CHAPTER 146

RADIATION INJURIES

Christopher B. Colwell

HISTORICAL PERSPECTIVE AND EPIDEMIOLOGY

The technology of the 20th and 21st centuries has ushered in the nuclear age. Nuclear energy has significant peaceful industrial and medical uses, but it poses great potential danger as well. Although the safety record involving the use of radiation and radioisotopes is excellent overall, the possible hazards involved are well known. The earthquake and subsequent tsunami in Japan on March 11, 2011, is yet another reminder of the dangers associated with nuclear energy. The near-disaster that occurred at Three Mile Island in Pennsylvania in 1979, the disastrous accident at the Chernobyl Nuclear Power Station in the former Soviet Union in 1989, and the potential for disaster that occurred at a uranium processing plant in Tokaimura, Japan, in 1999 are further reminders of this very real risk.[1,2] The potential contamination of large numbers of people will continue to stress the capabilities of existing emergency medical systems.

The only wartime use of atomic and nuclear energy was the detonation of atomic bombs over Hiroshima and Nagasaki in 1945. Many nations now have nuclear weapons in their arsenals, however, and the possibility for terrorist groups to obtain and to use such weapons does exist. Because the spent fuel from a nuclear power reactor can be reprocessed into plutonium, which can be used to produce nuclear weapons, more countries have now acquired the necessary raw materials to produce these weapons. The technology is available for the production and use of small, low-yield, tactical nuclear weapons and for megaton-yield, strategic nuclear weapons.

Although the proliferation of nuclear weapon technology along with the growth of global terrorism raises new concerns about a rogue nation or terrorist group, a more likely scenario is the production and detonation of a "dirty bomb." In contrast to a nuclear weapon, which would be difficult to produce, a dirty bomb can be produced and detonated with relative ease. The greatest threat from such a bomb lies in its potential to cause widespread terror from fear of radioactive contamination. Although the number of deaths and injuries resulting from a dirty bomb should not exceed those of a conventional explosion, the panic over radioactivity and evacuation measures and the prolonged cleanup efforts that would ensue could wreak prolonged havoc.

A dirty bomb can be produced from existing strontium-90 or cobalt-60 radioactive materials, such as radium and cesium-137 isotopes that are used in some forms of cancer therapy. These are found in many hospitals or university laboratories. Such a weapon can be produced by combining radioactive materials in solid or powder form with a conventional explosive that on detonation would send radioactive material into the area of the explosion and downwind. Although negligible or no harm would be likely from these sources of radiation, there could be tremendous psychological effects.[3,4]

It is technically much more difficult to produce a nuclear weapon than it is to manufacture a chemical or a biologic weapon. Use of a nuclear weapon by terrorists is highly unlikely unless they obtain such a weapon from existing stockpiles, which would include sources that may have been lost from governmental control in developing countries and areas of the former Soviet Union.

Injury from a nuclear explosion initially involves the mechanical effects of the blast wave that result in large-scale conventional types of blunt and penetrating trauma. Thermal or burn effects follow. The effects of ionizing radiation injury occur in proportion to the blast and thermal effects. In addition, radioactive fallout results from a nuclear weapon detonation on or above the ground. Detonation of a nuclear weapon could produce devastation and injury from its immediate and long-term effects (Table 146-1).[5]

Accidents involving peacetime nuclear energy include exposure to and contamination by radioactive sources. Medical, industrial, and laboratory accidents can expose people to unacceptably high doses of radiation. Increased commercial transport of such materials results in an increased risk of accidents during transport. Emergency physicians are concerned primarily with the acute effects of exposure and contamination. The long-term effects continue to be studied in the populace exposed to radiation as a result of the Chernobyl accident.[1]

Nuclear Reactor Incidents

A nuclear weapon, as distinguished from a nuclear reactor, is designed to be autocatalytic (i.e., rather than being self-sustaining, the power grows without bounds after the chain reaction is initiated). The water-cooled nuclear reactors in U.S. power plants are designed to operate in their most reactive configuration. Any material or geometric change (except for removal of the control rods) renders them subcritical. In the graphite-moderated, steam-cooled reactors operating in the former Soviet Union, a nuclear excursion or accident can occur because of loss of coolant, as at Chernobyl.[6]

Every nuclear reactor should be housed within a containment structure to prevent the accidental release of radioactivity. The Three Mile Island reactor has five defense layers. Thus the accident in 1979 resulted in very little radiation release into the environment. At Chernobyl, however, the containment structure failed, and all the radioactive material from the core of the reactor escaped into the environment. Although the amount of radioactive material released at Chernobyl was only approximately three times the Three Mile Island release, failure of containment resulted in a 5000 times greater dose of radiation within a 10-mile radius

Table 146-1 Approximate Distance from the Detonation Site at Which a 50% Fatality Rate Might Be Expected, According to the Size of a Nuclear Weapon

YIELD (kt)	SHOCK WAVE	THERMAL RADIATION (m)	IONIZING RADIATION Initial	Residual*
0.01	60	60	350	1270
0.1	130	200	460	2750
1	275	610	790	5500
10†	590	1800	1200	9600

Data from the National Council on Radiation Protection and Measurements: Management of Persons Accidentally Contaminated with Radionuclides. Washington, DC, National Council on Radiation Protection and Measurements, 1980. NCRP Report No. 65.

*Data are for residual radiation (mostly fallout) in the first hour.

†At yields exceeding 10 kt, the lethal range of the fireball extends several times farther than the lethal range of either the blast or the initial radiation.

of Chernobyl (40,000 mrem compared with 8 mrem from Three Mile Island).[1] Adding to the tragedy, the large amount of radioactive material released into the atmosphere at Chernobyl was carried aloft by prevailing winds.

As a result of human error at a uranium processing plant in Tokaimura, Japan, 49 people were exposed to radiation, two of whom received a potentially lethal dose. Enriched uranium was mixed with nitric acid in an open vessel, resulting in Cherenkov radiation. This radiation is released when the speed of a charged particle in a transport medium is so high that it exceeds the velocity of light in that medium. A visible flash results from radiation emitted when the uranium reaches a critical mass and triggers an uncontrolled chain reaction for 20 hours.

Finally, a terrorist attack on a nuclear reactor could result in an atmospheric plume of radioactive iodine and noble gases released through a breach in the reactor core. These gases could have immediate health effects nearby, and long-term effects from radioactive iodine could occur at great distances from the reactor.

