

# Chapter 3

## TRIAGE AND TREATMENT OF RADIATION AND COMBINED-INJURY MASS CASUALTIES

DANIEL F. FLYNN, MS, MD,\* AND RONALD E. GOANS, PhD, MD<sup>†</sup>

---

INTRODUCTION

TYPES OF NUCLEAR AND RADIOLOGICAL EXPLOSIVE WEAPONS

MEDICAL EFFECTS OF NUCLEAR WEAPON DETONATION

URBAN CASUALTY AND DESTRUCTION PATTERNS AFTER THE LOW-ALTITUDE NUCLEAR DETONATION AT HIROSHIMA

CURRENT PROJECTIONS OF URBAN CASUALTY, DESTRUCTION, AND FALLOUT PATTERNS AFTER A GROUND-LEVEL NUCLEAR DETONATION

PERSONAL PROTECTION AND LONG-TERM HEALTH RISKS FOR EMERGENCY RESPONSE PERSONNEL

TRIAGE: CONVENTIONAL, RADIATION-ALONE, AND COMBINED INJURIES

EVACUATION, RESUPPLY, AND AUSTERE MEDICAL CONDITIONS

ASSESSMENT OF RADIATION DOSE: CLINICAL AND LABORATORY

EMERGENCY TREATMENT OF COMBINED INJURIES

DEFINITIVE TREATMENT OF RADIATION INJURIES

DECONTAMINATION: EXTERNAL AND INTERNAL

PSYCHOLOGICAL EFFECTS ON MILITARY AND CIVILIAN PERSONNEL

SUMMARY

\*Colonel, US Army Medical Corps (Retired); Visiting Faculty, Radiation Emergency Assistance Center/Training Site, Oak Ridge, Tennessee 37831; New England Radiation Therapy Associates, Radiation Oncology Department, Holy Family Hospital, Methuen, Massachusetts 01884

<sup>†</sup>Senior Medical Advisor, MJW Corporation, Amherst, New York 14228; Senior Research Advisor/Physician, Radiation Emergency Assistance Center/Training Site, Oak Ridge, Tennessee 37831; Associate Professor, Tulane School of Public Health and Tropical Medicine, New Orleans, Louisiana 70112

## INTRODUCTION

In today's society, nuclear war between the world's major powers is considered by most to be an unlikely scenario; the threat of nuclear terrorism is now the major concern.<sup>1</sup> The current National Planning Scenario for the detonation of a nuclear weapon involves a 10-kiloton tactical weapon exploded at ground level in a major city.<sup>2</sup> This scenario would result in both a civilian and a subsequent military response, and it is a useful template for military medical preparedness for any nuclear detonation. Ten kilotons is a credible weapon yield, and in the worst-case scenario, an attack with such a weapon would involve a ground-level detonation in a densely populated area, resulting in radioactive fallout. Military operations could be impeded. Whether in the lead role or in a supporting role to civilian authority, military medical planning must account for this worst-case scenario, both in the United States and abroad.

The most severe consequence of a nuclear detonation in a densely populated area will be the surge of overwhelming casualties, which will have a tremendous impact on both military and civilian medical systems. Casualties in the immediate area will sustain various combinations of thermal burns, physical trauma, and radiation injuries. In addition, because the ground-level detonation will create a downwind, radioactive fallout plume, radioactive contamination will cause further casualties, primarily due to radiation-alone injury. The death toll, particularly during the first few days, will be high; however, there is the potential to save many thousands of seriously injured people by implementing appropriate triage and treatment strategies. The goal of this chapter is to address the triage and medical management of casualties primarily during the first 24 to 72 hours following a 10-kiloton, ground-level nuclear detonation.

## TYPES OF NUCLEAR AND RADIOLOGICAL EXPLOSIVE WEAPONS

Military medical planning and preparation for a 10-kiloton yield detonation is the same as preparation for a wide range of weapon yields: 1 kiloton, 100 kilotons, and 1,000 kilotons (1 megaton). Although the weapon yields are very different, the range (distance from the detonation point) at which a given effect occurs does not differ for explosions of different yields as much as one might expect. For example, the estimated distance for 50% lethality from nuclear radiation is about half a mile for a 1-kiloton explosion, about three

quarters of a mile for a 10-kiloton explosion, a little over a mile for a 100-kiloton explosion, and 1.62 miles for a 1-megaton explosion. The same trend is true for blast and thermal effects (Table 3-1).

An improvised nuclear device can be a modification of an existing nuclear weapon by a nongovernmental entity. It produces a nuclear detonation at full or partial yield, resulting in the identical pattern of damage and medical effects as a conventional nuclear weapon. A nuclear detonation results in an electromagnetic pulse

TABLE 3-1

### NUCLEAR DETONATION CASUALTY ESTIMATES VERSUS WEAPON YIELD BY MECHANISM OF INJURY\*

Mechanism of Injury	1 kiloton	10 kiloton	100 kiloton	1,000 kiloton (1 megaton)
Indirect blast (winds; 50% lethality, estimated 6 psi) <sup>1</sup>	0.43 km	1.0 km	2.1 km	4.4 km
Direct blast (50% lethality) <sup>2</sup>	0.14 km	0.30 km	0.65 km	1.4 km
Thermal radiation (50% second-degree burns) <sup>2</sup>	0.86 km	2.5 km	6.5 km	14 km
Ionizing radiation (50% lethality in weeks, estimated 450 cGy) <sup>2</sup>	0.77 km	1.2 km	1.7 km	2.6 km

\*The estimates of the effects were calculated using a Hotspot (Lawrence Livermore National Laboratory, Lawrence, CA) version 8.0, simulating a surface burst with no intervening shielding or sheltering.

(1) Walker RI, Cerveny TJ, eds. *Medical Consequences of Nuclear Warfare*. In: Zajtcuk R, Jenkins DP, Bellamy RF, Ingram VM, eds. *Textbooks of Military Medicine*. Washington, DC: Office of the Surgeon General, Department of the Army, Borden Institute; 1989. (2) US Department of the Army. *Treatment of Nuclear and Radiological Casualties*. Washington, DC: DA; 2001. Field Manual 4-02.283. Table 2-2.

that has no known medical effects but that damages electronic equipment, including communications and computers. The electromagnetic pulse effect for a surface detonation is not well understood and could extend for at least several miles from the detonation

point, thereby affecting some emergency medical response operations. A radiological dispersal device, or "dirty bomb," disseminates radioactive material across an area by means of a conventional explosive without a nuclear detonation (Table 3-2).<sup>3</sup>

**MEDICAL EFFECTS OF NUCLEAR WEAPON DETONATION**

The medical effects of nuclear weapon detonation include blast, thermal, and radiation effects, all of which cause significant injury.<sup>4-6</sup> Casualties at Hiroshima were generally due to a combination of effects; initial deaths during the first few days were attributed to serious blast and thermal injuries, rather than radiation injuries. However, many casualties had combined injuries.<sup>6</sup>

**Blast Injury**

Two types of blast forces occur simultaneously in the shock front of a nuclear detonation: direct blast wave peak overpressure, which is measured by the magnitude of the sudden rise in pressure over ambient pressure, and indirect blast wind forces, which are measured by wind velocities. The intensity of both blast forces decreases with increasing distance from the detonation site.

*Direct Blast Wave Peak Overpressure*

Overpressure refers to sudden pressure changes above the stable ambient pressure, which, at sea level,

is 14.7 pounds per square inch (psi). At a sudden peak overpressure of 1 psi (15.7 psi total), some windows may shatter. With respect to medical effects, rapid compression and decompression with transmission of pressure waves through tissues results in damage at junctions between tissues of different densities.<sup>7,8</sup> This damage is noted particularly at interfaces between air and tissue, such as the eardrums and lungs (Table 3-3). Tympanic membrane rupture may cause tinnitus, pain, and hearing loss, and there may be otoscopic evidence of perforation and blood in the external canal. The threshold overpressure for eardrum rupture is 5 psi. About 50% of eardrums rupture at 18 psi, which is nearly the threshold for lung injury. Thus, ruptured eardrums signal possible lung injury because pressure levels high enough to cause serious injury to the lungs have probably already ruptured the eardrums.

Injury to the lungs is the major cause of morbidity and mortality in direct blast injuries.<sup>7,8</sup> Clinically diffuse pulmonary contusions become apparent as local or diffuse infiltrates on radiographs over the course of hours. Symptoms may include chest tightness, pain, tachypnea, and hemoptysis. At the interface between soft tissue and air in the lung, the direct blast pressure wave results in local tensions that cause micro-

**TABLE 3-2**  
**EFFECTS OF DETONATION OF A RADIOLOGICAL DISPERSAL DEVICE AND AN IMPROVISED NUCLEAR DEVICE**

Effect	Radiological Dispersal Device ("Dirty Bomb")	Improved Nuclear Device (Nuclear Weapon)
Major damage to infrastructure	No	Yes
Expected casualty range	10-1,000	50,000-1,000,000
Risk of fatal contamination	Unlikely	Possible in high-fallout zone
Range of significant contamination	A few city blocks	Hundreds of square miles (or more with fallout)

**TABLE 3-3**  
**DIRECT BLAST EFFECTS**

Effect	Overpressure (psi)
Windows shatter threshold	1
Some vehicles overturn	5
Some houses collapse	5
Eardrum rupture threshold	5
Eardrum rupture (50% risk)	18
Severe lung injury threshold	20
Lethality (lung injury) threshold	40
Lethality (lung injury) 50%	62

Adapted from: Glasstone S, Dolan PJ. *The Effects of Nuclear Weapons*. 3rd edition. Washington, DC: US Department of Defense; 1977.

scopic tears; hemorrhage and edema then develop. An alveolar-pulmonary venous communication can be the source of air emboli, which can be immediately life-threatening. Pneumothorax, hemothorax, and mediastinal extravasation of air are all possible manifestations of very severe direct blast injury.

**Indirect Blast Wind Force**

A nuclear explosion generates winds much greater than hurricane force that cause flying debris to strike people, or that project people into the air to impact with other objects downwind. Traumatic injuries from blast wind effects, including penetrating trauma (eg, caused by glass or other debris at high velocity) and blunt trauma, are much more common than injuries from direct blast effects. Crush injuries may result from the collapse or fragmentation and displacement of buildings or large, heavy objects due to blast winds. Soldiers in armored vehicles, as well as people in well-constructed buildings, may be protected from most thermal and blast wind effects, but they may still be subject to direct blast effects (overpressures). For eardrum rupture in that scenario, treatment can be delayed.

There is a relationship between the direct blast wave peak overpressure and the maximum wind velocity at the blast wind shock front (Table 3-4). Both the blast wind velocity and the direct blast wave peak overpressure decline with increasing distance from the detonation. For example, for a 20-kiloton nuclear detonation,

the blast wind velocity is estimated at 180 mph at 0.8 mile. For a 1-megaton detonation, the estimated velocity of the blast wind is 400 mph at 1.1 miles, 180 mph at 3.0 miles, and 40 mph at 9 miles.<sup>4,5</sup>

**Thermal Injury**

Thermal burns will probably be the most common immediate serious injury following nuclear weapon detonation. The intense heat of the expanding fireball and thermal infrared radiation cause thermal injury consisting of flash burns, flame burns, temporary flash blindness (ranging in duration from seconds to a few minutes as a result of a sudden peripheral observation of intense light), and retinal burns (relatively rare). Thermal effects also decrease with increasing distance from the detonation. In a 10-kiloton detonation, second-degree burns on exposed skin are seen on people located up to 1.4 miles from the site, and first-degree burns (similar in appearance to severe sunburn) are seen on those up to 2 miles from the site. In a 1-megaton detonation, second-degree burns are seen on people at distances up to 10 miles, and first-degree burns are seen on those up to 15 miles away.<sup>4-6</sup>

**Flash Burns**

Flash burns are caused by thermal infrared radiation that travels in a straight line. Exposed skin absorbs the infrared radiation, and the victim is burned on the side of the body facing the explosion (profile burns). At a sufficient distance from the detonation, objects covering the skin, including clothing, may shield against this injury. A little closer to the detonation, where thermal energy is higher, thermal radiation can cause burns through clothing, even at temperatures below those required to cause ignition of clothing. Light-colored clothing reflects infrared radiation and dark-colored clothing absorbs it, which can result in pattern burns if the clothing is in actual contact with the skin.

**Flame Burns**

Flame burns are caused by ignition of clothing on those closer to the detonation than those with flash burns. Flame burns also result from secondary effects of fires. Firestorms cause many burn injuries and deaths as damaged buildings burn with people trapped inside. Severe thermal injuries include respiratory injuries from hot gases; respiratory system burns are associated with severe morbidity and high mortality rates. Close to the fireball of the explosion, everything is totally incinerated, with immediate 100% lethality.

**TABLE 3-4**

**INDIRECT BLAST WIND EFFECTS: MAXIMUM WIND VELOCITY OF SHOCK FRONT AND ASSOCIATED DIRECT BLAST PEAK OVERPRESSURE\***

Indirect Blast Maximum Wind Velocity (mph)	Direct Blast Peak Overpressure (psi)
2,078	200
1,415	100
934	50
294	10
163	5
70	2

\*The actual distance is not listed because it depends on the magnitude of the nuclear detonation yield.

Adapted from: Glasstone S, Dolan PJ. *The Effects of Nuclear Weapons*. 3rd edition. Washington, DC: US Department of Defense; 1977. Chapter 3.

## Nuclear Radiation Injury

### *Types of Ionizing Radiation After a Nuclear Detonation*

Radioisotopes are characterized by the energy and types of radiation they emit and by their half-lives (the time for radioactive decay to 50% strength). Heavy nuclei, as found in elements such as uranium, plutonium, and americium, emit charged alpha particles, which are not an external hazard because they cannot travel into tissue and are fully stopped by the outer clothing or by the outer (dead) layer of exposed skin. Absorption from wounds or inhalation is sometimes medically significant, but absorption by ingestion is generally not.

Radioisotopes, such as tritium and strontium, found in weapons fallout emit beta particles. Unlike alpha particles, beta particles can travel a short distance in tissue. Large quantities of beta particles deposited on the skin can damage the basal layer and cause radiation burns; large quantities are also important if they are inhaled or ingested.

Neutrons are uncharged particles that are emitted as prompt radiation in a nuclear detonation. They are deeply penetrating, causing a significant whole-body dose, but are not present in fallout radiation. Gamma rays are massless photons with characteristics similar to x-rays. They are produced by the nuclear decay of radioisotopes and account for a significant whole-body dose in both prompt and fallout radiation injuries. In fallout, they are also medically important if inhaled or ingested in significant quantities.<sup>9-13</sup>

### *Radiation Units and Measurements*

The conventional unit of radioactivity used to quantify contamination is the curie, defined as  $3.7 \times 10^{10}$  Bq, where 1 Bq is defined as 1 disintegration per second and is the International System of Units unit of radioactivity (Table 3-5). Published reports and information on the Internet may use different units to express radiation measurements. After a nuclear detonation, gamma and beta radiation levels, but not neutron irradiation, affect decontamination and response decisions.

For dose, 1 R is equal to:

- 1 rem (1,000 millirem),
- 0.01 Gy (1 cGy), or
- 0.01 Sv (10 millisievert).

For dose rate, 1 R/h is equal to:

- 1,000 mR/h,

TABLE 3-5

### COMMON UNITS USED IN RADIATION AND THEIR CONVERSIONS IN THE INTERNATIONAL SYSTEM OF UNITS

Conventional Unit	International System of Units (SI)
1 rad	0.01 Gy or 1 cGy
1 rem	0.01 Sv
100 rad	1 Gy
100 rem	1 Sv

- 1 rem/h,
- 0.01 Gy/h, or
- 0.01 Sv/h.

Dosimeters measure the total dose accumulated in rems, millirems, or sieverts. They are used by responders and healthcare providers to determine their own cumulative, total dose at the end of the mission or a defined period of time. Dose-rate instruments, such as radiation detection, indication, and computation (RADIAC) meters, can measure the radiation exposure rate at a certain point in roentgens per hour or milliroentgens per hour. Such instruments are essential in certain circumstances; for example, to assess a casualty's contamination level, potentially guide external decontamination efforts, and assess the effectiveness of decontamination efforts. These instruments are also used by emergency responders as they move through contaminated areas with varying radiation levels.

