Chapter 1

RADIOLOGICAL EVENTS AND THEIR CONSEQUENCES

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INTRODUCTION

Understanding the basic concepts of radiation physics, radiobiology, and the mechanisms by which radiation causes damage to the body is important to allow a coherent approach to radiation injury treatment. Wilhelm Conrad Roentgen reported the discovery of X-rays in 1895. Radiation damage to human cells was first recognized just 4 months later in 1896, when Dr John Daniel at Vanderbilt University found the irradiation of his colleague's skull resulted in hair loss, and English physician LG Stevens reported in the *British Medical Journal* that "those who work with X-rays suffer from changes to the skin which are similar in effect from the sun burn." Since then, many other biomedical effects of radiation have been described. Much of our basic understanding of mechanisms of injury has come from animal research and epidemiological studies of populations exposed during accidents and occupationally, and from the survivors of the atomic bombings of Hiroshima and Nagasaki, Japan. More recently, it has been possible to experiment on human cells maintained in tissue cultures.

The understanding of atomic physics increased rapidly in the early 20th century and culminated in the Manhattan Project, which harnessed the power of the atom in a bomb. Thus began the nuclear era in international relations and warfare, bringing new challenges to the military physician. When this volume was first published in 1989, the Cold War was in its final stages. Vast stockpiles of weapons were maintained and mutually targeted by the United States and the Soviet Union. Since the fall of the Soviet Union in December 1991, we have been forced to rethink what constitutes the most likely radiation threat to our country and our forces. Where the previous version of this chapter dealt strictly with nuclear warfare, a section has now been included that discusses radiological weapons; that is, the use of radioactive material to cause harm in a form other than a nuclear weapon.

In the 21st century, although more countries are developing or seeking to develop nuclear weapons (with a few notable exceptions), none is in a position to target them at the United States or our allies. We have, therefore shifted our focus away from all-out nuclear apocalypse and toward the possibility of one or more small tactical detonations carried out by terrorists or agents of a rogue nation, and to a threat not thought of in 1989: the radiation dispersion device (RDD), or "dirty bomb." The most likely situations requiring a military medical response are a terrorist act, an accident or incident involving a nuclear weapon, the use of a weapon against a deployed military force, or a developing-world conflict with collateral US casualties.

However, military medical preparedness must focus beyond nuclear weapon events. Today, nuclear material is used in medicine, industry, and power generation, bringing increased risk of occupational and accidental exposures. Radiation hazards during military operations in countries with limited oversight of radiological sources, or with sources abandoned by former occupiers, is now a cause of concern. Military physicians trained to respond to weapons-related injuries can bring expertise to these situations.

NUCLEAR AND PHYSICAL PROCESSES IN WEAPONS

Weapons-related injuries can be best understood after examining the destructive forces—blast, thermal, and radiation—that produce them. Generally, an explosion results from the very rapid release of a large amount of energy within a limited space. In comparison with a conventional explosive weapon, a nuclear weapon's effectiveness is due to its unequalled capacity to liberate many thousands (up to millions) of times more energy from a much smaller mass of material. This section presents a simple description of the physical processes taking place within the first few thousandths of a second after a nuclear weapon detonation.

Nuclear Energy

Energy may be broadly classified as potential or kinetic. Potential energy is energy of configuration, position, or the capacity to perform work. For example, the relatively unstable chemical bonds among the atoms that comprise trinitrotoluene (TNT) possess chemical potential energy. Potential energy can, under suitable conditions, be transformed into kinetic energy, which is energy of motion. When a conventional explosive such as TNT is detonated, the relatively unstable chemical bonds are converted into bonds that are more stable, producing kinetic energy in the form of blast and thermal energies. This process of transforming a chemical system's bonds from lesser to greater stability is exothermic (there is a net production of energy). Likewise, a nuclear detonation derives its energy from transformations of the powerful nuclear bonds that hold the neutrons and protons together within the nucleus. The conversion of relatively less stable nuclear bonds into bonds with greater stability leads not only to the liberation of vast quantities of kinetic energy in blast and thermal forms, but also to the generation of ionizing radiation.

