Chapter 10

RADIOLOGICAL CONSIDERATIONS IN MEDICAL OPERATIONS

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INTRODUCTION

From the time that the first nuclear weapon was used against Japan during World War II to the end of the Cold War during the early 1990s, the use of nuclear weapons in strategic nuclear war with rival nations was the primary radiological concern facing the US military. US defense strategies involved planning for the possibility that military installations and large elements of troops in theater would be targeted during large-scale nuclear attacks involving the launch of multiple nuclear weapons.

It would be naive to completely disregard the threat of strategic nuclear war; however, following the conclusion of the Cold War and after more recent incidents, such as the Oklahoma City bombing (1995) and the attacks on the World Trade Center and Pentagon (2001), the focus on the use of radiological and nuclear weapons has shifted toward the threat of use by terrorist organizations. This has greatly changed the way our society must plan to respond to radiological and nuclear attacks. Radiological and nuclear terrorism is more likely to occur on US soil, as opposed to being directed toward troops in theater. Attacking civilians to produce fear and panic is one of the primary goals of terrorist organizations, and both radiological and nuclear weapons could be used to accomplish this goal. A single, well-planned attack involving a dirty bomb could potentially result in hundreds of trauma casualties, as well as psychological casualties, contaminated victims, and concerned citizens numbering in the thousands. An even more ominous possibility, the detonation of an improvised nuclear device in a major city could result in numbers of casualties orders of magnitude greater than those expected to be caused by a dirty bomb.

Managing the consequences of such an incident would require the rapid coordination of extensive personnel, engineering, transportation, communications, and medical support, among other resources. No organization in the world is able to mobilize such capabilities as quickly and in such quantity as the US military. Because of the possibility that radiological or nuclear weapons could be used against the United States or its allies, our military forces, including medical support, must be prepared to provide assistance to both combatant commanders and civilian authorities if such an incident should occur.

Military medical resources will be involved, either directly or indirectly, with several important aspects of the response to a large-scale radiological or nuclear incident. These could include the search for and extraction of casualties; site survey and determination of hazard zones; decontamination of casualties; triage and treatment of casualties suffering from blast, burn, and radiation injuries; and evacuation of casualties to higher levels of care. Medical personnel will need to understand the radiological hazards associated with these activities so they can minimize the danger to victims and to themselves.

RADIATION FUNDAMENTALS

Radiation and its properties are concepts of which few truly have a thorough understanding. Radiation is not tangible; it makes no characteristic sound or smell, and radioactive materials have no distinct taste. Unlike the popular misconception, radioactive materials generally do not glow, except when produced by a handful of materials under certain conditions. Some high-level radioactive sources will give off heat, but the presence or absence of heat neither confirms nor rules out the possibility of radiation being present. Because we are not able to sense radiation, it can be a difficult concept to comprehend. This can lead to fear, which is often unwarranted. Hollywood and the media have capitalized on our fears of radiation by exaggerating the effects radiation produces, further distorting the general public's understanding of it. Without a doubt, high doses of radiation can cause serious health effects and death, but by taking the appropriate precautions to protect ourselves, we can minimize the risk presented by radiation hazards. Understanding the basic physical properties and biological effects of radiation will help people develop a respect for radiation while demystifying unfounded misconceptions.

Radiation is the emission of energy in the form of waves or particles. Radiation that is emitted as a wave (or ray) is called electromagnetic radiation. Examples of electromagnetic radiation include (in order of increasing energy) radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays, and gamma rays. Physically, all types of electromagnetic energy are composed of the same thing—photons—but vary in frequency, wavelength, and energy, giving the different types their characteristic physical properties. Radiation that is emitted in particulate form typically occurs as alpha particles, beta particles, or neutrons. There are other, less common types of particulate radiation, but they are not relevant to the topic of this chapter.

All types of radiation fall into one of two categories: ionizing and nonionizing, depending on how much energy the radiation has. Ionizing radiation includes only radiation that is energetic enough that a single particle or wave is able to break the bonds of a molecule or strip a bound electron from an atom or molecule. It is of particular interest because it can damage molecules in cells, such as DNA (deoxyribonucleic acid), resulting in damage or death to those cells. The focus of this chapter is on medical operations in which there is a hazard caused by ionizing radiation. In this chapter, the term "radiation" pertains exclusively to ionizing radiation. X-rays and gamma rays are the only two types of electromagnetic energy that are considered ionizing radiation. Each of the types of particulate radiation previously mentioned is considered ionizing radiation.

Types of Radiation

X-rays. X-rays are electromagnetic radiation emitted when energy is transferred to an electron of the orbitals surrounding the nucleus of an atom, or when charged particles in motion are decelerated. When energy is transferred to a bound electron of an atom, the electron can temporarily achieve a higher bound energy state. Eventually it will lose the excess energy to go back to its original, more stable energy state by emitting a photon, which will often be in the X-ray frequency range. If a moving charged particle, such as an electron, hits a surface, it will interact with the other electrons and nuclei of the atoms in the material, causing the particle to slow down and lose energy. Some of the energy it loses will be emitted in the form of photons and, in some cases, photons generated by this method will also be in the X-ray frequency range. X-rays can travel many meters through air and require dense materials, such as lead or concrete, to provide adequate shielding. They are often machine generated by equipment such as medical imaging devices and industrial radiography devices.

Gamma Rays. When certain types of nuclei are in an unstable energy state, they will eventually achieve a more stable energy state by emitting excess energy in the form of a photon, known as a gamma ray. This is sometimes accompanied by the emission of particulate radiation as well. Like X-rays, gamma rays can travel many meters through air and require dense materials for shielding. They are produced by many types of radioactive materials and are also produced during the detonation of a nuclear weapon.

Alpha Particles. A type of particulate radiation emitted from the nucleus of an atom that consists of two protons and two neutrons bound together is known as an alpha particle. The two protons result in a net charge of + 2 for alpha particles. Because of this net charge, alpha particles interact strongly with the electrons and nuclei of other atoms as they are passing through a material. They do not penetrate very deeply because of this strong interaction, traveling a distance of only a couple centimeters through air, and being completely shielded by material as thin as a sheet of paper. They do not pose a significant health threat when outside the body, since the alpha particles will be absorbed in the body's outer layer of dead skin cells; however, alpha particles can do substantial damage when inside the body, where there is no protective layer of skin cells. Nuclear fuel used in reactors and nuclear weapons contains alpha-emitting sources, as do some materials that could be used in radiological dispersal devices.

Beta Particles. Another type of particulate radiation emitted from the nucleus of an atom is known as a beta particle. These are either an electron (beta –) or a positron (beta +). A positron is physically identical to an electron, but has a charge of + 1 instead of – 1. Like alpha particles, the net charge on beta particles causes them to interact strongly with surrounding electrons and nuclei as they pass through a material. Therefore, they do not require dense material for shielding. Glass or plastic several millimeters thick is typically adequate for shielding beta radiation. These particles can travel distances on the order of several meters through air and they can penetrate several millimeters deep through the skin, so beta-emitting materials in direct contact with the skin can result in a skin burn (known as a beta burn) if there is enough of the material on the skin for a long enough period of time. Because clothing provides a protective barrier to beta particles, only exposed skin is vulnerable. The fission process that occurs in nuclear reactors and during a nuclear detonation creates beta-emitting radioactive materials, which are a component of nuclear fallout. Radiological dispersal devices and radiological exposure devices are also likely to involve beta emitters.

Neutrons. Neutrons are uncharged particles that are primarily produced during the fission process that occurs in nuclear reactors and during a nuclear detonation, although there are a few types of radionuclides that emit neutrons by undergoing spontaneous fission. Since they have no net charge, neutrons can travel many meters through air and require dense material for shielding. Neutron exposure presents a risk only after the initial pulse of radiation during a nuclear detonation, or in situations in which humans could be exposed to neutron flux during criticality incidents (eg, responding to a damaged nuclear reactor core). However, neutrons can cause nonradioactive materials to become radioactive. This phenomenon, known as induced radiation activation, occurs when the nuclei of nonradioactive material absorb some of the neutrons, thereby becoming unstable and resulting in the production of beta- and gamma-emitting radioactive materials.

Radiation Terms and Units

Radiation can be generated by machines, as is the case with linear accelerators, most diagnostic medical X-ray equipment, and some industrial radiography devices. The radiation generated by these machines, though ionizing, is generally produced by electromechanical means, not by radioactivity. The term "radioactivity" is reserved exclusively for materials that have atoms whose nuclei spontaneously emit radiation.

Atoms that are radioactive are called radionuclides. Both radioactive and nonradioactive atoms having a specific number of protons and a specific number of neutrons are indicated by specifying the chemical species, *X*, along with the mass number, *A*, and are written as ^{A}X or X – A, where *X* is determined by the number of protons in the nucleus and *A* is equal to the sum of the protons and neutrons in the nucleus. For example, if there are 27 protons in the nucleus, the chemical species is cobalt (Co). If each nucleus also has 33 neutrons, the mass number (*A*) is 27 + 33 = 60. This particular atom, cobalt-60, is radioactive and is represented by the symbol ^{60}Co or Co-60.

Atoms of the same chemical species (ie, having the same number of protons) can have differing numbers of neutrons. These atoms are called isotopes. For example, the isotopes of cobalt include Co-56, Co-57, Co-58, Co-59, and Co-60. All cobalt atoms have the same number of protons (27) in the nuclei of their atoms; however, these isotopes each have a different number of neutrons. The number of neutrons affects the stability of a particular isotope. Isotopes that are radioactive are called radioisotopes. The term "radioisotope" is often used synonymously with the term "radionuclide."

The rate at which a radioactive source emits radiation is known as activity. Activity is measured in units of bequerels (Bq) or curies (Ci), where 1 Ci equals 37 billion Bq. One bequerel is equivalent to one emission of radiation per second (Table 10-1).