Radon Exposure

Radon gas is the major source of radiation exposure to the general public. Radon and its breakdown products are in the decay chain of uranium-238. Because uranium-238 has a long half-life and is distributed throughout the earth's rocks and soil, its decay products are ubiquitous. The decay scheme of radon results in the production of four heavy metal isotopes with short half-lives termed radon daughters (Fig. 146-1). These isotopes include alpha-emitting solids that can be inhaled and deposited in the tracheobronchial tree.

Radon-222 is a colorless, odorless, natural radioactive gas that moves by diffusion and pressure flow into basements and lower levels of buildings, where concentrations may reach hazardous levels. Radon daughters can be collected on filters, and alpha activity can be measured. The major source of radon gas is soil containing high levels of radon, such as uranium tailings, which are waste byproducts, used for landfill beneath buildings. Sealing of basement cracks can decrease radon gas entry, and its removal can be enhanced by proper ventilation systems.[7]

Because radon and radon daughters result from the decay of uranium-238, uranium miners sustain some of the highest levels of occupational exposure. These individuals have an increased incidence of lung cancer and interstitial pulmonary fibrosis secondary to radon progeny exposure from inhalation of alpha

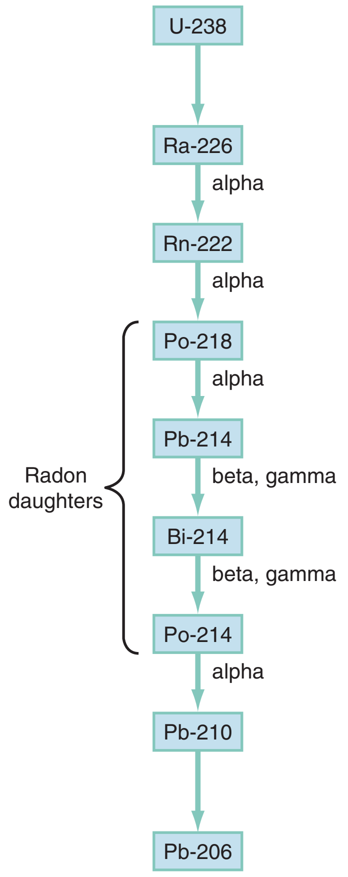


Figure 146-1. Radon and radon daughters in the major decay path of uranium-238. (Redrawn from Hart BL, Mettler FA Jr, Harley NH: Radon: Is it a problem? Radiology 172:593, 1989.)

particles.[8] It is estimated that radon exposure accounts for up to 33,000 lung cancer deaths in the United States each year. Radon is the second-leading cause of lung cancer after cigarette smoking. Each year, 15,000 lung cancer deaths in the United States may result from indoor radon exposure.[9]

PATHOPHYSIOLOGY OF RADIATION EXPOSURE

The electromagnetic spectrum (Fig. 146-2) encompasses a range from microwaves to gamma rays; it includes long-wavelength, low-frequency, low-energy forms of nonionizing radiation and progresses to short-wavelength, high-frequency, high-energy forms of ionizing radiation. The frequency and length of these waves determine the energy, measured in units called *photons*. *Frequency* is the number of times per second the crest of a wave passes a given point, whereas *wavelength* is the distance between crests.

Ionizing versus Nonionizing Radiation

Radiation is the transfer of energy in the form of waves, rays, or particles. The term *radioactivity* refers to the loss of particles (e.g., alpha, beta, or neutrons) or energy (e.g., x-rays and gamma rays) from an unstable atom that is spontaneously decaying. The spontaneous transformation of an unstable isotope to a stable one is referred to as *decay,* and it may involve the release of ionizing radiation. Understanding of the effects of radiation exposure on humans requires a distinction between ionizing and nonionizing

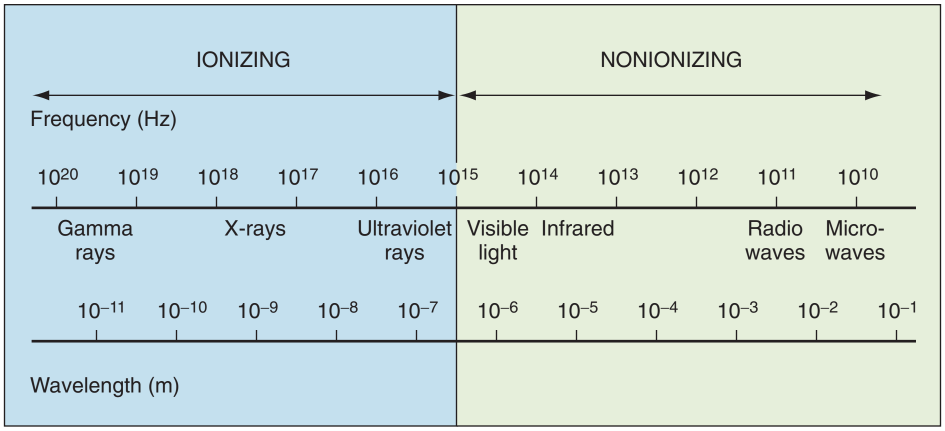


Figure 146-2. Electromagnetic spectrum.

radiation. *Nonionizing radiation* refers to all forms of the electromagnetic spectrum, with the exception of x-rays and gamma rays. Nonionizing (in contrast to ionizing) radiation has a long wavelength, low frequency, and low energy. As such, it does not carry enough energy to remove an electron from an atom and therefore does not produce charged ions on passing through matter. Examples of nonionizing radiation include visible light, radar, radio and television broadcasting, garage door openers, microwave ovens, relay stations, medical diathermy, and satellite communications.