To discover where these energies come from, consider the nucleus of the helium atom, which is composed of two neutrons and two protons bound tightly together by the strong (or specifically nuclear) force, also referred to as "nuclear binding energy." If we compare the bound neutrons and protons to those in the unbound state, we find that the total mass of the separate neutrons and protons is greater than their mass when they bind together to form the helium nucleus. The mass that has been lost in the process of forming the nuclear bonds is called the mass defect. Einstein's famous equation, $E = mc^2$ (energy equals mass multiplied by the speed of light squared), quantifies the conversion of this missing mass into the binding energy that holds together the helium nucleus. This is the potential energy stored in the bonds of the strong force. A small amount of mass, when multiplied by the speed of light squared (an extremely large number), has a large amount of binding energy. If the total binding energy for each element is calculated and divided by its total number of nucleons (that is, neutrons plus protons; for helium, two neutrons plus two protons equals four nucleons), a measure is obtained of how tightly the average nucleon is bound for that particular atom. Elements from hydrogen to sodium generally exhibit increasing binding energy per nucleon as atomic mass increases. This increase is generated by increasing forces per nucleon in the nucleus, as each additional nucleon is attracted by all of the other nucleons, and thus more tightly bound to the whole. The next region is the saturation region, which is quite stable and includes elements through xenon. In this region the nucleus is large enough that the nuclear forces do not extend all the way across its width. Above xenon, the binding energy per nucleon begins to decrease as the atomic number increases. At this point, electromagnetic repulsive forces start to gain and dominate against the strong nuclear force. A plot of this "average binding energy per nucleon" for each element gives the curve in Figure 1-1.

It is significant that this curve has a broad maximum. At the peak of the binding energy curve is iron-56, with the highest total binding energy (although the three highest binding energies per nucleon, in order

