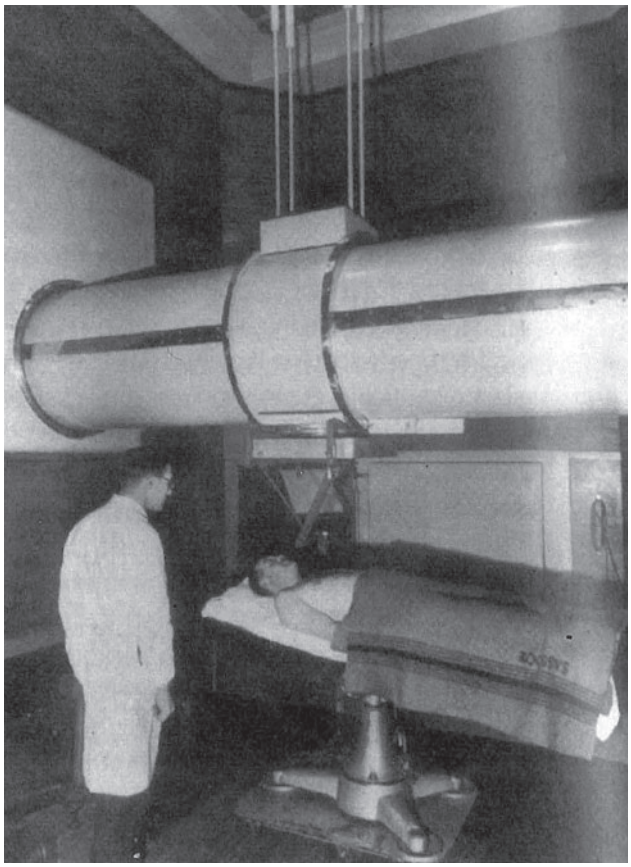

Figure 22-8. Dr Ralph Phillips and a patient to be treated using the 1-MeV therapy installation at St Bartholomew's Hospital, London. The unit created high-energy, penetrating x-rays used for treating cancers and other tumors. The immediate benefit to the patient of the tumor's eradication or reduction was generally thought to outweigh the risk of developing future cancers from the high radiation dose delivered.
Reproduced from: Jones A. The development of megavoltage x-ray therapy at St. Bartholomew's Hospital. *Br J Radiol.* 1988;22(suppl):3-10. Copyright: The British Institute of Radiology (used with permission).

England, under the supervision of Dr Ralph Phillips and George Innes. The therapeutic use of x-rays progressed after high-energy sources became available, and in 1940, Donald W. Kerst of the University of Illinois developed the betatron (Figure 22-9), 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, also 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

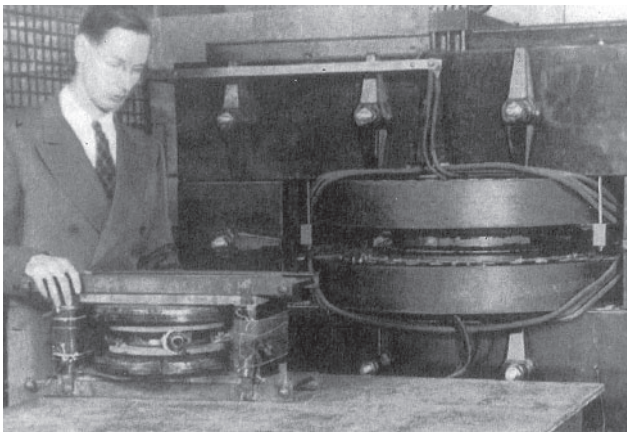

Figure 22-9. Professor Donald Kerst with two of his betatrons (electron accelerators) in 1940. These betatrons were compact and able to accelerate electrons to high energies. Electrons that reach sufficiently high energies are able to penetrate deeply into tissue; therefore, accelerated electrons can be used therapeutically. Additionally, the betatron-accelerated electrons were relatively monoenergetic, and their energy was easy to control.
Reproduced from: Laughlin JS. Radiation therapy. *RadioGraphics.* 1989;9(6):1245-1266; Figure 8. Copyright: The Radiological Society of North America (used with permission).

had been partially excised. The patient eventually succumbed to cancer, but the autopsy revealed no viable neoplastic cells in the irradiated region.[14] The same year, the Allis-Chalmers Manufacturing Company developed a commercial version of the betatron with improvements for medical use.

The development of the linear accelerator (LINAC) 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.[14] At the end of the war, the technology was refined and applied to the advancement of the LINAC (Figure 22-10), which has become the predominant modality for delivering modern radiation teletherapy treatment (see further discussion below).

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 inspection (NDI) method for examining metals. NDI is the characterization of an object or material with a technology that does not affect its future usefulness.[15] During World War II, General Electric Company physicist E. Dale Trout was assigned to work with the military on radiographic NDI. Trout assured the quality and integrity of the templates for all B-17, B-24, B-29, and B-50 aircraft using x-rays for NDI. 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 Hunter's Point.[16]

Fluoroscopy, which produces x-ray images in real time, lends itself to use on conveyor production lines or assembly lines, and is used for NDI and 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 now permits inspection of heavier materials.

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 it utilizes the differences in absorption of the various elements.

Both the military and private industry use 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-MeV resonant transformer x-ray apparatus. Some applications of electron-beam

Figure 22-10. A linear accelerator (LINAC). The LINAC is used extensively for teletherapy treatment at military medical hospitals within the United States and at overseas military bases.
Image courtesy of Elekta.

processing include sterilizing foods and drugs, exterminating insects in seeds, toughening polyethylene containers (inducing cross-linkage of polyethylene molecules), and activating chemical reactions in petroleum processing.

Digital Radiography

Digital radiography (DR) is now extensively used by the military and the private sector in both industry and medicine. Industrially, DR provides another method to perform nondestructive testing using x-rays to verify a material's integrity, density, and internal contents. The x-rays produced go through the material and then interact with a digital detector that can create and save a computerized digital image. The digital image, either still or continuous, is displayed on a computer for further analysis by the radiographer.[15]

A benefit of using DR is that the radiographer can use a smaller tube potential or kilovolt peak (kVp) value to achieve an acceptable image. By using a smaller kVp setting, the exposure to the radiographer and other nearby personnel is reduced. Also, with DR, film processing is eliminated. This reduces the cost of maintenance and has less impact on the environment. DR provides immediate results for real-time viewing; images can be stored for further use or transmitted electronically to other experts who can help verify the object's integrity and reliability of the object being analyzed.

In military medicine, DR images can be transmitted from the battlefield to fixed facilities or a mobile device for further analysis. DR has replaced the development of x-ray film in the dark room, reducing the use of chemical solutions in hospital radiology departments. DR reduces exposure to the patient and providers by using smaller tube current and/or time of exposure settings on the x-ray system. If required, DR films can be printed.

Another form of NDI utilizing DR is CT. Much like medical CT, industrial CT uses a computer system that reconstructs an object's image using the different cross-sections created by x-rays. CT produces both two- and three-dimensional images of the object being studied. With industrial CT, objects can be viewed internally, and dimensional and spatial analysis can be performed, as well as identification of anomalies to help verify structural integrity. The capability to view parts of the object from different angles eliminates interference caused by other internal components in standard radiography.[15]

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 March 1, 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 cassette he had placed under the uranium. When the sky became cloudy, Becquerel interrupted the test and set the cassette aside. He processed the cassette a few days later and found that its emulsion had developed identically to that of cassettes 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.[5] The emanations of uranium were initially named Becquerel rays; however, this discovery received surprisingly little attention until subsequent work was done by Marie and Pierre Curie. In fact, the Curies coined the term *radioactivity* to describe the phenomenon. Becquerel and the Curies worked together after Marie Curie took an avid interest in Becquerel's report in 1897.

In July 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 of radium, which allowed them to establish its atomic weight 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.[5]

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 established the field that 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 nonradioactive lead atoms in qualitative and quantitative processes. His first experiment using the tracer concept outside the laboratory resulted from a personal concern at his boarding house: convinced that the property owner 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.[17]

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 then 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 22-11). 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.[17]

The demand for radioactive materials soon exceeded the capacity of the few cyclotrons then operating, but the construction of the Oak Ridge reactor in Tennessee during World War II partially resolved this imbalance. However, the reactor was constructed under the secrecy of the Manhattan Project, so the phosphorus 32 produced by the reactor had to appear as if it had been produced by a cyclotron. To protect this secrecy, the phosphorus 32 was sent from Oak Ridge to the cyclotron group at the University of California at Berkeley, and distributed from there to medical centers that 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.[17] The work done in the development of the atomic bomb was responsible for this availability, thus contributing substantially to the medical applications of radionuclides.

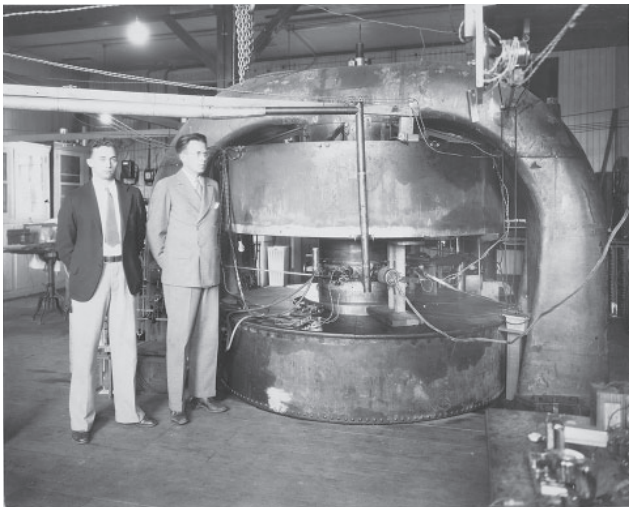

Figure 22-11. Stanley Livingston (left) and Ernest O. Lawrence (right) stand in front of a cyclotron particle accelerator that Dr Lawrence invented at the old Radiation Laboratory at the University of California, Berkeley, 1934. The cyclotron greatly expanded the number of radionuclides that could be used as tracers when the cyclotron accelerates charged particles to a very high velocity and slams them into a target, creating radioactive material in the process. National Archives and Records Administration photograph. Reproduced from Wikimedia Commons.