The AN/VDR-2 military dose-rate meter (or equivalent, commercially available Geiger-Müller counter) can measure and distinguish gamma and beta radiation over an extended range with an adjustable single probe. The military RADIAC meter AN/PDR-77 comes with different probes, including a separate probe to detect alpha particles. However, in the event of a nuclear detonation, it will likely be used for special purposes rather than as a general-purpose instrument like the AN/VDR-2 or the Geiger-Müller counter, which is commonly used by first responders. In a nuclear detonation scenario, it is not necessary for first responders to have an instrument to measure alpha particles. Contamination after the explosion will involve a mixture of many radioisotopes. When gamma (and beta) contamination is localized, all isotopes are localized, including alpha emitters. External decontamination of beta- and gamma-emitting isotopes decontaminates for all isotopes.

### Clinical Manifestations of Nuclear Radiation Injury

Acute radiation injury can occur either as the result of instantaneous exposure to radiation at the time of detonation in the impact area or as the result of early deposition of radioactive contamination from the immediate, downwind fallout zone (within minutes or hours following the detonation). The effects of whole-body irradiation increase with increasing radiation dose (Table 3-6), but a low dose of radiation does not produce acute effects (Table 3-7). The most reliable early clinical indicator of whole-body radiation injury is vomiting, which can be seen within minutes to hours after exposure. The most reliable early hematological indicator is reduced lymphocyte count, which is seen in less than 48 hours. Reduced neutrophil and platelet counts are seen at approximately 2 to 6 weeks. For an acute whole-body exposure, the lethal dose that will kill 50% (LD<sub>50</sub>) of an exposed group in 60 days is expressed as LD<sub>50/60</sub>. For untreated humans, LD<sub>50/60</sub> is approximately 3.5 to 4.0 Gy (350–400 cGy), which can

be increased to 5.0 to 6.0 Gy when antibiotics and transfusion support are provided.<sup>9</sup> With aggressive treatment in select patients, the LD<sub>50/60</sub> may rise further to 6 to 8 Gy with the use of hematopoietic growth factors (bone marrow colony-stimulating factors [CSFs]) and the availability of intensive-care-unit management.

Prompt radiation injuries are caused by instantaneous exposure to radiation at the time of the detonation. Most patients with prompt radiation injuries also have injuries from mechanical trauma and thermal burns. As with blast and thermal effects, radiation effects decrease with increasing distance from the detonation. With a 10-kiloton detonation, an absorbed prompt radiation dose of 4.5 Gy would be noted at a distance of about 0.7 mile from the detonation site, whereas this dose would be seen at a distance of 1.6 miles from the site of a 1-megaton detonation.<sup>4,5,13</sup>

Fallout injuries without significant mechanical or thermal trauma (radiation-alone injuries) are seen in the downwind area outside the impact zone within minutes to several hours. There, radiation exposure levels can be so high that a person outdoors can acquire a potentially lethal radiation-alone injury within a relatively short time. People should either take shelter or move from the dangerous fallout area when outside ambient radiation levels are low enough, as determined by command guidance.

Whether they are caused by prompt radiation or by fallout, the acute clinical effects of whole-body or significant (> 60%) partial-body radiation are characterized as acute radiation syndrome.<sup>14,15</sup> In addition

**TABLE 3-6**

#### WHOLE-BODY RADIATION DOSE-EFFECT RELATIONSHIP\*

Dose	Effect
10 cGy	No observable effects; threshold for minor chromosome changes in circulating blood lymphocytes
50 cGy	Minor lymphocyte depression
1 Gy	Symptom threshold for nausea and vomiting; mild lymphocyte depression at 48 hours; no deaths from acute effects of radiation
2 Gy	Nausea and vomiting within hours are commonly seen; moderate lymphocyte depression at 48 hours; few, if any, deaths, provided no combined injuries are present
3.5–4 Gy	Probable nausea and vomiting within hours; significant lymphocyte depression at 48 hours; 50% lethal within 60 days if untreated; more lethal if combined injuries are present
5–6 Gy	Nearly 100% nausea and vomiting within 2 hours; severe lymphocyte depression at 48 hours; 100% lethal within 60 days if untreated; nearly 100% lethal, even with treatment, if significant combined injuries are present

\*1 Gy = 1 Sv

Reproduced with permission from: Flynn DF, Goans RE. Nuclear terrorism: triage and medical management of radiation and combined-injury casualties. *Surg Clin N Am.* 2006;86:601–636.

**TABLE 3-7**

#### TYPICAL RADIATION DOSES RECEIVED IN THE UNITED STATES\*

Type of Dose	Amount of Radiation
Overseas roundtrip flight or a chest radiograph	10 mrem (0.01 cGy or 0.1 mSv)
Average annual absorbed dose (from natural background radiation to US population)	295 mrem (0.295 cGy or 2.95 mSv)
Diagnostic radiology computed tomography scan (chest and abdomen)	500 mrem (0.5 cGy or 5 mSv)
Maximum annual dose allowed a radiation worker	5,000 mrem (5 cGy or 50 mSv)

\*Asymptomatic and not associated with acute injury

Reproduced with permission from: Flynn DF, Goans RE. Nuclear terrorism: triage and medical management of radiation and combined-injury casualties. *Surg Clin N Am.* 2006;86:601–636.

**TABLE 3-8**  
**CLASSIC ACUTE RADIATION SYNDROMES\***

Dose	Clinical Status	Description
1–8 Gy	Hematopoietic syndrome	Results from the radiation-sensitivity of the rapid cell renewal system of the bone marrow (hematopoietic) stem cells. Clinical effects may include nausea, vomiting, skin erythema, fatigue, fever, mucositis, and diarrhea. The syndrome is not generally clinically significant for doses of 1–2 Gy. Laboratory analysis in cases with acute whole-body exposure greater than 2 Gy can show lymphocytopenia (8–48 h), neutropenia, and thrombocytopenia (20–30 days). Other common effects in the weeks following exposure include impaired wound healing (if there is concomitant trauma), bleeding (frequent gingival bleeding, petechiae, and ecchymoses of skin or mucous membranes), anemia, hair loss (scalp), increased infectious complications, and (if the radiation dose was high enough) death. With a sublethal dose, the bone marrow will recover. Death from hematopoietic syndrome may occur about 3–8 weeks after exposure.
8–20 Gy	Gastrointestinal syndrome	Results from the radiation sensitivity of the rapid-cell renewal system of the gastrointestinal stem cells in the small intestine crypts. Clinical effects include onset of severe nausea and vomiting, from minutes up to 1 hour after exposure, diarrhea (hours later, with or without rectal bleeding), fever, headache, fatigue, and dehydration. Death from gastrointestinal syndrome (added to severe hematopoietic syndrome) usually occurs 1–2 weeks after exposure.
> 20 Gy	Neurovascular/central nervous system syndrome	Clinical effects within minutes of exposure include early vomiting, early burning sensation, and prostration. Neurological signs include dizziness, ataxia, and confusion. Hypotension, high fever, and explosive diarrhea are seen. Death is inevitable, usually within 24–48 hours.
Varied	Cutaneous syndrome	May occur with any of the above three syndromes because radiation contamination on the skin can cause severe effects (beta burns) without contributing significantly to the whole-body dose. Clinical effects include a possible early but transient skin erythema. The principal effects are not noted until about 2–4 weeks after exposure. They include a brisk erythema, with blistering and wet desquamation at higher doses. At very high doses, ulcerations with necrosis may evolve.

\*Approximate dose ranges are a rough guide.

Adapted from: US Department of Homeland Security. *Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness*. Washington, DC: DHS; 2003. [www.au.af.mil/au/awc/awcgate/va/radiologic\\_medical\\_countermeasures.pdf](http://www.au.af.mil/au/awc/awcgate/va/radiologic_medical_countermeasures.pdf). Accessed March 23, 2012.

to nausea and vomiting, other clinical effects (sometimes delayed) may be noted, including erythema, fever, headache, diarrhea, hair loss, delayed radiation skin burns (as distinguished from prompt thermal burns), and fatigue. The three classic acute-radiation syndromes are hematopoietic, gastrointestinal, and neurovascular (Table 3-8). Persons with whole-body exposures up to 1 Gy are generally asymptomatic. Potentially survivable exposures are generally in the range of those associated with the hematopoietic syndrome (1–8 Gy). Even with aggressive treatment, no

one with a total body dose in excess of approximately 12 Gy will survive for more than about 4 months. Death results not only from the severe hematological and gastrointestinal effects, but also from the lungs' intolerance of a high single dose. For the very few who survive the combined bone marrow and gastrointestinal effects within the first 60 days, death from radiation pneumonitis is likely within 3 to 4 months after exposure. Other organ systems, such as the heart, kidneys, and liver, will sustain severe damage, resulting in organ dysfunction.

#### URBAN CASUALTY AND DESTRUCTION PATTERNS AFTER THE LOW-ALTITUDE NUCLEAR DETONATION AT HIROSHIMA

In 1945, the two nuclear bombs that exploded in Hiroshima and Nagasaki, Japan, were low-altitude bursts (2,000 ft) in the 15- to 20-kiloton range (equivalent to

30,000–40,000 lb of trinitrotoluene [TNT]). Rivers and concrete bridges throughout Hiroshima served as natural firebreaks. Nevertheless, immediately after

the explosion, thousands of independent fires ignited and eventually merged inside a roughly circular area of 4.5 square miles (1.2-mile radius) around ground zero. Firefighting resources were inadequate and made ineffective by wreckage in the streets. There were also broken water pipes in buildings, hydrants buried in debris, and pumping stations disabled by loss of electrical power with resultant low water pressure. Firefighting was limited to the perimeter of the firestorm. Most fires burned themselves out or were extinguished by the second day. Beyond the 1.2-mile-radius fire zone, the destruction or severe damage extended as far as another mile, affecting numerous buildings and other structures.<sup>6</sup>

Rescue, emergency medical care, and first aid in the 1.2-mile radius from ground zero were hampered by communication breakdown, blocking of streets and bridges by rubble, fires, and heavy smoke and dust in the air. Survivors fled to riverbanks and parks or were taken away in boats. An overwhelming number of casualties flooded the few functioning hospitals and first aid stations. It was initially impossible to give even basic medical care to more than a few people. A large part of the care was initially given by patients' relatives. There was a shortage of supplies in first-aid stations, particularly dressings to cover burns and

wounds, even before the surge of casualties was seen. Treatment in the first several days consisted largely of providing places of refuge. Patients were kept warm and administered analgesics. Additional first-aid and alternative care stations were established in schools and other buildings and on an island in the harbor. The mortality rate in first-aid stations was high.<sup>6</sup>

At Hiroshima, about 80% of the area's approximately 200 to 300 physicians and 1,800 nurses were dead or incapacitated. About 60 physicians and a number of nurses were able to give medical care despite their own injuries. However, the shortage of trained personnel was so grave that nursing students, medical students, and many untrained volunteers, especially patients' family members, were pressed into service.<sup>6</sup> Some hospitals and many clinics were located in wooden buildings, and many within a 2-mile radius of the detonation were damaged or destroyed. Only 3 of the city's 45 hospitals and clinics were initially usable: none had functioning blood banks. It is reported that blood transfusions were given to only a few patients during the first 4 days after the detonation. Medical supplies for Hiroshima were stored in adjacent villages but were inadequate. Dressings were scarce, and antibiotics, such as sulfonamides, were in short supply, given the extent of the casualties. There was

TABLE 3-9

**ZONAL CASUALTY (KILLED PLUS INJURED) RATES 4 MONTHS AFTER DETONATION IN RELATION TO DISTANCE FROM HYPOCENTER AT HIROSHIMA\***

Zone	Distance <sup>†</sup> from Hypocenter	Population	Casualty Rates (%)		
			Killed	Injured	Uninjured
1A	0–0.3 mi (0–0.5 km)	6,230	96.5	2.7	0.8
1B	0.3–0.6 mi (0.5–1.0 km)	24,950	83.0	11.3	5.7
2	0.6–0.9 mi (1.0–1.5 km)	45,270	51.6	32.9	15.5
3	0.9–1.2 mi (1.5–2.0 km)	67,900	21.9	41.2	36.9
4	1.2–1.6 mi (2.0–2.5 km)	30,600	4.9	34.0	61.1
5	1.6–1.9 mi (2.5–3.0 km)	30,600	2.7	38.4	58.9
6	1.9–2.5 mi (3.0–4.0 km)	29,400	2.5	22.7	74.8
7	2.5–3.1 mi (4.0–5.0 km)	20,310	1.1	8.2	90.7

\*The Joint Commission for the Investigation of the Effects of the Atomic Bomb on Japan was established within a few weeks to investigate medical effects of the bombings at Hiroshima and Nagasaki. It was composed of US military and civilian medical doctors, physicists, and other support staff, in addition to Japanese medical doctors and support staff. The US team entered Hiroshima on September 8, 1945, 33 days after the nuclear detonation, formed a joint medical team with the Japanese, and closely coordinated medical investigations. They investigated the effects up to 4 months after the detonation in seven zones at increasing distance from the hypocenter, for an estimated total at-risk population of approximately 255,000 people.

<sup>†</sup>Approximate miles/kilometers conversion.

Adapted from: Oughterson AW, Warren S. *Medical Effects of the Atomic Bomb in Japan*. National Nuclear Energy Series. Washington, DC: US Atomic Energy Agency; 1956:84.

a shortage of lactated Ringer's and other solutions, as well as blood products. Due to rapidly dwindling supplies, antibiotics and other medications had to be given in such low doses that they may not have been therapeutic.<sup>6</sup>

On the day following the bombing, some help (civil defense and police) was received from adjacent villages. Their principal activities were first aid, evacuation, disposal of the dead, and looting prevention. After the first day, 33 small relief stations were in operation and up to 150 physicians were on duty. However, there was still no substantial organized medical care for several days after the explosion. When some medical teams arrived from larger cities, they were still handicapped by limited supplies and poor conditions. When the public learned that there was radiation associated with the bomb, thousands of uninjured people reportedly crowded into the already overburdened first-aid stations and hospitals believing they might have been injured by radiation.<sup>6</sup> There were a number of military medical facilities in Hiroshima, away from the city center or on the outskirts. Within a few days, the military assumed responsibility for both civilian and military casualties for the subsequent 2 weeks. Surviving casualties were then gradually transferred to civilian hospitals.

The data from Hiroshima demonstrate the striking effect of distance from detonation on the rates of death and injury (Table 3-9). Distance and shielding are the principal factors influencing casualty rates. Both factors should be considered in combination whenever possible. One conclusion, based on the casualty volume and on the life-threatening but potentially survivable injuries, was that the peak of the medical load was located between 0.9 and 1.2 miles from the center.<sup>6</sup> Operationally, this could be expanded to 0.6 to 1.5 miles. Individuals located less than 0.6 mile from the center were unlikely to survive; those more than 1.5 miles away were less likely to have a life-threatening injury, and most injured casualties were ambulatory.

There were special situations at Hiroshima in which both the distance and the shielding factors for casualties were known. During the late wartime years, workers and volunteers in Japan were organized into groups to create firebreaks. The outcome of that effort demonstrates the effects of both distance and partial shielding.<sup>6</sup>

Outcome data were derived from several groups. One group consisted of a large population of students who were well defined in terms of location and shielding, and nearly all could be traced for outcome. Approximately 4,000 students were working outside on the firebreak project at various locations. They were considered unshielded from heat and radiation. Another

13,000 students were in school, most of them in typical wooden buildings. These were considered largely shielded against the thermal pulse, but unshielded against ionizing radiation. Table 3-10 demonstrates the effects of both distance and thermal shielding on casualty rates at Hiroshima. Between 1.5 and 2.0 km (0.9 and 1.2 miles), 14.2% of those who were thermally shielded versus 83.7% of those who were unshielded were dead or missing following the explosion.