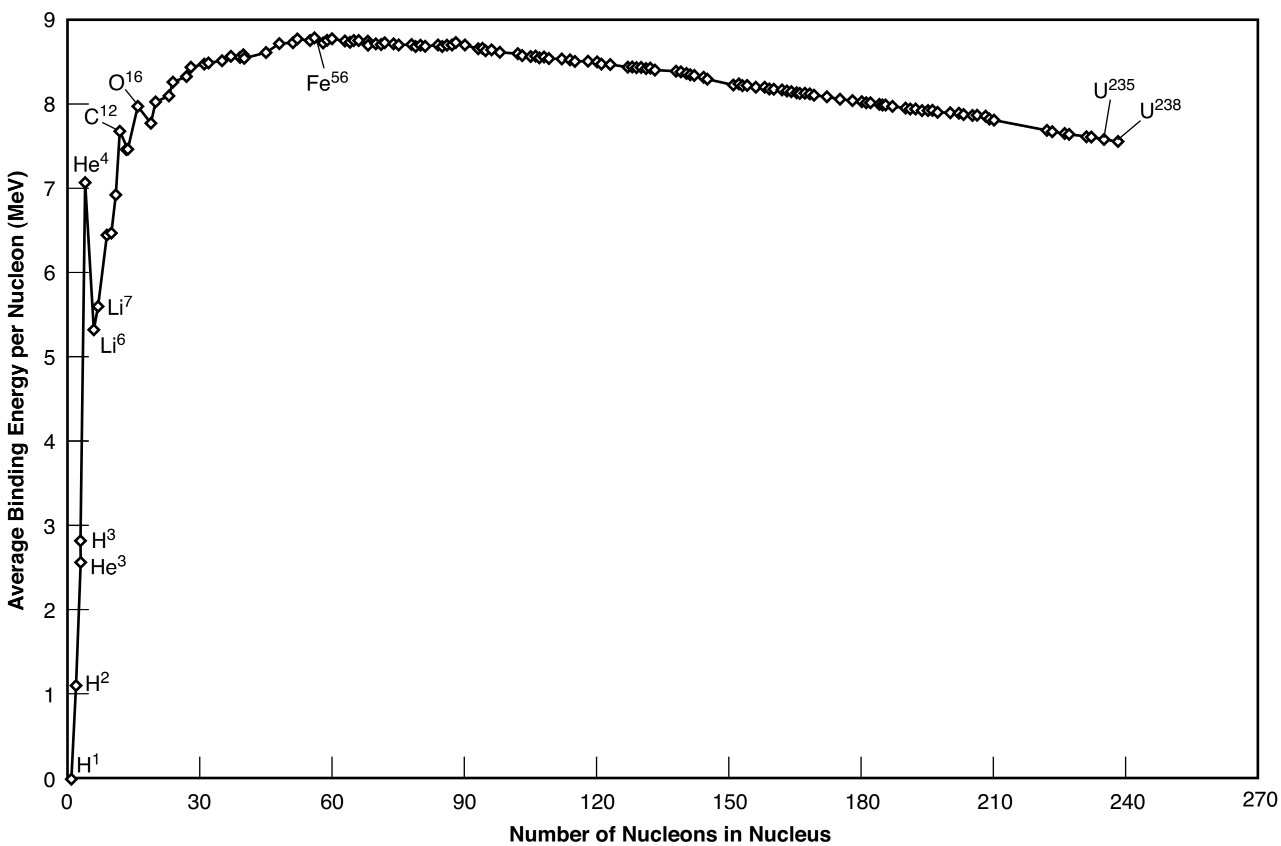

Figure 1-1. Curve of binding energy per nucleon.

highest to lowest, is as follows: nickel-62, iron-58, iron-56). These three isotopes are produced in large amounts as end products in the burn-up of stars. This is generally why iron and nickel are found in large quantities in planetary cores. Since there is a range of elements for which the neutrons and protons are most tightly bound and, thus, have the most stable nuclear bonds, nuclei having less stable nuclear bonds can be converted into ones with more stable bonds, allowing the system to pass from a state of lesser to greater stability and releasing energy. This serves as the energy source of nuclear weapons. The process can occur in two ways: via fission or fusion. Fission is the process of breaking less stable larger elements (such as uranium and plutonium) into two of the more stable midrange elements. Fusion is the process of combining lighter nuclei (such as those of deuterium and tritium, which are isotopes of hydrogen) into heavier elements lying further up the curve of binding energy per nucleon.

Energy Release in Nuclear Weapons

A fission nuclear device is practical for only three elements: uranium-233, uranium-235, and plutonium-239. In order to construct an efficient weapon, instability is induced in one of these nuclei by striking it with a neutron. The unstable nuclear bonds are broken, the nucleus splits apart, and relatively more stable nuclear bonds are reformed by each of the two midrange fission fragments. This is accompanied by the release of a large quantity of energy and the prompt emission of gamma rays and neutrons (initial nuclear radiation). It is important to note that approximately 82% of the fission energy is released as kinetic energy of the two large fission fragments. These fragments, which are massive, highly charged particles, interact readily with matter. They transfer their energy quickly to the surrounding weapon materials, which rapidly become heated. The fission fragments consist of over 300 different isotopes of 38 separate chemical elements. Most of the fragments are highly unstable radioactively and will later contribute to the radiologically and chemically complex fallout field.

One fission event alone does not make a weapon; a weapon requires a self- perpetuating, exponentially escalating chain reaction of fissions. This is achieved by the suitable physical arrangement of certain nuclear materials. Also, since the weapon must not reach the proper, or "critical," configuration until the desired time of detonation, some way must be found to make the transition on demand from a safe, or subcritical, condition to the critical state. In a functioning fission device, this is done by altering the mass, shape, or density of the nuclear materials.

The two basic classes of fission weapons are the gun-assembled device and the implosion device. The gun-assembled weapon is a mechanically simple design that uses a "gun tube" arrangement to blow together two small masses of uranium-235 to form a supercritical mass. The 15-kt yield weapon used at Hiroshima was a gun-assembled device (1 kt equals the energy released by detonation of 1,000 short tons of TNT, and 1 megaton equals 1,000,000 short tons of TNT). The implosion weapon uses an extremely complex system of precisely formed, conventional, chemical-explosive lenses to crush a mass of plutonium-239 to supercritical density. The first tested nuclear weapon (the Trinity device) and the 21-kt-yield weapon used at Nagasaki were implosion devices. From the viewpoint of a weapon's accessibility, it is fortunate that the much more easily constructed gun-assembled weapon cannot effectively use the more readily producible plutonium-239, which can be obtained by using naturally occurring uranium in a breeder reactor. Instead, it must be fueled with uranium-235, which is more difficult to obtain.