As the nuclei of a radioactive material emit radiation, the material becomes less radioactive over time. This process is called radioactive decay. Radioactive decay can be expressed in terms of the physical half-life of the material. The physical half-life is the amount of time after an initial measurement of activity that it

TABLE 10-1

RADIATION UNITS AND CONVERSIONS

Physical Property	Description	Traditional Unit	SI Unit	Conversion
Activity	Amount of radiation emitted per unit of time for a given amount and type of radioactive material	Ci	Bq	1 Ci = 37,000,000,000 Bq
Exposure	Amount of ionization produced by X-rays or gamma rays in a given volume of air at a given time	R	C/kg	1 R = 0.000258 C/kg of air
Absorbed dose	Amount of radiation energy absorbed per unit of mass of material	rad	Gy	1 rad = 0.01 Gy
Dose equivalent	Absorbed dose multiplied by a weighting factor taking into account the biological effects caused by the particular type of radiation involved	rem	Sv	1 rem = 0.01 Sv

Bq: becquerel
C: coulombs
Ci: curie
Gy: gray
R: roentgen
rad: radiation absorbed dose
rem: roentgen equivalent in mammal
SI: international system of units
Sv: sievert

takes for a radioactive source to decay to half of the activity that was measured initially. After two half-lives have elapsed, a source will have decayed to one fourth the initial activity. After three half-lives, it will have decayed to one eighth, and so on. Each type of radioisotope has its own characteristic physical half-life, and half-lives can vary from fractions of a second to billions of years, depending on the type of radioisotope.

The activity of a source, *A(t)*, at a specific time after an initial measurement of activity is given by the following relationship:

$$A(t) \approx A(0) \bullet e^{-0.693 \bullet t/T_{P½}}$$

In this equation, *A(0)* is the activity that was initially measured, *t* is the amount of time that has elapsed since the activity was initially measured, and $T_{P½}$ is the physical half-life of the isotope. This equation can be used to determine how long it will take for a known source to decay to a safe level.

As radioactive materials decay, they do not vanish; they are converted into some other type of atom. The resulting atom is called a daughter product or a decay product. In some cases, the daughter product will be stable; in other cases, the daughter product will be radioactive. If it is radioactive, it will subsequently decay to form its own daughter products. This process can involve many subsequent generations of daughter products, resulting in a decay chain until a stable daughter product is produced, or it could involve just a single generation, depending on the original radionuclide.

When in the presence of radioactive materials, the magnitude of the hazard depends on more than just the type of radionuclide and its activity. The health threat depends on the amount of radiation to which one is exposed. Radiation exposure is a measure of the amount of ionization produced by the radiation in a given volume of air. The unit of measure of exposure is called the roentgen (R), and is equivalent to 0.000258 coulombs per kilogram of air. Some types of radiation detection equipment measure the exposure rate (exposure per unit time) present at a given location and time. Direct measurements of exposure are valid for only X-ray and gamma radiation, but not particulate forms of radiation (see Table 10-1).

A quantity that is more directly related to the magnitude of the health threat presented by radiation is the absorbed dose. The absorbed dose is a measure of the radiation energy absorbed by a material per unit mass of the material (see Table 10-1). It applies to all types of radiation and materials. The unit of absorbed dose is the gray (Gy) or the rad, where 100 rad equals 1 Gy. In the context of medical operations following a radiological or nuclear incident, a measurement of 1 R of exposure can be assumed to be equal to 0.01 Gy (1 rad) of absorbed dose when measuring X-ray or gamma radiation.

TABLE 10-2

RADIATION QUALITY FACTORS

Type of Radiation	Quality Factor
X-rays, gamma rays, beta particles	1
Alpha particles	20
Neutrons of unknown energy	10

Data source: US Army Center for Health Promotion and Preventive Medicine. *The Medical CBRN Battlebook*. Aberdeen Proving Ground, MD: USACHPPM; 2008. USACHPPM Technical Guide 244.

Not all types of radiation are equally damaging to the cells of the body. Because of their physical properties, alpha particles and neutrons transfer much more energy than beta particles, X-rays, or gamma rays. Therefore, alpha particles and neutrons have the potential to do more damage to the cells with which they interact. A quantity known as the dose equivalent takes into account both the amount of radiation to which one is exposed and the relative amount of damage to the body associated with the type of radiation causing the exposure (see Table 10-1). The dose equivalent, *H*, is calculated using the following equation:

$$H = Q \bullet D$$

In this equation, *Q* is a weighting factor (quality factor) corresponding to the type of radiation, and *D* is the absorbed dose. When calculated using *D* in rads, the units of *H* are roentgen equivalents mammal (rem); when calculated using *D* in grays, the units of *H* are sieverts (Sv; 100 rem = 1 Sv). Note that for X-ray, gamma, and beta radiation, *Q* equals 1 (Table 10-2), so there is a one-to-one relationship between the value of the dose equivalent and the value of the absorbed dose for these types of radiation. However, this is not the case for types of radiation that have a *Q* value that is not equal to 1 (see Table 10-2).

Radiation Protection

Whenever there exists the possibility of exposure to radiation, the amount of exposure should be kept as low as reasonably achievable (ALARA). In radiation safety, this concept is known as the principle of ALARA. In other words, people should not subject themselves or others to any more exposure to radiation than is absolutely necessary to accomplish the task resulting in the exposure. During a radiological or nuclear incident, many of the victims will be exposed to radiation, and exposure to workers during the response effort will be unavoidable. However, there are some basic tenets of radiation safety that, if followed, will minimize the doses of radiation received by both the victims and the response personnel. These tenets include time, distance, shielding, and contamination control.

Time. Absorbed dose is a cumulative quantity that increases with the amount of time for which one is exposed. The less time a person spends in a radioactively contaminated environment or near other sources of radiation, the lower the dose received.

Distance. The amount of radiation to which one is being exposed decreases as the distance from the source of radiation increases. For point sources (sources with dimensions that are small compared to the distance between the source and the location at which the dose rate is to be determined), the dose rate and the distance are related by the following relationship, known as the inverse square law:

$$D'_1 X_1^2 = D'_2 X_2^2$$

In this equation, X_1 and X_2 represent two separate distances from a point radiation source, and D'_1 and D'_2 represent the corresponding absorbed dose rates at X_1 and X_2, respectively. This relationship is not a valid approximation for sources that are not point-like, but for non-point-like sources, the dose rate will still decrease as the distance from the source increases. By maximizing the distance from radiation sources, radiation dose rate can be minimized.

Shielding. As radiation passes through a material, it becomes attenuated in intensity as the particles or waves of radiation interact with the electrons and nuclei of the material. Various materials can be used as shielding to reduce the amount of radiation exposure. Shielding materials should be selected based on the type of radiation. Dense materials, such lead, concrete, or the ground, will shield radiation more effectively than less dense materials, and hydrogenous materials, like water, are effective at shielding neutrons. Additionally, the amount of shielding provided by a given material increases with the thickness of the material.

Contamination Control. Radiological and nuclear incidents are likely to result in the spread of radioactive materials. Radioactive material located in an area in which its presence is not intended is known as contamination, and it can occur in the environment or on equipment, buildings, and vehicles, and both outside and inside the human body. It is important to clarify the difference between contamination and exposure. Exposure occurs when a person or object is in the field of radiation being emitted by a source. Radiation exposure can damage the cells of the body; however, it does not result in the person or object that was exposed becoming radioactive (except in the case of a large dose of neutrons). Therefore, exposure to radiation does not cause a person or object to become a radiological hazard, and the exposed person or object is not necessarily contaminated. A person or object can be considered contaminated only if it has radioactive materials on or inside of it; thus, the contaminated person or object receives a certain amount of exposure from the contamination. Additionally, the contamination could cause exposure to anything else that is in the vicinity, and it could lead to cross-contamination (contaminating something that was not previously contaminated). Therefore, people and objects that become contaminated must be decontaminated to prevent unnecessary exposures and further spread of contamination.

Human contamination will occur in one of two types: external or internal. External contamination is defined as contamination located outside the body, either on the skin, clothing, or hair. Removing external radiological contamination is relatively straightforward. Removing clothing will eliminate most of the external contamination. Rinsing with warm water and soap will typically remove the rest. Warm water is preferred over cold because cold water can cause pores to constrict, trapping radioactive materials in the skin.[1] Similarly, warm water is preferred over hot because hot water can cause pores to expand, allowing contamination to be absorbed into the skin more readily.[1] Washing with water and shampoo will remove contamination in the hair, but conditioner should be avoided.[2] If contamination is still present in the hair, hair can be clipped, but in most cases this will not be necessary.

It should be noted that field decontamination methods, such as the M291 Individual Skin Decon Kit and the M295 Individual Equipment Decon Kit issued to service members, are intended to neutralize contamination from chemical agents, not radiological agents. They will be ineffective against radiological contamination. Radioactivity is a property of the nuclei of the atoms and cannot be neutralized. Using these chemical decontamination kits and similar methods in which a substance is rubbed over exposed body parts and equipment to neutralize chemical agents will only result in further spreading radiological contamination. Radiological contamination must be physically removed from the body and from equipment.

Internal contamination is defined as contamination located within the body. Humans can become internally contaminated through several routes of exposure, including inhalation, ingestion, injection, absorption of soluble radionuclides through the skin or wounds, and radioactive fragments becoming embedded in the body following an explosion involving radioactive materials. Methods of removing internal contamination from the body vary depending on the type of radioactive material involved and the route of exposure.

Radioactive fragments that are embedded in the body can have high levels of activity, resulting in a significant, potentially life-threatening dose to both the victim and others who are near the victim.[1] While this scenario would be relatively rare, if it is determined that a patient has been contaminated with highly radioactive fragments, the fragments must be immediately removed and placed in a secure location away from others so as not to present a hazard.

For soluble radionuclides that have been absorbed into the skin, normal external decontamination procedures might not fully remove the contamination. Applying sweat-inducing materials to the contaminated portions of the body or having the contaminated individual perform light exercise can reduce the amount of contamination remaining in the skin by causing it to be sweated out.