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. Although crude, the scintillation detector was more sensitive than a Geiger-Mueller tube (which used pressured air or gas in a sealed container or tube, with positive and negative connections to create electrical charges in the presence of radiation). R. Hofstadter modified the scintillation detector's basic design to enhance its 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.[17]

The original commercial gamma camera, which is composed of an array (group) of scintillation detectors, has been surpassed by improvements in crystal size and the design of the scintillators. Today's machines also utilize larger detectors, adjustable peak-energy detection, tomographic techniques, and high-speed computers. Single photon emission computerized tomography (SPECT) and PET scanning techniques allow for true three-dimensional image acquisition. All of these improvements have increased the image contrast and resolution of the camera, making nuclear medicine a much more valuable diagnostic modality.[18]

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 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. Flow or diffusion measurements also assess cardiac output and peripheral vascular disorders.

Biochemical concentration techniques are used to diagnose liver, cardiac, and kidney function; help diagnose thyroid disorders; and locate and evaluate 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 show the location of the metastatic tumors. PET has become a diagnostic aid to surgeons and oncologists attempting to stage certain cancers in their patients, thereby helping to guide the appropriate therapy. PET scans have also been helpful in finding and characterizing suspicious lung nodules seen on CT scan, some as small as 10 mm in diameter. Simultaneous PET and CT scanners can pinpoint foci of cancerous cells in a patient's body. There is also an expanding role for radionuclides in the therapeutic radiology realm.

In recent years the number of radionuclides, and the materials that they are tagged to, have increased. A partial list of radionuclides routinely compounded and used for diagnostic or therapeutic use includes iodine 123, iodine 125, iodine 131, indium 111, technetium 99m, gallium 67, gallium 68, thallium 201, xenon 127, xenon 133, cobalt 57, carbon 11, nitrogen 13, oxygen 18, fluorine 18, rubidium 82, strontium 87m, strontium 90, and radium 223. These elements are gamma ray or beta emitters, but some decay by emitting positrons.[18]

Therapeutic Uses

Pierre Curie's observation that diseased tissue is sensitive to radiation prompted new attempts to treat malignancies with radiation. In the early years of such procedures, glass seeds containing radon were implanted in tumors. Marie Curie personally supervised not only the systematic production of radon from her own radium source, but also the construction of radon-generation systems worldwide. 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.[5]

Brachytherapy

In 1939, Ralston Paterson and Herbert Parker of the Christie Hospital in Manchester, England, published a system for using radium implants in brachytherapy.[14] 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, iridium 192 and cesium 137 have primarily 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, gold 198, or palladium 103 encapsulated in seeds, wires, or needles allows the radioactive source to be inserted directly into the tumor.

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. Strontium 89 has been used to palliate bone pain caused by metastatic prostate, breast, lung, and renal cancer. Other radioisotopes are also currently being investigated for this purpose.[18]

Teletherapy

Cobalt 60 teletherapy, introduced in 1951, employs a penetrating beam clinically equivalent to the beam from a 2-MeV linear accelerator. The encapsulated radioactive source is usually located at least 80 cm from the patient. Teletherapeutic doses are typically divided into daily treatment fractions (over 5 to 40 days), 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. The units can be installed almost anywhere. However, they also have some significant disadvantages: compared with LINACs, 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. Teletherapy is generally no

longer used in the United States. Instead, radiation therapy has been focused on the use of LINACs for cancer treatment.

The search for therapeutic uses of radioisotopes has continued; new studies are investigating californium 252 and energetic heavy particles such as neutrons, protons, and alpha particles.[14,16] Despite these advances and improvements in safety, when devices 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 (Exhibit 22-2).[19–23]

Industrial Uses

Radioisotopes are useful in industry because they are portable, easily applied in physically awkward areas (such as a gooseneck pipe), 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.

Nondestructive Inspection

In industrial radiography, the radiation produced by radioisotopes is gamma radiation. The radioisotopes most commonly used in NDI 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 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.

Neutron radiography, another form of NDI, is used regularly to complement traditional industrial radiography.[24] Because of the high attenuation of thermal neutrons by materials with low atomic numbers (those that are hydrogenous in nature) and very low attenuation to heavy metals, the processed image of a source being studied is reversed in comparison to a typical x-ray image. Lighter materials will appear clearly defined or white on the film. Therefore, items such as sealants, adhesives, lubricants, or plastics will appear clearly on the photographic image.[24] Heavier materials, on the other hand, will appear transparent or dark on the film. Because of its high sensitivity to materials that are hydrogenous or very light, neutron radiography can be employed to study sources that have organic contents within a metal source. Items such as rubber, glue, fluids, and C4 explosive material can be detected easily on the image, whereas with x-ray radiography, they would be obscured by the more metallic and dense material of the source.

Radioactive Commodities

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 DU munitions, luminous light sources on fire-control devices, engine components, muzzle reference sensors, and compasses and watches (Figure 22-12). The complete list is found in US Army Technical Bulletin 43-0116, *Identification of Radioactive Items in the Army*.[25]

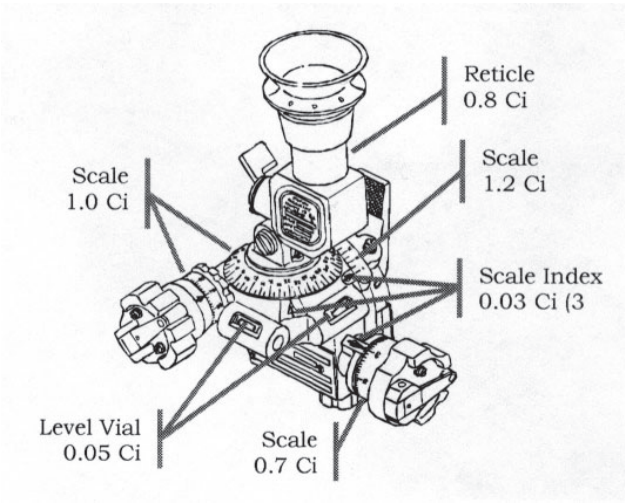

Figure 22-12. The M64A1 sight unit with M9 elbow telescope allows observers to see enemy formations from behind a wall or fortified location. Both units combined contain 5.79 Ci of tritium (3H).
Reproduced from: The US Army Center for Health Promotion and Preventive Medicine. *Radiological Sources of Potential Exposure and/or Contamination.* Aberdeen Proving Ground, MD: USCHPPM; June 1999. Technical Guide 238.

EXHIBIT 22- 2

THE ACCIDENT AT GOIÂNIA, BRAZIL

[A]n irresponsibly abandoned radioactive source [that] was . . . found by innocent, unsuspecting, and uninformed persons seeking potential gain … led to this tragedy.[1]

On Sunday, 13 September 1987 . . . a source assembly containing a 50.9-TBq (1,375-Ci) 137Cs source was removed from a radiotherapy unit by two scavengers that was 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.[2]

[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.[3]

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 outpatients. 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.[4]

Fourteen persons developed bone marrow failure and eight of them experienced the prodromal phase of the acute radiation syndrome (ARS).[5]

. . .

Four . . . died during the first month after the accident from complications of ARS, including bleeding diathesis and infection.[5] [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.[1]

1. The Goiânia radiation accident. *Health Phys*. 1991;60(1):1–113.
2. Oliveira AR, Hunt JG, Valverde NL, Brandão-Mello CE, Farina R. Medical and related aspects of the Goiânia accident: An overview. *Health Phys*. 1991;60(1):17–24.
3. Lipsztein JL, Bertelli L, Oliveira CA, Dantas BM. Studies of Cs retention in the human body related to body parameters and Prussian blue administration. *Health Phys.* 1991;60(1):57–61.
4. The Goiânia radiation accident. *Health Phys*. 1991;60(1):1–113.
5. Brandão-Mello CE, Oliveira AR, Valverde NJ, Farina R, Cordeiro JM. Clinical and hematological aspects of 137Cs: the Goiânia radiation accident. *Health Phys.* 1991;60(1):31–39.

Many of these commodities use radioactive materials applied in paints to achieve luminosity.[26] 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 226 was used in luminous paints for such items as watch dials and the instruments in military vehicles. However, radium 226 is both an external hazard and significant internal hazard (if inhaled or ingested) and has been 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. Also, 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 usually measure the density and moisture content of soils and asphalt with 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; 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 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 common 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 often employed 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.

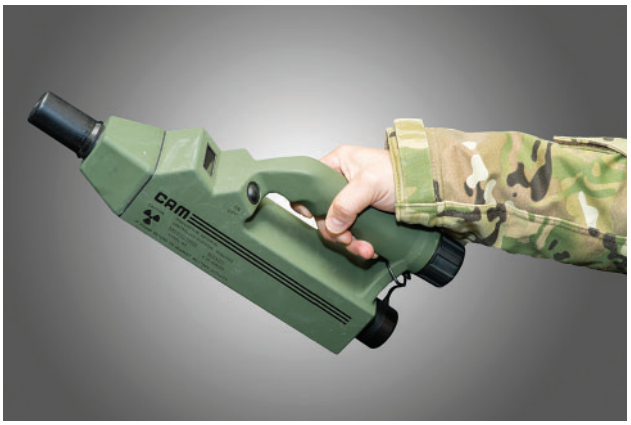

Figure 22-13. The chemical agent monitor (CAM) contains up to 15 mCi of nickel 63 used to ionize air molecules as the air passes through the CAM. The CAM is used to detect nerve and mustard chemical agents.
Photograph courtesy of the US Army Public Health Center.