The limit on a fission weapon's yield, from an engineering viewpoint, is several hundred kilotons. Therefore, the multimegaton weapons in nuclear inventories are fusion weapons (often referred to as "hydrogen" or "thermonuclear") that derive much of their power from the combination of light isotopes of hydrogen (deuterium and tritium) and heavier nuclei lying farther up the curve of binding energy per nucleon. Because of the powerful forces of electrostatic repulsion, initiating fusion of deuterium and tritium requires extremely high temperatures, about 50,000,000°C. The only practical way to achieve those temperatures in a weapon on earth is to detonate a fission device inside the fusion materials. The deuterium and tritium then fuse and release energy, partly in the form of highly energetic and penetrating fusion neutrons, which have energies about ten times the typical energies of fission-generated neutrons. The fusion weapon then uses these high-energy fusion neutrons to cause secondary fissions. Thus, a fusion weapon actually generates power from both the fission and fusion processes, usually in roughly equal proportions. Only five or six countries have conducted thermonuclear tests (India claims to have tested a thermonuclear device, but many experts are skeptical).[1]

There is one other type of nuclear weapon that bears mention. While technically a small modified thermonuclear device, an enhanced radiation weapon (ERW; neutron bomb) produces a very different damage profile. The goal of this type of weapon is to reduce blast damage and fallout while increasing the radius of the lethal radiation dose. The neutron production of an ERW is around one order of magnitude greater than that of a standard fission weapon of the same yield. The neutrons born from fusion are around 14 mega electron volts (MEV), whereas fission neutrons are only about 2 MEV. The higher yield and energy of neutrons from the weapon increases the radius for a given radiation dose by about 50% and also increases the radiation from activation products. However, since the half-life of the activation products is generally shorter than those of fission fragments, the duration of radiations from induced radiation and fallout materials is lower. Since the radiation dose is distributed over a greater range than a similar or slightly larger-yield fission warhead with less blast and thermal damage, these weapons are considered "surgical strike" weapons. A 1-kt ERW will produce approximately two times the casualties, with one fifth the area of blast damage, compared to a 10-kt fission weapon. Published reports state that five countries, including the United States, have produced these weapons.[2]

Production of Blast and Thermal Effects

The blast and thermal effects of detonation produce by far the greatest number of immediate human casualties in nuclear warfare. One of the important differences between a nuclear and a conventional explosion is the large proportion of thermal energy released by a nuclear weapon. The temperatures reached in a nuclear explosion reach tens of millions of degrees, as opposed to a few thousands in a conventional explosive. The nuclear reactions within the weapon have died out after the first one-millionth of a second, and the fission and fusion events have produced a vast quantity of energy that has been rapidly and locally transferred to the bomb materials in the form of heat. The weapon's materials (bomb casing, electronics, chemical explosive residues, and a large percentage of the original nuclear fuels), which, even in a relatively efficient (about 40% maximum efficiency) device remain unreacted, now exist as a highly energetic plasma of positive ions and free electrons at high temperature and high pressure. Through a process of electron-ion interaction known as "bremsstrahlung," the plasma becomes an intense source of X-rays. These X-rays leave the vicinity of the bomb materials at the speed of light, heat the first several meters of air surrounding the weapon, and generate a fireball with an initial temperature up to several tens of millions of degrees. The intensely hot fireball reradiates thermal energy of a longer wavelength at infrared, visible, and ultraviolet frequencies. The first pulse delivers approximately 1% of the thermal radiation due to its very short duration (about a tenth of a second). Most of this energy is in the ultraviolet region and is readily attenuated in air. The second pulse may last for several seconds and is of a lower temperature than the first pulse. This means that most of the rays reaching the earth are in the visible and infrared regions. This radiation is the main cause of skin burns and eye injuries suffered by those exposed to a nuclear detonation.

At about the same time, the weapon's materials have started to expand supersonically outward, dramatically compressing and heating the surrounding air. This high-pressure wave moves outward from the fireball and is the cause of much destruction in the form of the blast wave and further thermal radiations. The high-temperature blast wave travels out from the point