Radioactive materials inhaled, ingested, or injected into the body, and soluble radioactive materials that get into the bloodstream via absorption through the skin or wounds will either be distributed uniformly throughout the body or will accumulate in one or more target organs, depending on the chemical configuration of the radionuclide. For example, strontium is chemically analogous to calcium, so it deposits primarily in the bones, whereas cesium is chemically analogous to sodium and potassium, which are found in the components of all cells; therefore, cesium becomes distributed throughout the body. Radionuclides deposited in the body will be excreted over time at a rate related to the biological half-life of the radioactive material. The biological half-life is similar to the physical half-life in that it is equal to the amount of time it takes for half of an initial amount of a substance to be excreted from the body. The amount of activity of a radionuclide incorporated into the body decreases over time as a function of both the physical half-life and the biological half-life of the radionuclide. The effective half-life is defined as:

$$T_{Eff\frac{1}{2}} = (T_{P\frac{1}{2}} \bullet T_{B\frac{1}{2}}) / (T_{P\frac{1}{2}} + T_{B\frac{1}{2}})$$

In this equation, $T_{P1/2}$ is the physical half-life and $T_{B\frac{1}{2}}$ is the biological half-life. The amount of activity of a radionuclide in the body will decrease according to the effective half-life. The activity in the body, $A_i(t)$, at a given time, t, after the initial uptake can be calculate from the equation:

$$A_i(t) \approx A_i(0) \bullet e^{-0.693 \bullet t / T_{Eff\frac{1}{2}}}$$

Here, $A_i(0)$ is the initial amount of the radionuclide incorporated into the body.

In the event of internal contamination, there are treatments that can be administered to patients to increase the rate of excretion or to minimize the uptake in target organs (for example, chelating agents, such as diethylenetriamine pentaacetic acid [DTPA; used for plutonium]; ion exchange resins, such as ferric hexacyanoferrate (II) [Prussian blue; used for cesium and thallium]; and blocking agents, such as potassium iodide [KI; used to prevent uptake of radioactive isotopes of iodine]).

RADIOLOGICAL AND NUCLEAR SCENARIOS

This chapter focuses on medical operations following a large-scale radiological or nuclear incident resulting in many injuries or contamination to the population. There are several generic scenarios by which this could occur, and these scenarios are briefly discussed to distinguish the types and magnitude of casualties expected to result from each scenario, as well as identifying other factors that will affect medical operations during each type of scenario.

Radiological Exposure Device

The radiological exposure device (RED) is the simplest method of using radioactive material to cause injury and panic. An RED is a high-level radioactive source hidden so as to cause exposure to those who are in its vicinity. The sources used for these devices will most likely be gamma emitters, since gamma rays can travel a great distance and can penetrate through material concealing the RED, whereas alpha and beta particles do not have as great a range and would most likely be shielded by materials used for concealment. REDs can cause acute radiation syndrome (ARS) if the activity of the source is high enough and if nearby individuals are exposed for long enough. REDs will not result in contaminated casualties, since there would be no radioactive material on the victims. If an RED were concealed under a chair or desk in an office, it would likely affect only a handful of individuals who work in the vicinity of the location where it was hidden.

However, if an RED were hidden on a bus or passenger train, it could potentially result in many more casualties, and the casualties would not come from an isolated location. Radiation exposure due to an RED would likely be initially overlooked unless the presence of the RED was already known. This is because prodromal symptoms of ARS are similar to many other illnesses, and the lack of contamination on victims means that radiation detection equipment would not provide any indication of their potential exposure. Once news of an RED hits the media, a large number of concerned individuals, many of whom will not have received any exposure at all, will seek medical screening for health effects caused by radiation exposure.

Radiological Dispersal Device

A radiological dispersal device (RDD) is any type of device that is used to spread radioactive contamination. The most likely method of developing an RDD is to combine radioactive materials with a conventional explosive and then detonate it, thereby spreading radioactive contamination. This type of RDD is also called a dirty bomb. The magnitude of the explosion produced by a dirty bomb would not be any greater than if it were caused by the explosives alone. Adding radioactive materials does not increase explosive power, but the radioactive material will introduce additional factors that will affect the response effort. The number and types of physical injuries associated with a dirty bomb attack would be about the same as those for a conventional bomb and, in addition, both victims and responders would be potentially vulnerable to inhaling airborne radioactive materials. There is also the possibility of radioactive fragments being embedded in victims who were near the explosion. Contamination on the ground and on the skin and clothes of victims will not likely present an immediate health hazard because spreading the contamination over a large area will reduce the concentration to relatively low levels; however, contaminated individuals will still require decontamination even for low levels of contamination.

Another type of RDD scenario is the dispersal of airborne radioactive materials via crop duster or other methods by which aerosolized particulates are introduced into the atmosphere. This method could affect a very large area—possibly many square miles. As is the case with dirty bombs, spreading the radioactive material over a large area would most likely reduce the concentration of the contamination enough so that it is not an immediate external hazard, but would still require decontamination and would present an inhalation hazard to anyone in the affected area.

These two examples are not the only possible methods by which an RDD can be employed, but they are two of the most commonly suggested designs and they illustrate the radiological concerns associated with an RDD attack. In addition to the spread of radiological contamination and the potential for the contamination to become an internal hazard, it is also important to point out that for every person who becomes contaminated after an RDD attack, there will likely be many more people who were not contaminated who will seek monitoring for contamination and screening for health effects. This is the factor that makes RDDs desirable as a weapon of terror, since the use of radioactive materials can produce widespread panic and result in a surge that rapidly overwhelms medical and other resources.

Nuclear Reactor Incident

One of the most infamous radiation accidents in history was the reactor accident at Chernobyl in Ukraine in April 1986. An experimental test at one of the Chernobyl reactors caused steam in the reactor core to build up. The increase in steam pressure caused the core to burst and produced a fire that burned for several days, releasing large amounts of radioactive material into the atmosphere in the plume of smoke. More recently, in March 2011 an earthquake and subsequent tsunami caused severe damage to the reactor containment and spent fuel storage tanks at the Fukushima Daiichi nuclear power plant in Japan, resulting in an extensive release of radioactive material into the environment. These two incidents demonstrate how wide-ranging the effects of a major reactor accident can be. The population within a 20-km radius surrounding the Fukushima plant had to be evacuated, and a 30-km evacuation radius was implemented around the Chernobyl plant; that area is still uninhabited today. It has also been speculated that nuclear reactors might be targeted by terrorists, either by crashing aircraft into a reactor or spent fuel storage area, or by using explosives to attack a reactor and spent fuel storage from inside the walls. There are design precautions and security measures in place to deter attacks such as those described; however, consideration should still be given to the consequences of such an incident when planning for radiological response.

Unspent reactor fuel, which consists primarily of isotopes of uranium (U) or plutonium (Pu), is a relatively minor external hazard and is nonexplosive. Nuclear detonation can be achieved only through the use of a nuclear weapon. Rather, nuclear fuel is used in a reactor to generate heat during a process called fission, in which U-235 nuclei or Pu-239 nuclei split into two or more smaller nuclei, called fission products. A large amount of energy is released during fission, including the emission of gamma rays and neutrons. Additionally, the resulting fission products consist of a composite of numerous isotopes, many of which are highly radioactive beta and gamma emitters. For this reason, spent nuclear fuel (fuel that has undergone fission) can present a serious radiological hazard.

After an attack on a reactor or spent fuel storage area, there would likely be trauma and burn injuries from the attack, and workers and responders could receive high doses of radiation resulting in ARS if the reactor core or spent fuel storage is compromised. If a reactor incident results in a fire or an explosion, radioactive fission products and unspent fuel could be released into the atmosphere, affecting the local population. The radioactive contamination released into the atmosphere is known as fallout, and it is both an external hazard, which can cause large whole-body doses and beta burns, and an internal hazard if inhaled or ingested. The affected population will have to be advised to shelter in place or evacuate, depending on which course of action will result in a lower radiation dose, and decontamination of humans, equipment, and the environment will be necessary. Contamination can have long-term effects by accumulating in crops intended for consumption by humans and animals. After the Chernobyl incident, there was an extremely high additional incidence of thyroid cancer in children who drank milk from cows who had ingested crops that had an uptake from the fallout. Radioactive isotopes of iodine are one of the fission products found in abundance in fallout, so the affected population and responders may be advised to take potassium iodine tablets early on to block accumulation of radioactive iodine in the thyroid.

Nuclear Weapon Incident Without Nuclear Detonation

If a nuclear weapon becomes damaged, either due to an accident or as a result of malicious activity, it can cause injuries and contamination even if a nuclear detonation does not occur. A nuclear detonation is produced by first detonating conventional explosives to compress highly enriched nuclear material in the weapon, but damage to the weapon can cause these conventional explosives to detonate without initiating the nuclear detonation. The resulting explosion would spread contamination consisting of highly enriched uranium or plutonium and possibly tritium. The consequences of such an incident would be very similar to those produced by a dirty bomb attack, resulting in the spread of radioactive material and injuries primarily caused by the blast. There could also be significant chemical hazards associated with this type of incident. The radioactive materials used in nuclear weapons are not an immediate external hazard, but they can present an internal hazard. The primary route of exposure would most likely be inhalation of particles suspended in the air following an explosion. Some Department of Defense (DoD) publications discuss specific guidelines for responding to an incident involving a damaged nuclear weapon.[3]

Nuclear Detonation

An attack involving detonation of a nuclear weapon would be far more devastating than any of the other scenarios previously described. Nuclear weapons could be used by either an enemy nation or in an attack in which a terrorist organization obtains a nuclear weapon or acquires the materials and technology to construct their own weapon, known as an improvised nuclear device.

The magnitude of a nuclear detonation is measured in terms of how many tons of trinitrotoluene (TNT) it would take to produce an equivalent explosion. For example, a nuclear weapon that produces a 10-kt nuclear yield would have an explosive power equivalent to that produced by 10,000 tons of TNT. A detonation caused by terrorists would most likely produce a yield of approximately 10 kt or less; however, an attack using a military nuclear weapon could result in yields on the order of megatons (millions of tons of TNT).[4]

When a nuclear weapon detonates, it produces a powerful blast wave followed by forceful winds. The blast wave and winds will drag people across the ground or throw them into objects, resulting in contusions, abrasions, and puncture injuries. Other objects can be thrown through the air, causing projectile injuries. Injuries caused by broken glass are expected to be very common. Additionally, structures will collapse under the pressure from the blast, crushing those in buildings or trapping them inside, resulting in injuries similar to those caused by an earthquake (for more information on blast injuries, see Chapter 3, Triage and Treatment of Radiation and Combined-Injury Mass Casualties).