**TABLE 3-10**

**ZONAL MORTALITY FOR THERMALLY SHIELDED (WOODEN SCHOOL BUILDINGS) AND THERMALLY UNSHIELDED STUDENTS ACCORDING TO DISTANCE FROM HYPOCENTER AT HIROSHIMA**

Thermally Shielded Students		
Distance	Number Shielded	Dead or Missing
0–0.6 mi (0–1.0 km)	969	588 (60.5%)
0.6–0.9 mi (1.0–1.5 km)	3,959	761 (19.2%)
0.9–1.2 mi (1.5–2.0 km)	957	136 (14.2%)
1.2–1.9 mi (2.0–3.0 km)	3,922	99 (2.5%)
1.9–2.5 mi (3.0–4.0 km)	2,077	11 (0.5%)
Thermally Unshielded Students		
Distance	Number Unshielded	Dead or Missing
0–0.6 mi (0–1.0 km)	2,436	2,282 (93.7%)
0.6–0.9 mi (1.0–1.5 km)	484	413 (85.3%)
0.9–1.2 mi (1.5–2.0 km)	135	113 (83.7%)
1.2–1.9 mi (2.0–3.0 km)	76	11 (14.5%)
1.9–2.5 mi (3.0–4.0 km)	No data available	No data available

Reproduced from: Oughterson AW, Warren S. *Medical Effects of the Atomic Bomb in Japan*. National Nuclear Energy Series. Washington, DC: US Atomic Energy Agency; 1956. Table 3.3 (p 35) and Table 5.2 (p 103).

A second group of firebreak workers was divided into two subgroups. The first subgroup consisted of 168 workers at 0.62 mile from the hypocenter. All but three of them were shielded from direct thermal effects, but not from ionizing radiation, by a row of two-story, light, wooden structures. They were standing in formation, awaiting roll call for the beginning of the workday, in the shadow of the thermal pulse of the detonation. Six died of crush injuries from the blast effects, and all three of those who were exposed to the thermal pulse soon died of burns. The 159 immediate survivors later developed some hair loss, and 90% developed cutaneous petechiae (purpura). Ninety-three of the immediate survivors (58.5%) died, primarily of radiation injuries, all between days 20 and 38,<sup>6</sup> consistent with the hematopoietic syndrome timeline following a fatal whole-body exposure.

The second subgroup of 166 workers had just started their workday near the first subgroup, also at 0.62 mile from the hypocenter. All were in the open and completely unshielded from the explosion. Following the detonation, all showed evidence of immediate, severe thermal burns; 101 died on the first day, and 55 died within 2 weeks (most within the first 4 days). The 10 who survived for 2 weeks showed evidence of radiation injury. At 14 weeks, all 10 were still alive but were reported to be too weak to work. No further follow-up was reported.

The death rate, in general, was highest among those who were outdoors; it was lower for those in residential structures, and lowest for those in reinforced concrete buildings. The reinforced buildings provided protection from blast, thermal, and radiation injuries, unless they were very close to ground zero. For 1,600 individuals (combined total from Hiroshima and Nagasaki) in reinforced concrete buildings, between 0.3 and 0.75 mile from ground zero, the following immediate fatality rates were correlated with the severity of the structural damage<sup>5</sup>:

- Severe damage: 88% fatality rate
- Moderate damage: 14% fatality rate
- Light damage: 8% fatality rate

In addition, 11% of those in severely damaged buildings were reported as seriously injured, for a total rate of death or serious injury of 99%.<sup>5</sup>

The high fatality rates in severely damaged buildings compared with less damaged buildings is believed to be due primarily to two effects: first, from severe, often fatal crush injuries resulting when concrete buildings collapse; and second, from inescapable secondary fires after entrapment in a building. Photographic evidence from Hiroshima and Nagasaki showed that a number

of reinforced concrete buildings within half a mile of ground zero were still standing, but most of them had severe thermal damage inside, where everything flammable was incinerated with the thermal pulse and ensuing fires.<sup>4-6</sup> In the event of a nuclear detonation today in a major city center, this observation raises concern for tall buildings exposed directly to a thermal pulse and located less than half a mile from ground zero. Buildings that do not collapse may contain large internal fires that prevent people from escaping.

Among the three causes of death in Hiroshima (blast, thermal, and radiation injuries), it has been estimated that perhaps 50% of the deaths were due primarily to thermal burns.<sup>4-6</sup> Flash burns from direct exposure to the thermal pulse were more common than flame burns from secondary fires. First-degree flash (profile) burns occurred at distances of up to 2.8 miles, but second-degree burns with blistering were rarely seen beyond 2 miles. Flash burns of skin directly exposed within 1.2 miles were usually third-degree burns or mixed second- and third-degree burns, and third-degree burns were most common within 0.6 mile. However, many of those within 0.6 mile died quickly, before the severity of the burns could be manifested. It was also difficult to distinguish and classify between a second- and third-degree burn in the early stages.<sup>5</sup>

In addition, people sheltered or trapped in buildings or tunnels close to ground zero may have been killed by the depletion of oxygen or inhalation of hot gases, smoke, and dust as a result of the firestorm. Almost all deaths of those out in the open and unsheltered within 1.1 miles of ground zero are thought to have been caused primarily by thermal burns, although the burns were usually combined with other injuries.<sup>4-6</sup>

There are fewer data on casualties caused by blast winds, since those caught in the open with severe blast wound trauma also had severe burns and injuries that often resulted in death. Direct blast injuries occurred in people who were shielded inside reinforced concrete buildings up to 0.6 mile from ground zero.<sup>6</sup> Most immediate deaths from blast wind injuries near ground zero were due to crush injuries from falling buildings. Outside the ground zero area, there were cases of fractures as a result of blast winds, although fewer were reported than expected. Blunt and penetrating trauma also occurred, usually caused by multiple projectiles causing multiple wounds. Beyond 1 mile, flying debris, such as glass, caused the greatest number of blast wind injuries, most of them nonfatal.<sup>6</sup> The degree of injury was related to the velocity of the glass or other debris, which, in turn, was related to the distance from the explosion. Many casualties who were between 1 and 2.5 miles from ground zero were treated for lacerations from glass fragments and small debris lodged

superficially in the skin and subcutaneous tissues; those closer to the explosion had more serious, deeper, more penetrating wounds.<sup>4-6</sup> Complications after treatment were usually associated with infections and slow wound healing.<sup>5</sup>

Among the casualties who survived the first few days following the explosion, a number died weeks later, with symptoms ascribed to nuclear radiation. These fatalities were estimated at 5% to 15% of the total number of deaths. A rough estimate indicated that about 30% of those who died at Hiroshima had received a lethal dose of nuclear radiation, although this was not always the immediate cause of death. A more recent International Atomic Energy Agency review, referring to the inner blast area around ground zero, indicated that the immediate deaths were due to blast and thermal effects, not to radiation exposure, since no one would have been able to survive the lethal blast and thermal effects only to die of radiation effects later.<sup>16</sup>

For injuries due to radiation, the data collected at Hiroshima<sup>6</sup> were based on studies of patients known to be alive 20 days or more after the detonation. A history of vomiting on day 1 and of epilation, purpura, and oropharyngeal lesions later correlated with the radiation dose, as estimated by the distance from the explosion and the degree of shielding. The higher the dose, the earlier the manifestation of radiation injury. The Joint Commission's summary report noted that in the most heavily exposed patients, a severe, dysentery-like diarrhea started early following detonation and persisted until death. This often occurred together with gastrointestinal bleeding. Bleeding sometimes developed from other sites, such as the gums. Vomiting within 3 hours after the explosion was associated with severe cases of radiation injury.<sup>6</sup> Vomiting is not specific for radiation injuries because it may result from other causes, such as physical or psychological trauma, following such an explosion. Some casualties did not vomit, including even some who were within 0.6 mile of the explosion; however, those who were that close would have had a significant degree of ionizing radiation shielding, since they obviously had shielding that protected them from being killed on the first day by the thermal or blast effects. Nevertheless, vomiting, which later correlated with radiation injury, was reported as the most common early symptom at both Hiroshima and Nagasaki. Oropharyngeal lesions (painful oral mucositis) caused by radiation sometimes appeared 3 to 5 weeks after the explosion. These lesions were considered suggestive of radiation injury but not specific. In a study of a large sample of 20-day survivors, the criterion for the diagnosis of significant whole-body radiation injury by the Hiroshima joint medical teams was determined to be the development

of epilation and/or purpura. The peak onset of epilation occurred 14 to 21 days after the explosion, and that of purpura 20 to 35 days after the explosion. The occurrence of epilation and purpura together, particularly with an earlier onset for either, was associated with very severe radiation injury. The incidence of such injury according to this criterion was 86% up to 0.62 mile from the explosion, 39% at 0.62 to 0.93 mile, and 10% at 0.93 to 1.24 miles.<sup>6</sup> Partial shielding from ionizing radiation may have prevented the percentage of epilation or purpura from being higher. The degree of radiation injury was not well defined quantitatively in terms of hematological laboratory studies, such as the degree of neutropenia, because data were limited and fragmented, and because no blood tests were done on the vast majority of casualties due to resource limitations. Generally, only one blood specimen was obtained from those who did undergo blood testing; however, a limited number of patients with presumed radiation injuries who survived the first 20 days had variable blood counts done between the third and fifth weeks after detonation. The Joint Commission concluded that "few instances were reported where recovery occurred with white-blood-cell counts of less than 500 [per cubic millimeter]."<sup>6</sup>

The data on delayed epilation, purpura, and oropharyngeal lesions are relevant for current medical planning for a nuclear detonation. Some individuals who have little or no trauma injury may self-evacuate the area, unaware of having sustained significant radiation injury. This would be particularly true for those who were outside the thermal blast zone but were in the dangerous fallout zone for a sufficient period of time. Two weeks after a detonation, public health advisories could target symptoms of epilation, purpura, or oropharyngeal lesions and urge anyone who has or subsequently develops these symptoms to immediately seek medical attention. Unexplained persistent fever and burns 2 or more weeks after the detonation could be warning signs of bone marrow or cutaneous radiation injury. Therefore, the public health advisory should also urge these individuals to immediately seek a medical checkup. A simple physical examination and blood tests 2 or more weeks after the detonation would include, at a minimum, hemoglobin, hematocrit and lymphocyte, neutrophil, and platelet counts to help determine whether there was a clinically significant, whole-body radiation exposure.

In a 1962 updated analysis of the casualty zones after the Hiroshima bombing, the number of zones was reduced from seven to three.<sup>5</sup> Although some information is lost, the three-zone approach is easier in terms of medical planning, particularly for rescue operations. The updated estimates of the number of

people at risk and the number of casualties are within 1% of the estimates given in Table 3-9 for 4 months after detonation.

- **Inner zone or severe damage zone (ground zero up to 0.6 mile):** Population 31,200, with 86% killed and 10% injured. Extensive destruction with a high fatality rate and survivors with very serious injuries. Most concrete buildings collapsed except for a few, most of which had some serious damage. Photographic evidence of large piles of rubble blocking streets; many concrete buildings, which had initially appeared to be relatively sound from the outside, were internally damaged and gutted by fire.
- **Middle zone or moderate damage zone (0.6–1.6 miles):** Population 144,800, with 27% killed and 37% injured. Many concrete buildings standing but severe destruction of most small masonry and lightweight structures, including residences, as well as overturned vehicles and some secondary fires. Significant fatality rate and many serious life-threatening injuries.
- **Outer zone or light damage zone (1.6–3.1 miles):** Population 80,300, with 2% killed and 25% injured. Destruction of some lightweight structures. Low fatality rate. Many casualties were ambulatory, with minimal injuries. Others who were in locations nearer to the border of the middle zone had moderately serious injuries. First-degree burns (profile burns) were very common among those who were outdoors.<sup>6</sup>

The differences in early fatality rates between zones are striking: 86% in the inner zone, 27% in the middle zone, and 2% in the outer zone. The injuries among the few survivors in the inner zone were usually severe, whereas there were very few severe injuries in the outer zone. A conclusion for casualties in the middle zone (0.6–1.6 miles) was that “a larger proportion of the population would probably have survived if immediate medical attention had been available.”<sup>4,5</sup> This is consistent with the 1956 published report on the seven-zone analysis of casualties.<sup>6</sup> There were 91,000 injured who survived day one who would potentially have benefited from some level of medical care (Table 3-11). Many of the 45,000 who died on day one were killed immediately. Many others who were severely injured also died on day one before receiving medical care. However, today, some of the severely injured might have survived long enough to be triaged and

TABLE 3-11

APPROXIMATE CASUALTY RATE AT HIROSHIMA FROM DAY 1 TO 4 MONTHS AFTER DETONATION

Estimated population at risk	255,000
Uninjured	119,000
Total casualties	136,000
Dead day 1	45,000 (33% of total casualties)
Surviving casualties day 1	91,000
Dead day 2 to month 4	19,000 (86% of those died within 20 days)
Total dead month 4	64,000
Surviving casualties month 4	72,000

Adapted from: Oughterson AW, Warren S. *Medical Effects of the Atomic Bomb in Japan*. National Nuclear Energy Series. Washington, DC: US Atomic Energy Agency; 1956: 86.

provided emergency medical care. Therefore, medical treatment planning for a Hiroshima-like scenario would mean planning for 100,000 or more injuries exclusive of radiation-alone injuries from fallout.

For medical planning, it is necessary to consider not only the number of injured requiring care but also estimates of the numbers of people with each different type of injury. In Hiroshima, the core of the medical load was reported between 0.6 and 1.6 miles (1.0–2.5 km), after which there was a sharp drop in zonal population density, in addition to the lower percentage of dead or severely injured people with increasing distance from ground zero (see Table 3-9). Much effort was put into the post-detonation analysis and quantification of types of single injuries (thermal, blast, or radiation) and the major injury components for combined injuries. An estimated 70% of survivors had blast injuries, 65% had thermal burns, and 30% had radiation injuries. However, there are no precise data available on the relative significance of each injury type.<sup>4,6</sup> Although the predominant type of serious injury was often thermal, it is expected that those who died early with very severe, visually obvious burns also may have had undiagnosed, underlying, fatal, internal traumatic injuries. Therefore, for those fatalities in the inner zone, trauma as the primary cause of death is likely to be underreported. With a ground-level detonation, additional radiation injuries would be expected for those in the heavy fallout zone because of radioactive contamination.

Military medical planning for operations also

involves a review of previous after-action reports for lessons learned from similar past military operations. At Hiroshima, after several months of investigation, it was concluded that “the methods adopted for treating casualties were far below standard because of the shortage of supplies and equipment and the extraordinary demands made on crippled staffs.”<sup>6</sup> Members of a Joint Commission of US and Japanese physicians speculated as to what the mortality rate would have been if there had been satisfactory facilities available, with enough medical personnel and adequate supplies to treat the casualties soon after the explosion. In addition to sufficient personnel and basic supplies for burns and wounds, they also recommended having sufficient

quantities of resuscitative fluids available, including parenteral fluids (eg, lactated Ringer’s), plasma (and plasma volume expanders), and whole blood; equipment for sterile techniques and wound debridement; and an ample supply of antibiotics.<sup>6</sup> However, in this government report, finally published in 1956 after some years of delay, the commission concluded it was doubtful whether more than 5% to 10% of the deaths from all injuries could have been prevented.<sup>6</sup> More resources, such as broad-spectrum antimicrobial agents and cytokines (CSFs), have become available since the Hiroshima bombing. However, the need for adequate basic supplies for overwhelming casualties remains unchanged.

### CURRENT PROJECTIONS OF URBAN CASUALTY, DESTRUCTION, AND FALLOUT PATTERNS AFTER A GROUND-LEVEL NUCLEAR DETONATION

The US Department of Homeland Security National Planning Scenario No. 1 involves planning for a ground-level, 10-kiloton nuclear detonation in a major urban environment.<sup>2</sup> The nuclear blast would result in physical destruction of buildings and other structures, with the amount of damage decreasing with increasing distance from ground zero.

For a nuclear detonation at ground level, the three-zone (light damage, moderate damage, and severe damage) approach at Hiroshima will be similar in terms of severity of structural damage and survivability of casualties. However, unlike Hiroshima in 1945, a major city center today is typically surrounded by a great number of tall buildings. There would be significant shadowing (shielding) effects from blast winds, thermal radiation, and prompt nuclear radiation provided by these buildings. Shielding would also be provided by any hills and rolling terrain around ground zero. The zones, therefore, would not be concentric circles, as in Hiroshima. However, in some directions around ground zero, there are likely to be some relatively open sectors between groups of tall buildings where the blast, thermal, and radiation effects would be channeled in full force along corridors. The outer boundary of the light damage zone along these unshielded open corridors is estimated at 3 miles, similar to the outer boundary of the light damage zone at Hiroshima.