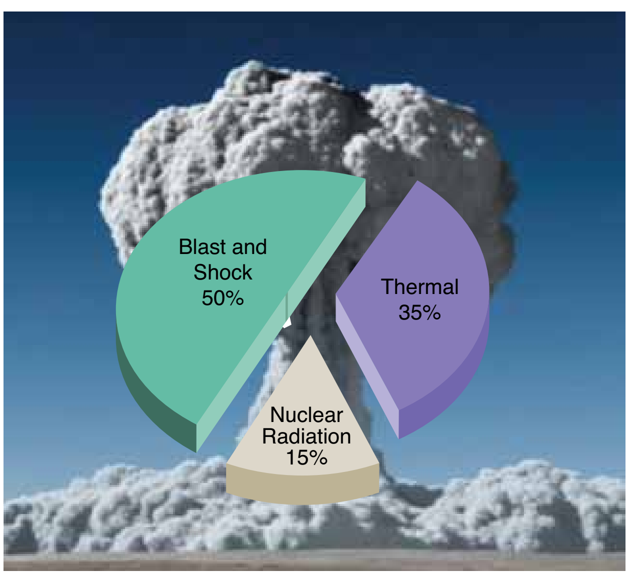

Figure 1-2. Energy distribution of a nuclear weapon.

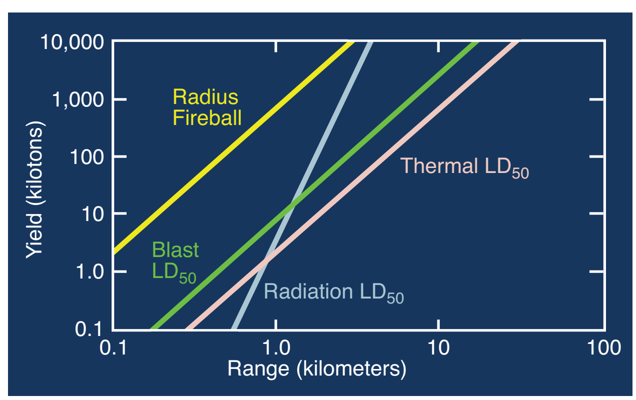

Figure 1-3. Range of nuclear weapon effects.

of detonation, gradually decreasing in velocity and overpressure based on the yield of the weapon. Added to these blast and thermal effects is the initial nuclear radiation (primarily neutrons and gamma rays) that is produced promptly by the fission and fusion processes, and the residual radiation (primarily gamma rays and high-energy electrons), which are produced later by decay of the radioactive fission fragments composing the fallout field (Figure 1-2).

The range of the blast, thermal, and radiation effects produced by the detonation of a nuclear weapon depends on many factors, perhaps the most significant of which, for the battlefield soldier, is total weapon yield (Figure 1-3). Initial radiation is the dominant threat for only very small tactical devices, and thermal effects are dominant for large-yield strategic weapons.

BLAST, THERMAL, AND RADIATION EFFECTS

The destructive blast, thermal, and radiation effects of a fission or fusion weapon all stem from the device's capacity to transform the very strong nuclear bonds of uranium, plutonium, deuterium, and tritium from a relatively unstable state to a more stable one. The quantitative difference between the effects of a nuclear weapon and the effects of a conventional explosive is the result of the dramatically greater strength of the nuclear bonds compared to the chemical bonds of a conventional explosive. A qualitative difference arises from the production of initial nuclear radiations from the fission and fusion processes themselves and from delayed radioactivity resulting from decay of the unstable fission fragment by-products.

Blast Effects

During the detonation of a standard fission or fusion nuclear device, the sudden liberation of a tremendous amount of potential energy causes a huge increase in temperature and pressure, converting everything into hot compressed gases and plasma. This rapidly expanding plasma gives rise to a shock or blast wave that is responsible for dissipating about 50% of the total energy of the weapon into the surrounding air, water, or earth. This represents a tremendous amount of energy, even in small, tactical-sized weapons of a few kilotons. Most of the material damage to structures, vehicles, and other objects caused by a surface or low air burst is due to this blast wave. As the blast wave travels outward from the site of the explosion, it is composed of static and dynamic components that are capable of producing medical injuries and structural damage. The static component of the shock or blast wave is a wall of compressed air that causes an overpressure (an excess over atmospheric pressure) that exerts a crushing effect on objects in its path. The dynamic component is the movement of air caused by and proportional to the difference between the static overpressure and the ambient pressure. In this discussion, the static and dynamic components will be called the blast wave and blast wind, respectively.