A rapidly expanding fireball will be produced at the center of the detonation. The fireball radius will not travel nearly as far out as the blast wave, but virtually any object within the fireball will be incinerated. In addition to the fireball, there will be a thermal pulse consisting of intense ultraviolet, visible, and infrared energy that radiates outward and will produce effects even farther out than the blast. The thermal pulse will result in flash burns to humans directly exposed to it, and it can start fires in buildings, resulting in secondary flame burns to humans. The intense flash of visible light can cause retinal burns and temporary flash blindness, which can indirectly cause injuries such as car crashes (for more information on thermal injury, including flash and flame burns, see Chapter 3, Triage and Treatment of Radiation and Combined-Injury Mass Casualties).

Neutrons and gamma rays will be emitted from a nuclear detonation, traveling out farther than the fireball, but not as far as the thermal pulse. Humans directly exposed to the initial flux of gamma rays and neutrons could receive doses of radiation high enough to cause ARS. For ground bursts or very low altitude air bursts, the area in the immediate vicinity of the detonation can become radioactive as a result of beta-gamma–emitting activation products produced by the neutron flux. This region can pose a significant hazard to response personnel who enter the highly radioactive area in search of casualties.

Additionally, there will be a large quantity of dust and debris that is pulled up into the air in the low-pressure region produced following a ground burst or low altitude air burst. This plume of dust and debris will also include fission products generated during the detonation, activation products created by the release of neutrons, and weapons-grade uranium or plutonium that was not consumed during the detonation. The plume can disperse highly radioactive fallout over tens or even hundreds of square miles, and the affected population will need to be advised to shelter or evacuate. Exposure to the fallout can cause whole-body gamma doses resulting in ARS, and direct contact with the skin can cause beta burns. Fallout is also an internal hazard if inhaled or ingested. Response to fallout produced from a nuclear detonation would be similar to the response to fallout from a nuclear reactor incident.

The energy released during a nuclear detonation will cause atoms and molecules in the atmosphere to become ionized. This separation of charges will result in a powerful, short-lived, electric field known as an electromagnetic pulse (EMP). The EMP will not produce direct physiological effects in humans; however, it can induce a voltage spike in long power lines, which can overload electronic devices that are connected to the power grid. This can result in malfunction or inoperability of communication devices, water distribution that operates off electric pumps, electronic medical equipment, and other systems that involve electronics. The EMP could even damage some electronic devices that are not connected directly to the power grid, such as the control modules of vehicles. It can have effects ranging out several miles from a ground burst. For a high-altitude (100–200 miles) burst, it is estimated that there could be effects hundreds of miles away. Emergency planners and medical officers should have contingency plans in place to take into account the effects of EMP.

OPERATIONS

Radiation Detection Equipment

Because our senses are not able to measure the magnitude of radiation or even detect its presence, we must rely on various types of detection equipment to provide this information. Different types of radiation detection equipment will be needed, depending on the application for which it is required. For example, survey meters—including ion chambers, Geiger-Müller counters, proportional counters, and scintillation counters—are used to measure the levels of radiation present at a given location and time. These instruments will typically measure radiation in terms of exposure rate (ie, roentgens per hour), or count rate (ie, counts per minute). Ion chambers are usually the best instruments to use when measuring levels of radiation for the purpose of setting up radiation control boundaries. A Geiger-Müller counter with a pancake-style probe is usually preferred for detecting beta-gamma contamination on people or equipment. For contamination caused by alpha emitters, scintillation counters designed specifically for detecting alpha particles are preferred.[5]

Dosimeters are worn to measure the amount of radiation to which one has been exposed over a given time period when working around sources of radiation. Electronic personal dosimeters (EPDs) are ideal for emergency responders going into areas where high levels of radiation could be found, since EPDs provide a direct measurement of either the exposure rate or the absorbed dose (sometimes both), and most EPDs have alarms that can be set to go off when specified dose levels or exposure rates are exceeded. Pocket ion-chamber dosimeters will also provide a direct measurement of the absorbed dose; however, they do not measure exposure rate and most do not have alarms that can be set.

A thermoluminescent dosimeter (TLD) is a type of passive dosimeter often used to measure occupational exposure to low levels of radiation. It does not provide a direct measurement of dose or exposure rate. After the wear period, a TLD must be processed with specialized equipment to determine the accumulated radiation dose. After the TLD is processed, the data can be used to provide a record of the wearer's exposure history. If the availability of dosimeters is limited during a radiological or nuclear emergency, priority for dosimetry should go to those who are likely to be exposed to the highest levels of radiation. When distributing dosimeters, EPDs are preferred if real-time data is required, followed by pocket ion-chamber dosimeters, followed by TLDs. If radiation dose rates are relatively low, or if a high level of confidence in the accuracy of data is needed for regulatory purposes, TLDs are the industry standard.

A spectrometer is a type of device that can be used to identify the particular type of radioisotope involved. Radioactive materials emit radiation at characteristic discrete energy levels, depending on which radioisotope is producing it. A type of spectrometer known as a multichannel analyzer measures the energy of radiation emitted and compares the measured energy to a database of energies from known radioisotopes to determine the most likely radioisotope involved. In addition to identifying unknown sources of radiation, many multichannel analyzers work in combination with instruments that measure exposure rates or dose rates.

For any radiological or nuclear incident in which there is an inhalation hazard, it will be necessary to determine the extent of airborne radioactive material. Air sampling equipment designed to measure the quantity of radioactive material present in the air will have to be used to obtain this data. Once this data has been collected, it should be used to make corrections to computer-simulated dispersal models.

Radiation Dose Limits to Workers

Federal regulations specify the doses of radiation allowed to both the general public and radiation workers in the United States (Table 10-3). For members of the general public, defined as those who have not willingly accepted a risk of exposure to radiation as a consequence of their occupations and are not under medical surveillance for radiation exposure, the radiation dose limit is 0.1 cSv (0.1 rem) annually.[6] For adult radiation workers, defined as those over 18 years of age who have willingly accepted a risk of exposure to radiation as a consequence of their occupations and are under medical surveillance for radiation exposure, the annual whole-body dose limit is 5 cSv (5 rem).[6] For radiation workers who are minors, the annual limit is 0.5 cSv (0.5 rem), and declared pregnant radiation workers are limited to a dose of 0.5 cSv (0.5 rem) over the duration of the declared pregnancy.[6]

Following a radiological or nuclear incident, first responders will likely have to go into areas that are contaminated with radioactive material to search for and stabilize casualties, medical personnel will receive casualties who are radiologically contaminated, and cleanup crews will have to go into the contaminated region during the recovery phase to clear debris and remove contamination. It will not be possible for these workers to perform their duties without incurring exposure to radiation, and it is recognized that during response to a large-scale radiation emergency, the dose limits to the general public and the occupational dose limits might be too restrictive. Therefore, various agencies have developed recommendations for dose limits applicable to emergency situations (see Table 10-3).

In situations in which the dose limits to the general public and occupational dose limits are not practical, the US Environmental Protection Agency recommends limiting responder dose to 10 cSv (10 rem) if incurring such a dose is necessary to protect critical facilities that are essential to the welfare of the community (eg, power generation stations, water treatment plants, hospitals).[6] For lifesaving operations, the Environmental Protection Agency suggests a dose limit of 25 cSv (25 rem), with higher doses permitted on a voluntary basis.[4,6]

The EPA also recommends that if responders are subjected to these higher doses, they should be informed beforehand of the risk. For doses less than approximately 100 cSv (100 rem), the primary risk is an increased chance of getting cancer. However, exposure to radiation causes a much smaller increase in cancer risk than many people realize; especially when compared to baseline cancer rates, which are comparatively very high.[7]

The threshold dose necessary to cause ARS is around 100 cSv (100 rem). The National Council on Radiation Protection and Measurements suggests a factor of safety of 2 to avoid exceeding this threshold, recommending a dose of 50 cSv (50 rem) as the turnback dose limit for responders.[2]

If a high level of risk is acceptable during critical missions or if an extremely high level of risk is acceptable during priority missions, the DoD's recommended operational exposure guidance (OEG) to commanders is to limit forces to 75 cGy (75 rad). If an extremely high level of risk is acceptable during critical missions, 125 cGy (125 rad) is the recommended OEG. Commanders must remember to take into account a unit's previous exposure when determining the appropriate OEG for a particular mission.[8]

It is important to note that the emergency dose limits to responders suggested by the various agencies are only recommendations and are not intended to limit the authority of the commander. It is the commander's responsibility to define dose limits for responders

TABLE 10-3

REGULATORY DOSE LIMITS AND RECOMMENDATIONS FOR EMERGENCY DOSE LIMITS

Population or Body Region	Dose Limit
General public	0.100 cSv (0.100 rem) total effective dose equivalent per calendar year
Adult occupational radiation workers	5 cSv (5 rem) total effective dose equivalent per calendar year
Lens of eye	15 cSv (15 rem) effective dose equivalent per calendar year
Individual organ	50 cSv (50 rem) deep dose equivalent plus committed dose equivalent per calendar year
Skin or extremity	50 cSv (50 rem) shallow dose equivalent per calendar year
Declared pregnant worker	0.5 cSv (0.5 rem) for duration of pregnancy, not to exceed 0.05 cSv (0.05 rem) per month
Occupational exposure to minors	0.5 cSv (0.5 rem) total effective dose equivalent per year
EPA recommendation for saving valuable property in emergencies	10 cSv (10 rem)
EPA recommendation for lifesaving in emergencies	25 cSv (25 rem), higher doses on voluntary basis after being informed of risk
NCRP recommendation for turn-back decision during emergencies	50 cSv (50 rem)
OEG to military commanders when high risk is acceptable for critical missions or when extremely high risk is acceptable for priority missions	75 cGy (75 rad)
OEG to military commanders when extremely high risk is acceptable during critical missions	125 cGy (125 rad)

EPA: Environmental Protection Agency
NCRP: National Council on Radiation Protection and Measurements
OEG: operational exposure guidance
Data sources: (1) US Army Center for Health Promotion and Preventive Medicine. *The Medical CBRN Battlebook*. Aberdeen Proving Ground, MD: USA CHPPM; 2008. USACHPPM Technical Guide 244. (2) National Council on Radiation Protection and Measurements. *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism*. Bethesda, MD: NCRP; 2005. NCRP Commentary 19. (3) US Homeland Security Council Interagency Policy Coordination Subcommittee. *Planning Guidance for Response to a Nuclear Detonation*. Washington, DC: DHS; 2009. (4) US Department of the Army, US Department of the Navy, US Department of the Air Force, US Coast Guard, US Marine Corps. *Operations in Chemical, Biological, Radiological, and Nuclear (CBRN) Environments*. Washington, DC: DA, DN, DAF, USCG, USMC; 2008. Joint Publication 3-11.

under his or her command, and that decision must be based on the risk associated with exposure versus the benefit gained from carrying out the tasks that result in the exposure. The commander should follow the principle of ALARA in defining dose limit goals, setting the limits at the lowest level practical for a given mission.