Zones are defined by the degree of structural damage as emergency responders move in the direction of ground zero.<sup>2</sup> There are no clear boundaries between the three zones, but the visual evidence of degree of structural damage and measured radiation levels will help responders and their commanding authorities define the operational boundaries. There will also be a dangerous fallout zone that overlaps with and extends beyond the three blast zones<sup>2</sup>:

- **Light damage zone:** At the outer boundary, the incidence of shattered glass windows is roughly 25%. As emergency responders move inward, the damage gradually worsens, with increased litter, rubble, light wooden-structure damage, some downed power lines, and detectable radiation levels. The zone is characterized by minimal injuries to individuals, the most common being very superficial injuries from flying glass and debris carried by blast winds of diminished velocity, and some thermal profile (flash) first-degree burns. More significant injuries will be noted as responders approach the moderate damage zone boundary.
- **Moderate damage zone:** There will be overturned automobiles, downed power lines, some ruptured gas and water lines, significant structural damage, and substantial rubble; many light commercial and residential buildings will be unstable or collapsed (most brick or wood-framed structures will have collapsed); there will be poor visibility as a result of smoke from secondary fires and dust from collapsed buildings. There will be elevated radiation levels, but monitored early entry of emergency responders is possible. Many injuries in the moderate damage zone will be serious or life threatening but potentially survivable. Injuries from high-velocity flying glass and debris will be more severe than in the light damage zone because the higher velocity of the blast winds will cause deeper tissue penetration. Responders should focus their medical attention primarily on this zone and not be distracted by minimally

injured individuals when they pass through the light damage zone, which would delay their deployment into the moderate damage zone. Victims in this zone, compared to those in other zones, will benefit the most from priority emergency care. These conclusions are in agreement with the conclusions of the Hiroshima studies conducted more than 60 years ago.

- **Severe damage zone:** This is a no-go zone for responders, best characterized by the complete destruction of most buildings. Very few reinforced buildings will still be standing, but all will be damaged, structurally unstable, and most will probably be gutted by fire. As a consequence, there will be large mounds of rubble. All effects will be more severe than those in the moderate damage zone. There may be more extensive fires, smoke, and dust from collapsed buildings that will limit visibility, and there will be high levels of radiation. Most of the initial survivors will have nonsurvivable injuries. This zone is characterized as a no-go zone for responders until radiation levels are sufficiently reduced through nuclear decay of most isotopes.
- **Dangerous fallout zone:** This zone is not defined by structural damage but by an exposure rate of 10 R/h (10 cGy/h) at the boundary.<sup>2</sup> For example, for a 10-kiloton weapon, if the outer boundary of the blast zones is about 3 miles, the dangerous fallout zone may extend 20 miles away from ground zero in the direction of the prevailing winds.<sup>17,18</sup> The fallout zone overlaps sectors of the severe, moderate, and light damage zones. For example, if the fallout moves northeast from ground zero, the northeast sectors of the moderate and light damage zones will have very high radiation levels during the first day. The severe damage zone will already have very high levels, regardless of the fallout direction.

A massive amount of downwind fallout is produced in a ground-level detonation, unlike in the low-altitude detonations in Japan.<sup>17-20</sup> A nuclear explosion at ground level results in vaporized and irradiated earth and debris being pulled up into the fireball, which rises rapidly into a towering mushroom cloud; as the fireball cools off, the material is carried in the direction of the prevailing winds before falling to the ground. The detonation creates radioactive fission products that attach to particles of debris to form fallout, which becomes the main source of ground contamination.

The larger, heavier particles, which are visible as fine, sand-sized grains, fall to earth in a few minutes. The lighter, fine particles, which are not necessarily visible, travel farther downwind. The fallout will reach the ground in less than a day, with the most intense fallout reaching the ground in the proximal area in less than an hour. The primary medically significant types of radiation will be due to gamma and beta radiation. In the dangerous fallout zone, external exposure to gamma radiation is the predominant risk because of the whole-body effects; however, beta radiation can cause severe cutaneous burns (beta burns) if uncovered skin sustains prolonged contact with fallout.

The fallout will not exactly follow the computerized plume-modeling projections. In the atmosphere, the descending fallout is blown by winds whose speed and direction vary at different elevations, so that the fallout pattern may not be evident from ground-level wind direction alone. Therefore, in addition to the use of computerized fallout-plume models, appropriate ongoing radiation monitoring must be performed to define the dangerous fallout zone, which changes as a function of time. Computerized modeling estimates the maximum dose rate 15 minutes after a ground-level 10-kiloton detonation to be about 1,500 cGy/h (15 Gy/h) at a location on the ground under the middle of the fallout plume 1.6 miles downwind from the explosion.<sup>17,18</sup> This would result in a probable lethal dose in only about 20 minutes. This dose rate decreases to 180 cGy/h at 2 hours, and to about 7 cGy/h at 2 days, due to the rapid decay of many of the short-lived radionuclide fission products. During the first 2 hours, the cumulative dose for a person outdoors and under the center of the plume would be approximately 600 cGy at 2.5 miles downwind of the detonation, 300 cGy at 5 miles, 100 cGy at 9 miles, and only 50 cGy at 12 miles, at which point there would be no symptoms and no acute radiation injury.

Therefore, not only does fallout decrease sharply with distance, it also decays quickly with time. Fallout is most dangerous in the first few hours after an explosion. The rapid decay in fallout radiation dose rate follows a standard 7-to-10 rule for decay: for every sevenfold increase in time after the detonation, the radiation dose rate decreases tenfold.<sup>2</sup> For example, if the radiation dose rate at 2 hours after detonation is known, in 14 hours ( $7 \times 2 = 14$ ) the dose rate will be decreased to one tenth of the dose rate at 2 hours. At 98 hours after detonation ( $7 \times 7 \times 2$ ), the dose rate will be decreased to one hundredth of the dose rate at 2 hours. Therefore, it is prudent for the public to seek shelter immediately after a detonation, such as in the basement of a home, workplace, or school, or in an underground metro station. Military personnel will receive a degree

of protection in lightly armored vehicles.

The first public response should generally be to find shelter. Sheltering (particularly at home) is prudent early in a radiological event because families can congregate at home where showers, uncontaminated replacement clothing, food, and water are available. Sheltering also provides authorities time to assess the situation more completely. Evacuation might be indicated later for people in some locations, depending on the specific situation and the extended dose estimates. In other locations, remaining sheltered may result in much lower radiation exposure. This underscores the importance of sheltering immediately following the detonation. Unfortunately, many civilians who choose to self-evacuate immediately after the blast may find themselves stuck in traffic, which would become gridlocked due to mass panic and possibly damaged roads and bridges. Those under the plume area will be exposed to a higher radiation dose if they are outdoors or in a vehicle, where their proximity to

the radioactive material on the vehicle's roof will result in a much higher dose than if they were in a basement, far removed from the radioactive material on the roof of the house or building. The policy guidance today should be early, adequate shielding followed by informed, delayed evacuation.

Uncontrolled mass self-evacuation will not only hinder emergency responders and supplies from entering the area, but it will also hinder the evacuation of the critically injured. Contamination from fallout may impede military and civilian response operations. This will delay some actions, such as rescue operations, until sufficient radioactive decay has occurred. Since the fallout is subject to rapid radioactive decay, the radiation exposure rate at a given location will diminish rather quickly with time. The dangerous fallout zone will subsequently shrink dramatically in size each day, which will be taken into account in implementing operations. Continuous monitoring of ground radiation levels is imperative.

## PERSONAL PROTECTION AND LONG-TERM HEALTH RISKS FOR EMERGENCY RESPONSE PERSONNEL

Both military and civilian emergency responders have operating guidelines to ensure their safety during rescue operations. They also have protective equipment to help safeguard them against acute and long-term effects of radiation. Both have dosimetry equipment and are under their respective command authorities. In any mission, command authority always weighs the importance of the mission, whether military or civilian, against the possible risks to the responders' health and safety.<sup>2,20-27</sup>

### Medics and Military Personnel

Military emergency responders train for chemical, biological, radiological, and nuclear (CBRN) attacks. Under military CBRN policy, decontamination of persons exposed to chemical and biological agents takes place before they are admitted to a medical facility (such as a combat support hospital) because even small amounts of some chemical or biological agents create a potential risk. Persons with radiological contamination, however, pose no significant medical risk to healthcare personnel who use proper decontamination techniques. In addition, unlike biological and chemical contamination, the level of radiation contamination can be monitored easily by hand-held instruments, such as a RADIAC meter.<sup>9,25</sup>

Standard military-issue protective masks plus complete protective overgarments (mission-oriented protective posture level 4 [MOPP 4]) protect against

inhalation of most radioactive material and contamination, as well as against chemical and biological agents. Military emergency responders will have personal dosimeters and RADIAC meters. In most radiation environments outside the high-radiation zone, a lower degree of protection is adequate compared to that needed for chemical and biological threats. Because it is difficult to accomplish sustained rescue operations in MOPP 4, the command authority will determine the appropriate MOPP level of protection based on the risks of the specific situation. In some situations where the protective mask and heavy gloves are not required, rescue operations can be accomplished faster and with greater efficiency without undue risk. In other situations, anticontamination suits may be preferred if heat stress in MOPP suits is a concern, and when the contamination threat is only ionizing radiation (not combined with chemical agents, for example). This would require approval from the command authority.

Mission-specific, risk-based dose limits include limits for those engaged in lifesaving activities, as seen in current military doctrine.<sup>2,20</sup> Whereas military commanders set their operational exposure guidance (ie, dose limits to military personnel) at any level in a nuclear war, the risk analysis for extremely high-priority missions, which includes saving lives, yields a maximum operational exposure guidance of 125 cGy (1.25 Sv). If this dose is reached, some soldiers may be symptomatic (with temporary nausea and possible vomiting) but will not be at risk for acute lethal effects.

For operations other than war, and based also on mission priorities and risk analysis, military commanders limit maximum operational exposure guidance levels to 75 cGy (0.75 Sv).

### **Civilian Personnel**

Civilian emergency responders who enter an area after a nuclear detonation may be knowingly exposed to certain levels of radiation to save lives, but they need to stay as safe as possible.<sup>2</sup> Civilian responders need personal protective equipment, such as anticontamination suits and respirators similar to those used by the military, while working under the guidance of the civilian incident commander.<sup>2</sup> Initial emergency responders should have meters, such as Geiger-Müller counters, to measure dose rates and dosimeters to show the total accumulated dose received.<sup>25,26</sup> Incident commanders will make every effort to employ the “as low as reasonably achievable” principle when supervising emergency responders on such a mission.<sup>27</sup> The incident commander will weigh the likelihood and significance of a proposed mission’s success against the health and safety risks to emergency response personnel. The risks involve not only high radiation levels but also widespread fires, smoke, dust, chemicals, downed power lines, and unstable structures. For radiation limits, some nonmilitary government agencies have established a maximum-dose guideline of 50 cGy (0.5 Sv, 50 rem) for first responders trying to rescue people who would otherwise die. There are no expected acute symptomatic effects at this dose and no risk of acute lethal effects. The “turn-back” dose for emergency responders can be lower (or higher) than the guideline based on the case-specific circumstances. In higher-radiation areas, where 50 cGy or more could be received, emergency responders should have proper training to understand the risks and be allowed to volunteer for the mission.<sup>2</sup> Any rescuer who

vomits should be removed from the site and medically screened. Vomiting would imply that although the accumulated dose was estimated to be 50 cGy, it might have been higher, since vomiting is not common at a dose of 50 cGy.

### **Long-Term Health Risks**

In addition to considering a high dose of ionizing radiation that may result in acute effects, both military commanders and civilian incident commanders should consider possible long-term effects (primarily lifetime cancer risks) on emergency response personnel under their command.

Data from the National Academy of Sciences report *Biological Effects of Ionizing Radiation (BEIR VIII)*<sup>28,29</sup> estimate that 43 of every 100 people in the United States will be diagnosed with cancer in their lifetime. It is also estimated that one cancer per 100 people (1%), or about one fatal cancer per 200 people (0.5%), would eventually result from a single exposure of 10 cGy (0.1 Sv) above average natural background radiation levels. A 10-cGy dose is roughly equivalent to that obtained from 20 diagnostic chest and abdominal computed tomography scans and is a dose causing no acute side effects (see Table 3–7). Therefore, a medic or other emergency responder (police officer, firefighter, etc) who received a whole-body gamma dose of 10 cGy (0.1 Gy) from an exposure during a rescue mission would not have acute symptoms, but the additional lifetime risk of developing cancer would be about 1%, for a total risk of 44% instead of the projected 43%. If the dose were 20 cGy (0.2 Gy), the person would be asymptomatic, but the additional risk would be 2%, yielding a 45% chance of cancer in a lifetime versus 43% without such acute exposure. However, the delay in acquiring a radiation-induced cancer may range from 5 to 40-plus years, and about half of all cancers are curable with treatments available today.

## **TRIAGE: CONVENTIONAL, RADIATION-ALONE, AND COMBINED INJURIES**

### **US Military Triage System**

Military triage is a dynamic process and occurs at every level of care, from initial casualty sorting, first-responder care, clinical triage, prioritizing for surgery, and intensive care, to the evacuation system. The conventional military triage system used today to sort and prioritize trauma patients is referred to as “DIME” (delayed, immediate, minimal, expectant; Exhibit 3-1).<sup>8</sup> The DIME system is currently used to train medical and evacuation personnel and is helpful when mass casualties may overwhelm available

medical resources. US Army medical units and hospitals currently drill using this triage system for mass casualties, and it has been applied in operations in Iraq and Afghanistan. The DIME system, sometimes with minor variations, is used by the North Atlantic Treaty Organization (NATO) and also by individual countries, among them Russia, Japan, Finland, Israel, Germany, France, and the United Kingdom.

There are a number of other triage systems available for mass casualty events, such as START (simple triage and rapid treatment), a similar system often used in the civilian sector, and SALT (sort, assess,

**EXHIBIT 3-1****“DIME” TRIAGE CATEGORIES**

**Delayed (D):** Patients require less urgent treatment than those in the immediate treatment category. This group includes those wounded and in need of surgery but whose general condition permits delay without unduly endangering life. The types of injuries in this category include fractures of major bones, relatively stable intraabdominal or thoracic wounds, and burns on less than 50% of the total body surface area (and not involving the face and without respiratory distress). Preoperative resuscitative treatment will be required (eg, stabilizing intravenous fluids, blood transfusions, antibiotics, and pain relief). Delayed-treatment patients will be monitored in case there is a significant change in condition that warrants a change in triage category.

**Immediate (I):** Patients require immediate treatment to save life, limb, or sight (highest triage priority). This group includes those requiring immediate life-saving surgery. The surgical procedures should not be time consuming and should involve only those unstable patients with a high chance of survival (eg, surgically correctable respiratory compromise, such as with upper airway obstruction or pneumothorax, or surgically correctable hypovolemic shock due to hemorrhage, etc).

**Minimal (M):** Patients require outpatient treatment and are often returned to duty. These casualties (the “walking wounded”) have relatively minor injuries (eg, minor lacerations, abrasions, contusions, sprains, fractures of small bones, and minor burns) and can effectively care for themselves or can often be helped by nonmedical personnel. They may sometimes be returned after a short time to some form of duty, depending on their condition and on military needs.

**Expectant (E):** Patients require extensive treatment and resources and usually have a very poor prognosis, even with treatment (lowest triage priority). Casualties in this category have wounds that are so extensive that even if they received the benefit of optimal medical resource application, their chances of survival would be poor. Expectant-treatment casualties are unresponsive patients with penetrating head wounds, mutilating explosive wounds involving multiple anatomical sites and organs, second- and third-degree burns in excess of 60% of total body surface area, profound shock with multiple injuries, open pelvic injuries with uncontrollable bleeding, and agonal respiration.

lifesaving interventions, treatment and/or transport), a more recently proposed system.<sup>2</sup> Because there are no established and widely accepted medical triage systems for a nuclear detonation, the existing DIME triage algorithms are used with modification for the impact of radiation injury.

### **Triage and Emergency Medical Treatment of Mass Casualties**

The first responders to casualties, whether military or civilian, will be under protective-action command control that will limit their radiation dose exposure by determining which areas they may enter. Medical treatment facilities (MTFs) will be at a sufficient distance from very high-radiation areas to avoid excessive radiation exposure. Healthcare personnel have never received a significant radiation dose, in the military or civilian setting, while providing care to contaminated radiation casualties.

For overwhelming mass casualties, the speed of assessing and categorizing patients' status is key to effective triage. A patient's location at the time of the detonation is extremely important. Patients who were in the open (unshielded) and relatively close to the detonation site will have serious blast and thermal injuries and significant whole-body radiation exposure

and are presumed to be expectant. Resources will be limited, and transferring obviously expectant patients to the MTF, where they would be clinically triaged, is inappropriate. At the other end of the spectrum, those who were not close to the detonation and were not near the dangerous fallout zone, and who are ambulatory and without significant symptoms, burns, or blast injuries, can be given a brief evaluation and initially presumed to have experienced insignificant trauma and radiation dose. They can be classified in the minimal category and not sent to an MTF.