Other pieces of equipment typically used by the military to help detect chemical agents on personnel and equipment and in the environment are chemical agent detectors (CADs) or monitors (CAMs). These detectors are usually battery operated. The radioisotopes commonly used in CADs and CAMs (Figure 22-13) are americium 241 or nickel 63.[26,27]

IONIZING RADIATION IN MILITARY OPERATIONS

Nuclear Reactors

The US Army currently maintains one active nuclear research reactor, located in the White Sands Missile Range, New Mexico. The reactor is designed to simulate neutron and gamma radiation that would be encountered in tactical and strategic nuclear environments. The fast-burst reactor (FBR) system operates in both pulse and steady-state modes (to simulate battlefield conditions) and produces neutron and delayed gamma radiation. The 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.

An additional four reactors in the US Army inventory are inactive. The Army Corp of Engineers currently manages three of these reactors (Fort Belvoir, Fort Greely, and James River Reserve Fleet), which have been deactivated but not yet decommissioned. All fuel has been removed from them. The fourth reactor, in Aberdeen Proving Ground, Maryland, is also an FBR; it was fully decommissioned in 2015.[28]

Radiation Produced by Nuclear Weapons

Nuclear weapons are militarily unique sources of ionizing radiation; however, recent events have increased the likelihood of their use as a terrorist weapons in improvised nuclear devices. During the fission process (the process used in atomic bombs), neutrons bombard the nucleus of a heavy element, causing it to simultaneously split into nuclei of lighter elements and release energy. The most commonly used fissionable radioisotopes are uranium 235 and plutonium 239. In contrast, in fusion (the process used in hydrogen bombs), light-weight 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 generate gamma and neutron radiation, which are highly penetrating (the *initial* nuclear radiation). In addition, radioactive material from fallout and neutron-activation products remains after a nuclear explosion (the *residual* nuclear radiation), emitting alpha, beta, and gamma radiation. Exposures to either initial or residual radiation possess a potential risk.

Depleted Uranium

DU is a waste product of the enrichment process of natural uranium. Enriched uranium, processed by the Department of Energy, is typically used for fuel in nuclear reactors or for nuclear weapons. Natural uranium is composed of uranium 238, but it also contains smaller amounts of uranium 234 and uranium 235.[26] DU has a lower content of uranium 235, hence the word "depleted." The typical decay from uranium is an alpha emission; additionally, beta and gamma radiation is emitted by the daughter products of uranium decay. DU also emits this form of radiation but on a much smaller scale. DU, which is 40% less radioactive than enriched uranium, is considered more of a heavy metal hazard than a radiation hazard.

DU has high mass density and strength. Because of these properties, the military has used DU for the manufacturing of armored components of M1A1 and M1A2 Abrams tanks. The DU found in Abrams tanks provides defense against projectiles of less density than that of armored DU, avoiding penetration of the foreign round and maintaining integrity of the Abrams. DU was extensively used by the military during Operation Desert Storm/Desert Shield and more recently during Operation Iraqi Freedom and Operation Enduring Freedom.

DU is also utilized for the manufacture of armor-piercing projectiles in a sabot configuration (Figure 22-14). Because of the high density, strength, and kinetic energy of the DU sabot round, not only can it pierce through less dense material, but it is also self-sharpening and pyrophoric. Different types of DU ammunition are manufactured for the Abrams tanks, the Bradley Armored Vehicle, the Air Force A-10 Thunderbolt II, and the Marine Corps Harrier aircraft.[27]

Physical Security Systems

Although physical security systems using ionizing radiation have been used for many years, the increased threat of terrorism around the world has prompted the development of several new systems. Physical security systems range from small battery-operated x-ray systems to large, high-energy particle accelerators. Most of these systems image the contents of a package, container, or vehicle in ways similar to how medical x-ray systems are used to image the body. A few systems were also developed specifically for security screening, allowing personnel to conduct quick and nonintrusive security inspections.

Imaging Techniques

The simplest imaging technique is to place the item being inspected between an ionizing radiation source and some type of image receptor, as is done in common medical imaging. This is called *transmission* imaging

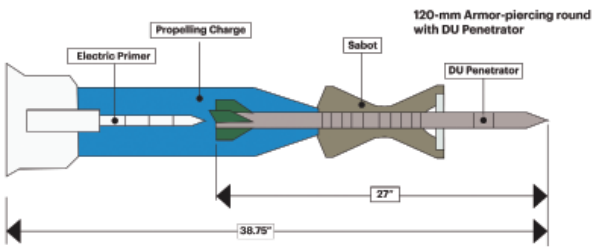

Figure 22-14. Depleted uranium (DU) is used in the construction of A1 Abrams tank armor and kinetic DU penetrators placed in 120-mm sabot rounds (used as ammunition for the Abrams).
Diagram courtesy of the US Army Public Health Center.

because the image results from the radiation that is transmitted through the item to the receptor. Areas of high density in the inspected item block more of the radiation than areas of low density, and the image is constructed based on the amount of radiation reaching a specific part of the receptor. X-ray tubes are the most common ionizing radiation source currently used, but some systems use a sealed capsule of radioactive material (usually cesium 137 or cobalt 60). Each source has advantages and disadvantages. For a portable x-ray system used to image small items, the most common image receptor is standard x-ray film, but most systems use some type of digital image receptor.

Another imaging technique is *backscatter* imaging. Whenever x-rays or gamma rays impinge upon an item, a small fraction of the incident radiation is scattered backward from the item. In backscatter imaging, the radiation source and an array of radiation detectors are placed on the same side of the item being inspected. A narrow, pencil-shaped x-ray beam sweeps across the item as it moves by (or as the source moves by the item), and detectors measure the intensity of the backscattered radiation. A computer algorithm constructs an image of the scanned item.

Each method is useful for imaging specific items. Dense objects such as metal are generally very easy to see on a transmission image. Low-density items, such as drugs and explosives, may be more difficult to see in a transmission image but will show up clearly on a backscatter image. In some physical security systems, both techniques are used simultaneously.

Baggage and Mail Inspection Systems

Baggage and mail inspection systems are used in airports, building entrances, and many mailrooms, employing transmission imaging, backscatter imaging, or both. Current systems employ x-ray sources; gamma ray sources (radioactive materials) are not currently in use. Most baggage and mail inspection systems are considered cabinet x-ray systems, and their manufacture is regulated by the Food and Drug Administration Center for Devices and Radiological Health.[29] The regulations establish limits on the radiation levels permitted outside the cabinet and require safety features such as interlocks, warning lights, and labels. By design, people cannot accidentally insert any part of their body into the x-ray beam.

Cargo and Vehicle Inspection Systems

Cargo and vehicle inspection system are similar in many ways to baggage and mail inspection systems. However, they are typically much larger and use higher energy x-rays or gamma rays. These systems can be either stationary or mobile. Stationary systems are permanently installed at an inspection site, and the cargo container or vehicle is brought to the system for inspection. Stationary systems may be mounted on rails or otherwise able to move over a limited distance in order to scan a vehicle or cargo container, or the vehicle or container can be moved past the system. Other cargo and vehicle inspection systems are mobile, truck-mounted versions that can be moved to any location where cargo or vehicles may need to be inspected (Figure 22-15).

Most cargo and vehicle inspection systems are not cabinet systems, and although they have safety features such as warning lights, labels, and interlocks, a

Figure 22-15. Cargo and vehicle inspection systems. The radiation beam is directed toward the detector tower mounted on the truck. This system can acquire both transmission and backscatter images. The x-ray source is located inside the truck box and the radiation beam is directed outward. Photographs courtesy of Leidos.

person can easily enter the inspection area, including stowaways hidden inside cargo container or vehicles. This creates an increased potential for exposure. For cargo and vehicle inspection systems, following correct operating procedures is a key aspect of radiation protection.

Personnel Security Screening Systems

Most personnel screening systems use low-energy x-rays and a backscatter imaging technique to identify items hidden under a person's clothing. These backscatter systems create an image of the body surface and any items hidden on it. Due to the detail of these images, one of the primary concerns people have about this type of screening is privacy. The radiation dose to the scanned individual is very low for backscatter systems. Most US organizations involved in personnel security screening are considering backscatter systems.

Personnel security screening systems are categorized as either general-use or limited-use systems.[30] A general-use system is considered acceptable for general screening of large numbers of people. To be considered a general-use system, the dose an individual receives for a single scan must not be greater than 0.1 μSv (10 mrem). A limited-use system is considered acceptable for occasional scanning of individuals based on a specific need. To be a limited-use system, the dose from a single scan can be greater than 0.1 μSv (10 mrem) but must not be greater than 10 μSv (1 mrem).

Transmission screening systems are capable of locating items that have been swallowed or hidden inside body cavities; however, the dose to the screened individual is somewhat higher than for a backscatter system, so use limits are required. A current transmission screening application is the prevention of diamond theft by employees at diamond mines.

Neutron analysis systems are somewhat different than the x-ray and gamma-ray systems discussed above in that they are generally not used to produce an image of the item being inspected. Instead, the item is bombarded with neutrons, causing some of the atoms in it to emit gamma rays. The gamma rays are emitted at specific energies characteristic of the elements present in the item. A radiation detector measures the energy of the gamma rays emitted, and the composition of the item can then be determined. This technique has been used in industrial applications for many years, but its application to security screening is still in the development and testing stage.