If at all possible, worker doses should be recorded. This is best accomplished by providing each worker with a physical dosimeter, such as an EPD, a pocket dosimeter, or a TLD. If dosimetry is not available, health physics personnel can assist in determining a reasonable dose estimate. Consideration should be made to avoid assigning pregnant workers to tasks that will result in radiation exposure.[1]

Surveying Patients for Contamination

Both injured and noninjured individuals involved in a nuclear or radiological incident could have external contamination on their clothing or bodies. To determine if and where contamination is located on a person, a contamination survey should be performed. Ideally, a detector with a pancake-design Geiger-Müller probe will be the best type to use for detecting localized contamination from beta-gamma–emitting isotopes. For contamination by alpha emitters, a probe designed specifically for detecting alpha radiation should be used.

The calibration date of the detector should be verified before performing the contamination survey. The calibration date will most likely be indicated on the side of the instrument. Typically, detectors must be calibrated at least every 2 years.[5] A detector that is not due for calibration is preferred; however, during emergencies, instruments that are not calibrated may have to be used, since an out-of-calibration detector is better than having no detector at all. After verifying the calibration date, the battery check function should be inspected to ensure that there is sufficient battery life (not all detectors will have a battery check function). Spare batteries should be readily available. If a check source is available, the instrument should be turned on and the probe brought near the check source to verify that the instrument is working properly. Next, background levels of radiation should be measured and recorded. Background levels must be measured in an area that is known to be free of sources of radiation.

When surveying someone for contamination, it is important to hold the probe very close to the surface being surveyed so it will be able to detect low levels of contamination. For beta-gamma contamination, the probe window should be held approximately 1 inch from the surface,[9,10] whereas for alpha contamination, it may have to be held even closer. Care should be taken not to touch the probe to the contaminated surface, since this could result in the transfer of contamination to the probe that would cause false-positive readings and could be difficult to remove. If the contamination is known to contain beta-gamma emitters, a protective cover, such as a thin plastic bag or rubber glove, can be placed over the probe.[5] The probe will still detect the contamination and if the protective bag or glove becomes contaminated, it can be easily removed and replaced. This technique will not work for detecting alpha emitters because a protective cover will prevent the instrument from detecting alpha particles. The rate of travel at which the probe is used to survey a surface must not be too rapid to avoid missing small, localized areas of contamination. Typically, the probe should travel at a rate of about 1 to 2 inches per second.[9,10]

If able, an individual being surveyed should stand with arms out and feet slightly wider than shoulder width (Figure 10-1). The probe should be scanned over all surfaces on the anterior of the person's body, beginning with the top of the person's head and continuing

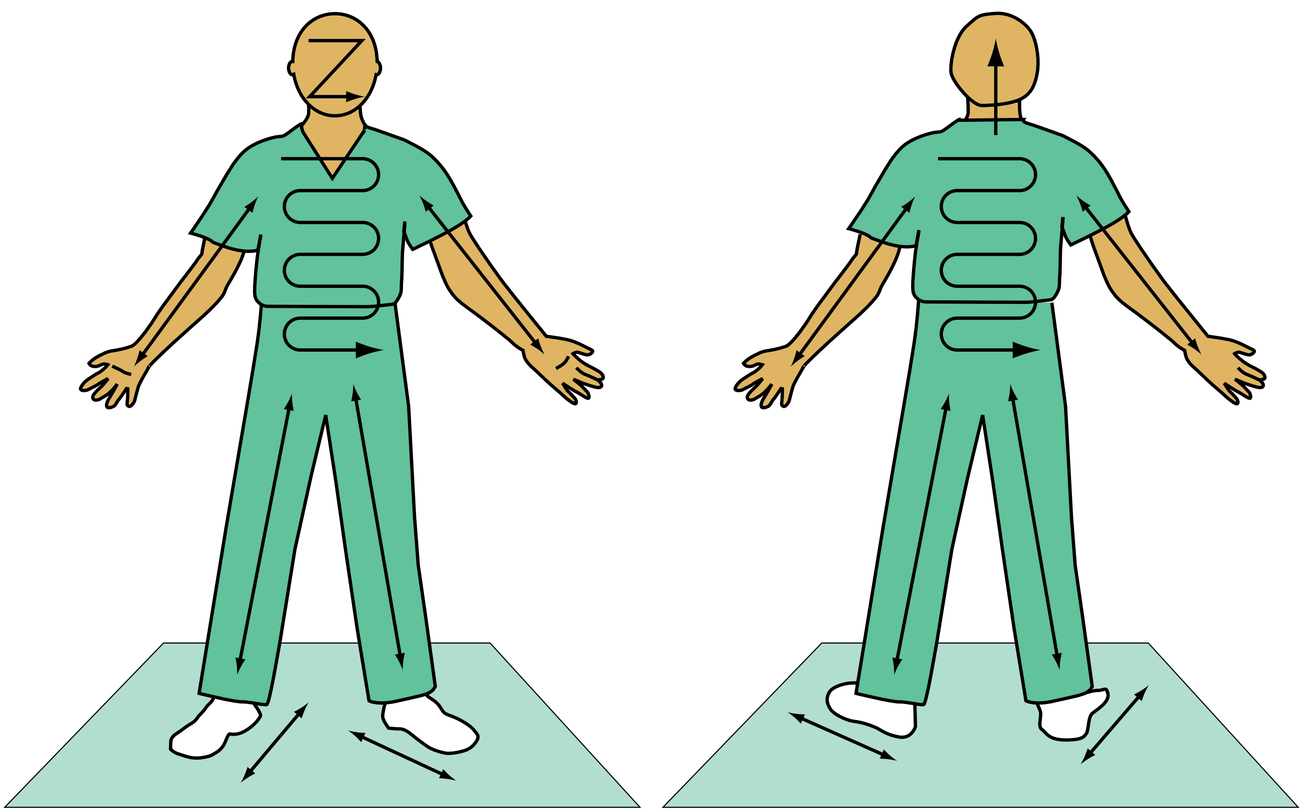

Figure 10-1. Path of detector travel during ambulatory patient contamination survey.
Reproduced with permission from: Radiation Emergency Assistance Center/Training Site, Oak Ridge, TN.

to the face, neck, and shoulders; front of the arms, palms of the hands, and fingertips; armpits; chest; abdomen; sides; crotch; front, inside, and outside of the legs; and finishing with the top of the feet. Then the individual should be asked to turn around and the probe should be scanned over all posterior surfaces of the body, again beginning with the top of the head and ending at the feet. Lastly, the bottom of the individual's shoes should be checked for contamination. Variations in this procedure can be implemented for nonambulatory patients.

It can take a long time to survey a person's entire body by this method. Therefore, in situations in which the number of individuals requiring contamination surveys is so great that the time required to survey all of them by this method will have an adverse impact on other operational aspects of the mission, a more expedient contamination survey can be implemented.[5] The expedient method consists of surveying the person's face, shoulders, hands, and bottom of the shoes, since these are the areas that are most likely to be contaminated if there is contamination present. If other parts of the body are contaminated, the levels of contamination will most likely be very low, and when clothing is removed, the contamination will likely be removed along with it.

Search and Rescue

It is highly probable that emergency response personnel will have to go into the affected area to perform search and rescue operations after a large-scale radiological or nuclear incident. Reaching victims quickly will be important, since many may have life-threatening injuries and could be trapped in locations with dangerously high radiation levels. However, responders must use caution to ensure that they do not rush into high-level radiation areas indiscriminately and become casualties themselves.

Following a release of radioactive material, response units should immediately begin coordinating with agencies that have computer-modeling capabilities to obtain models of the affected area. There are software programs that can provide overlays of estimates for blast, thermal, initial radiation, and fallout distribution, as well as casualty estimates for these effects based on the type and magnitude of the incident. The models generated can be used to get a preliminary estimate of radiation levels and the most probable locations of victims who will require extraction. Some local response agencies can produce these models, and National Guard Weapons of Mass Destruction Civil Support Teams have modeling capability for domestic incidents. The US Department of Homeland Security's Interagency Modeling and Atmospheric Advisory Center is responsible for modeling large-scale domestic incidents for the federal government,[4] and the DoD's Defense Threat Reduction Agency has advanced modeling capability for both foreign and domestic incidents.