Emergency rescuers and medics must make decisions as to which trauma patients require priority evacuation to an MTF, particularly to one with surgical assets. Some of these priority patients may require timely lifesaving surgery and must therefore be transferred immediately, regardless of whether there is radioactive contamination on them. Simple, hasty decontamination can be performed as long as it does not delay transfers. Lives will be lost if there are inappropriate delays in transporting critical patients who are contaminated, or if potentially lifesaving surgery is delayed.

### **Conventional-Injury Triage**

Initial primary clinical triage is based on conven-

tional injuries (mechanical trauma and burns), not on radiation dose. In the first days after a nuclear detonation event with overwhelming mass casualties, trauma will be the life-threatening problem to address.<sup>2,3,8-12</sup> Upon the patient's arrival at the MTF, rapid triage will be performed by a triage officer. The surgeon will make the final decision as to whether surgery is needed, the timing of surgery, and the priority of multiple surgical patients. The triage officer and surgeons should identify patients who require early evacuation. Casualties must be moved expeditiously to the next echelon of care when appropriate; otherwise, valuable resources will be consumed in maintaining patients, thereby preventing other casualties from receiving care. After a nuclear detonation, as in wartime, it cannot be assumed that it is possible to rapidly and reliably transport the wounded. In the confusion, casualties with a wide variety of injuries might arrive at the nearest MTF, regardless of its capability. Extra effort will be needed to keep patients moving forward in the system to an appropriate level of care. The greatest number of lives will be saved only by ensuring that time and materials are not allocated to expectant cases or to those whose injuries are such that definitive care can be postponed (minimal trauma or radiation-alone casualties). Knowing how and when to resupply internal resources may prove critical in decision-making for casualty treatment.

All patients receive a triage evaluation, but only some receive priority operative intervention. With an overwhelming number of trauma patients, time on the operating room table is the chokepoint. Trying to include all the factors that influence triage decision-making would be encyclopedic and of little benefit in a mass casualty situation; it is best to rely on the judgment of the trauma surgeons at the various MTFs.

DIME is the first approach in a mass casualty situation. Many patients in the immediate- and delayed-treatment categories require surgical intervention within minutes or hours, respectively. In forward locations where there are no surgical capabilities, patients classified as immediate who require surgery will need rapid transport to facilities capable of performing emergency surgery. It is likely that there will be many more patients in the immediate category than the operating room has the capacity to handle. Given two equally compelling immediate patients requiring emergency surgery, the one estimated to require less operating room table time should be taken first. A patient requiring only one surgical procedure generally has a higher priority than one requiring multiple procedures. Occasionally, with the operating rooms full, emergency lifesaving surgery may be performed outside the operating room; for

example, a patient bleeding uncontrollably from a dysfunctional extremity who requires an emergency amputation.

Surgeons will prioritize operative management. In the initial surge of patients received at an MTF (such as a combat support hospital or a fixed civilian or military medical center), those immediate and delayed patients awaiting surgery will be resuscitated and stabilized as much as possible. For example, at a combat support hospital, if the preoperative area becomes full, the critical presurgery patients can be stabilized in available intensive-care and medical or surgical beds. Thus, while awaiting surgery, immediate- and delayed-treatment patients receive respiratory support, stabilizing intravenous (IV) fluids, efforts to control bleeding, blood transfusions, antibiotics, and pain control, along with any additional external decontamination that may be necessary.

A patient presenting with hypotension must be presumed to be hypovolemic as a result of trauma and not as a result of a massive radiation dose. Therefore, hypotensive patients must be evaluated quickly to determine if their hypotension has a surgically correctable cause (eg, hemorrhage). The medical condition of those awaiting surgery will be monitored, and changes in triage category can be made. For example, given two patients in the immediate category, the patient who fails to respond rapidly to initial fluid resuscitation but who is still considered salvageable can be retriaged (or prioritized) ahead of a patient with a good response to fluid replacement. Alternatively, a nonresponder who is deteriorating rapidly and judged unlikely to be resuscitated and stabilized may be retriaged into the expectant category.

In a mass casualty situation, time itself is a resource that must be carefully managed. Aborting a surgical procedure and retriaging a patient to the expectant category may be necessary if the patient's condition deteriorates during surgery (for example, when extensive injuries are discovered intraoperatively that are not likely to be surgically correctable, with low chances of survival, compared to other patients who are potentially salvageable and urgently awaiting lifesaving surgery).

The decision to delay or withhold care from a wounded patient who, in another less-overwhelming situation, might be salvaged is difficult both for the medic or first responder out in the field and for the surgeon at the MTF. Nonetheless, making the difficult decisions in sorting casualties as quickly as possible is the essence of military triage. The goal is to save as many lives as possible with the available resources. Patients in the expectant category are given comfort care. Once the immediate and delayed patients have

been cleared, available treatment resources should be focused on surviving expectant patients, followed by any minimal patients still requiring care

### Radiation-Injury Triage

Trauma patients take priority over all radiation-alone patients. Casualties who have no trauma or burns because they were outside the immediate detonation impact area, but who were in the adjacent, downwind, heavy-fallout area, may have been exposed to a high radiation dose if they were unsheltered on the first day. For radiation-alone patients, four basic treatment categories, based on the severity of presumed radiation exposure, can be used to guide triage and treatment. The four categories are:

#### Mild (< 2 Gy)

- Triage by symptoms, lymphocyte count
- Close observation and complete blood cell count with differential
- Outpatient management is appropriate in the absence of significant mechanical trauma or burns

#### Moderate (2–5 Gy)

- Possible hospitalization
- Consider early growth factor (cytokine) therapy
- Consider viral prophylaxis
- Consider early antifungal therapy
- Administer antibiotics for febrile neutropenia; consider elective antibiotics for afebrile neutropenia in certain cases

#### Severe (5–10 Gy)

- Hospitalization
- Reverse isolation and intensive care, if possible
- Early growth factor (cytokine) therapy
- Early viral prophylaxis
- Early antifungal therapy
- Early antibiotics for anticipated profound neutropenia

#### Lethal (> 10 Gy)

- Symptomatic and supportive care only; if there are no mass casualties or if resources become adequate, some of these patients can be treated as if in the severe group.<sup>30,31</sup>

The assumption is that these patients do not have significant conventional injuries (trauma or burns). The four groups are roughly parallel to the four groups in the military triage DIME system for conventional injuries.

People who have received a mild radiation dose

without other injury can be placed in a minimal treatment category because they are expected to survive with no immediate treatment. Those who have received a lethal radiation dose would be placed in the expectant category and given comfort care. Clinical resources would be prioritized to treat casualties in the moderate and severe groups, parallel to trauma and burn patients in the delayed and immediate trauma triage categories. Patients in these two groups require the assistance of a hematologist knowledgeable in treating severe pancytopenia, and the assistance of an infectious disease expert knowledgeable in treating resistant opportunistic infections with anticipation of profound febrile neutropenia. However, the care of radiation-alone patients can be deferred for a few days, if necessary, until the priority trauma and burn patients are cleared. Patients in the military immediate-treatment category, by strict definition, are those requiring immediate lifesaving intervention. No patients with radiation-alone injuries require immediate intervention in a mass casualty situation. Those exposed to a treatable, life-threatening radiation dose are in the hematopoietic syndrome range and will not die during the first week (but are at risk after several weeks)<sup>32</sup>; however, trauma patients with potentially treatable, life-threatening injuries may die within an hour if untreated. Therefore, patients who have trauma and are triaged to the immediate or delayed categories will take priority over all radiation-alone patients, regardless of their triage category.

### Combined-Injury Triage

Combined injury is defined as concurrent trauma (mechanical or thermal) and significant whole-body radiation injury. The prognosis is much worse for victims who have serious combined injuries than it is for those with the same degree of trauma without radiation injury.<sup>3,9-12</sup>

A major difference between conventional and radiation injuries is the time line. Many immediate-treatment patients with only trauma die within hours. Survivable injuries caused by radiation alone do not cause death in the first week. Thermal burns manifest immediately, but radiation burns do not manifest themselves for several weeks. A death caused by radiation alone within the first week indicates a dose so high that it would have been nonsurvivable regardless of treatment (eg, a dose high in the gastrointestinal syndrome or the neurovascular syndrome range; see Table 3-8). For this reason, initial care within the first 24 to 72 hours in a combined-injury scenario focuses on serious mechanical trauma and thermal burns.<sup>33</sup>

A theoretical combined-injury triage guide that

tried to factor in radiation dose would be difficult to implement because of the uncertainty of radiation dose during initial overwhelming mass casualty triage. In the 2004 recommendations of the Strategic National Stockpile Working Group (Table 3-12), delayed-treatment patients with a dose of 1.5 to 4.5 Gy were placed in variable triage categories depending on the nature of the trauma. However, those with a dose of 4.5 Gy have a much worse prognosis than those with a dose of 1.5 Gy. All patients in the minimal-treatment category were kept in that category regardless of how high the radiation dose because treatment for the presumed minor conventional injury plus the significant radiation injury could be postponed without appreciably affecting the chances of survival. However, early group evacuation of significantly radiation-injured individuals would be advantageous. Also in the Strategic National Stockpile Working Group schema, immediate-treatment trauma patients are kept in the immediate category even if they also have serious whole-body radiation injuries. However, suppose two immediate-treatment trauma patients, whose conventional injuries are equally compelling, require lifesaving surgery. If one of them has received an estimated radiation dose of 1.5 to 4.5 Gy, the surgeon will take the other, nonirradiated patient first because the patient with significant combined injuries requires more resources and has a poorer prognosis than the patient with trauma-alone injury. The essence of military triage is to operate first on casualties with life-threatening injuries that require limited resources and have the greatest likelihood of survival. Therefore, an immediate-treatment

trauma patient who was also exposed to an estimated radiation dose of 1.5 to 4.5 Gy would either be kept as a lower-priority immediate patient or triaged to expectant. What will actually happen depends on the number of immediate casualties without significant radiation injury (< 1.6 Gy), the available resources, and the available evacuation options. It is sometimes difficult to prescribe in advance an appropriate triage category for some combined-injury patients.

Regardless of the triage schema used, it is probable that some combined-injury patients who should have been in the expectant category will have received treatment for immediate trauma injuries. This is because there will be cases where life-threatening injuries will be treated immediately, before a radiation dose estimate is available. In an overwhelming mass casualty situation in which patients need immediate lifesaving treatment, including surgery, there would be limited opportunity to accurately estimate, early on, the absorbed radiation dose. Furthermore, a patient could receive a nonuniform dose due to partial shielding that protected viable hematopoietic bone marrow stem cells from injury. Information on the patient's distance from the detonation and the degree of shielding is important for estimating the radiation dose; however, even if such information is available, unknown shielding factors of the physical environment could partially block the

**TABLE 3-12**  
**CONVENTIONAL VERSUS COMBINED-INJURY TRIAGE (2004 RECOMMENDATIONS)**

Conventional Triage Categories	Expected Change*		
	< 1.5 Gy	1.5–4.5 Gy	> 4.5– < 10 Gy
Immediate (I)	I	I	E
Delayed (D)	D	Variable <sup>†</sup>	E
Minimal (M)	M	M	M
Expectant (E)	E	E	E

\*Conventional triage categories with added whole-body irradiation  
<sup>†</sup>Triage category depends on the nature and extent of physical injury  
 Data source: Waselenko JK, MacVittie TJ, Blakely WF, et al. Medical management of the acute radiation syndrome: recommendations of the Strategic National Stockpile Radiation Working Group. *Ann Intern Med.* 2004;140(12):1037–1051.

**TABLE 3-13**  
**CONVENTIONAL VERSUS COMBINED-INJURY TRIAGE (2009 RECOMMENDATIONS)**

Conventional Triage Categories	Expected Changes*		
	< 2 Gy (Vomit > 4 h)	2–6 Gy (Vomit 1–4 h)	> 6 Gy (Vomit < 1 h)
Immediate (I)	I	Variable (I, E)	E
Delayed (D)	D	Variable (D, I)	E
Minimal (M)	M	D	Variable (D, E)
Expectant (E)	E	E	E

\*Changes in triage categories after whole-body irradiation  
 Data sources: (1) Radiation Event Medical Management Web site. [www.remm.nlm.gov](http://www.remm.nlm.gov). Accessed February 22, 2010. (2) Homeland Security Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats. *Planning Guidance for Response to a Nuclear Detonation*. Washington, DC: Office of Science and Technology Policy, Executive Office of the President; 2009. [www.usuhs.mil/afri/outreach/pdf/planning-guidance.pdf](http://www.usuhs.mil/afri/outreach/pdf/planning-guidance.pdf). Accessed March 23, 2012.

amount of radiation received.

Using clinical symptoms, specifically time to first emesis, is very helpful for a triage officer (Table 3-13). This measure is much more reliable than early erythema for a dose greater than 6 Gy; early erythema is an unreliable indicator of radiation injury because it may be related to thermal or medical treatment effects, rather than ionizing radiation effects, and therefore is subject to misinterpretation. All minimal-treatment trauma patients, primarily the “walking wounded,” who are also irradiated can be evacuated by mass transit to centers well outside the impact area that can deal with radiation injury in the hematopoietic syndrome range.

Immediate- and delayed-treatment trauma patients who have received a dose of 2 to 6 Gy or more than 6 Gy can be made lower-priority patients in their same triage categories, since trauma patients without irradi-

ation, or having sustained doses less than 2 Gy, would have priority over patients with greater radiation doses in the same triage category. Alternatively, immediate-treatment trauma patients who have received doses of 2 to 6 Gy or more than 6 Gy could be temporarily designated as expectant until the immediate-treatment patients without irradiation and those exposed to doses less than 2 Gy are cleared. Close and urgent attention must be paid to those patients classified as immediate or delayed upon initial clinical triage who may be potential candidates for priority evacuation. The medical facilities in the area around the impact and fallout zones will be overwhelmed. It is likely there will be many more immediate and delayed patients requiring surgery than the available area resources can handle. This could result in a significant delay in surgery for some immediate-treatment patients unless they can be quickly evacuated.

### **EVACUATION, RESUPPLY, AND AUSTERE MEDICAL CONDITIONS**

Evacuation assets should be mobilized simultaneously with the medical response for triage and treatment. There can be many thousands of individuals inside the dangerous fallout zone who have received a significant whole-body radiation dose. Some may also have minimal conventional injuries. Public transportation assets, such as chartered airplanes, trains, and bus convoys, could be used to evacuate many people in less than 48 hours. They could be organized and escorted in groups of up to 500 individuals or more and sent to distant sites that are able to deal with serious, but potentially survivable, radiation injuries long before such injuries manifest clinically. Individuals with radiation-alone injuries or with minimal trauma do not need medical care during transport in a mass casualty scenario; an early group evacuation policy would take a major burden off local medical resources.

For more serious immediate- and delayed-injury patients, medical evacuation assets can sometimes be expanded under austere conditions. Medical transportation assets, such as air and ground ambulance, with the ability to provide medical care in transit, will be in short supply. The hospitals in the broad area around the detonation site will be overwhelmed with casualties. It is expected that some critical trauma patients who would normally be treated locally may need to be evacuated even when their injuries cannot be completely stabilized prior to transport. In an overwhelming mass casualty scenario, definitive care may be substantially delayed because too many casualties will require immediate care and resources will be taxed. A recent review of the aftermath of a potential 10-kiloton detonation in a major US city concluded

there were not enough burn beds in the United States to handle the expected patients with serious burns, even if all the beds were empty and available.<sup>2,17</sup> Under austere conditions, the “burn bed” should be redefined as any bed or cot set up where at least some basic burn care can be provided, such as IV fluid and electrolyte replacement, pain control, systemic antibiotics, and skin care. Those with minimal or no trauma injuries but with serious yet potentially salvageable radiation injuries can afford to have treatment delayed while they are evacuated to appropriate medical centers throughout the country. Critical trauma patients cannot afford such a delay.