In discussing the structural damage to buildings after a nuclear detonation, it is difficult to separate the effects of the static component from those of the dynamic component. For example, the 5-psi blast wave and 160-mph blast winds associated with the blast wave's passage would destroy a two-story brick house. However, the medical problems resulting from exposure to the shock wave can be divided into those that result from the static component and those that result from the dynamic component. Injuries resulting from the blast waves will be caused by exposure to high pressures with very short rise times, and will consist primarily of internal injuries. For example, the threshold level for rupture of the eardrum is about 5 psi. Although this injury is very painful, it would not limit the accomplishment of a critical military mission. The 160-mph winds that accompany the passage of a 5-psi blast wave would be sufficiently strong to cause displacement and possible injuries. At the other end of the spectrum, a pressure level of 15 psi will produce serious intrathoracic injuries, including alveolar and pulmonary vascular rupture, interstitial hemorrhage, edema, and air emboli. If the air emboli make their way into the arterial circulation, cerebral and myocardial infarctions may ensue. The initial outward signs of such pulmonary damage are frothy bleeding through the nostrils, dyspnea, and coughing. Victims may be in shock and lack visible wounds. In addition, serious abdominal injuries, including hepatic and splenic rupture, may result from a rapid and violent compression of the abdomen. The LD_{50} (lethal dose, or fatal injury, for 50% of cases) for static effects occurs at around 50 psi of overpressure.

The blast winds that accompany the blast wave can also produce injuries. Debris carried by the wind may cause missile injuries ranging from lacerations and contusions to fractures and blunt trauma, depending on the projectile's size, shape, and mass. Wind velocity of 100 mph will displace a person, resulting in lacerations, contusions, and fractures from tumbling across the terrain or from being thrown against stationary structures. Winds capable of causing displacement injuries or missile injuries would be produced by a blast wave with an overpressure of less than 5 psi. At this pressure level, the blast winds are more significant in producing injury than is the static component of the blast wave. At high pressure levels, both the static and dynamic components are capable of producing serious injuries.

The LD_{50} from impact occurs when a body strikes a solid surface at about 37 to 38 mph. For a small tactical weapon or terrorist device with a yield of 1 kt, the range for this level of overpressure would extend to slightly over a tenth of a mile. For larger tactical or strategic weapons with yields of 100 and 1,000 kt, the range for the LD_{50} would expand to just under 1 mile and just under 2 ¼ miles, respectively.

Protection from the effects of the blast wave is difficult to achieve because the wave is an engulfing phenomenon. The best protection can be found in a blast-resistant shelter. However, protection from the effects of the blast winds can be achieved in any location offering shielding from the wind. If adequate shelter is not found, the best defense against blast effects is to lie face down on the ground, covering the head, and with head pointed toward ground zero. This reduces the body's surface area that is exposed to wind-borne debris and offers less resistance to the force of the blast wind.

Thermal Effects

One important difference between conventional high-explosive and nuclear detonations is the large proportion of energy released as thermal (heat) radiation during a nuclear explosion. Following the detonation of a standard fission or fusion device, approximately 35% of the weapon's energy is dissipated as thermal energy. The general types of injuries resulting from this energy are burns, including flash burns and flame burns, and certain eye injuries, including flash blindness and retinal burns.

The thermal output after a nuclear detonation occurs in two distinct pulses as a result of the interaction of the shock wave with the leading edge of the fireball. The first pulse contains only about 1% of the total thermal energy output and is composed primarily of energy in the ultraviolet range. Because the first pulse is of very short duration and the ultraviolet energy is rapidly absorbed by the surrounding atmosphere, it does not contribute significantly to producing casualties. The second pulse, which may last for several seconds depending on the weapon yield and is of lower temperature than the first, is composed primarily of energy in the infrared and visible portions of the electromagnetic spectrum. This pulse contains about 99% of the thermal energy liberated by the nuclear detonation and is responsible for subsequent burns and vision problems.