Computer models should be used only as an initial estimate and must not be assumed to represent real conditions with complete accuracy. As soon as possible, field data must be obtained using radiation detection equipment to accurately plot the levels of radiation. The National Council on Radiation Protection and Measurements recommends identifying two radiation control perimeters that define an inner extreme caution zone and an outer low radiation zone (Figure 10-2). The inner perimeter corresponds to an exposure rate of 10 R/h (approximately 0.1 Gy/h), and operations within this perimeter should be limited to

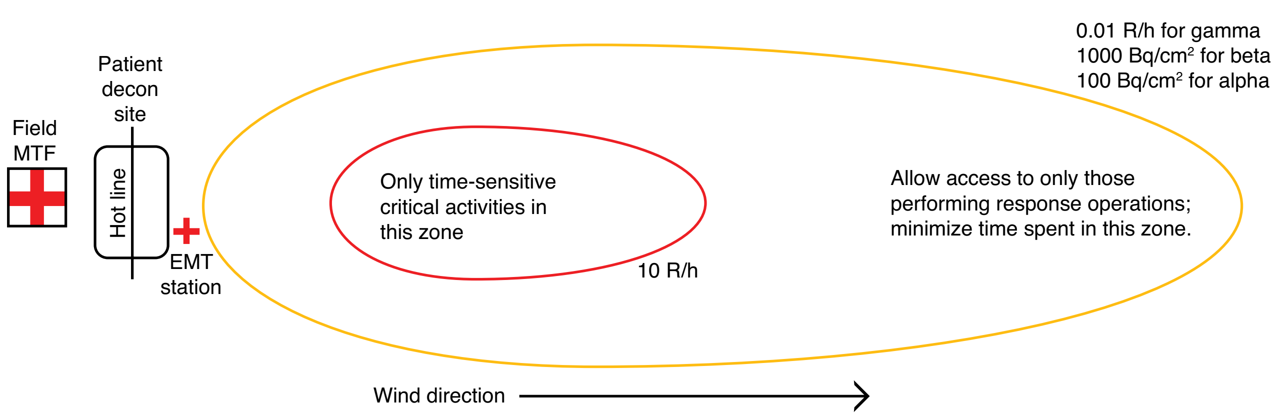

Figure 10-2. Recommended radiation control zones. Figure not drawn to scale.

only time-sensitive critical activities, such as lifesaving.[2] The outer perimeter corresponds to an exposure rate of 0.01 R/h (approximately 0.0001 Gy/h), or 1,000 Bq/cm^2 for beta-gamma contamination, or 100 Bq/cm^2 for alpha contamination, whichever is farther out. Access to the area within this perimeter should be limited to those performing response operations.[2] Depending on the size of the area effected, the radiation control perimeters might be too large to completely surround with markers, such as warning tape or flags; in which case, the perimeters might need to be defined using landmarks such as roads and terrain features. If the affected area is large enough, additional intermediate radiation control perimeters can be implemented, if warranted. The markers defining these zones must be clearly communicated to all response personnel, including those who will remain outside these zones.

Personnel performing search and rescue operations in a radiologically contaminated environment must use personal protective equipment (PPE; Table 10-4). Standard firefighting gear (bunker gear), including self-contained breathing apparatus (SCBA), helmet, and thermally insulated coat, pants, boots, and gloves will provide adequate protection for responders entering the controlled zones.[2,11] If radioactive materials are the only hazard present, the level of PPE can be downgraded to an anticontamination suit, protective boots and gloves, and either a nonpowered, full-face, air-purifying respirator, or, preferably, a powered air-purifying respirator. A powered air-purifying respirator is preferred because many powered models do not require fit testing. Combination high-efficiency particulate air (HEPA) or P-100 filters and organic vapor/acid gas cartridges should be used with these respirators.[11] Either type of air-purifying respirator will be equally as effective as SCBA, since the inhalation hazard presented by the radioactive materials will be almost entirely in the form of airborne particulates, which are readily filtered out by air-purifying respirators. Additionally, the wear time for SCBA is limited by the amount of air contained in the tank, whereas air-purifying respirators do not have this limitation.

TABLE 10-4

RECOMMENDED PERSONAL PROTECTIVE EQUIPMENT FOR VARIOUS OPERATIONAL FUNCTIONS

Type of Operation	Recommended Protective Equipment
Responders entering radiation control zones when fires are present	Dosimetry (EPDs preferred) and standard firefighting gear: SCBA, helmet, thermally insulated coat, pants, boots, and gloves
Responders entering radiation control zones when radioactive materials are the only hazard Crew members transporting contaminated patients in vehicles Medical and decontamination personnel on the contaminated side of the patient decontamination hot line	Dosimetry (EPDs preferred) and level C HAZMAT gear: anticontamination suit, protective boots and gloves, powered air-purifying respirator (preferred) or full-face, nonpowered air-purifying respirator, combination HEPA or P-100 filter and organic/acid gas cartridges
Workers on the clean side of the patient decontamination hot line Workers at field MTFs Hospital workers	Dosimetry and standard hospital infection control precautions: disposable gowns, hospital gloves, shoe covers, hair covers, and N95 respirators (preferred) or surgical masks

EPD: electronic personal dosimeter
HAZMAT: hazardous material
HEPA: high-efficiency particulate air
MTF: medical treatment facility
SCBA: self-contained breathing apparatus
Data sources: (1) National Council on Radiation Protection and Measurements. *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism*. Bethesda, MD: NCRP; 2005. NCRP Commentary 19. (2) Centers for Disease Control and Prevention; Smith JM, Spano MA. *Interim Guidelines for Hospital Response to Mass Casualties from a Radiological Incident.* Atlanta, GA: CDC; 2003. (3) US Army Center for Health Promotion and Preventive Medicine. *Personal Protective Equipment Guide for Military Medical Treatment Facility Personnel Handling Casualties from Weapons of Mass Destruction and Terrorism Events*. Aberdeen Proving Ground, MD: USACHPPM; 2003. USACHPPM Technical Guide 275. (4) Occupational Safety and Health Administration. *OSHA Best Practices for Hospital-Based First Receivers of Victims from Mass Casualty Incidents Involving the Release of Hazardous Substances.* Washington, DC: OSHA; 2005. (5) Departments of the Army, Navy, and Air Force. *NATO Handbook on the Medical Aspects of NBC Defensive Operations*. Washington, DC: DA, DN, DAF; 1996. AMed P-6(B), FM 8-9, NAVMED P-5059, AFJMAN 44-151.

However, SCBA must be used when entering areas with some types of chemical hazards, fires, confined spaces, unknown hazards, or in any situation in which the environment could be depleted of oxygen.

Anticontamination suits and respirators will minimize external and internal contamination to the wearer, but they do not shield the wearer from exposure to gamma or neutron radiation. Responders going into the radiation control zones should wear dosimeters to monitor the amount of radiation to which they have been exposed. Ideally, EPDs are the dosimeters of choice because they provide a real-time measure of the radiation exposure rate and the accumulated radiation dose. The dose alarm and the exposure rate alarm should be set based upon the dose limits defined by the incident commander. For responders entering areas that could have very high dose rates, the National Council on Radiation Protection and Measurements recommends setting the EPDs to alarm at a dose of 0.50 Gy (50 rad), and an exposure rate of 10 R/h (approximately 0.10 Gy/h).[2] If EPDs are not available, the next best choice is a pocket dosimeter, which will still provide an immediate measure of accumulated radiation dose (although it will not measure exposure rate and most do not have alarms that can be set). If neither EPDs nor pocket dosimeters are available, TLDs can be used. Ideally, each responder should have a dosimeter, and the dose to that responder should be recorded and included in the individual's medical history. If there are not enough dosimeters for each responder, one dosimeter can be given to each team of workers and the dose measured by the dosimeter can be assigned to every team member.

As responders exit the outer radiation control perimeter, they should be surveyed for contamination and, if necessary, decontaminated. A separate decontamination site exclusively for responders coming out of the radiation control zones can be set up to expedite the process. Responders can usually decontaminate themselves by carefully doffing protective clothing, making sure not to contaminate previously uncontaminated parts of their clothes and bodies. Any remaining contamination can usually be removed by brushing it off or by spot decontamination with tape or soap and water. Equipment being brought out of the radiation control zones should also be surveyed and decontaminated, if necessary.

Radiologically contaminated injured casualties should be evacuated by ambulance or other vehicle. If casualties have serious injuries, transportation to higher levels of care always takes priority over contamination control. The amount of contamination on a casualty being transported will not be an immediate hazard to either the casualty or to others in the vehicle, whereas the injuries the victim has sustained could very well be immediately life threatening. The only way to confirm whether a casualty is radiologically contaminated is to use detection equipment. If contamination is confirmed or suspected, the casualty should be lightly dusted off and, if necessary, he or she should be wrapped in a sheet or blanket before being loaded into the vehicle for transport.[11,12] This will minimize the amount of contamination transferred from the victim to the vehicle. It is recommended that workers who are in the vehicle with the contaminated casualty wear protective outer garments, gloves, boots, and either nonpowered, full-face, air-purifying respirators, or, preferably, powered air-purifying respirators (see Table 10-4). After contaminated casualties are transported, the vehicle can be decontaminated by vacuuming it, scrubbing surfaces with soap and water, and collecting the runoff. When the level of contamination is equal to or less than two times background levels, the vehicle can be considered free of contamination.

Nuclear Weapon Damage Zones

A system for estimating the most likely location of casualties with severe but survivable injuries has been developed for use in the event of a nuclear detonation (see also Chapter 3, Triage and Treatment of Radiation and Combined-Injury Mass Casualties). Three zones are defined based on the extent of physical damage to the infrastructure (Figure 10-3).[4] The innermost zone, known as the "no-go" or severe damage zone, is the region surrounding the hypocenter of the detonation. It will be characterized by buildings that are completely destroyed. Radiation levels will be very high in this zone, possibly preventing responder access. The number of casualties with survivable injuries in this zone will be minimal.

Surrounding the no-go zone is the moderate damage zone. This zone will be characterized by substantial building damage and rubble, fires, overturned vehicles, and downed utility poles. There will be many casualties with serious injuries in this zone, but many of the injuries will be survivable with prompt medical attention. Lifesaving efforts should focus on this zone.

Surrounding the moderate damage zone will be the light damage zone. This zone will be characterized by damage consisting mostly of broken windows and light damage to buildings. Most injuries sustained in this zone will be relatively minor and can be treated by self-care or outpatient care.