In addition to evacuating casualties, immediate resupply of resources and personnel needs to be addressed. Within a day or two, there will be local shortages of supplies, such as IV fluids and blood, needed for the enormous number of thermal burn and trauma patients awaiting treatment or evacuation. Supplies of drugs, such as narcotics and antibiotics, may be depleted quickly. When first-choice drugs run out, alternative antibiotic regimens can be considered, as recommended by infectious disease clinicians. Oral drugs, including antibiotics, are preferred whenever possible because they can be administered by non-medical personnel under medical supervision. It is also important that limited medical resources not be used in excess for those with minimal injuries or for hopeless expectant casualties.

Within 24 hours after the start of a mass casualty situation, many healthcare personnel, including surgeons and operating room personnel, will be totally exhausted. Work shifts will be extended throughout

the hospital, and extreme fatigue will rapidly set in. Traditionally, two surgeons operate as a team on a complicated trauma case. Insufficient surgical staff levels could be augmented by incorporating the skills of other healthcare personnel. For example, under austere conditions, retired surgeons, surgical resident physicians-in-training, and experienced veterinary surgeons could play a role in assisting surgeons. This would depend on the specific case and the judgment of the primary surgeon in charge; however, using these resources would allow short sleep intervals for some surgeons on the brink of exhaustion after a prolonged surge of trauma cases. The surgical surge period could last up to a week.

Nonmedical volunteers, nursing students, and medical students could also be allowed to work under medical oversight. Each volunteer could be trained to perform a single function (eg, starting IVs, cleaning wounds, decontaminating casualties, acting as litter-bearers, distributing specific oral medication, giving

intramuscular pain medication to expectant casualties). Most doctors and nurses at Hiroshima were casualties, and most hospitals were damaged. However, there was an innovative response from available medical and many nonmedical personnel, including those who themselves had minimal injuries.<sup>5,6</sup> The nonmedical personnel provided whatever assistance they could to others, usually under some medical direction.

In a present-day situation, the number of people with radiation contamination, whether minor or significant, will be overwhelming. Initially, there will be severe shortages of trained personnel and instrumentation to address contamination issues. There will be a great need to mobilize health physicists, medical physicists, and associated technical staff, such as health physics technologists or nuclear medicine technologists. All provide critical support in assessing contamination and evaluating decontamination. These individuals may bring their own instrumentation with them to assigned areas requiring health physics support.

### ASSESSMENT OF RADIATION DOSE: CLINICAL AND LABORATORY

#### Clinical Assessment

Once the immediate medical needs of a patient with mechanical or thermal trauma have been met, radiation decontamination should begin and the radiation dose should be estimated. Assessing the radiation dose can be important for modifying patient triage, and it can be estimated by the time to first emesis. The Radiation Emergency Assistance Center/Training Site (REAC/TS) in Oak Ridge, Tennessee, records and maintains worldwide accident data (Table 3-14) and reports that the time to first emesis decreases with increasing radiation dose in a predictable pattern.<sup>14</sup> The estimated average whole-body dose resulting in emesis in 50% of patients was 2.4 Gy. When a dose is absorbed over a short period of time (ie, at a high dose rate), the dose resulting in emesis in 50% of the patients is expected to be significantly lower, as consistent with clinical experience in radiation oncology treatment where the dose is delivered in a few minutes. Although a relatively small percentage of patients acutely exposed to a dose of 1 Gy vomit, most vomit when the dose is higher than 2 Gy, provided the dose is absorbed over a very short time rather than over many hours or days. As a guide for rapid clinical radiological triage in a mass casualty situation, it has been proposed, based on REAC/TS data, that individuals who vomit within 4 hours after exposure be referred for hospital evaluation and possible admission.<sup>34</sup> Those who do not vomit within 4 hours can be referred for delayed evaluation some days later. If they have no serious concurrent

injury, outpatient care is probably appropriate. If no vomiting occurs during the first 4 hours after an acute exposure, one may assume that severe clinical effects are unlikely unless there are significant conventional injuries. If there is insufficient laboratory support in a mass casualty situation, casualty triage according to radiation dose depends on the length of time to initial vomiting. More recently, REAC/TS reported that if the time to emesis is less than 2 hours after exposure, the effective whole-body dose is probably at least 3 Gy.<sup>35</sup> Patients who have radiation-induced emesis within 1 hour have received a whole-body dose that probably exceeds 4 to 6 Gy. The median radiation dose for

**TABLE 3-14**  
**ESTIMATES OF TIME TO VOMITING AFTER WHOLE-BODY RADIATION DOSE**

Percentile of Dose	Radiation Dose	
	> 4 h to Vomiting	< 4 h to Vomiting
25th	0.5 Gy	2.5 Gy
Median	0.9 Gy	3.6 Gy
75th	1.7 Gy	6.0 Gy

Data source: US Department of Homeland Security. *Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness*. Washington, DC: DHS; 2003. [www.au.af.mil/au/awc/awcgate/va/radiologic\\_medical\\_countermeasures.pdf](http://www.au.af.mil/au/awc/awcgate/va/radiologic_medical_countermeasures.pdf). Accessed March 23, 2012.

patients vomiting less than 1 hour after exposure is 6.5 Gy, with an interquartile range (25%–75%) of approximately 5 to 11 Gy.<sup>34</sup> Conversely, if the patient has not vomited within 8 to 10 hours after the event, the whole-body dose is probably less than 1 Gy. However, vomiting can occur for reasons other than radiation (eg, as a result of psychological effects).

### Laboratory Assessment

#### Lymphocyte Count Depression

Ideally, a complete blood cell count with differential to evaluate lymphocytes (and neutrophils) should be performed initially, then every 6 hours if resources permit, or at least at 24 and 48 hours. The peripheral blood lymphocyte count (lymphocytes/mm<sup>3</sup>) is a sensitive indicator of radiation dose and follows a predictable, radiation dose-dependent, exponential decline in the first few days after a significant whole-body dose. For example, at 24 hours after exposure, if the lymphocyte count is less than 10% of normal, the exposure is lethal, even with treatment. If it is 90% or more of normal, survival is likely, even without treatment.<sup>36</sup> If it is about 50% of normal, the corresponding dose is in the mid-hematopoietic syndrome range. In that case, aggressive treatment should ideally be started before the end of the first week to decrease the risk of death in the following weeks.<sup>37,38</sup> REAC/TS developed a predictive algorithm to estimate the effective whole-body dose soon after an exposure.<sup>34</sup> The method uses the measured lymphocyte depletion rate from serial complete blood cell counts performed within the first 8 to 12 hours after exposure. This algorithm was developed to provide physicians and health physicists with an early approximation of the dose so that cytokine therapy, if indicated, can begin early. A rough estimate of the whole-body dose may be obtained by using the REAC/TS data and taking the absolute lymphocyte count at approximately 8 to 12 hours after exposure (Table 3-15). The dose estimate is independent of the preirradiation lymphocyte count, which is often unknown. This technique is designed to be a radiation triage mechanism applied early after exposure and should be considered along with the time to radiation-induced emesis. Between 12 and 48 hours after exposure, the lymphocyte count continues to drop exponentially. The lymphocyte counts of patients receiving different radiation doses will differ more at 48 hours than at 12 hours because the counts decrease at different dose-dependent depletion rates; therefore, a better estimate of dose and prognosis can be made at the 48-hour point (Table 3-16).<sup>39</sup>

Algorithms from the Armed Forces Radiobiology

**TABLE 3-15**

#### WHOLE-BODY, APPROXIMATE DOSE ESTIMATES BASED ON EARLY LYMPHOCYTE COUNT DEPRESSION\*

Absolute Lymphocyte Count 8–12 Hours After Exposure*	Estimated Absorbed Dose (Gy)
1,700–2,500/mm <sup>3</sup>	1–5
1,200–1,700/mm <sup>3</sup>	5–9
< 1,000/mm <sup>3</sup>	> 10

\*A whole-body dose of 1 Gy or less should not noticeably depress the lymphocyte count below the normal range, taken as 1,500 to 3,500/mm<sup>3</sup>.

Data source: US Department of Homeland Security. *Department of Homeland Security Working Group on Radiological Dispersal Device (RDD) Preparedness*. Washington, DC: DHS; 2003. [www.au.af.mil/au/awc/awcgate/va/radiologic\\_medical\\_countermeasures.pdf](http://www.au.af.mil/au/awc/awcgate/va/radiologic_medical_countermeasures.pdf). Accessed March 23, 2012.

Research Institute biodosimetry assessment tool combine various factors, including time to emesis and lymphocyte depletion rate, to estimate the radiation dose and help guide therapy (see [www.afrii.usuhs.mil](http://www.afrii.usuhs.mil)).<sup>9</sup>

**TABLE 3-16**

#### PROGNOSIS AT 48 HOURS BASED ON LYMPHOCYTE COUNT DEPRESSION AFTER ACUTE WHOLE-BODY EXPOSURE

Minimal Lymphocyte Count 48 Hours After Exposure	Approximate Absorbed Dose (Gy)	Prognosis
1,000–3,000/mm <sup>3</sup> (normal range)	0–0.5	No significant injury
1,000–1,500/mm <sup>3</sup>	1–2	Significant but probably non-lethal injury, good prognosis.
500–1,000/mm <sup>3</sup>	2–4	Severe injury; fair prognosis
100–500/mm <sup>3</sup>	4–8	Very severe injury; poor prognosis
< 100/mm <sup>3</sup>	> 8	High incidence of lethality even with hemapoeitic stimulation

Reproduced with permission from: Koenig KL, Goans RE, Hatchett RJ, et al. Medical treatment of radiological casualties and current concepts. *Ann Emerg Med*. 2005;45:643–652.

### **Cytogenetic Studies**

The radiation dose may be subsequently confirmed with a chromosome-aberration bioassay in cultured peripheral blood lymphocytes.<sup>40</sup> Chromosome dicentrics are interchanges between two chromosomes that form a distorted chromosome with two centromeres. The frequency of chromosome dicentrics correlates better with the absorbed dose than does lymphocyte count depression, and changes may be detected with a dose as low as 0.2 Gy. The

technique is labor intensive, however, and results cannot be obtained rapidly; even in ideal situations, results may not be available until days after exposure. Thus, the method has limited usefulness in a mass casualty situation. However, cytogenetics can guide crucial therapy in selected cases. In the United States, the current laboratories with cytogenetic capability that are dedicated to radiation dose assessment are at the Armed Forces Radiobiology Research Institute in Bethesda, Maryland, and at REAC/TS in Oak Ridge, Tennessee.

## **EMERGENCY TREATMENT OF COMBINED INJURIES**

Basic life-support concerns need to be addressed quickly for casualties in the immediate category; airway, adequate ventilation, and circulatory function should be ensured for patients whose injuries are correctable. Concerns about internal or external contamination from radioactive material should be secondary. During the first 72 hours, the initial phase of treatment will be directed toward trauma and burns, with simultaneous integration of external decontamination, as appropriate. After detonation of a nuclear weapon, most casualties will be combined-injury patients.

Emergency surgical care involves resuscitation, hemorrhage control, and minimizing sepsis with debridement. Traditionally, combat and traumatic wounds are left open. However, there has been concern that in the significantly irradiated patient (hematopoietic syndrome range), wounds left open may serve as a nidus for infection, based in part on animal studies and on observations at Hiroshima. However, in the Hiroshima experience, when wounds were open, antibiotics were in extremely short supply, so they were often diluted and may not have reached therapeutic blood levels.<sup>6</sup> Wounds in the combined-injury patient might be debrided thoroughly and closed early, when possible. However, early closure may not be possible or practical in many circumstances, such as when multiple debridements are needed or in the case of significant devitalized tissue and subsequent morbidity of closed-space contamination. For a patient who has received a whole-body radiation dose over 2 Gy and also has a traumatic wound, therapeutic countermeasures are available today to reduce the risk of radiation-induced neutropenia and subsequent sepsis when a wound must be left open:

specifically, cytokines to stimulate the bone-marrow stem cells and more potent antibiotics to prevent or treat infection.

Topical antibiotics and nonadherent dressings are essential to treating wounds and burns, with systemic antibiotics added if appropriate. Major surgical procedures are prioritized for unstable but salvageable patients. Ideally, if surgical correction of major injuries is required, it should be performed as soon as possible. Otherwise, major surgical procedures should be postponed, when possible, until late in the convalescent period following hematopoietic recovery. However, patients requiring critical surgery during the first 2 months should receive it even without full hematopoietic recovery.

For vomiting, treatment includes drugs such as granisetron and ondansetron. Vomiting usually abates within 48 hours, making prolonged antiemetic therapy unnecessary. For diarrhea, treatment includes drugs such as loperamide and diphenoxylate hydrochloride with atropine sulfate.

Casualties who have mild, uncomplicated injuries may be kept in alternative care facilities established in response to the overwhelming mass casualties. Patients who have significant (2–6 Gy) but potentially salvageable whole-body radiation injury should begin to receive aggressive treatment within the first week. They may be transferred to oncology centers equipped to treat potential opportunistic infectious complications of bone marrow failure. One national resource, the Radiation Injury Treatment Network, is partnered with the US Department of Health and Human Services and provides coordinated medical care with a large number of specialty centers.<sup>41,42</sup>

## **DEFINITIVE TREATMENT OF RADIATION INJURIES**

### **Hematopoietic Injury**

During the first 72 hours of the emergency treatment phase, while clinical and laboratory whole-body

dose assessments are being made, potentially salvageable patients may be identified who are destined to develop radiation-induced bone marrow aplasia of the hematopoietic syndrome. Early in the definitive

treatment phase of casualties, within the first week in an overwhelming mass casualty scenario, the initiation of cytokines (such as granulocyte CSF) and antimicrobials will improve the chances of survival for these patients.<sup>33,35,41-45</sup> Essentially, of the patients treated for significant radiation exposure, those with a chance for survival will be those without serious mechanical or thermal trauma, with a dose limited to the hematopoietic syndrome range (up to 8 Gy). Both in the immediate posttraumatic period and later during the manifestation of hematopoietic radiation injury, blood products should be transfused when indicated.

Hematopoietic growth factors or cytokines (CSFs) are endogenous glycoproteins that induce bone marrow stem cells to proliferate and differentiate into specific mature blood cell types. For those who receive radiation doses above 3 Gy, successful treatment depends on maintaining a surviving fraction of stem cells capable of spontaneous regeneration, assuming that any nonhematopoietic injuries are survivable. For neutropenic patients receiving myelosuppressive chemotherapy, available CSFs include filgrastim, pegfilgrastim, and sargramostim (granulocyte-macrophage CSF). These, along with newer growth factors under development, are potent stimulators of hematopoiesis by the bone marrow. CSFs will usually decrease the duration of radiation-induced neutropenia and stimulate neutrophil recovery. The results of several radiation accidents suggest that prophylactic CSFs should be initiated early, within 3 to 4 days whenever possible, in patients who have been exposed to potentially survivable whole-body doses of radiation and are at risk for hematopoietic syndrome. This may not always be possible in a mass casualty scenario. For patients who were not given early granulocyte-macrophage CSF and who later become profoundly neutropenic (ie, an absolute neutrophil count < 500/mm<sup>3</sup>), a CSF should be employed. This can sometimes be effective, as demonstrated in patients who received chemotherapy and subsequently developed febrile neutropenia.

In a nuclear detonation, most casualties exposed to a dose exceeding 6 to 8 Gy may also have significant blast and thermal injuries that preclude survival, regardless of treatment. Bone marrow transplantation and other aggressive treatment cannot salvage anyone who has received a whole-body dose of about 12 Gy because serious radiation injury to the lungs and other vital organs would result in nonsurvivable conditions. For patients who undergo bone marrow transplantation after radiation accidents, outcomes have been poor. Bone marrow transplantation would have no role in a mass casualty situation given the presence of current alternative therapies (such as cytokine therapy), the probability of combined injuries,

uncertainties about radiation dose, and nonuniform exposure of radiation victims.<sup>42,46</sup> The patient's physical environment often affords partial shielding, resulting in variability in the absorbed dose. Because the absorbed radiation dose is nonuniform, there may be unexpected reservoirs of viable hematopoietic stem cells that received a lower dose than the average whole-body dose. Both spared and radiation-resistant stem cells are capable of promoting hematologic reconstitution. This ability appears to be augmented by CSF therapy.