The primary adverse effects of nonionizing radiation are related to local heat production because the energy of nonionizing radiation is essentially all expended in heat. This effect depends directly on the intensity of the source, the distance from the source to the person exposed, and the duration of exposure.[5] Long-term exposure to microwave irradiation at some distance from the source has received extensive study. The most thorough example involves U.S. State Department employees exposed to long-term microwave irradiation in the U.S. chancery in Moscow. This building was subjected to a direct beam that resulted in exposed rooms having a higher power density than that usually found on the ground near transmission towers. After extensive study, it was concluded that no adverse health effects occurred from this exposure. This and other studies performed on various groups of workers exposed to radiofrequency radiation concluded that the present exposure levels (including microwaves) do not cause significant adverse health effects to the general public. Specifically, there is no evidence of either decreased longevity or an increased incidence of cancer. The possibility of hazardous health effects resulting from low-level microwave exposure is an area of ongoing study.[10]

A microwave oven generates 2450-MHz microwaves. This megahertz wavelength can produce hyperthermia above a 25-mW level with a penetration of several centimeters. If a microwave oven has a door leak, a person can be exposed to the thermal effect of microwaves only by placement of a body part in direct contact with the area. Electromagnetic waves dissipate at a rate directly related to the square of the distance from the source. In other words, exposure is cut to one fourth at twice the distance from the source. No thermal effect exists at a distance of several feet, but a potential exists for deleterious effects on electronic devices that are sensitive to the wavelength of this electromagnetic radiation.

Ionizing radiation has a short wavelength, high frequency, and high energy. The photons of ionizing radiation carry 1 billion times more energy than the photons of nonionizing radiation. Ionizing radiation induces injury by directly causing cell death or by damaging DNA and other components and interrupting the cellular reproductive process. This in turn can lead to cellular dysfunction or death. Ionizing radiation is emitted in the form of alpha and beta particles, gamma rays, and x-rays.

Irradiation versus Contamination and Incorporation

Irradiation

A radioactive substance is one that emits ionizing radiation. It is referred to as a radionuclide or radioisotope. If such radiation passes through a nearby object, the object is said to have been irradiated. With the exception of the situation in which there is direct exposure to neutrons, the object that is irradiated does not become radioactive. When a person is irradiated but not contaminated, such as the post–radiation therapy patient, no hazard exists to medical personnel, and the patient may be handled like any other emergency patient.

Contamination

Radioactive contamination is essentially radioactive particulate matter (alpha and beta particles) on an exposed surface. Contamination is not an acute threat to the life of the patient or the provider, and its presence should not preclude institution of lifesaving measures. This radioactive particulate matter may emit radiation with an effect that is directly related to the time of exposure, distance from the source, and type of contamination. The four types of radiation that exist with the potential to contaminate are alpha, beta, gamma, and neutron radiation, and each presents different hazards (Fig. 146-3).

Alpha radiation consists of particles that are highly charged and composed of two protons and two neutrons. *Alpha particles* dissipate their energy quickly and travel only a few centimeters in the air. They cannot even penetrate paper and are therefore easily shielded. When they directly contact skin, penetration is limited to the thickness of the epidermis. Alpha radiation therefore presents a significant biohazard only when it is internalized. Alpha particles are produced by alpha emission from many of the heavy radioactive elements, such as plutonium and uranium decay. Newer Geiger-Mueller counters are able to detect alpha particles and are excellent for detection of beta and gamma radiation. *Beta particles* have a smaller mass and charge than alpha particles and tend to have a greater velocity. They have a tissue penetration of approximately 8 mm and can cause significant skin burns, although these burns are not generally visible immediately after the exposure. Because clothing effectively shields covered areas, the primary danger is to exposed skin. Standard skin cleansing

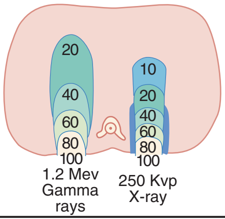
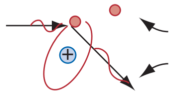
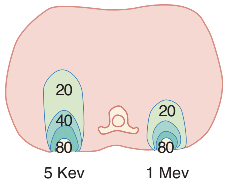
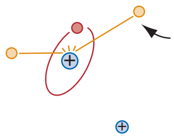
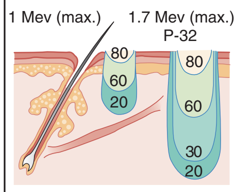
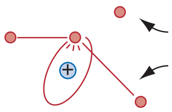
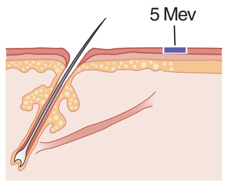
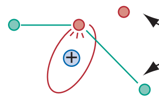
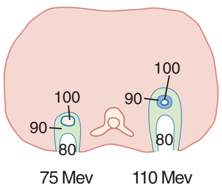
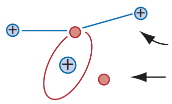
TYPE OF RADIATION	SYMBOL	USUAL SOURCE	PENETRATION OF EXTERNAL RADIATION	PRINCIPAL TYPES OF INTERACTION
X-rays Gamma rays	x γ	X-ray machines and accelerators Most radioisotopes emit a gamma ray following beta decay	 X- and γ rays penetrate deeply, for only a fraction of the rays interact with each layer of tissue	 Ejected electron loses energy by causing additional ionization Deflected x- or γ ray may interact again some distance away Ionized atom formed after electron ejection
Neutrons	n	Neutrons are generally produced by critical assemblies, nuclear reactors, or accelerators	 Neutrons penetrate deeply, for only a fraction of the neutrons interact with each layer of tissue	 Deflected neutron may interact again some distance away Recoil proton loses energy by causing ionization
Beta particles	β	Most radioisotopes decay by beta emission, usually followed by gamma emission	 Penetration depends on energy of beta but is usually limited to less than 8 mm in tissue	 Ejected electron loses energy by causing additional ionization Deflected electron or beta particle causes additional ionization Ionized atom formed after electron ejection
Alpha particles	α	Many of the heavy radioactive elements such as plutonium decay by alpha particle emission	 Penetration is limited to about the thickness of the epidermis	 Ejected electron loses energy by causing additional ionization Deflected alpha goes on to cause additional ionization Ionized atom formed after electron ejection
Protons	p	Energetic protons are found only near particle accelerators	 Penetration depends on energy of the proton	 Deflected proton causes additional ionization Ejected electron loses energy by causing additional ionization Ionized atom formed after electron ejection

Figure 146-3. Types of radiation and possible external hazards. (Redrawn from Andrews GA, Cloutier RJ: Accidental acute radiation injury: The need for recognition. Arch Environ Health 10:499, 1965.)

procedures remove most of this contamination. The only means of detection is a radiation-sensing instrument (Geiger-Mueller counter). If exposure to beta particles is allowed to continue, significant exposure to gamma radiation can occur because most radioisotopes decay by beta radiation followed by gamma emission.