It must be noted that these three zones do not provide a reliable measure of the levels of radiation present and are independent of the radiation control

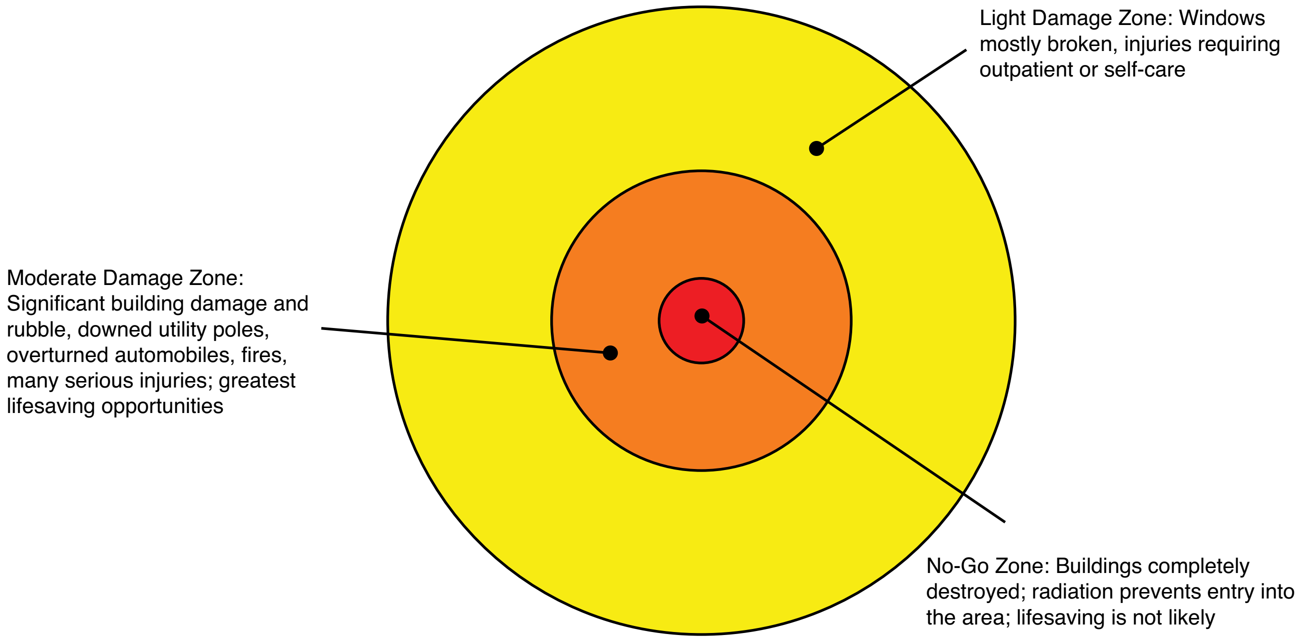

Figure 10-3. Nuclear weapon damage zones.

zones described earlier. These zones are used only to get an estimate of the location where there will be the greatest number of casualties with serious but survivable injuries. One must also take into account the area affected by fallout and the threat the fallout presents to response operations, as well as the impact that radiation exposure from fallout will have on the survivability of injuries.

Patient Decontamination Site

To receive potentially contaminated casualties, patient decontamination sites should be positioned upwind from the site of the incident at a point near the outer radiation control perimeter (see Figure 10-2).[5] Immediately downwind of the patient decontamination station there should be an emergency medical technician (EMT) station where patients first arrive to receive initial triage and basic lifesaving first aid while waiting to go through decontamination (see Figure 10-2). During initial triage, those who are in the greatest need of medical care should receive priority for decontamination. If the patient's condition is such that taking time for surveying and decontamination prior to providing urgent care will result in regression to a more severe medical state, decontamination should be bypassed and the patient should be transferred directly to the medical treatment facility (MTF). Much of the contamination originally on the patient will have shaken off or have been brushed off by this time, and the patient might have already received initial mass decontamination by first responders. Therefore, the amount of contamination left on the patient upon arrival at the MTF will not present an immediate hazard to either the patient or medical personnel. The radiological contamination on the patient can eventually present a hazard if one is exposed to it for a long enough period of time, but the more immediate concern will be the patient's physical injuries. Treatment of life-threatening injuries always takes priority over radiological decontamination.

Patients who are stable enough to go through decontamination before going to the MTF should proceed from the EMT station to the patient decontamination site. There, a contamination control line (hot line) should be designated and clearly marked, with the contaminated side being established downwind and the clean side upwind. While on the contaminated side, the patient should first be surveyed for contamination. Prior to decontamination, nasal swabs should be taken from each nostril of all patients suspected of being internally contaminated as a result of inhalation. When using a Geiger-Müller pancake probe, count rates of 100,000 counts/min around the head, face, and shoulders are a strong indicator of possible internal contamination.[5]

If localized contamination is found during the survey, spot decontamination can be performed by removing clothing that is contaminated and either using adhesive tape to remove contamination or washing affected areas of the skin. If the contamination is over the person's entire body, clothing should be completely removed and the parts of the body that were not covered by clothing should be washed with soap and water. In some cases it will be necessary to wash the entire body. Water alone will usually be adequate if soap is not available. Scrubbing should not be too vigorous or it could result in abrasion of the skin, allowing for an additional route of exposure for internal contamination. Special precautions must be taken for patients with burn injuries. No scrubbing should be performed on the portion of the skin that is burned, and rinsing must be very gentle so as not to remove the burned tissue. Washing can place patients with extensive burns in danger of hypothermia and hypotension, so medical officers should be consulted before decontaminating these patients.[1] Decontamination should not be performed if it will put the patient at greater risk than the contamination itself presents. The contamination will remain in burned skin because there is no circulation and most of it will eventually slough off with the burn eschar.[1,7]

Contaminated clothing should be collected and brought to a secure location away from the decontamination site. If possible, personal items belonging to the patient should be decontaminated, placed in a plastic bag, and kept with the patient. After decontamination, the patient should be surveyed again to ensure that contamination has been reduced to acceptable levels. As a rule of thumb, count rates of two times background or less are desired.[1] Under some circumstances, levels up to 10 times background can be considered acceptable if achieving lower levels of contamination is not practical. After repeated washing, if the count rates do not drop, external decontamination should cease and internal contamination should be suspected. Once external decontamination is complete, the patient should be transferred across the hot line and should proceed to the MTF. Information suggesting possible internal contamination should be recorded, and this data, along with any nasal swabs that were collected, should be kept with the patient as he or she is transferred to the MTF.

During a radiological mass casualty situation, the patient decontamination site can quickly become overwhelmed by casualties with varying degrees of injuries and levels of contamination. Those who are externally contaminated but are uninjured and are not suspected of having internal contamination should be directed to an alternate decontamination site dedicated exclusively to the external decontamination of people who do not need medical care.[5] The alternate decontamination site should be at a location where radiation levels are near background, and it should also be upwind from the incident site. If contamination on a patient is less than 1,000 counts/min on a Geiger-Müller pancake probe, the patient can be given instructions on self-decontamination and sent home.[5] For large-scale incidents in which decontamination personnel and resources are severely limited, contaminated individuals can be sent home to self-decontaminate at levels up to 10,000 counts/min.[5] Self-decontamination consists of removing the clothing and placing it in a bag to be stored in a secure location, such as the furthest corner of a garage, a storage shed, or in an isolated portion of the house as far away from the inhabitants as possible, and then showering with soap and shampoo (without conditioner).

PPE for decontamination team members on the contaminated side of the hot line, including workers at the EMT station, should consist of anticontamination suits, protective boots and gloves, and either a full-face air purifying respirator or, preferably, a powered air-purifying respirator with a minimum protection factor of 1,000.[11,13] Combination P-100 or HEPA filters and organic vapor/acid gas cartridges should be used with these respirators (see Table 10-4).[11] Workers on the contaminated side should be surveyed and decontaminated as necessary before crossing over to the clean side. Workers can usually decontaminate themselves by carefully doffing their protective clothing on the contaminated side, making sure not to contaminate themselves further. Contaminated clothing and equipment should remain on the contaminated side of the hot line until it has been decontaminated. For workers on the clean side of the hot line, standard precautions, including the use of disposable gowns, hospital gloves, hair covers, and shoe covers, are adequate (see Table 10-4).[11] If available, respiratory protection, such as N95 respirators, should be used on the clean side. If N95 respirators are not available, surgical masks will typically provide adequate protection.[10] Dosimeters should be used by workers on both the contaminated side and clean side; however, if the supply of dosimeters is limited, priority should go to those on the contaminated side.

It is important to ensure that there are enough workers to receive nonambulatory patients on both the clean and contaminated sides of the hot line. Additionally, patient decontamination can be very tiring and the protective clothing can be hot. During prolonged operations, it will be necessary to implement rotating work–rest cycles for decontamination personnel.

Modesty can be a concern among those who require decontamination, so patients who are able to decontaminate themselves unassisted should be allowed to do so. Written instructions can be provided to guide them through decontamination procedures and, if necessary, a decontamination team member of the same sex can observe to ensure thoroughness of decontamination.

Logistical coordination will need to take place in advance to ensure that an adequate number of towels and gowns are available for those who are decontaminated. Additionally, operations might have to be carried out in cold weather or in the evening, so blankets, heating, and lighting might be necessary as well.

When setting up the decontamination site, consideration should be made as to how to contain contaminated runoff from decontamination operations, and reasonable efforts should be made to collect the runoff, if feasible. However, collecting contaminated water should not detract from resources needed for emergency lifesaving operations. While protecting the environment is an important consideration, lifesaving operations take priority. Personnel and other resources will be severely limited and time will be precious during a large-scale radiological or nuclear incident. Therefore, resources should first be used for emergency operations that support lifesaving and protecting critical facilities essential to the welfare of the community. As the situation stabilizes and resources become more readily available, additional resources can be shifted toward environmental protection.[2,10,13]

Field Medical Treatment Facility

After a large-scale radiological or nuclear incident, many nearby hospitals could be destroyed or in the dangerous fallout plume, or if the incident occurs away from a city, there might not be any preexisting hospitals in the vicinity. In any of these cases, it might be necessary to establish an MTF near the incident site. If a field MTF is to be established, it should be located about 30 to 50 meters upwind of the patient decontamination site (see Figure 10-2).[13] In addition to injured patients who have been decontaminated, the field MTF must be prepared to receive contaminated casualties who have bypassed the decontamination site upon direction of the EMT station triage officer. Although the level of contamination on casualties who bypass decontamination will not present an immediate hazard, protective measures should still be implemented to minimize cross-contamination and keep exposure levels as low as reasonably achievable. Separate entrances to the MTF can be designated for contaminated and noncontaminated patients and, if feasible, contaminated patients should be treated in a separate section from uncontaminated patients. Traffic flow through the MTF should be directed such that contaminated patients do not pass through uncontaminated areas and uncontaminated patients do not pass through contaminated areas.[14] If possible, contaminated equipment should be segregated from uncontaminated equipment.