Radiation Dispersal Devices

A radiation dispersal device (RDD), commonly known as a "dirty bomb" (though a dirty bomb is only an example of these devices), is an improvised assembly or process, other than a nuclear explosive device, designed to disseminate radioactive material to cause destruction, damage, or injury. Such a weapon can be easily developed and used by a terrorist with explosives (or other means of dissemination) and access to radionuclides. The material dispersed can be obtained from any location that uses radioactive sources, such as a nuclear waste processor, nuclear power plant, university research facility, medical radiotherapy clinic, or industrial complex. The radioactive material is dispersed using explosives or other means (eg, crop-dusting aircraft).[27,31]

There are several likely scenarios for the development of an RDD. Most involve the use of radioactive material in solid form with radiation exposure levels low enough that the terrorist's ability to carry out an attack is not inhibited.[32] Such weapons would not cause a significant number of acute radiation casualties; however, they might cause a large psychosocial impact and potentially overload medical and support systems with patients complaining of psychosomatic symptoms.[32]

Although the use of large sources with highly penetrating radiation in an RDD is possible, these devices would be difficult to handle safely and are easily detectable by law enforcement.[32] In addition, the shielding required by those who would fabricate and deploy these devices complicate their use as an effective terrorist weapon. Though difficult to deploy and requiring shielding, RDDs that could cause significant radiation casualties could be deployed by perpetrators with considerable technical expertise and sophisticated resources.[32]

Radiological Base Camp Assessments

Radiological base camp assessments[33] are used to determine radiological health risks associated with deployment to an area known to have radiological contamination or a history of radiation or radioactive material uses. The assessment's purpose is to characterize external radiation exposures and to collect radiological air, soil, and water samples from their associated pathways that could have a potential negative impact on soldiers' long-term health.

The radiological base camp assessment process[33] has evolved over the past decade due to a shift in doctrine concerning soldiers' exposure to ionizing radiation. During the Cold War, the military used two

distinct policies for protection against ionizing radiation. In garrison situations and in peacetime, military regulations for radiation protection were patterned after those of civilian regulatory agencies such as the Nuclear Regulatory Commission, Occupational Safety and Health Administration, and Environmental Protection Agency. At the strategic level and during war, only short-term radiation exposures that affected mission accomplishment were considered.

In the years following Operation Desert Shield and Operation Desert Storm, the Department of Defense (DoD) has improved its doctrine for protecting soldiers from ionizing radiation and other toxic industrial chemicals and materials. Several directives, such as Presidential Review Directive-5[34] and DoD Instruction 6490.03,[35] issued in 2006, state that the military will identify, minimize, and assess exposure to radiation and other toxic substances before, during, and after all military operations including war. To comply with these directives, the DoD has developed processes to conduct occupational and environmental health surveillance and joint medical surveillance to anticipate, manage, evaluate, and control health and safety risks encountered during the full cycle of predeployment, deployment, employment, and postdeployment activities. As part of this effort, radiological base camp assessments were performed during Operation Enduring Freedom and Operation Iraqi Freedom in several countries throughout the world (Figure 22-16).

Figure 22-16. Health physics personnel from the US Army Public Health Center perform field radiation measurements during a field exercise.
Photograph courtesy of the US Army Public Health Center.

BIOLOGICAL EFFECTS OF RADIATION

The biological effects of radiation exposure depend on the type, dose rate, and total dose an individual receives. The term *exposure* is generally used qualitatively to mean the circumstance in which a person moves 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 absorbed by a medium (eg, an individual or an individual's organs or tissues). Dose is measured in units of grays (Gy) or rads, where 1 Gy is equivalent to 1 joule (J) per kilogram of absorbing medium, and 1 Gy is equivalent to 100 rads. To put these amounts in perspective, a posteroanterior-lateral 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 rem, 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 rem/year.

The amount of radioactive material is described by the term *activity*. 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 billion 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 adverse effects on health. Reports of skin reactions such as erythema and loss of hair from prolonged x-ray exposure increased during 1896.[5] These effects were initially considered trivial, and only years later were the cumulative damage and late complications of 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 technique 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.[8]

Incidents of roentgen-ray burns had been induced by prolonged and frequently repeated exposures, one of which is shown in Figure 22-17. Borden's account continues, describing a patient's exposure:

> 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, extended, and was accompanied by marked pain and hyperesthesia. The inflammatory action continued until the burn nearly covered the entire 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.[8]

During the early years of x-ray use, the fluoroscopic hand test (Figure 22-18) was routinely taught.[4] This procedure, in which the radiologist or an assistant 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 22-19).[5]

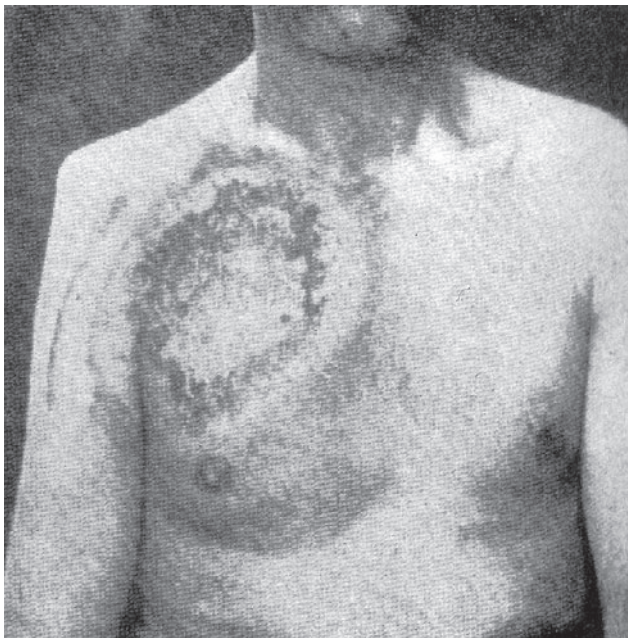

Figure 22-17. Radiation injury to the skin of a Spanish-American War soldier as a result of an x-ray examination, 1898. The radiation exposure necessary to cause this type of burn is greater than 600 R. Current technology allows a radiologist to obtain better diagnostic information at exposures that are 1,000-fold lower than the exposure this patient received. Reproduced from: Borden WC. *The Use of the Roentgen Ray by the Medical Department of the United States Army in War with Spain (1898).* Washington, DC: Office of The Surgeon General, DA; 1900.

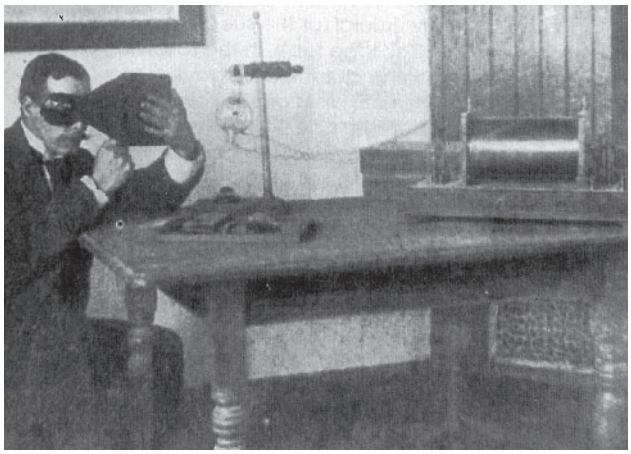

Figure 22-18. The classical posture of the radiation pioneer, shown in 1896 using his hand to test the hardness of the x-ray beam. The term "hardness" was used to describe the energy of the x-ray beam: the more penetrating the x-ray, the harder the beam. An x-ray beam that was too soft would not pass through the tissue of the hand onto the film; one that was too hard would not be stopped by dense material such as bone, and contrast on the film would be lost. Therefore, operators often used their own hand as the imaging object, adjusting the unit to balance penetrability with contrast. Repeated exposures of this type over several years cost many their fingers and hands.
Reproduced from: Feldman A. A sketch of the technical history of radiology from 1896 to 1920. *RadioGraphics.* 1989;9(6):1113–1128. Copyright: The Radiological Society of North America (used with permission).

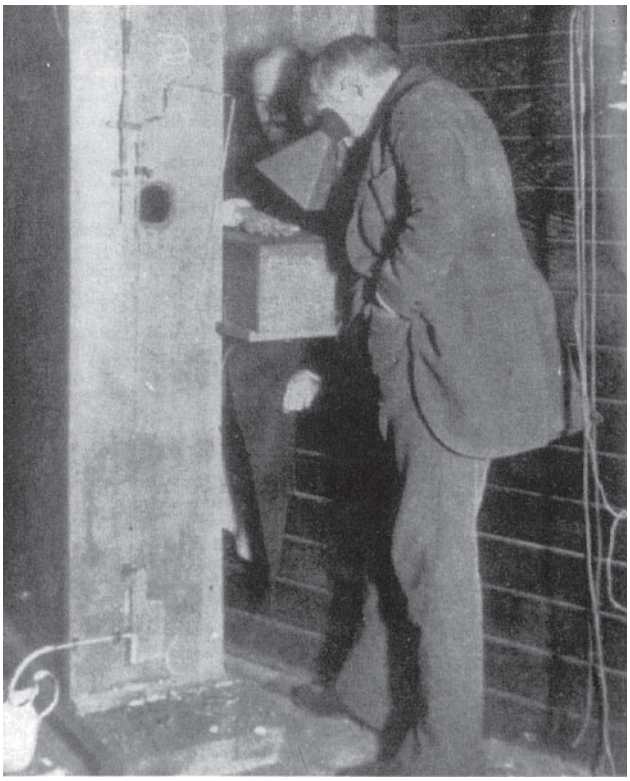

Figure 22-19. Thomas Edison looks through the fluoroscope; his subject is his assistant, Clarence Dally, who died in 1904 due to his frequent exposure to x-rays.
Reproduced from: Feldman A. A sketch of the technical history of radiology from 1896 to 1920. *RadioGraphics.* 1989;9(6): 1113-1128: Copyright: The Radiological Society of North America (used with permission).