Gamma rays are electromagnetic waves with no mass and no charge that travel quickly and penetrate tissue deeply, with a fraction of the rays interacting with every layer of tissue. Gamma rays are the most penetrating type of ionizing radiation and travel several meters in air and many centimeters into tissue. Gamma rays are emitted from radioisotopes after beta decay and are the primary cause of the acute radiation syndrome.

Neutrons are unique. When they are stopped, or “captured,” after emission, they commonly cause a previously stable atom to become radioactive. This is the source of radioactive fallout. A surface burst of a thermonuclear weapon instantly vaporizes tons of surface soil, transforming it into highly radioactive material by the intense neutron bombardment. This cloud rises with the fireball and is carried away by the prevailing winds at high altitudes. Its radioactive particles ultimately descend as fallout.

Some gamma exposure also occurs with neutron exposure. In peacetime, significant neutron exposure is likely to occur only around nuclear reactors and accelerators. Quantization of the radioactive material induced by neutron irradiation is helpful in estimating neutron exposures and, sometimes indirectly, the dose of gamma radiation. The induced radioactivity is primarily sodium-24, which can be detected by a whole-body counter or in blood samples. If neutron exposure is suspected, all feces and urine should be refrigerated and saved when possible. All clothing, especially items containing metal parts, such as belt buckles, should also be saved for analysis of neutron-induced radioisotopes.

Incorporation

Incorporation occurs when a radioactive material is ingested, inhaled, or absorbed through an open wound.

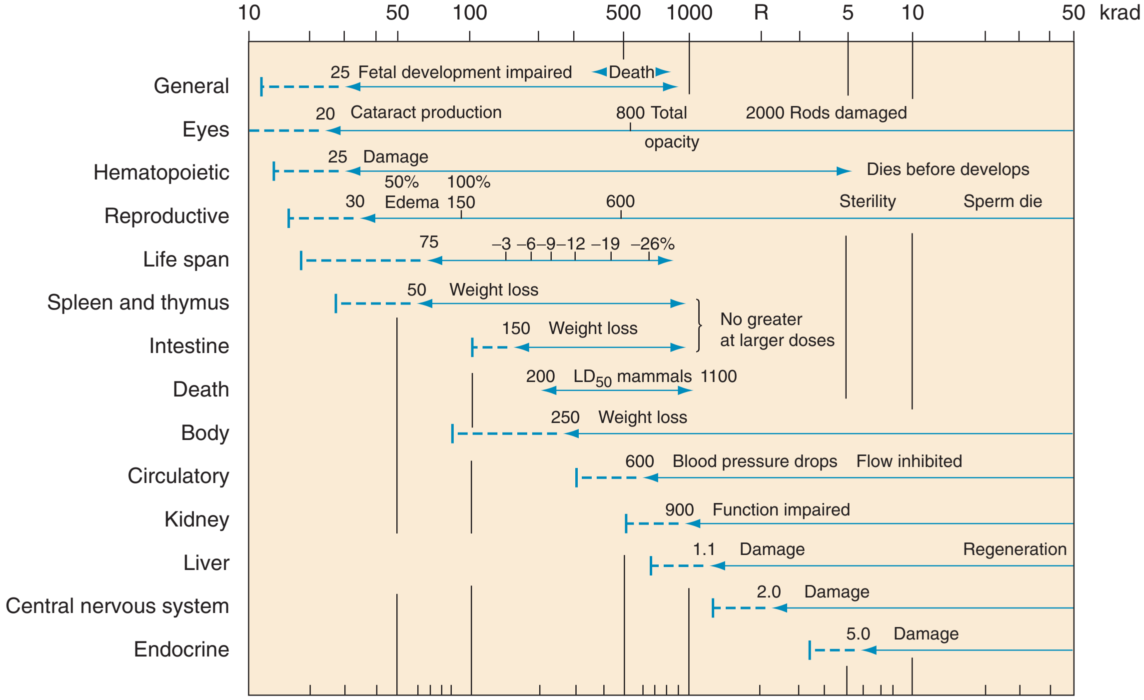


Figure 146-4. Organ and tissue sensitivity in mammals. The dose values are for whole-body, acute, x-ray, or gamma ray exposures. For low-intensity or fractionated exposure, the lines would be moved toward the right (higher doses). Radiosensitivity is directly related to the proliferative rate of the cells of the organs. (Redrawn from Auerbach PS, Gehr EC: Management of Wilderness and Environmental Emergencies. New York, Macmillan, 1983.)

TYPES OF EXPOSURE

- *External radiation* exposure results from partial-body or whole-body irradiation from an outside source. The patient may have received a lethal dose but presents no radioactive hazard to other people or the environment. Examples include accidental irradiation of personnel working with fissionable materials in laboratories or with nuclear reactors in nuclear power plants.
- *Incorporation and internal contamination* generally result from inhalation or ingestion of radioactive substances but can also occur from absorption of radioactive substances through open wounds. When this occurs, even alpha particles, which normally present no real health hazard with external exposure, can have long-term effects, including the development of lung cancer. The treatment of this type of exposure is often similar to that of acute poisoning with heavy metals.
- *External contamination* involves surface exposure to radioactive materials that remain in contact with the skin, such as dirt or liquids. Care must be taken to confine this contamination. Emergency treatment consists of removal of clothing and careful cleansing of exposed parts.
- *Wound contamination* involves exposure of an open wound to radioactive material that results in some degree of internal contamination.

Combinations of these types of radiation exposure can occur. The traumatic blast effects of a thermonuclear explosion could result in exposure to all types of radioactivity in addition to causing radioactively contaminated wounds.

CLINICAL FEATURES AND DIAGNOSTIC STRATEGIES

Symptoms and Signs

Radiation injury is caused by deposition of energy in tissue. This energy can lead to damage of cellular structures such as DNA from free radical formation. Cellular repair mechanisms will be less effective with more rapid delivery of higher doses of radiation. *Acute radiation syndrome* is a symptom complex that occurs after whole-body irradiation. It varies in nature and severity by dose, dose rate, dose distribution, and individual susceptibility. This syndrome can result from external or internal exposure to radiation during a short time. The patterns of symptoms and signs of acute radiation syndrome overlap and contain many variables (Fig. 146-4).