### Infectious Complications

Controlling infection during the critical neutropenic phase is a major factor for producing a successful outcome in patients who have absorbed a radiation dose in the hematopoietic syndrome range.<sup>33,43,44</sup> Infections are a major cause of mortality in irradiated casualties because of the immunosuppressive effects that result from declining lymphohematopoietic elements secondary to radiation-induced bone marrow aplasia (reversible or irreversible). Life-threatening, gram-negative bacterial infections are universal among neutropenic patients. Oral fluoroquinolones may be used electively in severely neutropenic patients. Managing established or suspected infection in irradiated patients with fever and neutropenia is similar to managing infection in febrile neutropenic patients undergoing chemotherapy. For those who have significant neutropenia (absolute neutrophil count < 500/mm<sup>3</sup>), the use of broad-spectrum prophylactic antimicrobials is indicated because the duration of neutropenia is likely to be prolonged. Treatment might include a fluoroquinolone with streptococcal coverage (with penicillin or amoxicillin, if the streptococci are not inherently covered by the fluoroquinolone); an oral antiviral agent, such as acyclovir; and an oral antifungal agent, such as fluconazole. Acyclovir is effective against herpesvirus, which has a high risk of reactivation during periods of immunosuppression. Fluconazole has been shown to reduce fungal infections and mortality in immunosuppressed patients undergoing allogeneic bone marrow transplantation.<sup>47</sup> Other antifungals, such as voriconazole, could be used for infections that do not respond to fluconazole, such as those from *Aspergillus* or resistant *Candida* species.

Antimicrobial agents should be continued until the treatment fails, the patient has a neutropenic fever, or the patient shows evidence of neutrophil recovery (absolute neutrophil count rising and > 500/mm<sup>3</sup>). The fluoroquinolone should be stopped in patients who develop fever while receiving it. Urgent parenteral therapy should be used if fluoroquinolone-resistant, gram-negative bacteria are suspected, in particular *Pseudomonas aeruginosa*, because gram-negative infec-

tions may be rapidly fatal. Vancomycin should be added if a resistant gram-positive infection is suspected. The prevalence of life-threatening, gram-positive bacterial infections varies greatly among hospitals, and therefore antimicrobial therapy should be matched against hospital susceptibility patterns.

The specific hematopoietic and antimicrobial treatment described are examples of several approaches to treating victims who have received radiation doses in the hematopoietic syndrome range. Hematologists and infectious disease physicians will determine the actual approaches to treatment. Infectious disease physicians will be the center of the decision-making process regarding opportunistic, drug-resistant infections in patients who have altered immunity or burns. For patients who develop febrile radiation-induced neutropenia, adherence to the new guidelines of the Infectious Disease Society of America<sup>48</sup> is recommended. The society has also endorsed comprehensive new guidelines for preventing infections associated with combat-related injuries,<sup>49</sup> and it periodically updates its treatment guidelines on its website. A truly overwhelming mass casualty situation may, to some degree, preclude the strict application of a formulated approach. For example, oral antimicrobials might be used when there is limited capability for IV therapy,<sup>50</sup> or injections of a specific cytokine might not be given daily because of resource limitations. Because some drug supplies would run short in a mass casualty scenario, available second-choice drugs could be used on the basis of ongoing expert guidance.

### Cutaneous Syndrome

In contrast to thermal skin burns appearing immediately following a nuclear detonation and release of thermal radiation, radiation burns occur later, with delayed erythema and desquamation or blistering developing in 2 to 3 weeks. This radiation injury can be caused either by the prompt ionizing radiation released immediately by the detonation or by the radioactive fallout, particularly on the first day. If there is radioactive contamination on the skin, decontamination needs to be done early because reducing the time the radioisotopes remain in contact with the skin reduces the severity of the injury that develops later (Table 3-17).

Skin injury effects, as a function of increasing dose from ionizing radiation after a nuclear detonation, are similar to those seen when normal skin is irradiated as part of cancer treatment. Unlike the erythema that develops in a dose-dependent fashion at 2 weeks, the early transient erythema threshold reported at 6 Gy is not reliably observed, particularly in radiation oncology treatments with 6 Gy given to skin in a single

TABLE 3-17

### CUTANEOUS EFFECTS AS A FUNCTION OF A RADIATION DOSE (SINGLE ACUTE EXPOSURE)

Dose	Cutaneous Effects
3 Gy	Epilation of the scalp threshold, typically beginning at 14–21 days after incident
10–15 Gy	Dry desquamation* of the skin usually seen about 3 weeks after incident; desquamation of large, macroscopic flakes of skin
20–50 Gy	Wet desquamation* (partial thickness injury) at least 2–3 weeks after exposure
> 50 Gy	Overt radionecrosis* and ulceration

\*Dry desquamation, wet desquamation, and radionecrosis are preceded by erythema, which starts around the second week after exposure.

Data source: Goans RE. Critical care of the radiation-accident patient: patient presentation, assessment and initial diagnosis. In: Ricks RC, Berger ME, O'Hara FM, eds. *The Medical Basis of Radiation-Accident Preparedness: The Clinical Care of Victims*. Boca Raton, FL: Parthenon Publishing Group, CRC Press; 2002.

dose. After a nuclear detonation, early erythema from ionizing radiation may be masked by the immediate effects of thermal radiation.

The two main approaches to managing radiation skin injury are nonoperative and operative treatment. Sometimes both approaches are necessary to manage the cutaneous syndrome. Generally, nonoperative treatment is the initial approach. Treatment consists of gentle flushing and early superficial debridement of potentially septic tissue. Steroid ointment should be used for relatively intact skin, a topical antibiotic with dressings should be used for the blistering phase, and silver sulfadiazine cream and nonadherent dressings (without topical antibiotic treatment) should be used for wet desquamation. Wet desquamation may be complicated by secondary infections. Depending on the specific case, systemic antibiotics may be added. Decisions regarding surgical treatment may be impossible at an early stage because it may be many weeks before the radiation burn fully evolves. Once indications for surgery appear (eg, radiation ulcers, localized necrosis without signs of regeneration, and severe, intractable pain), surgical intervention, such as amputation of a necrotic extremity, should not be delayed. Tissue grafts may be required for some cases; necrotic tissue must be excised and the least irradiated skin harvested or transposed for coverage. Cutaneous injuries in some individuals may be protracted and eventually require the expertise of reconstructive surgeons and other specialists.

## DECONTAMINATION: EXTERNAL AND INTERNAL

### Initial Management

The initial management of a casualty contaminated by radioactive material involved performing all life- and limb-saving actions without regard to contamination.<sup>2,3,9-12</sup> Decontamination should be integrated with medical care in a way that does not interfere with urgent care.<sup>31,51</sup> Contaminated casualties should never be barred entry to a medical facility if entry is necessary for emergency care. Significant decontamination can be achieved by clothing removal. After a nuclear detonation, it is not possible for a living patient to be contaminated enough to become an immediate threat to healthcare providers; therefore, radiological decontamination should never interfere with medical care priorities.

Radiological decontamination is performed in a manner similar to chemical decontamination. However, whereas chemical decontamination may be an emergency, radiological decontamination is not.<sup>2,9</sup> Radiological contamination can be readily confirmed and localized by passing the probe of the radiation detector (RADIAC or other Geiger-Müller counter) over the entire body. It would be advantageous to cover the probe with a surgical glove to prevent contamination of the probe itself. A person trained in and familiar with radiation equipment can supervise, interpret contamination measurements, and advise the medical staff on the contamination levels.<sup>52-54</sup>

Emergency rescuers and first responders, including medics, who enter high-radiation areas need augmented personal protection and radiation monitoring devices. Initial triage on site may include a hasty decontamination performed on priority casualties who will be sent directly to the MTF for clinical retriage and treatment. This may consist, for example, of removing outer, contaminated clothing and quickly wiping the face and exposed skin while the person awaits transport to the MTF. However, a patient with life-threatening injuries should not be decontaminated if doing so would delay transport. A brief, hasty decontamination can also be performed during transport.

Casualties who have both radiation contamination and wounds must be directed to an MTF or, if one has been established, to a designated medical triage station. The first or second decontamination may occur at the MTF. Personnel providing decontamination at the MTF must protect themselves from most radiation contamination. They do not require augmented protection, as do first responders and emergency rescuers. For emergency treatment and decontamination, adequate protection is provided by standard hospital barrier clothing as used in universal precautions,

which consists of a surgical gown or other protective outer clothing and lightweight surgical apron, gloves, shoe covers, surgical mask, and cap to cover the hair.

Contaminated personnel without injuries, as well as ambulatory casualties with minimal injuries, should not be decontaminated at the MTF, which will be overwhelmed by casualties with significant mechanical and thermal trauma. They should be sent to decontamination sites for self-decontamination, washing their exposed skin and hair (and showering, if possible) after removing and bagging their contaminated clothing. Clothing and footwear should either be replaced or shaken or brushed to remove loose contamination. Families should not be separated, and parents should decontaminate their children. Those not capable of decontaminating themselves should receive assistance.<sup>2,3</sup> However, with overwhelming numbers of contaminated individuals, the decontamination staff will be limited. The decontamination staff is also tasked with using detectors to evaluate decontamination levels. To assist decontamination efforts, the staff should seek volunteers from among those who were not contaminated or who have already been decontaminated.<sup>3</sup> Ideal decontamination sites would be located where there are sources of water for washing and showering, preferably separated by gender, such as those found in school gymnasiums, health clubs, and indoor sports arenas.

### External Decontamination

Decontamination of radionuclides is a second priority after the initial resuscitative support of casualties with salvageable life-threatening injuries.<sup>2,9,31,32</sup> For immediate-treatment patients requiring surgery, lavage of contaminated open wounds can be done before and also during surgery. However, aggressive surgery, such as amputation, should not be undertaken to eliminate contamination as long as the contamination poses no serious acute risk to the patient or the medical staff. The surgical damage will far exceed any potential reduction of lifetime risk due to radiation exposure.

Removing outer clothing and shoes and washing exposed skin and hair should eliminate 95% or more of the external radioactive contamination. Regular soap and water is the preferred method to remove external contamination. Casualties entering an MTF must be assumed to be contaminated and must therefore undergo at least simple, hasty decontamination if radiation-monitoring devices are not available. During decontamination in the receiving medical facility, wounds get first priority. Bandages are removed and

wounds are decontaminated first and copiously irrigated with normal saline or water; the bandages are then replaced, if appropriate. Stubborn contamination after irrigation may require wound debridement and further irrigation. Burns should be rinsed gently with water and cleared of debris. In patients whose burn wounds cannot be completely decontaminated, most of the contamination will remain in the burn eschar when it sloughs. After wounds, priority is given to the nose, mouth, eyes, and ears.

After outer clothing removal and wound decontamination, intact skin can be decontaminated, if indicated. A wet washcloth with soap and a basin of water may be used to remove a significant amount of superficial contamination. To prevent cross-contamination, wounds and burns can be covered with waterproof dressings before the skin is decontaminated. Abrasions and lacerations are usually relatively easy to decontaminate. Gentle brushing may help remove contamination from the skin, but care should be taken not to irritate or abrade the skin because some contamination can be absorbed through injured skin. Hair (and skin) can be decontaminated with any commercial shampoo. Cutting or clipping the hair or beard (not shaving) can also remove contaminants. Fingernails and toenails should be checked and cut if necessary. Contaminated wastewater can be disposed of without restriction.

After each skin or wound decontamination, the patient should undergo another contamination check with a radiation detector to determine the effectiveness of the decontamination. The goal, which cannot always be reached, is to decontaminate to a level two or three times below the background radiation level. An alternative goal is to stop if subsequent decontamination attempts are ineffective at reducing the count rate by more than 10% to 20% of the prior count rate. At this time, there is no universally accepted threshold of radioactivity (external or internal) above which a person is considered contaminated and below which a person is considered decontaminated.<sup>2,25,32</sup>

### **Internal Decontamination**

Internal contamination is more likely if high levels of contamination are found on the face, particularly at the nostrils. Nasal swabs that show a strong, positive indication of contamination will also indicate the probable inhalation of radioactive particles. However, one may assume that some inhalation has occurred in most patients in the mass casualty phase after a nuclear

detonation, but immediate treatment for internal contamination, in general, is not necessary. Fortunately, the amount of internal contamination is usually a very small fraction of the external contamination, which is generally of greater concern but more easily removed. Therefore, in a nuclear detonation scenario, a radiation dose received from internal contaminants will not be a major concern compared to mechanical or thermal trauma or to the potentially large external radiation dose received from exposure either at the time of detonation or later from fallout.<sup>2</sup> A recent independent review of the issue concluded that internal decontamination will not be a high priority in the immediate aftermath of a nuclear detonation.<sup>55</sup> However, there may be a few special cases that will warrant relatively early treatment. Clinical judgment needs to be exercised as to whether internal decontamination is needed. Internal contamination is minimized by reducing absorption, increasing excretion, or both. Medical management, when it is necessary, depends on the type of isotope. Techniques to be applied may include the following:

- Oral and nasopharyngeal suction.
- Increased oral fluid intake versus IV hydration (and possibly diuretics); this is effective for any isotope, including iodine, phosphorus, and tritium.
- Administration of laxatives (cathartics), such as a bisacodyl or phosphate soda enema, or magnesium sulfate to speed gastrointestinal transit time.
- Stomach lavage.
- Administration of antacids, particularly aluminum hydroxide, to reduce absorption.
- Administration of therapeutic agents including blocking or diluting agents, such as potassium iodide for radioactive iodine; mobilizing agents, such as ammonium chloride for radiostrontium; chelating agents, such as calcium or zinc diethylenetriaminepentaacetic acid for plutonium and americium; other specific agents, such as ferric ferrocyanide (Prussian blue), which has proven useful for cesium and thallium internal contamination; and sodium bicarbonate, which is used to prevent kidney toxicity from uranium.

Detailed information on treatment for exposure to a range of radioisotopes is available from the National Council on Radiation Protection and Measurements.<sup>56</sup>

## **PSYCHOLOGICAL EFFECTS ON MILITARY AND CIVILIAN PERSONNEL**

Overwhelming casualties and radiation exposure create stress and fear in both military and civilian

populations. Traditional treatment for combat stress has involved rest for several days in physical prox-

imity to the soldier's unit rather than reassignment and evacuation. Counseling during the rest period involved a positive expectation that soldiers would be able to return to their units. However, this traditional military doctrine is not as practical in the event of a single, geographically localized nuclear detonation as it was during conventional wars of the past century. In modern times, it is evident that nonessential personnel need to be removed from the area of operations. The number of military combat stress casualties depends today, as it did in the past, on the prior training, leadership, and cohesiveness of a unit.<sup>8,9</sup>

There is less cohesiveness and practiced discipline among the civilian population, and a nuclear detonation will result in widespread fear and panic.<sup>2,17</sup> Many will immediately self-evacuate, not realizing that by doing so they may be putting themselves, and their families, at even greater risk. Others, anxious to be checked for contamination (or have their children checked), will flood emergency rooms or tie up communication channels. Reactions to this kind of psychological trauma will produce symptoms ranging from insomnia and anxiety to irrational and aggressive behavior. Occasionally, psychosomatic symptoms that mimic symptoms of exposure to high radiation (eg, nausea, rashes) may be seen in patients who were not significantly exposed.

Firm command and control needs to be established in the civilian sector. Civilian authority will likely request military support. In a mass casualty situation, those who request medical care for themselves or ask to be checked for radiation could be stopped

at roadblocks leading to medical facilities, with clearance required to proceed. Otherwise, hospital access and medical treatment for the seriously injured will be severely impeded. The noninjured requiring only radiation checks and those with minor injuries who have external contamination would be diverted to appropriate nonmedical decontamination facilities.<sup>3,42,54-57</sup> These facilities will be staffed with decontamination teams plus several medical personnel to evaluate and handle first aid, triage, and medical problems that might arise. Security personnel will be needed at decontamination sites, triage sites, evacuation sites, hospitals, alternative care sites, and along roads leading to them. A single, unified federal command must be maintained over numerous federal, state, and local entities. The public will respond to strong, effective leadership. People need to believe that leadership decisions are rational; communication to affected populations on the verge of panic must convey reassurance that the leadership is aware of and concerned about radiation effects, that radiation exposure levels will be monitored, and that injuries will be treated. Communication, at the appropriate time, should convey the overall expectation that, based on experience gained from accidents at Chernobyl and Goiânia, most people exposed to contamination will remain asymptomatic and will not suffer severe adverse health effects. The general public needs accurate and timely information and reassurance. In the months that follow the radiation event, treatment needs for those who suffer from posttraumatic stress disorder should be anticipated and planned for.