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.[5]

Most of the general public and the industrial community were oblivious to 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 226 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.[36]

The health effects of radium exposure accompanied 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 bombarded the bone and its marrow with alpha particles and gamma rays.[36]

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 37 kBq (1 μCi) of radium 226 and an equal amount of radium 228 in one-half ounce of water.[15] His avid consumption of the elixir led to his death in 1932, which was reported nationally.[36]

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 developed cataracts, and her hands had sustained radiation damage.[37]

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.[5]

Categories and Mechanisms of Effects

The early recognition of harmful effects were associated with doses at least 10-fold higher than the current occupational limit for radiation workers (50 mSv/y). By consensus within the radiological community, these effects are categorized as *somatic* (to non-germ 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 succeeding generations. Although genetic effects have been documented in animal studies, no genetic effects have been confirmed in humans. Teratogenic effects occur in children who were exposed during their embryonic or fetal stages of development. Fetal exposure to even low doses of radiation can cause central nervous system 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.

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 at a high dose rate 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; 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* means, for the effect in question, that 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 because 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 1 to 2 Sv will experience leukopenia (an abnormally low number of circulating leukocytes). The exact dose level that causes 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, people who have received therapeutic radiation or doses of radioactive material, and uranium-mine workers at risk of lung cancer. Several complications limit the application of these data to radiation-risk assessments, however. For example, all the observed effects occurred in populations who received doses much higher than those currently allowed for occupational exposures.

In a 2005 report,[38] the National Academy of Sciences estimated the lifetime excess risk of death from cancer after an acute, whole-body dose of 0.1 Sv to be 0.8%. 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 22%. Therefore, exposure to 0.1 Sv of ionizing radiation raises the total risk to 22.8%. These risk estimates, however, 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.[38]

PROTECTION AGAINST RADIATION

As adverse radiation effects became better documented and understood, the field of radiation protection 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.

Scientists began to formulate 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 aboveground 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.[39]

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 US Public Health Service (USPHS) initiated a nationwide program to monitor air, water, and food for radioactivity. Responding to public concern, the scientific community also focused on limiting exposures from diagnostic x-rays. In the early 1960s, the USPHS initiated a program to reduce these exposures. 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 disseminated to the medical profession emphasized that medical professionals should exercise sound judgment concerning the clinical necessity for any x-ray examination they order.[39] 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.[40]

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 he suggested that fluoroscopists be provided with leaded-glass goggles and x-ray systems outfitted with shielded tube housings.[40]

World War I spawned increased x-ray hazards, as more people used and were exposed to radiation from 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 with wartime experiences with radiation returned to the civilian community. Also at this time, the death rate among radiologists from radiation exposure was noted to be rather high.[36] 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 cumulative exposures that could lead to cancer.

Dr George Pfahler, a Philadelphia radiologist, and Dr J.S. Shearer, a Cornell University physicist, contributed to the understanding of the hazards that medical radiation poses to both the patient and medical personnel. Shearer, who had served in the US Army during World War I, developed a portable bedside x-ray unit for field use. He was also involved in initiating and conducting an x-ray training school in New York for Army personnel.[16]

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 to discuss 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 Congress's 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 (ICRP), also was founded at this meeting.[37] Since 1928, this group has established the basic pattern for radiation protection recommendations throughout the world. Lauriston S. Taylor of the National Bureau of Standards was also 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 (NCRP), to promote radiation protection in the United States.[36] 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 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.[37]

The Manhattan Project prompted the next surge of radiation-protection activity. Physicists recognized that the project would create a new and intense source of radiation and radioactivity. Ernest O. Wollan, a cosmic-ray physicist at the University of Chicago, was asked to form a group to study and control the resulting radiation hazards.[16] The quantities and varied characteristics of the new radionuclides created by nuclear fission would require the full-time attention of a new group of specially trained professionals: health physicists.[37]

The radiation-exposure safeguards developed and used during the Manhattan Project include 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. These measures form the basis of radiation protection today.[36]

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 carrying an unexposed photographic plate in his pocket each day, and then developing it to determine if he had been exposed to x-rays.[16] 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.[16] The US Army initially used film badges to monitor radiation exposure but replaced them with thermoluminescent dosimeters (TLDs) between 1985 and 1989. From that period on, the TLD became the device of choice for monitoring personal radiation exposures in industrial and medical settings within the US Army. All TLDs are collected and processed, and final results are recorded and archived at the US Army Dosimetry Center (ADC) at the Army's Redstone Arsenal in Alabama.

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 cGy in modern units).[16,37] In June 1915, the British organized a radiation-protection interest group charged with preparing a brief outline of protection requirements for the safe operation of x-ray equipment.[16] World War I interrupted this work, but the members regrouped after the war and drafted extensive recommendations for radiation workers, encompassing both diagnostic and therapeutic protection.[16]

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. In 1924, Arthur Mutscheller made the first real attempt to define the tolerance dose, and his work served as the basis for radiation safety standards for nearly 2 decades.[37] As the quantitative means to measure radiation exposure were developed, tolerance doses were expressed in quantitative form. 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 10% of the erythema dose per month. Swedish physicist Rolf Sievert, working independently, proposed the same tolerance dose in 1925. 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.[37] By 1928, most physicists in the health field accepted Mutscheller's proposed tolerance dose. In 1931, the ICRP recommended shielding tables based on a tolerance dose of 0.00001 R/second.[36]

In 1934, the American Advisory Committee on X-ray and Radium Protection suggested a tolerance dose for radium exposure of 0.1 R/day to the whole body and 5 R/day to the fingers. The committee had actually calculated a dose of 0.24 R/day, but, concerned about the assumptions used to arrive at that value, it decided to take a conservative approach and proposed 0.1 R/day instead. The same year, the ICRP 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 ICRP was less conservative in its approach.[36]

In 1941, the National Bureau of Standards published *Safe Handling of Radioluminous Compounds*,[41] 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 [3.7 MBq] of radium, based on the work of Robley Evans), and a *maximum permissible concentration* of a radionuclide in the workplace (10 pCi [0.37 Bq] of radon per L of ambient air). Also 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,[37] and the same year Taylor recommended that the permissible level for external exposure be reduced to 0.02 R/day, which is approximately 5 rem/year (50 mSv). The rem unit, which accounts for the biological effectiveness of the radiation and the maximum permissible concentration for inhaled radioactivity, was a byproduct of the Manhattan Project.[16]

After World War II, the NCRP, 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 by the US Advisory Committee on X-ray and Radium Production,[39] changed to 15 rem/year in 1948, and then to 5 rem/year in 1958.[37] In 1949, the NCRP introduced the concept of a lower radiation level for non-occupational exposure. This level was 10% of the allowable exposure for radiation workers.

Regulatory Agencies

A decade of federal involvement in radiation protection began in 1959. Members of key agencies involved in nuclear work formed the Federal Radiation Council (FRC), charged with providing regulatory guidance concerning radiation protection to federal agencies. In 1970, the FRC was abolished, and the Environmental Protection Agency (EPA) assumed its responsibilities. Today, the regulatory structure includes the Occupational Safety and Health Administration (OSHA) and the US Nuclear Regulatory Commission (NRC) 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.[39] As a result of the act, the USPHS assumed responsibility for regulating the performance of imaging equipment and promulgated the first standard for diagnostic x-ray equipment.

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 reasonably achievable (ALARA).

The Atomic Energy Commission, which had been established in 1946,[42–44] was dissolved in 1975, and its activities relating to technology promotion were assigned to the Energy Research and Development Administration (later incorporated into the Department of Energy); its regulatory authority was assigned to the newly created NRC. Today, the Department of Energy 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 currently has several programs in place to protect people and the environment from the potentially harmful effects of ionizing radiation. 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 EPA, the NRC, OSHA, and the individual states all promulgate limits based on recommendations of international or national scientific advisory bodies. However, for US Army personnel, allowable exposure limits in the workplace (Exhibit 22-3) are prescribed by Department of the Army Pamphlet (DA PAM) 385-24,[45] which is in accordance with Title 10, Code of Federal Regulations (10 CFR), Part 20.[46] Planned special exposures, while defined in 10 CFR, Part 20, and permitted under NRC licenses under very limited, highly controlled circumstances, cannot be performed by Army or Defense Logistics Agency NRC license holders without a waiver.[46]

The occupational dose limits presented in both 10 CFR, Part 20,[46] and DA PAM 385-24[45] are as follows.

- For the annual whole-body dose limit, the more limiting of either:
  - the total effective dose equivalent being equal to 5 rem (0.05 Sv), or
  - the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye being equal to 50 rem (0.5 Sv).
- For the annual limits to the lens of the eye, the skin of the whole body, and the skin of the extremities:
  - a lens dose equivalent of 15 rem (0.15 Sv), and
  - a shallow-dose equivalent of 50 rem (0.5 Sv) to the skin of the whole body or to the skin of any extremity.

Emergencies may require first responders or occupational radiation workers to exceed the dose limits prescribed above in order to save lives or valuable property. In an emergency, responders or workers must weigh the benefit of action against the relative risk of radiation exposure. When exposure limits will be exceeded, the incident commander, to the extent the situation allows, should consider the following[47]:

- Acute effects are likely at about 1,000 mSv (100 rem).
- The lethal dose to 50% in 60 days is about 4,000 mSv (400 rem).
- Rescuers must be volunteers and must be fully informed of the risk if the dose equivalent expected is greater than 250 mSv (25 rem). Rescuers' dose equivalent should not exceed 500 mSv (50 rem).
- Rescuers should be briefed on the potential acute radiation effects and statistically inferred increased risk for cancer from doses that may be received during the operation.
- When emergency actions do not involve life-saving rescue, but may include protection of valuable property or equipment, exposures should not exceed 100 mSv (10 rem).

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 around 3 mSv/year. Occupational radiation doses below the background are not necessarily acceptable from a public health planning perspective, because the risk of developing a fatal cancer from radiation exposure potentially increases with increased dose. Therefore, occupational health programs consider all occupational ionizing radiation exposure to be potentially harmful and attempt to keep exposures ALARA.