The principal units used to express the dose of radiation absorbed in living tissue are the *gray* (Gy; 1 Gy = 1 joule of radiation absorbed per kilogram of tissue) and the *radiation absorbed dose* (rad; 1 rad = 0.01 Gy, so 1 Gy = 100 rad). The *roentgen equivalent man* (rem) is the dosage of ionizing radiation equal to 1 rad of x-radiation (1 rad = 1 rem). A chest radiograph equals 45 mrem, and flying 3000 miles in a jet at 35,000 feet results in 4 mrem of exposure.

The relative sensitivity of organ systems exposed to the radiation determines the clinical symptoms. Because it is often impossible to accurately quantitate the absorbed dose of radiation, the symptoms and signs determine the diagnosis, therapy, and prognosis. An excellent screening tool to detect those who require more urgent medical investigation is the presence and time at onset of nausea and vomiting.[11] Symptoms may occur at doses as low as 0.75 Gy.[12] When the time to emesis is less than 4 hours after exposure, the effective whole-body dose is likely to be at least 3.5 Gy. If the time to emesis is less than 1 hour, the whole-body dose is likely to exceed 6.5 Gy and the outcome may be fatal. In most radiation accidents, exposed individuals are not wearing a monitoring device that can measure high doses of radiation. The radiation dose should be estimated from its biologic effects. The earliest indicator of a significant radiation exposure is the decrease in the absolute lymphocyte count, which can occur within 48 hours after exposure (Table 146-2).[5]

Tissues with greater rates of cellular division, particularly the hematopoietic and gastrointestinal systems, are the most radiosensitive (see Fig. 146-4). With intense irradiation exposure,

Table 146-2 Prognosis According to the Lymphocyte Count within the First 48 Hours after Acute Exposure to Penetrating Whole-Body Radiation

MINIMAL LYMPHOCYTE COUNT (per mm^2)	APPROXIMATE ABSORBED DOSE (Gy)	EXTENT OF INJURY	PROGNOSIS
1400-3000 (normal range)	0-0.4	No clinically significant injury	Excellent
1000-1499	0.5-1.9	Clinically significant but probably nonlethal	Good
500-999	2-3.9	Severe	Fair
100-499	4-7.9	Very severe	Poor
100	8	Most severe	High incidence of death even with hematopoietic stimulation

however, central nervous system (CNS) symptoms can result, even though the CNS has a low cellular turnover rate. Invariably, all organ systems are involved in whole-body irradiation. At doses less than 1 Gy (100 rem), most cells survive but may be susceptible to radiation-induced cancer. Leukemia can develop as quickly as 2 years after exposure, whereas solid tumors are more likely to develop during several decades.[5,13,14]

The LD_{50} or median lethal whole-body dose (the dose that is lethal for 50% of test subjects), assuming proper medical care, is estimated to be approximately 4.5 Gy.[6] Whole-body exposure of 10 Gy is the maximal survivable dose even with the best medical therapy.[5] Doses greater than 20 Gy commonly produce CNS symptoms. These symptoms occur immediately after exposure and include headache, altered mental status, prostration, vertigo, tinnitus, and sensory and motor changes. If the individual is exposed to a nonuniform dose and the gastrointestinal and hematopoietic systems are spared, there is a chance of survival after resolution of the CNS symptoms. If more than 20 Gy of whole-body exposure occurs, however, fulminating gastrointestinal and CNS symptoms ensue, sometimes within 30 minutes. This indicates a supralethal dose of radiation, and for triage purposes, the death of these patients should be classified as "impending" or "expectant." If medical resources are scarce, sedation and analgesia should be the only therapies. With whole-body exposure of more than 10 Gy, mortality approaches 100%. If the patient survives the CNS and gastrointestinal system insults, hematopoietic complications are lethal.

The gastrointestinal syndrome occurs regularly at doses higher than 1 Gy. In general, the higher the absorbed dosage, the sooner the onset of symptoms. In its mildest form, nausea and vomiting are short-lived. More protracted nausea and vomiting are seen with higher exposures. The onset of high fever and persistent bloody diarrhea are ominous signs. Death from hematopoietic system failure may result despite aggressive fluid and electrolyte therapy.

A latent period lasting 2 days to 4 weeks from the time of exposure often occurs before the signs of hematopoietic system involvement develop. The earliest sign is often pancytopenia resulting from marrow suppression. This hematopoietic syndrome includes leukopenia and thrombocytopenia with fever, increased susceptibility to infection, petechiae, and hemorrhagic diatheses. The absolute lymphocyte count 48 hours after exposure is a good predictor of hematopoietic system involvement (see Fig. 146-4). If the absolute lymphocyte count is greater than 1200 cells/μL, it is unlikely that the patient has received a clinically significant dose of radiation. If the absolute lymphocyte count falls between 100 and 500 cells/μL at 48 hours, a significant or even lethal dose of radiation should be suspected. A level in this range is an indication for protective isolation. Levels less than 500 cells/μL suggest procedures such as the use of hematopoietic growth factors.[5,15] If a patient is symptomatic, serial complete blood counts should be performed. Hemorrhagic complications should be treated with platelet concentrates and whole blood or fresh frozen plasma when necessary. Anemia resulting from erythropoietic suppression is not generally of clinical significance.

Erythema from skin burns may be delayed in onset. When skin burns are secondary to penetrating radiation, they indicate high exposure. Severe skin burns may be a result of nonpenetrating radiation, such as beta particle contamination without accompanying systemic symptoms. These burns can be prevented or tempered by early decontamination. When present, they should be treated like any thermal or chemical burn.

Skin changes that occur can help quantify radiation exposure. Epilation occurs after exposure to 3 Gy, erythema is seen after exposure to 10 Gy, wet desquamation occurs after 20 Gy, and necrosis occurs after 30 Gy of localized skin exposure.[5] These responses are similar to those of severe chemical burns.

A key historical point in the evaluation of a suspicious burn is whether the patient had contact with a hot object or caustic chemical. If the patient does not give a history that clearly explains the burn, particularly if there is a history of carrying a bright metal object that may have been a radioisotope source, the possibility of a radiation burn should be considered.

MANAGEMENT

Out-of-Hospital Care

The history obtained from field personnel is crucial. The exact type of exposure (external versus internal, whole body versus partial body) should be ascertained. If internal exposure is suspected, the portal of entry (inhalation, ingestion, or absorption) and the radioactive material involved should be investigated.