Standard precautions used on the clean side of the patient decontamination hot line also constitute adequate PPE for workers in the field MTF (see Table 10-4).[2,11] Individual dosimeters should be worn if they are available. Workers should be surveyed for contamination before going from contaminated sections of the MTF to clean sections. Maintaining good hygiene and changing out protective clothing when going from contaminated sections to clean sections of the MTF will minimize the spread of contamination. Contaminated protective clothing should be collected and kept in containers clearly marked as containing radioactive waste. When containers become full, they should be transferred to a designated radioactive waste storage area that is in a secure location away from people.

Radiological contamination on a patient will not present an immediate threat to either the patient or medical staff, so decontamination procedures should not impede injury treatment. Patients should be surveyed for contamination and decontaminated if necessary; however, this can likely be carried out at the same time that the patient is being treated without interfering with treatment procedures. Removing the patients' clothing will eliminate most of the contamination. Sponges and moist wipes can be used to remove remaining contamination on the skin, and contaminated wounds should be gently irrigated. After decontamination, the patient should be surveyed again to ensure contamination levels have been reduced to appropriate levels. Levels two times background are usually considered acceptable.[1] Contaminated wipes, sponges, clothing, and other wastes should be collected, marked as radioactive, and brought to the radioactive waste storage area. A reasonable effort should be made to collect liquids that contain contamination.

Although it is unlikely for radioactive fragments to become embedded in a victim's body, it is a possibility. Fragments could be highly radioactive and could result in dangerously high doses to both the patient and medical staff;[1] they should be removed immediately, placed in a container that will provide shielding, marked as radioactive, and brought to the radioactive waste storage area. Workers should maximize their distance and minimize the amount of time they spend near these fragments.

Nasal swabs collected at the decontamination site or at the field MTF should be tested at the MTF using the appropriate type of detector (beta-gamma or alpha) to determine the possible presence of internal contamination due to inhalation. The time after exposure that the nasal swabs were collected should be recorded and the nasal swabs should be saved and eventually processed by a laboratory that has the analytical capabilities to obtain a more quantitative measure of internal contamination. When using a Geiger-Müller pancake probe, count rates of 100,000 counts/min around the head, face, and shoulders prior to decontamination are also an indicator of possible internal contamination.[5] For cesium-137, a radioisotope likely to be used in RDDs and a fission product generated during nuclear reactions, an exposure rate of 0.1 mR/h measured at the surface of the victim's chest after decontamination indicates probable internal contamination from inhalation.[5] If possible, bioassays, such as urine and fecal samples, can be collected at the field MTF and sent to an appropriate laboratory to determine if the patient is internally contaminated. The presence of both external and internal contamination should be documented in the patient's records. Treatments for internal contamination should be administered at the field MTF, if available. If bioassay capabilities or treatments for internal contamination are not available at the field MTF, these steps might have to be performed at a higher level of care.

Higher Level Medical Treatment Facilities

Many casualties will report to nearby hospitals on their own, while others will be transferred to hospitals by medical evacuation following large-scale radiological or nuclear incidents. Often those who self-refer to hospitals will have minor injuries or no injuries at all, but will be concerned about exposure to radiation.[10] Hospitals can become quickly overwhelmed by the surge of people seeking medical care. As soon as hospitals receive word of a radiological or nuclear emergency, they should activate their emergency management plans and begin preparing for mass casualties. Mutual aid agreements with other hospitals will most likely need to be invoked to compensate for the excess patient load. Specific entrances should be designated for hospital staff and for patients arriving from the incident site in order to control patient flow into the building. All other entrances should be locked down.[10]

Many people will go directly to hospitals without having received mass decontamination by first responders or technical decontamination at the field decontamination site. The hospital decontamination team should be activated immediately and positioned at the entrance designated to receive patients. Operation of the hospital decontamination site should be similar to the operation of the field decontamination site, with patient flow first being directed to an EMT station on the contaminated side of the hot line for triage and basic lifesaving first aid. Additional security measures might have to be implemented to control the flow of patient traffic. To accommodate the massive surge of patients, an alternate decontamination and assessment facility might need to be established for those who do not have serious injuries.[14,15] Those who are uninjured or have minor injuries should be directed by the EMT station to the alternate decontamination and assessment facility. The location and staffing of potential alternate facilities should be coordinated in advance during the emergency-planning phase.

If patients' injuries are severe, they may be directed by the EMT station triage officer to bypass decontamination and go directly to the emergency department. Lifesaving treatment always takes priority over radiological decontamination. Patient decontamination procedures should be similar to those used at the field decontamination site. Protective equipment for workers on both the clean and contaminated sides of the hot line should also be generally the same as those used by workers on the clean and contaminated sides of field decontamination sites, respectively (see Table 10-4).[11]

Hospital worker PPE should generally be the same as that used at field MTFs (see Table 10-4),[2,11,13] as should contamination control procedures. Additionally, the floor over which contaminated patients will be traveling can be covered with paper or plastic sheeting.[1] If contaminated patients must pass through uncontaminated areas of the hospital, they should be wrapped in a sheet to minimize the spread of contamination.[1,12] Equipment that is not in use should be removed or covered to reduce the likelihood that it will need to be decontaminated later.[12]

Nuclear medicine, radiology, and radiation therapy clinics might have specialized equipment that can be used to detect both internal and external contamination. This equipment might include whole-body counters, gamma cameras, and survey meters. Hospital workers specializing in medical physics, radiation safety, nuclear medicine, and radiation oncology can offer advice relating to the management of external and internal contamination and treatment of radiation injuries.

Several specialized government organizations, including the Armed Forces Radiobiology Research Institute's Medical Radiobiology Advisory Team, the US Army's Radiological Advisory Medical Team, and the Department of Energy's Radiation Emergency Assistance Center/Training Site can be contacted to provide expertise related to medical effects of radiation and medical management of radiation casualties.

SUMMARY

The radiological and nuclear threat poses several potential scenarios in which medical personnel might find themselves caring for victims who have been exposed to high levels of radiation or who have been contaminated with radioactive material. These patients may also have conventional trauma and burn injuries. In caring for these victims, workers must ensure that they minimize the spread of contamination and do not expose themselves to any more radiation than is necessary.

Specialized radiation detection equipment will be needed to identify the presence or absence of radiation and determine the magnitude of the radiological hazard. Selecting the appropriate detection equipment will depend on the application for which it is to be used. Some types of detection equipment are designed to measure the amount of radiation present at a given location, some measure the amount of radiation to which one was exposed over a given time period, some are used to identify the type of radioisotope producing the radiation, and some are used to measure the amount of radioactive material in the air.

Regulatory radiation dose limits should not be exceeded by workers if possible. However, under emergency conditions, commanders are authorized to set higher dose limits for workers if regulatory dose limits must be exceeded to save lives and protect critical facilities that are essential to the welfare of the community. Various agencies have their own recommendations for emergency radiation dose limits, but it is ultimately the incident commander's responsibility to determine acceptable dose limits for workers.

Responders might have to go into potentially contaminated areas with high levels of radiation to perform search and rescue missions. To protect these responders, radiation control zones should be identified around the incident site and PPE should be implemented. Standard firefighting gear will protect search and rescue workers from most hazards, and dosimetry should be issued to each responder.[2,11] If radiation is the only hazard, the primary concerns to workers will be minimizing contamination and preventing inhalation of radioactive materials. In this case, dosimetry, air-purifying respirators, anticontamination suits, and protective gloves and boots will be adequate.[11]

Victims will need to be surveyed for contamination; those who are contaminated will require decontamination. Therefore, a patient decontamination site must be established, along with an EMT station for patient triage and lifesaving first aid prior to decontamination. Dosimetry and PPE for workers on the contaminated side of the hot line should be the same as that for search and rescue workers operating in an area where radiation is the only hazard.[11,13] PPE equivalent to standard hospital infection control precautions, along with dosimetry, will be adequate for workers on the clean side.[11] Radiological decontamination is usually accomplished by removing contaminated clothing and performing spot decontamination using tape or soap and water or, for more extensive contamination, completely showering with soap and water. Contamination levels are usually considered acceptable if they are equal to or less than two times background levels.[1] If patients have serious life-threatening injuries, they should bypass decontamination and be transferred directly to an MTF. Major trauma and burn injuries will be more of a threat to the patient's life than radiological contamination, and the patient can usually be decontaminated while receiving medical attention.

In some cases, a field MTF will need to be established; in other cases, patients will be transferred directly to nearby hospitals. In either case, contaminated patients who have been directed to bypass decontamination because of the severity of their injuries will not present a significant hazard to workers. However, contaminated patients will still require decontamination at some point, and methods of controlling the spread of contamination should still be implemented as long as they do not interfere with medical care. This can include designating separate treatment areas for clean patients and contaminated patients, covering floors with paper or plastic sheets, and controlling the flow of traffic to avoid cross-contamination. Patients can be decontaminated during treatment by removing clothing and using sponges or moist wipes to clean affected areas. PPE, such as that used for standard infection control precautions, is sufficient, and dosimetry should be used if available.[2,11]

High levels of radiation can present a hazard to both victims and response workers, and even low levels of radiological contamination will require time and resource-intensive contamination control efforts. These factors can have a negative impact on medical operations if preparations are not made. However, by understanding radiation and ensuring readiness to handle these issues, we can still function safely and effectively following a radiological or nuclear incident.

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