Non-occupational Dose Limits

In an attempt to limit radiation exposures from the use of sources of ionizing radiation, non-occupational dose limits were developed both for individuals in the general public and for the population as a whole. The

EXHIBIT 22-3

ARMY PERSONNEL IONIZING RADIATION EXPOSURE STANDARDS

Category	Maximum[1,2,3]
Member of the general public	1 mSv (100 mrem) (TEDE) in calendar year[4]
Fetus/embryo of occupationally exposed declared pregnant woman	5 mSv (500 mrem) (DDE of mother + ED due to radionuclides in fetus/embryo) for gestation period, not to exceed 0.5 mSv/month
Occupational exposure of adults	50 mSv (5 rem) (TEDE) in calendar year
Lens of the eye	0.15 Sv (15 rem) (EDE) in calendar year[3]
Skin or extremity	0.5 Sv (50 rem) (SDE) in calendar year
Occupational exposure of minors	10% of limits for adults

1. From 10 CFR 20. Refer to 10 CFR 20 for detailed standards.
2. Abbreviations: TEDE = total effective dose equivalent; DDE = deep dose equivalent; ED = effective dose; EDE = effective dose equivalent; CDE = committed dose equivalent; SDE = shallow dose equivalent.
3. OSHA standard for occupational exposure of adults and for the lens of the eye is 1¼ rem (12.5 mSv) in calendar quarter. OSHA standard for skin of whole body is 7½ rem (75 mSv) in calendar quarter. OSHA standard for hands and forearms; feet and ankles is 18¾ rem (187.5 mSv) in calendar quarter.
4. The dose in any unrestricted area from external sources, exclusive of the dose contributions from patients administered radioactive material and released in accordance with applicable regulations, will not exceed 2 mrem (0.02 mSv) in any one hour.

Reproduced from: US Department of the Army. *The Army Radiation Safety Program.* Washington, DC: DA; 2015. DA Pamphlet 385-24: 23.

accumulated radiation dose equivalent to the whole body for a person in the general public *must not exceed* 1 mSv in any calendar year (100 mrem/y). This limit excludes natural background radiation, prescribed medical and dental exposures, and the contribution from any authorized disposal of licensed radioactive material into the sanitary sewage system. Authorization to exceed 1.0 mSv/year (but not to exceed 5 mSv/y [500 mrem/y]) must be requested, through command channels, from the director of Army safety. NRC licensees must request authorization from the NRC per 10 CFR, Part 20.[46]

MEDICAL RESPONSE TO RADIATION INCIDENTS

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 high-energy x-ray systems or uses or stores radioactive material. Such an event could produce individual to several hundred casualties, even to several thousand in a terrorist incident. It is probable that at least some medical personnel and facilities would be available to respond, and while such an event would certainly be a catastrophe, it probably would be manageable.[47]

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, needle sticks, 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 administered within a few hours after radioiodine I 131 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 US Army Public Health Center (APHC)[48] or the Armed Forces Radiobiology Research Institute.[49]

External Irradiation

External irradiation can cause partial or whole-body exposures. The most common 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 contrast, external irradiation of the whole body typically involves exposure to an un-retracted 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 injuries are medically independent and the treatments are completely different. 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. Casualties with combined injuries should be treated in the following sequence:

1. Treat life-threatening physical trauma first, to the extent necessary to stabilize the patient, and to permit decontamination and attention to severe radiation injuries.
2. Perform initial decontamination and wound debridement, but terminate this phase if the patient's condition deteriorates; begin again when the patient is medically stable.
3. Finish decontaminating the patient.
4. Complete the short-term trauma care.
5. Estimate the dose sustained from external irradiation and attempt to estimate the extent of internal deposition.
6. Implement appropriate therapy for the radiation injuries.
7. Initiate definitive medical care for physical trauma.
8. Initiate long-term follow-up care.

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, the victim will not become a high-level source of radiation, especially if any degree of decontamination has been performed. The exception is a 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 US Army's *Emergency War Surgery* handbook, 4th edition, discusses the debridement of penetrating injuries contaminated with radioactive debris.[50]

Mass Casualties

"Mass casualties" is a relative term, depending on the ratio of casualties to the medical resources available. When medical resources are plentiful, mass casualties are triaged according to the urgency of the victims' medical needs (as are casualties 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 expended in a peacetime radiation accident that produces only one casualty, an accident producing mass casualties would probably require the resources of several hospitals.

If mass casualties occur in a setting where medical resources are limited, then triage must be similar to that used by the military medical departments during wartime. Military medical departments are charged *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 injuries will rarely be so severe that their treatment takes priority in triage. Even for a patient with very high levels of contamination in their body, or with a high-level radiation exposure, physical trauma will probably be the greatest immediate threat to life or limb.

Procedures for Whole-Body Exposures

The treatment of patients with significant whole-body radiation exposures is a complex medical problem. Current knowledge of ionizing radiation and its pathophysiology and treatment is based on data from the accidents in Chernobyl, USSR (1986), and Goiânia, Brazil (1987 [see Exhibit 22-2]); wartime detonations of atomic bombs in Hiroshima and Nagasaki, Japan (1945); and a vast amount of laboratory experimentation. *Medical Consequences of Radiological and Nuclear Weapons* discusses the subject in detail.[2]

Low-Dose Exposures

Medical intervention is rarely necessary for patients who have sustained low doses (< 50 cGy) of radiation. Minimally irradiated patients should be placed in a holding area or available hospital beds. The most important therapy is assuring and reassuring these patients that their exposure was non-threatening. 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 (less than about 100 mSv), the risk of fatal cancer increases to about 1.0% over the normal incidence of fatal cancers (approximately 25%) to approximately 26%.[51] Long-term follow-up, which must be continued throughout the patient's life, should focus on solid tumors and, less likely, on leukemia.

Intermediate-Dose Exposures

Medical care is usually necessary for patients who have sustained intermediate doses (50–500 cGy) to survive acute radiation injury syndrome. Those exposed to the lower end 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 end of the 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 prodromes, 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, followed by a latent period of up to 3 weeks. Doses at the lower end of the range cause a later appearance of prodromes. The lower-dose prodromal phase is shorter in duration than that associated with the upper-dose range, and the latency for lower-range doses is longer than for upper-range doses.

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 decrease in blood values, the onset of aplastic anemia, and gastrointestinal bleeding and other sequelae of small bowel injury.

Statistically, a dose between 300 and 500 cGy will kill 50% of irradiated individuals within 60 days, even if antibiotics and other supportive care are provided. 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 and no medical care is provided.[47]

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 at levels 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.[47]

Protecting the Medical Team

Protection of the medical staff against external irradiation is afforded by minimizing the amount of time they are near the radiation, maximizing the distance from the source, and placing a shield between staff and the radiation source. Contamination (whereby radioactive material on or in the casualty becomes deposited on or in the medical worker's body) is an unlikely hazard to the medical response team. However, to be prudent, 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's exposed areas and, as time permits, decontamination of the whole body.

The risk to the members of the medical team who treat a victim of a radiation accident depends on the victim's level of radiation contamination and is usually low. Medical personnel receive annual refresher training to reinforce concepts for treating various radiation injuries and to allay any fears that the risk levels may be higher than they are.

Low Risk

Victims exposed to an x-ray beam pose no risk to the medical team. Likewise, those who have sustained internal deposition from an accidental needle stick 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.

In general, externally contaminated patients pose a low risk to the medical team. The primary hazard to medical personnel is that the victim's external contamination will transfer to the medical personnel and deposited internally via ingestion, inhalation, or accidental needle stick. Although 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, these preventive measures should be followed:

- 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.

Moderate and 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, although it is very unlikely*. They require significant medical attention, and their level of physical trauma may make the removal of the radioactive material prior to treatment difficult or impossible to achieve.

All the preventive measures taken with a low-risk casualty apply in moderate-risk or 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, nonessential personnel should be kept out of the treatment area, and anyone should step away from the patient when their presence is not mandatory. When *time* is employed, only essential procedures should be performed initially, as quickly and carefully as possible. 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 procedure could have a severe impact if the contaminated area is a critical component such as an operating room; therefore, a small, non-critical room should be used to treat contaminated patients. Vigorous efforts must also be exerted to keep 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 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, and 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, anti-contamination gear, and a brief standard operating procedure (SOP) on radiation injury treatment;
- preparation of the receiving and treatment areas before the casualties arrive at the MTF to facilitate containment of contamination and 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 with media and local government officials.

The Fukushima Incident

On March 11, 2011, a 9.0-magnitude earthquake occurred off the east coast of Japan. As a result of the earthquake, a large tsunami destroyed Fukushima and the towns surrounding the city. The tsunami wave also affected three nuclear power reactors located in Fukushima. It was the largest earthquake and tsunami ever recorded in Japan. Electrical power was lost to the Fukushima Daiichi nuclear power station because of the increased water levels overflowing the Fukushima reactors (Figure 22-20).

Figure 22-20. Reactor buildings 3 and 4 at Fukushima Daiichi nuclear power station following the fire and explosion that occurred when cooling water was disrupted due to flooding following the earthquake and tsunami.
Reproduced with permission from the Tokyo Electric Power Company.

The plant's emergency generators began providing critical electrical power; however, an hour after the earthquake, a wave over 30 feet high crossed over the lower protective sea walls of the facility and flooded the station, resulting in extensive damage and a complete loss of power to five of the six nuclear reactors. Despite heroic repair efforts by the plant's workers, cooling to the reactors was eventually lost. Explosions occurred in Fukushima reactors 1 through 3, which resulted in the release of significant amounts of radioactivity into the atmosphere and the ocean.