## SUMMARY

The most severe consequence of a nuclear detonation in an urban environment will be the overwhelming surge of casualties. For a 10-kiloton, ground-level nuclear detonation, nearly all deaths, serious injuries, and structural damage in the impact (blast) zone will occur less than 3 miles from the point of detonation. In addition to the predominant thermal and blast injuries, prompt radiation injuries within the blast zone will be caused by radiation instantaneously released at the moment of detonation. Fallout radiation injuries without significant blast or thermal trauma will also be seen in the downwind area outside the impact zone minutes to several hours later. Emergency responders will have radiation-dose measuring devices and operating guidelines to ensure their safety during rescue operations. The death toll, particularly during the first few days, will be high. It can be mitigated in part by effective triage, treatment, and evacuation strategies.

The triage of patients with conventional injuries, radiation-alone injuries, and combined injuries will

overwhelm the area's medical resources for days. Patients will first be triaged on the basis of their thermal burns and blast trauma, since these conventional injuries will account for nearly all lethal or immediately life-threatening injuries during the first 72 hours. Patients will receive appropriate treatment for conventional injuries. During that period, assessment of the probable degree of radiation injury will be made based on symptoms, laboratory data, and geographic location relative to both the detonation site and the dangerous fallout zone.

Triage of patients with thermal burns and blast injuries can be based on the military DIME system used in a mass casualty situation: delayed (second priority), immediate (highest priority), minimal (lower priority), and expectant (lowest priority). It is likely that there will be more immediate patients during the first few days than available resources. Among the immediate patients requiring surgery, surgeons will select those with life-threatening conditions who cannot tolerate

delay but have a good chance to be saved in a timely fashion without excessive resource use. During the first day, triage priority modifications may occur as information on total body radiation-dose estimates becomes available. Casualties with two or three types of significant injury have a much worse prognosis than those with one significant injury type. Those with more than one life-threatening injury will be classified as expectant rather than immediate.

Distance from ground zero and shielding were the principal factors influencing casualty rates at Hiroshima and Nagasaki. For any given distance from ground zero, the lethality was much higher for those who were outdoors. Unlike Hiroshima in 1945, there are tall buildings in US urban environments that will provide some shielding, so there will not be uniform zones around the detonation point. There may also be some relatively open sectors without tall buildings where the blast, thermal, and radiation effects will be channeled in full force along corridors. Given the important data from the zonal casualty-rate analysis at Hiroshima, current planning in the United States involves a modification of the three Hiroshima blast zones. There will be no precise circular boundaries, but visual evidence of the degree of structural damage will define the operational boundaries of the three blast zones.

Unlike the low-altitude detonations in Japan, a ground-level detonation will result in downwind radioactive fallout. The first public response should be to take shelter, since being outdoors in the dangerous fallout zone during the first day could result in lethal radiation injury. People who were outdoors prior to sheltering will probably be contaminated with radioactive fallout particles. Almost all fallout will be removed by showering and changing clothing. For those requiring medical treatment, decontamination of fallout material should be integrated with medical care in a way that does not interfere with urgent medical care. Immediate treatment for internal contamination, which is generally a very small fraction of the amount of external decontamination, is in general not necessary but will be reserved for special cases.

In the first few days following a nuclear detonation, a scarcity of resources will develop in local healthcare facilities. This will include personnel and medical supplies. In austere conditions, treatment protocols may need to be modified. The overwhelming number of casualties and the radiation exposure will create extreme stress in the affected population and result in the need to address management of posttraumatic stress in the weeks and months following a radiation event.

## REFERENCES

1. Mettler FA, Voelz GL. Major radiation exposure—what to expect and how to respond. *N Engl J Med*. 2002;346:1554–1561.
2. National Security Staff Interagency Policy Coordination Subcommittee for Preparedness and Response to Radiological and Nuclear Threats. *Planning Guidance for Response to a Nuclear Detonation*. 2nd ed. Washington, DC: Executive Office of the President; 2010. [http://www.hps.org/hsc/documents/Planning\\_Guidance\\_for\\_Response\\_to\\_a\\_Nuclear\\_Detonation-2nd\\_Edition\\_FINAL.pdf](http://www.hps.org/hsc/documents/Planning_Guidance_for_Response_to_a_Nuclear_Detonation-2nd_Edition_FINAL.pdf). Accessed October 12, 2010.
3. Flynn DF, Goans RE. Nuclear terrorism: triage and medical management of radiation and combined-injury casualties. *Surg Clin N Am*. 2006;86:601–636.
4. Glasstone S, Dolan PJ, eds. *The Effects of Nuclear Weapons*. 3rd ed. Washington, DC: US Government Printing Office; 1977.
5. Glasstone S, ed. *The Effects of Nuclear Weapons*. Revised ed. Washington, DC: US Government Printing Office; 1962.
6. Oughterson AW, Warren S. *Medical Effects of the Atomic Bomb in Japan*. In: *National Nuclear Energy Series, Manhattan Project Technical Section*. Vol 8. New York: NY; McGraw-Hill; 1956.
7. Stein M, Hirsberg A. Medical consequences of terrorism. *Surg Clin North Am*. 1999;79(6):1537–1552.
8. US Department of Defense. *Emergency War Surgery*, 3rd United States Revision. Burriss DG, Dougherty PJ, Elliot DC, et al, eds. Washington, DC: US Department of the Army, Borden Institute; 2004.
9. Military Medical Operations, Armed Forces Radiobiology Research Institute. *Medical Management of Radiological Casualties*. *Online Third Edition (June 2010)*. Bethesda, MD: AFRRRI; 2010. AFRRRI Serial Publication 10-1. <http://www.afrrri.usuhs.mil/outreach/pdf/3edmmrhandbook.pdf>. Accessed July 27, 2012.

10. NATO Handbook on Medical Aspects of NBC Defensive Operations. NATO AMED P-6(B). US Army Field Manual 8-9, US Navy Publication NAVMED P-5059, and US Air Force Pamphlet 161-3. Washington, DC: DA, DN, and USAF; 1995.
11. NATO Handbook on the Concept of Medical Support in NBC Environments. NATO AMED P-7(A). Brussels, Belgium: North Atlantic Treaty Organization; 1978.
12. US Department of Defense. *Treatment of Nuclear and Radiological Casualties*. Washington, DC: Departments of the Army, Navy, Air Force, and Commandant, Marine Corps; 2001. Army FM 4-02.283, Navy NTRP 4-02.21, Air Force AFMAN 44-161(1), Marine Corps MCRP 4-11.1B. <http://www.globalsecurity.org/wmd/library/policy/army/fm/4-02-283/fm4-02-283.pdf>. Accessed October 18, 2010.
13. Alt LA, Forcino CD, Walker RI. Nuclear events and their consequences. In: Walker RI, Cervený TJ, eds. *Medical Consequences of Nuclear Warfare*. In: Zajtcuk R, Jenkins DP, Bellamy RF, Ingram VM, eds. *Textbooks of Military Medicine*. Washington, DC: Office of the Surgeon General, Department of the Army, Borden Institute; 1989.
14. Ricks RC, Berger MC, Ohara FM. *The Medical Basis for Radiation Accident Preparedness: Clinical Care of Victims*. Boca Raton, FL: CRC Press; 2002.
15. Gusev IA, Guskova AK, and Mettler FA. *Medical Management of Radiation Accidents*. 2nd ed. Boca Raton, FL: CRC Press; 2001.
16. Gonzalez AJ, Lauriston S. Taylor lecture: radiation protection in the aftermath of a terrorist attack involving exposure to ionizing radiation. *Health Phys.* 2005;89(5):418–446.
17. Buddemeier B. Effects of a 10-kt IND detonation on human health and the area health care system—delayed effects of fallout. In: Benjamin GC, McGeary M, McCutchen SR, eds. *Assessing Medical Preparedness to Respond to a Terrorist Nuclear Event: Workshop Report*. Washington, DC: Institute of Medicine of the National Academies, The National Academies Press; 2009: 16–20.
18. Buddemeier B. Improving response to the aftermath of radiological and nuclear terrorism. Publication number LLNL-PRES-404937-rev1. Paper presented at: 2008 Bio-Dose Conference; September 8, 2008; Hanover, NH.
19. Dallas CE, Bell WC. Prediction modeling to determine the adequacy of medical response to urban nuclear attack. *Disaster Med Public Health Prep.* 2007;1(2):80–89.
20. Department of the Army; Department of the Navy; Department of the Air Force; Department of the Coast Guard. *Operations in Chemical, Biological, Radiological, and Nuclear (CBRN) Environments*. Washington, DC: Department of Defense; 2008. Joint Publication 3-11. [www.dtic.mil/doctrine/new\\_pubs/jp3\\_11.pdf](http://www.dtic.mil/doctrine/new_pubs/jp3_11.pdf). Accessed August 31, 2010.
21. US Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. *Guidance on Emergency Responder Personal Protective Equipment (PPE) for Response to CBRN Terrorism Incidents*. Atlanta, GA: CDC; 2008. <http://www.cdc.gov/niosh/docs/2008-132/pdfs/2008-132.pdf>. Accessed August 31, 2010.
22. National Council on Radiation Protection and Measurements. *Key Elements of Preparing Emergency Responders for Nuclear and Radiological Terrorism*. Bethesda, MD: NCRP; 2005. Commentary No. 19.
23. National Council on Radiation Protection and Measurements. *Management of Terrorist Events Involving Radioactive Material*. Bethesda, MD: NCRP; 2001. NCRP Report No. 138.
24. US Department of Homeland Security, Federal Emergency Management Agency. Planning guidance for protection and recovery following radiological dispersal device (RDD) and improvised nuclear device (IND) incidents. *Fed Regist.* 2008;73:45029. [http://www.fema.gov/good\\_guidance/download/10260](http://www.fema.gov/good_guidance/download/10260). Accessed October 18, 2010.
25. Conference of Radiation Control Program Directors, Inc. *Handbook for Responding to a Radiological Dispersal Device. First Responder's Guide—The First 12 Hours*. Frankfort, KY: CRCPD; 2006. [http://www.crcpd.org/RDD\\_handbook/RDD-handbook-forWeb.pdf](http://www.crcpd.org/RDD_handbook/RDD-handbook-forWeb.pdf). Accessed August 31, 2010.

26. Musolino SV, Harper FT. Emergency response guidance for the first 48 hours after an outdoor detonation of an explosive dispersal device. *Health Phys.* 2006;90:377–388.
27. Musolino SV, DeFranco J, Schloeck R. The ALARA principle in the context of a radiological or nuclear emergency. *Health Phys.* 2008;94:109–111.
28. National Research Council of the National Academies. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2.* Washington, DC: The National Academies Press; 2006.
29. Mettler FA, Upton AC. *Medical Effects of Ionizing Radiation.* Philadelphia, PA: Saunders; 2008.
30. Ricks RC. Data presented at: Annual Meeting of the American Society for Therapeutic Radiology and Oncology; October 19, 2003; Salt Lake City, Utah.
31. MacVittie TJ, Weiss JF, Browne D, eds. Advances in treatment of radiation injuries. In: *Advances in Bioscience.* Vol 94. New York, NY: Pergamon; 1996.
32. Berger ME, Leonard RB, Ricks RC, Wiley AL, Lowry PC, Flynn DF. *Hospital Triage in the First 24 Hours After a Nuclear or Radiological Disaster.* Oak Ridge, TN: Radiation Emergency Assistance Center / Training Site; 2004. <http://orise.orau.gov/files/reacts/triage.pdf>. Accessed August 31, 2010.
33. Waselenko JK, MacVittie TJ, Blakely WF, et al. Medical management of the acute radiation syndrome: recommendations of the Strategic National Stockpile Radiation Working Group. *Ann Intern Med.* 140(12):1037–1051;2004.
34. US Department of Homeland Security. *Working Group on Radiological Dispersal Devices (RDD) and Preparedness, Medical Preparedness and Response Subgroup Report.* Washington, DC: DHS; 2003. <http://www.va.gov/emshg>. Accessed September 30, 2010.
35. Goans RE, Waselenko JK. Medical management of radiological casualties. *Health Phys.* 2005;89(5):505–512.
36. Andrews GA. Medical management of accidental total-body irradiation. In: Hubner K, Fry S. *Medical Basis for Radiation Accident Preparedness.* New York, NY: Elsevier; 1980.
37. Goans RE, Holloway EC, Berger ME, Ricks RC. Early dose assessment following severe radiation accidents. *Health Phys.* 1997;72(4):513–518.
38. Goans RE, Holloway EC, Berger ME, Ricks RC. Early dose assessment in criticality accidents. *Health Phys.* 2001;81(4):446–449.
39. Koenig KL, Goans RE, Hatchett RJ, et al. Medical treatment of radiological casualties. *Ann Emerg Med.* 2005;45:643–652.
40. Blakely WF, Salter CA, Prasanna P. Early-response biological dosimetry—recommended countermeasure enhancements for mass-casualty radiological incidents and terrorism. *Health Phys.* 2005;89(5):494–504.
41. Weinstock DM, Case C Jr, Bader JL, et al. Radiologic and nuclear events: contingency planning for hematologists/oncologists. *Blood.* 2008;111(12):5440–5445.
42. Hrdina C, Coleman CN, Bogucki S, et al. The “RTR” medical response system for nuclear and radiological mass-casualty incidents: a functional TRIage-TReatment-TRansport medical response model. *Prehosp Disast Med.* 2009;24(3):167–178.
43. Dainiak N, Waselenko JK, Armitage JO, MacVittie TJ, Farese AM. The hematologist and radiation casualties. *Hematology Am Soc Hematol Educ Program.* 2003;473–496.
44. Bader JL, Nemhauser J, Chang F, et al. Radiation event medical management (REMM): website guidance for health care providers. *Prehosp Emerg Care.* 2008;12(1):1–11.
45. Berger ME, Christensen DM, Lowry PC, Jones OW, Wiley AL. Medical management of radiation injuries: current approaches. *Occup Med.* 2006;56:162–172.

46. Baranov A, Gale RP, Guskova A, et al. Bone marrow transplantation after the Chernobyl nuclear accident. *N Engl J Med*. 1989;321:205–212.
47. Hamza NS, Ghannoum MA, Lazarus HM. Choices aplenty: antifungal prophylaxis in hematopoietic stem cell transplant recipients. *Bone Marrow Transplant*. 2004;34:377–389.
48. Freifeld AG, Bow EJ, Sepkowitz KA, et al. Clinical practice guideline for the use of antimicrobial agents in neutropenic patients with cancer: 2010 update by the Infectious Diseases Society of America. *Clin Infect Dis*. 2011;52(4):e56–e93. <http://www.cid.oxfordjournals.org/content/52/4/e56.full>. Accessed January 27, 2012.
49. Hospenthal DR, Murray CK, Andersen RC, et al. Guidelines for the prevention of infections associated with combat-related injuries: 2011 update: endorsed by the Infectious Diseases Society of America and the Surgical Infection Society. *J Trauma*. 2011;71(2 Suppl 2):S210–S234.
50. Pizzo PA. Fever in immunocompromised patients. *N Engl J Med*. 1999;341(12):893–899.
51. Radiation Emergency Assistance Center/Training Site (REAC/TS). *Medical Aspects of Radiation Incidents*. Revised 4/19/2011. <http://www.orise.orau.gov/reacts>. Accessed January 27, 2012.
52. Miller K, Erdman M. Health physics considerations in medical radiation emergencies. *Health Phys*. 2004;87(suppl 2):S19–S24.
53. Smith JM, Ansari A, Harper FT. Hospital management of mass radiological casualties: reassessing exposures from contaminated victims of an exploded radiological dispersal device. *Health Phys*. 2005;89(5):513–520.
54. Miller K, Groff L, Erdman M, King S. Lessons learned in preparing to receive large numbers of contaminated individuals. *Health Phys*. 2005;89(suppl 2):S42–S47.
55. Institute of Medicine of the National Academies. *Assessing Medical Preparedness to Respond to a Terrorist Event—10-Kiloton Nuclear Detonation at Ground Level in an Urban Environment*. Washington, DC: The National Academies Press; 2009. Workshop report.
56. National Council on Radiation Protection and Measurements. *Management of Persons Contaminated with Radionuclides: Handbook*. Bethesda, MD: NCRP; 2009. No. 161.
57. US Department of Health and Human Services, Centers for Disease Control and Prevention. Population monitoring in radiation emergencies: a guide for state and local public health planners. Published August 2007. <http://emergency.cdc.gov/radiation/pdf/population-monitoring-guide.pdf>. Accessed September 21, 2010.