Reducing Exposure

The protection of providers involves reducing exposure to levels that are as low as reasonably achievable. The three classic and effective methods to reduce radiation exposure can be summarized as *time, distance,* and *shielding*. The absorbed dose is directly proportional to time. In addition, radiation exposure follows the inverse square law, and it decreases to one fourth at twice the distance from the source. Effective shielding varies from a sheet of paper for alpha particles to less than an inch of aluminum for beta particles and several inches of lead for gamma rays.

Decontamination

If the patient's condition permits, decontamination should usually be initiated at the scene because many communities lack an emergency department (ED) designed for this procedure. In an industrial or laboratory accident, each facility should have a specific protocol and equipment available to initiate the decontamination process. All out-of-hospital personnel should be trained in the decontamination process. Universal precautions, including rubber gloves, shoe covers, and respirators if airborne contamination is suspected, are effective in protecting personnel and the work area from contamination. The only variation from normal universal precautions is a recommendation to wear two sets of gloves and to change the outer pair when appropriate to avoid cross-contamination.[16]

The patient's clothing should be removed and placed in plastic bags. If possible, soap and water cleansing of exposed skin should be performed. All materials, including wash water, should be placed in containers and labeled as radioactive waste. Performance of these tasks at the scene minimizes contamination of the ambulance and the ED.

If the patient is unstable, rapid and partial decontamination procedures, such as clothing removal, should be initiated at the scene before expeditious transportation to an ED. Radio contact with the receiving hospital should be provided to the ED to facilitate preparations. If the community disaster plan has a designated hospital for radiation-contaminated victims, they should be transported directly to that facility. Physicians wishing to establish a comprehensive plan to manage radiation accident victims are referred to the National Council on Radiation Protection and Measurements.[17]

Emergency Department

Every ED designated a decontamination facility should have a radiation accident protocol. An excellent prototype is that published by Leonard and Ricks.[18] This protocol should be included in the policies and procedures manual and posted in the decontamination facility.

Preparation

The chaos that ensued in the wake of the Three Mile Island experience suggests that a community disaster plan should be developed with a predetermined individual empowered to make decisions about evacuation and other issues concerning the at-risk population. On notification of the numbers and types of patients involved in a radiation exposure accident, a decision should be made about implementation of a full disaster plan versus a limited response. The *radiation control officer,* usually a radiologist or pathologist, should be contacted immediately. The radiation control officer should monitor all patients and medical personnel with a radiation counter and should supervise the "cleanup" and the routing of patients to minimize "tracking," or spread, of contamination. The role of informational services is critical. Timely and accurate information and instructions should be given to a public relations person for dissemination to the news media to minimize the chaos and paranoia that inevitably result from such incidents.

Decontamination

Contaminated patients should be decontaminated in the field. If they arrive at the ED contaminated, they should enter through a separate, protected entrance or be isolated until a decontamination tent can be erected. Because the risk to staff from radioactive contamination is minimal with universal precautions, medical stabilization and treatment of the patient supersede decontamination efforts in a radiologic emergency.

There is a significant distinction between patients contaminated with radioactive material and those who arrive contaminated with chemical or biologic agents, for which decontamination may need to take precedence. All medical personnel should wear protective, disposable clothing, including surgical gloves and shoe covers. Respirators are not required at the hospital but should be used by first responders who are entering a highly contaminated area.[5] The emergency suite should contain all equipment necessary for a major resuscitation. If decontamination occurs inside the ED, it must have a contained drainage and ventilation system to prevent the spread of water-borne or airborne radioactive contamination. In some hospitals, the only area equipped with such facilities is the autopsy room or morgue. The radiation disaster plan may necessitate taking resuscitation equipment to this area and providing decontamination and initial care there if this cannot be done in a decontamination facility outside of the ED. As opposed to chemical and biologic hazards, radioactive contamination is relatively easy to detect with commonly available survey meters, such as a Geiger-Mueller instrument, often referred to as a Geiger counter. This should be available in any ED that may receive patients exposed to radioactive contamination. Although historically survey meters have not been able to detect alpha radiation, many of the newer devices can detect even small amounts of radioactive contamination and will typically be capable of distinguishing alpha, beta, and gamma radiation.

The patient should be undressed immediately and all clothing placed in sealed containers labeled "radioactive waste." Removal of clothing can reduce contamination on the patient by 90%.[19] Exposed skin should be cleansed with soap and water. Overly aggressive skin washing should be avoided because abraded skin openings could allow increased absorption of radioactive material. Hair should be shampooed. All wastewater, washcloths, and towels should be saved in properly labeled containers. The cleansing process should be repeated as frequently as necessary until the area measures less than twice the background reading on the Geiger-Mueller survey meter or until there is no significant reduction in the level of contamination between washes.[16] Long hair may need to be trimmed. The nails should be trimmed and meticulously scraped to remove contamination.

Wound Management and Treatment

If the patient has open wounds, the surrounding skin should be decontaminated by scrubbing with soap and water. Adhesive, disposable surgical drapes should be applied, and the wounds should be prepared and irrigated with copious amounts of saline. Frequent monitoring for radioactive contamination determines when irrigation can be discontinued. Surgical débridement should be performed according to the usual indications of dirt and nonviable tissue or continued high readings of radioactive contaminants. The normal principles of wound closure should be followed for contaminated wounds. The wounds in patients who have received whole-body radiation greater than 1 Gy should be closed primarily to prevent infection.[5]

Because there is minimal risk to providers using universal precautions, emergency surgery or other necessary procedures should not be delayed by contaminated skin or wounds. Surgical interventions should be performed within 48 hours of the injury when possible in patients who have suffered high-level radiation exposure and trauma. Acute radiation syndrome may be complicated by fluid and electrolyte disturbances. After 48 hours, surgical interventions may need to be delayed until hematopoietic recovery occurs.[16]

Treatment

The indications for pain management and antiemetics should be liberalized. Treatment of acute radiation syndrome should also focus on the prevention of infection. Neutropenia and fever should be managed with antibiotics, although routine enteric prophylaxis is not indicated.[20]