In response to the Fukushima incident, the US DoD established the Operation Tomodachi Registry (OTR). The OTR includes nearly 75,000 DoD-affiliated individuals who were on or near the mainland of Japan during the period from March 12, 2011, to May 11, 2011, along with their corresponding whole-body and thyroid radiation doses. Over 58,000 individuals were associated with one of thirteen shore-based locations, which included DoD military installations and major cities where the majority of the DoD-affiliated population worked or lived. Nearly 17,000 individuals were associated with US Navy fleet-based locations, which included 25 Navy ships in the area during this period.[52]

THE DEPARTMENT OF DEFENSE RADIATION SAFETY PROGRAM

The primary goals of all radiation protection programs are to (1) maintain both individual and collective exposure ALARA, and (2) minimize the release of radioactive effluents into the environment. Through these goals, the DoD Radiation Safety Program[45] seeks to protect all personnel from unnecessary exposure

to ionizing radiation in accordance with national and international scientific recommendations.[53,54] These recommendations include the following:

- **Justification**. No procedure shall be adopted unless its introduction produces a positive net benefit.
- **Optimization**. All exposures shall be maintained ALARA.
- **Limitation.** Dose equivalent limits for individuals shall not exceed the limits recommended for the appropriate circumstances by the DoD and NRC.[45,46,53]

Program Responsibilities

Although there are differences in implementation between the uniformed services' radiation safety programs, their broad contours are very similar. Within the US military, installation and activity commanders are responsible for the Radiation Safety Program (referred to as the Radiation Protection Program in Navy and Air Force regulations) at their respective commands. Both the Navy and Air Force maintain master licenses through the NRC for their radioactive material, allowing these two services to issues use permits directly to their subordinate commands. The Army maintains a number of independent licenses directly with the NRC for radioactive commodities, including at research laboratories, field activities, and MTFs with nuclear medicine departments. The commander is designated as the NRC 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, the general public, and workers from unnecessary exposure to radiation. The Radiation Safety Program is managed for the commander through the Radiation Safety Committee (RSC) and the radiation safety/protection/health officer (hereafter referred to as the RSO).

Radiation Safety Committee

Organizations that use radioactive material under a specific NRC license, DoD permit, or other military radiation authorization must appoint an RSC,[45,46] an advisory body that assists the commander in establishing local rules and procedures for the safe use of radioactive materials and machine-produced ionizing radiation sources. The committee accomplishes this task by reviewing any matter affecting radiation safety and making recommendations for senior management approval. Although the RSC's membership varies among organizations, the core should include a top-management representative (deputy commander or equivalent) who is not a radiation user, the RSO, a representative from each unit in the installation (or department in an MTF) that uses radioactive material, and a medical representative. The RSC is responsible for establishing policy and providing oversight to:

- ensure the safe use of radiation sources and radiation-producing devices;
- ensure compliance with regulations;
- ensure that the use of the radiation is consistent; and
- identify problems and their solutions within the program.

To meet these responsibilities, RSC members should possess experience and competence in the safe use of radioactive material, and be familiar with the institutional Radiation Safety Program and applicable regulations. In general, the RSC meets at least once in each 4-month period at the call of the chair[45,46] and keeps written records or minutes of the meeting. Within the Army system, an RSC must exist before an organization applies for an NRC license. For medical programs that employ radioactive material for human use, specific requirements for the composition of an RSC and its responsibilities are listed in 10 CFR, Part 35[55]; DA PAM 385-234[45]; Army Regulation 385-10, *US Army Safety Program*[56]; and the NRC license application specific to the individual licensee.[46,55]

Radiation Safety Officer

Because the commander bears the ultimate responsibility for the radioactive materials used under his or her command, the commander will designate, in writing, a qualified individual as the RSO to manage the Radiation Safety Program.[45,46] The qualifications of the RSO 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 RSO. Because the RSO must make decisions that affect the current and future lives and well-being of personnel, he or she should report directly to the commander. According to 10 CFR, Part 35,[55] the commander shall provide the RSO sufficient authority, organizational freedom, time, resources, and management prerogative, to:

- identify radiation safety problems;
- initiate, recommend, or provide corrective actions;

- stop unsafe operations; and
- verify implementation of corrective actions.

The RSO's role is to provide specialized assistance and guidance in developing the radiation safety aspects of the Radiation Safety Program.[45,46] The RSO determines if established programs are being maintained and are adequate for present needs. However, the RSO's oversight function in no way diminishes the responsibility of the user or supervisor to conduct operations in a safe and legal manner. Although the RSO usually takes charge of regulatory compliance actions (such as surveys and personnel dosimetry), it is the licensee and/or the commander, not the RSO or the radiation safety staff, whom the NRC holds personally responsible for assuring both the safe performance of licensed activities and adherence to NRC requirements.

Program Elements

A radiation protection program may include some or all of the following elements, depending on extent and type of the radiation hazard and the number of monitored personnel: (*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 SOPs, training, and designation of restricted areas.

Standard 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 examiner because its 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:

- type of protective apparel required,
- posting requirements,
- radiation monitoring devices required,
- personnel dosimetry requirements,
- bioassay types and frequency required,
- recordkeeping requirements,
- reiteration of any other applicable administrative requirements, and
- any other 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). The review should include the radiation supervisor, the RSO, and the RSC. 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,
- 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 safety training program. Although the RSO is responsible for implementing program policies and providing subject matter expertise to develop the policies and procedures relating to radiation safety for all staff members, management's commitment to radiation safety should also be obvious. The scope of training varies greatly depending on job requirements. For example, physicians who treat patients with radioisotopes are required to be 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.[55] All personnel who work in radiation areas or controlled areas should receive extensive training specific to the potential hazards and appropriate mitigation of hazards in these areas.

Other personnel such as firefighters, security forces, housekeeping personnel, facility engineers, nurses, and medical maintenance personnel should also receive training; even though they do not work with radiation directly, they might be required to

EXHIBIT 22-4

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

ALARA: as low as reasonably achievable
SOP: standard operating procedure

enter radiation areas. All personnel should receive training before entering or beginning work in a radiation area or controlled area. They should also receive training annually thereafter, more often if policies and procedures change. Exhibit 22-4 lists some safety subjects common in radiation protection training (this list is not exhaustive). Program requirements, the audience, and their educational needs dictate the depth of these subjects. In some instances, particularly if a serious, acute health hazard exists, training with mock sources or facilities will familiarize personnel with the actions required in an emergency.

One area of training that requires special consideration is the instruction of women who might become pregnant. Because a fetus is highly sensitive to ionizing radiation, the RSO or other qualified individual should advise women of childbearing age about the special need to limit their exposure. Additionally, pregnant women, and those planning a pregnancy, must be counseled on the options available to limit the fetus's exposure to radiation.[57]

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 DoD, NRC, and OSHA have all established special controls, particularly training requirements, that apply whenever personnel enter a controlled radiation 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 design and construction of safety systems employs the *fail-safe* principle whenever possible. A fail-safe system causes the device to shut down without exposing personnel to radiation during any malfunction, including the malfunction of the fail-safe system itself.

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:

- general facility layout, incorporating 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 contain 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 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

Routine medical examinations for individuals occupationally exposed to ionizing radiation are usually not necessary. A reported overexposure does not necessarily indicate the need for a medical examination. The circumstances associated with the reported overexposure and the estimated organ or whole-body dose should help determine the type and extent of any examination, as well as the types of laboratory or medical tests. The supporting medical commander to units on installations, in consultation with the unit and installation RSO, will determine if a medical examination is necessary for individuals occupationally exposed to radiation. The medical commander and RSO will refer any individual suspected of having received a radiation dose in excess of the limits specified in DA PAM 385-24 to a physician.[45] The supporting medical commander and the supporting occupational health physician will determine the appropriate level of examination and treatment. Personnel potentially exposed to nonionizing radiation should receive appropriate medical examinations as specified in DoD Instruction 6055.11[58] and TSG policy directives.

The following factors should be considered when determining an appropriate medical examination:

- total actual or suspected dose,
- types of radiation to which the individual was exposed,
- portion of the body exposed,
- target organ dose,
- time elapse between the exposure and notification, and
- other appropriate factors.

Copies of reports documenting reported overexposures must be forwarded to APHC for archiving whether or not an actual overexposure occurred. Documenting a determination that a suspected overexposure did not occur is as important as documenting actual overexposures.[45,46]

Personnel Monitoring

Personnel monitoring includes monitoring devices, such as thermo-luminescent dosimeters (TLDs) and self-reading pocket dosimeters, and bioassays. *Dosimetry* measures exposure to radiation, and a *dosimeter* is a device used to provide a quantitative estimation of the dose received. Each person who might receive an accumulated dose equivalent in excess of 10% of the applicable dose limits must wear a dosimeter. In addition, any employee who enters a high-radiation area must wear a supplementary dosimeter, usually a self-reading electronic one (Figure 22-21). Electronic dosimeters are similar to pocket dosimeters in that they contain a small ion chamber, but their readout is in the form of a digital display, and they are not as sensitive to being physically jarred as pocket dosimeters. Dosimeters used should provide accurate, reproducible readings; be capable of measuring all radiation exposures that personnel encounter; and be simple, convenient, small, and inexpensive.

Figure 22-21. Three types of dosimeters. The instrument on the left is an IM 93A/UD pocket dosimeter used in a tactical military environment. The IM-93A/UD can detect gamma radiation between 0 and 600 R. The middle instrument is a thermoluminescent dosimeter (TLD) used in both medical and industrial settings within the Department of Defense to determine radiation doses workers are exposed to. TLDs also have been used in tactical environments. The four tissue-equivalent materials within a TLD can show the radiation dose from different forms of radiation. The range of the TLD is from 0.5 mSv to 10 Sv. On the right is the AN/UDR-13 electronic dosimeter, which is used extensively in the military. The compact and rugged AN/UDR-13 is capable of detecting gamma and neutron radiation doses, as well as the dose rate for gamma radiation. This dosimeter's capability is 1 to 999 cGy for dose detection, and 0.1 to 999 cGy/h for dose rate. Photograph courtesy of the US Army Public Health Command, Aberdeen Proving Ground, Maryland.