Internal Contamination

Oral ingestion of radionuclides presents special challenges. After ingestion, there is usually a variable time before cellular absorption and uptake. Therapy with blocking or chelating agents is determined by the elements involved. A *blocking agent* is a chemical that saturates a tissue with a nonradioactive element, reducing

Table 146-3 Medication Options for Internal Contamination

MEDICATION	RADIOACTIVE ISOTOPE
Ferric hexacyanoferrate (Prussian blue)	Cesium-137, thallium
Ca- and Zn-diethylenetriaminepentaacetate (DTPA)	Plutonium, americium, curium
Potassium iodide	Radioiodine
Penicillamine	Radioactive heavy metal poisoning (lead)

the uptake of the radionuclide. An example is potassium iodine (KI), which reduces the uptake of radioactive iodine in the thyroid. The American Thyroid Association currently suggests that KI pills be distributed to households within 50 miles of a nuclear power plant and be available to those within a 200-mile radius for the purpose of protection from radioactive fallout during evacuation efforts in the event of a nuclear accident.[21]

Chelating agents bind metals into complexes, which prevents tissue uptake and allows urinary excretion. Two examples of chelating agents are calcium disodium edetate and penicillamine, both of which treat radioactive lead poisoning. Ideally, these agents should be administered soon after exposure, before significant uptake of the radionuclide can occur. A poison information center should be contacted for recommendations about the dosages of chelating and blocking agents and other treatment modalities, including induced emesis, cathartics, activated charcoal, and lavage.[22] All excretions (urine, feces, emesis, and lavage fluid) should be saved in specially labeled containers for dosimetry and proper disposal. The decision to treat suspected internal contamination should not be delayed for sample analysis, which typically will take 24 hours. Medications that may be administered to patients thought to be internally contaminated with some radioactive isotopes are listed in Table 146-3.

Acute inhalation of radionuclides is a problem. Emergent bronchopulmonary lavage may be effective in partial removal of the radioactive contaminants. Nasal swabs subsequently tested for radioactivity may help determine if inhalation of radioactive material has occurred. Chelating and blocking agents may be used if significant inhalation is suspected. Chronic low-level inhaled contaminants are more common, and long-term sequelae occur. Extensive cutaneous radiation fibrosis occurred in some survivors of the Chernobyl accident, and interferon therapy is of benefit.[23]

Triage Classification, Further Treatment, and Disposition

Triage is facilitated by presenting symptoms into three categories: survival probable, survival possible, and survival improbable. The *survival probable group* consists of patients having either no initial symptoms or mild symptoms that subside within a few hours. Radiation exposure in this group is usually less than 2 Gy (200 rem or rad). The initial laboratory studies and serial complete blood counts reveal no depression of the leukocyte count.

The *survival possible group* includes patients in whom nausea and vomiting are relatively brief (lasting 24-48 hours), followed by an asymptomatic (latent) period. After the initial symptoms, these patients exhibit the typical hematologic changes of thrombocytopenia, granulocytopenia, and lymphopenia. The severity of these changes depends on individual susceptibility and the level of the initial radiation dose. These patients should be admitted for fluid and electrolyte therapy if vomiting is severe. Antiemetics may be ineffective. Also, protective isolation precautions are indicated, particularly if there is significant granulocytopenia at 48 hours.

The exposure dosage range for patients in the survival possible group is estimated to be 2 to 10 Gy, with the LD_{50} approximately 3 to 5 Gy. The LD_{50} varies by the vigor of supportive therapy. In mass casualty situations, the LD_{50} is in the range of 3.5 to 4.5 Gy. The concept of calculating the LD_{10} versus LD_{90} for human radiation exposure helps determine what level of therapeutic intervention is indicated. A patient who has received an LD_{90} exposure may survive only if hematopoietic growth factors are used, whereas a patient with an LD_{10} exposure may need only low-risk supportive care, such as reverse isolation and intravenous fluids.

The therapy for the survival possible group is based on the exact hematologic derangements. Platelet concentrates are recommended if the count falls below 25×10^3 cells/μL. Appropriate broad-spectrum antibiotics should be considered only if clinical signs of infection appear. Prophylactic antibiotics may be indicated if serious gastrointestinal symptoms, such as vomiting and diarrhea, are present. Recommended approaches for antibiotic and myeloid cytokine use (for both prophylaxis and treatment) after radiation exposure largely follow algorithms for the treatment of chemotherapy-associated neutropenia.[24,25] Prophylactic antifungal agents, such as amphotericin B, may also be indicated. Acyclovir may be useful for oral herpes simplex infection. Colony-stimulating factors (cytokines) that induce bone marrow hematopoietic cells to proliferate may have substantial benefit, with little risk in victims predicted to have moderate or severe bone marrow failure.

Filgrastim (granulocyte colony-stimulating factor) and sargramostim (granulocyte-macrophage colony-stimulating factor), both used in treatment of patients with neutropenia resulting from myelosuppressive chemotherapy, are useful in radiation accident victims and may hasten recovery of neutrophil counts. Cytokine therapy (filgrastim 5 μg/mg/day, subcutaneously (SC) and sargramostim 5-10 μg/mg/day [200-400 μg/m^2/day]) is recommended in healthy individuals with no other injuries who receive exposures estimated to be in excess of 3 Gy and in patients with multiple injuries or burns who receive exposures in excess of 2 Gy. These myeloid cytokines may be beneficial even several weeks after exposure. Intravenous hyperalimentation may be necessary for the successful treatment of the gastrointestinal syndrome.

The third group is the *survival improbable group*. The exposed dose range in this group is estimated to be greater than 10 Gy whole-body exposure. These patients experience rapid onset of fulminating nausea, vomiting, and diarrhea. Aggressive fluid and electrolyte and hyperalimentation therapy may initially stabilize these patients. They later experience bone marrow aplasia and pancytopenia that is generally fatal. If CNS symptoms appear early, the patient has received a very large dose of radiation. In mass casualty situations, these patients should be triaged into the impending or expectant death category and provided comfort care. In the situation in which a sufficient dose of radiation causes irreversible bone marrow damage, allogeneic hematopoietic stem cell transplantation (HSCT) has the potential to restore hematopoietic function. Whereas HSCT demonstrates a survival benefit in animal models, there is no evidence that HSCT improves survival in humans exposed to nontherapeutic radiation.[26]

Consultative Resources

The U.S. Department of Health and Human Services launched the *Radiation Emergency Medical Management* (REMM) website in March 2007 as a resource for radiation exposure training, communication, and pre-event and postevent information. The goals of REMM are to guide health care providers in the diagnosis and treatment of radiation emergencies and to provide evidence-based information for those without formal radiation medicine expertise. The website is www.remm.nlm.gov/.[27] For questions about radiation exposure and injuries, the U.S. Department of Energy can be contacted 24 hours a day at the Radiation Emergency Assistance Center/Training Site (REAC/TS) in Oak Ridge, Tennessee (telephone, 865-576-1005; interactive website, www.orau.gov/reacts). For information about the training of physicians, REAC/TS can be contacted at 865-576-3131. The *Medical Management of Radiological Casualties Handbook* is available online at www.afrri.usuhs.mil. The Chemical/Biological Hotline of the National Response Center is 800-424-8802.

KEY CONCEPTS

- Contaminated patients are "radioactive"; irradiated patients are not.
- No danger to medical personnel from contaminated patients exists with proper precautions and decontamination procedures.
- Decontamination should not delay or impede the stabilization of the patient in radiation emergencies.
- Careful evaluation of initial symptoms and signs is the most reliable indicator of the radiation dose received and the patient's prognosis.
- Most therapy is supportive and symptomatic except for exposures involving the ingestion or inhalation of radioactive material, when specific therapy with blocking or chelating agents may be indicated.
- Detonation of a "dirty bomb" would cause psychological terror and little or no radiation injuries.
- Formal consultation is available 24 hours a day and should be obtained when any patient with radiation injuries is evaluated.

The references for this chapter can be found online by accessing the accompanying Expert Consult website.

References

1. Gale RP, Thompson MA, Crawford MA: Recent radiation accidents. Chernobyl and Goiania: Their impact and global implications. *Ala J Med Sci* 1988; 25:439.
2. International Atomic Energy Agency: *One Decade after Chernobyl, Summing up the Consequences of the Accident*. Proceedings of an International Conference, Vienna, April 8-12, 1996. Vienna: International Atomic Energy Agency; 1996.
3. Council on Foreign Relations: *Terrorism: Questions and answers: Dirty bombs*, revised June 23, 2003. Available at www.cfr.org/publication/9548.
4. Centers for Disease Control and Prevention: *Radiation emergencies—dirty bombs*, revised March 2005, reviewed May 2006. Available at http://emergency.cdc.gov/radiation/dirtybombs.asp.
5. Mettler FA, Voelz G: Major radiation exposure: What to expect and how to respond. *N Engl J Med* 2002; 346:20.
6. Champlin HE, Kastenberg WE, Gale RP: Radiation accidents and nuclear energy: Medical consequences and therapy. *Ann Intern Med* 1988; 109:730.
7. Hart BL, Mettler FA Jr, Harley NH: Radon: Is it a problem? *Radiology* 1989; 172:593.
8. Archer VE, Renzetti AD, Doggett RS: Chronic diffuse interstitial fibrosis of the lung. *J Occup Environ Med* 1998; 40:460.
9. American Cancer Society online. Available at www.cancer.org. Accessed January 2008.
10. Goldsmith JR: Epidemiologic evidence relevant to radar (microwave) effects. *Environ Health Perspect* 1997; 105:1579.
11. Koenig KL, et al: Medical treatment of radiological casualties: Current concepts. *Ann Emerg Med* 2005; 45:643.
12. Coleman CN, et al: Triage and treatment tools for use in a scarce resources–crisis standards of care setting after a nuclear detonation. *Disaster Med Public Health Prep* 2011; 5:S111.
13. United Nations Scientific Committee on the Effects of Atomic Radiation: *Sources and Effects of Ionizing Radiation: UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes*. New York: United Nations; 2000.
14. Pierce DA, Preston D: Radiation-related cancer risks at low doses among atomic bomb survivors. *Radiat Res* 2000; 154:178.
15. MacVittie TJ, Weiss JF, Browne D, eds: *Advances in Treatment of Radiation Injuries*. New York: Pergamon; 1996. Advances in the Biosciences, vol 94.
16. Bushberg JT, et al: Nuclear/radiological terrorism: Emergency department management of radiation casualties. *J Emerg Med* 2007; 32:71.
17. National Council on Radiation Protection and Measurements: *Management of Persons Accidentally Contaminated with Radionuclides*. Washington, DC: National Council on Radiation Protection and Measurements; 1980. NCRP Report No. 65.
18. Leonard RB, Ricks RC: Emergency department radiation accident protocol. *Ann Emerg Med* 1980; 9:462.
19. Armed Forces Radiobiology Research Institute: *Medical Management of Radiological Casualties*, 2nd ed. Bethesda, Md: Armed Forces Radiobiology Research Institute; 2003. Available at www.afrri.usuhs.mil. Accessed January 2008.
20. Waselenko JK, et al: Medical management of the acute radiation syndrome: Recommendations of the Strategic National Stockpile Radiation Working Group. *Ann Intern Med* 2004; 140:1037.
21. American Thyroid Association: Questions and answers about potassium iodide (KI). Available at www.thyroid.org/professionals/publications/statements/ki/02_04_ki_qa.html. Accessed April 25, 2011.
22. National Council on Radiation Protection and Measurements: *Management of Internally Deposited Radionuclides*. Report No. 65. Bethesda, Md: National Council on Radiation Protection and Measurements; 1985. Report No. 65.
23. Peter RU, et al: Interferon gamma in survivors of the Chernobyl power plant accident: New therapeutic option for radiation-induced fibrosis. *Int J Radiat Oncol Biol Phys* 1999; 45:147.
24. DiCarlo AL, et al: Radiation injury after a nuclear detonation: Medical consequences and the need for scarce resources allocation. *Disaster Med Public Health Prep* 2011; 5:S32-S44.
25. Gourmelon P, et al: European consensus on the medical management of acute radiation syndrome and analysis of the radiation accidents in Belgium and Senegal. *Health Phys* 2010; 98:825-832.
26. Ledney GD, Elliott TB: Combined injury: Factors with potential to impact radiation dose assessment. *Health Phys* 2010; 98:145-152.
27. Bader JL, et al: Radiation event medical management (REMM): Website guidance for health care providers. *Prehosp Emerg Care* 2008; 12:1-11.