The dosimeter-wearing period is usually either every month or every 3 months for occupational doses; at the end of every month or every quarter, a new dosimeter is provided to the worker. Depending on specific radiological occupational exposure, other wearing periods may be arranged. The ADC, part of the US Army Materiel Command, supplies dosimeters to all Army, National Guard, and Defense Logistics Agency personnel.[59] Personnel at Army government-owned, contractor-operated (GOCO) facilities and contractor personnel who work in Army facilities and require dosimeters must use those supplied by the ADC unless a written contract specifically exempts them. (Non-GOCO

contract personnel working under provisions of an Army radiation permit may use contractor-supplied dosimetry.)[59]

Bioassays are considered the final quality control used to ensure adequate protection of workers against internal radiation exposure. 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). Requirements for bioassays are usually components of occupational health programs dealing with metals and other industrial chemicals.[60] Although the requirements of a bioassay program are beyond the scope of this chapter, International Commission on Radiation Protection Report No. 78, *Individual Monitoring for Internal Exposure of Workers*,[61] provides comprehensive information. Additional information is available in NCRP Report 87, *Use of Bioassay Procedures for Assessment of Internal Radionuclide Deposition*,[60] and the Health Physics Society document *Design of Internal Dosimetry Program*.[62]

Respiratory Protection

A respiratory protection program involves much more than issuing a respirator to an employee. The preferred methods to reduce risk of exposure to airborne contaminants are (*a*) reducing the air concentrations of hazardous substances by substitution with a less toxic substance and (*b*) engineering and administrative controls. However, an appropriate respirator must be selected for each type of exposure, and respirators must be appropriately fitted to the employee. Qualified medical and safety personnel are essential to an effective respiratory protection program. Employee training must include how to use and properly maintain the respirator. Medical clearance is also an essential part of the respiratory protection program.[45,46]

Respiratory protection is required wherever unsealed radioactive material is processed in such a manner that inhalable air concentrations pose a significant health threat to the radiation worker. As a guideline, respiratory protection must be evaluated whenever an individual is potentially exposed for 40 hours per week, for 13 weeks, to air concentrations equal to or greater than those listed in 10 CFR, Part 20.[46] Whenever respiratory protection is required, a bioassay program is also required.

The careful design of an air-sampling program can alert the RSO 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 ensure that adequate personnel protection is in place, it is imperative that the sample be representative of the situation under investigation. To accomplish this, a worker should wear a personal air sampler near his or her respiratory zone to collect an air sample. In addition, ambient air at the worker's height should be sampled to approximate the air concentration of the contaminant in the worker's breathing zone. The sampler should collect respirable-sized particles rather than the larger, heavier particles that settle out of the air onto the collector. The sample size must be large enough to represent a reasonably accurate estimate of the mean concentration of airborne particles and 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 referred to as *documentation*. Complete documentation should include information on radiation exposure patterns and working conditions. 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.

MEDICAL RESPONSE TO DEPLETED URANIUM EXPOSURE

Department of Defense Policy for Handling Exposures to Depleted Uranium

In its natural form, uranium is only slightly radioactive, and although DU is 40% less radioactive than natural uranium, its chemical or metal properties are the same as other forms of uranium.[59] DU must be taken into the body to be a potential health hazard. The potential for DU exposure among service members occurs through occupying vehicles penetrated by DU munitions, rescuing occupants of these vehicles, or performing other operational duties involving these vehicles (equipment removal, repair, salvage, etc). Exposures may also occur when a wounded individual retains fragments that contain DU in his or her body, breathes air containing DU dust, or transfers DU dust unintentionally from contaminated surfaces to the mouth or open wounds.

Since the end of the 1991 Persian Gulf War, the Army Medical Department has been actively involved in assessing potential health risks from exposure to DU during military operations. Army policy guidance

stems from DoD Health Affairs Policy 03-012 (issued May 30, 2003).[63] This policy calls for the referral of all service members who have embedded DU fragments or other evidence of significant DU exposure to the Department of Veterans Affairs (VA) DU Follow-Up Program. This program was developed during the Gulf War for ongoing monitoring of exposed service members, in order to identify any long-term implications of DU exposure. The policy requires the services to:

- Identify all service members who may have had internal exposure to DU.
  - Members may identify themselves as being exposed on the Post-deployment Health Assessment (Defense Department [DD] Form 2796) or by reporting for medical care.
  - The services must actively try to locate units involved in operations or incidents that might involve DU exposure.
- Have service members answer the DU Exposure Questionnaire (DD Form 2872) to help assess the level of risk associated with a possible exposure.
- Review the circumstances of the exposure and assess the level of risk.
  - Level 1. Personnel who may exceed occupational safety levels by taking in a sufficient amount of DU into the body.
  - Level 2: Personnel who are routinely exposed to DU-damaged vehicles or fires involving DU munitions.
  - Level 3: Personnel with incidental exposures to DU.
- Obtain DU bioassay material from all personnel found to have Level 1 or Level 2 exposure.
  - Urine uranium assays (for total uranium and DU) should be done as soon as operationally feasible, and preferably within 180 days of the most recent incident.
  - The Army tests specimens at the Laboratory Sciences Directorate of the APHC; Air Force testing is done at the Radioanalytical Laboratory at the Air Force School of Aerospace Medicine at Wright Patterson Air Force Base; and Navy and Marines testing is performed at the VA Medical Center in Baltimore, Maryland.
  - Uranium in urine results must be normalized to urine creatinine values, and a specimen aliquot must be retained indefinitely.
  - Level 3 exposure cases may be tested by request of the healthcare provider or the service member.
- Notify the service member of the testing results and ensure that the results are placed into the medical record.
- Offer those with significant levels of DU exposure, as evidenced by the bioassay material, referral to the VA DU Follow-Up Program.
  - Managed by the Baltimore VA Medical Center.
  - The VA follows a cohort of exposed individuals with medical exams, questionnaires, and additional medical testing for long-term effects of DU.
- Effectively communicate the current medical condition and future risks associated with DU exposure to service members and their family, using established risk-communication principles, addressing:
  - the reason they are being evaluated for DU,
  - the timeliness and nature of the assessment process,
  - potential individual risk from DU exposure,
  - the (generally) low incidence of significant DU exposure in theater, and
  - the medical follow-up available to service members.
- File an annual report of DU bioassay results with the Defense Health Agency. Health Affairs Policy 04-004[64] added additional requirements to the overall guidance for handling DU exposure cases:
  - Embedded DU fragments that are removed from service members must be analyzed for metal composition.
  - The Army tests specimens at the Laboratory Sciences Directorate, APHC; all others are performed at the Joint Pathology Center in Silver Spring, Maryland.[65]

Toxicology of Depleted Uranium Exposure

About 98% of any form of uranium entering the body via ingestion is not absorbed; rather, it is eliminated in the stool. The fraction of uranium absorbed in the blood is generally greater following inhalation. Of the uranium that is absorbed in the blood, approximately 70% is filtered by the kidney and excreted in the urine within 24 hours; this amount increases to 90% within a few days.[66] The remaining 10% is absorbed into the bones and organs, from which it leaches out into the blood over time.[67] The target organ for uranium toxicity is the kidney. The metal selectively injures the middle segments of the kidney's proximal convoluted tubule. Experimental animal models ex-

posed to uranium develop acute tubular necrosis that often leads to renal failure.[68]

Results of Depleted Uranium Exposure Follow-Up

Since 2003, the APHC has conducted DU analysis for over 3,000 urine specimens from almost 2,900 service members involved in overseas contingency operations. These individuals submitted 24-hour urine specimens along with exposure and specimen collection information vital for proper interpretation. Service members with verified DU intakes have been referred to the DU monitoring program at the Baltimore VA Medical Center.

The group with the longest follow-up period comprises 32 individuals who were victims of friendly fire involving DU weapons and had retained fragments of DU within their bodies. This cohort, followed at the Baltimore VA Medical Center, is regularly reported on in the medical literature. For evaluation, these victims were grouped according to their level of urine uranium concentrations. The low-level group had urine levels of less than 10 μg of uranium per gram of creatinine, and the high-level group had greater than or equal to 10 μg of uranium per gram of creatinine. There has been no detectable dose-related difference between these groups. Both groups have persistent elevations in urinary uranium levels, which may be to be due to ongoing mobilization of the retained DU. Renal function remains normal; however, there have been subtle changes indicative of early abnormalities in the proximal tubules of the kidneys. No significant uranium-related health effects have been observed in blood count, blood chemistries, neuropsychological measures, semen quality, or genotoxicity measures.[65,66]

Additional information on the physical aspects and toxicological profile of DU can be obtained through the World Health Organization[69] and the US Department of Human and Health Services.[66]

SUMMARY

Humans have always been exposed to ionizing radiation—from both outer space and the earth itself—and only during the past 100 years have humans harnessed the power of this radiation for their 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. Early radiologists and physicists developed cancers, some of which were fatal. As the deleterious effects 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. NDI 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. To counteract radiological threats from the potential use of weapons of mass destruction, US government agencies have had to implement the latest detection system technology. Each of these technologies can be used safely, but they can create a health hazard to radiation workers and to the public in general if not handled properly.

Although radiation is not detectable by the physical senses, it is relatively easy to detect and quantify with instrumentation. Physicists, physicians, and biologists have worked closely to establish quantitative estimates of risk and derive safe dose levels, and the scientific community has provided guidance and 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. Recent progress in radiation protection includes stricter regulatory 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 of successful outcomes for the patients.

At high doses, radiation can cause severe injury and even death. However, such large doses are rarely encountered in the military (apart from situations involving 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 currently of statistical concern only. The

challenge for the DA Radiation Safety Program and the DA Preventive Medicine Program[63] is to protect workers, the public, and the environment, while enabling the benefits of radiation to be exploited.

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