Burn injury. The two types of burn injury—flash burn and flame burn—are caused by different events and have different prognoses. Flash burn results from the skin's exposure to the second pulse of thermal energy. This absorption of a large quantity of thermal energy in a very brief time often leaves the affected area of the skin with a charred appearance. However, since the heat pulse occurs rapidly and the thermal conductivity of the skin is low, the burn is often superficial, killing only the outer dermal layers and leaving the germinal layer essentially undamaged. Often clothing, especially white or light colors, provides enough shielding to prevent flash burns on covered areas of the body. After the bombings of Hiroshima and Nagasaki, the majority of burns were first and second degree and healed fairly quickly. In contrast, flame burn results from contact with a conventional fire, such as clothing or the remains of a building ignited by the fireball's thermal pulse. In most cases, flame burns heal abnormally because the skin's germinal layer has been damaged. Of the Hiroshima casualties who survived to the 20-day point post-irradiation, fewer than 5% had flame burns; the results for the survivors of the Nagasaki bombing are similar. A much larger percentage of the 20-day survivors in both cities had flash burns.[3]

Fires due to nuclear weapons are caused either directly by the heat of the blast or indirectly due to the blast damage. Blast damage to stoves, water heaters, furnaces, electrical circuits, and gas lines would ignite fires where kindling fuel is plentiful. In Hiroshima, individual fires turned into a firestorm that burned a 4.4-square-mile area of the city and caused further burn casualties.

Because the heat pulse travels at the speed of light, protection from burns is not possible unless warning is given in time to find cover. The electromagnetic energy of the thermal pulse travels in a straight line, so any barrier placed in its path will offer some protection. As shown in Hiroshima and Nagasaki, even clothing will provide some protection from the deposition of thermal energy onto the skin. Because light colors tend to reflect rather than absorb thermal energy, light-colored clothing will offer more protection than dark.

For weapons of very low yield, the range for burn injury LD_{50} is about equal to the range for the LD_{50} from blast and radiation (see Figure 1-3). As the weapon yield increases, the range for burn injury increases much more rapidly than does the range for blast or radiation injury. This means that burns will always result after the detonation of a nuclear device, and, for weapons with a yield above 10 kt, burns will be the predominant injury. Because of the large number of burn casualties and the time and labor-intensive treatment that they require, burn injury is the most difficult problem to be faced by the military medical community in a nuclear conflict. Additionally, mortality of thermal burns markedly increases with exposure to radiation. Burns with a 50% normal mortality may increase to 90% or greater mortality after just 1.5 Gy of radiation exposure.

Eye injury. Thermal energy may also cause eye injury. Flash blindness is a temporary condition that results from a depletion of photopigment from the retinal receptors. This happens when a person indirectly (peripherally) observes the brilliant flash of intense light energy from a fireball. The duration of flash blindness can be as short as several seconds during the day, followed by a darkened afterimage for several minutes. At night, flash blindness can last three times longer, with a loss of dark adaptation for up to 30 minutes. This could seriously compromise military operations.

Another type of eye injury is retinal burn, which results from looking directly at the fireball and focusing its image on the retina. This intense light energy is strong enough to kill the retinal receptors and create a permanent blind spot. A retinal burn is no more or less detrimental to mission accomplishment than flash blindness, and neither of these injuries should create a burden on medical facilities.

To protect against injury, individuals can close and shield their eyes after being warned of a detonation. Using lead-lanthanum-zirconium-titanium goggles may provide further protection.

Effects of Initial and Residual Radiations

A detonating fission or fusion weapon produces a variety of nuclear radiations. Initial radiation occurs at the time of the nuclear reactions and residual radiation occurs long after the immediate blast and thermal effects have ended. The nuclear radiations include neutrons, gamma rays, alpha particles, and beta particles, which are biologically damaging and may significantly affect human health and performance. Alpha and beta particles have relatively short ranges and cannot reach the surface of the earth after an airburst. Even when the fireball touches the ground, they are not of great importance. Therefore, initial radiation is considered to consist of neutrons and gamma rays produced within the first minute after detonation. Both gammas and neutrons can travel long distances in air and are highly injurious to the cells in the human body. It is this combination of range and injury that makes these nuclear radiations a significant aspect of a nuclear weapons detonation.

In addition to the gamma rays produced during the actual fission/fusion process, other sources of gamma rays contribute to initial radiation. The mechanisms for producing these are inelastic scatter reactions with elements in the atmosphere surrounding the weapon and other weapons materials, and isomeric-decay and neutron-capture gamma rays. Inelastic scattering gammas are produced when neutrons with a high kinetic energy ("fast" neutrons) collide with certain other atomic nuclei and transfer a portion of their energy, leaving the nuclei in an excited state. The nucleus will then emit its excess energy as gamma rays in order to stabilize itself back to its normal ground energy state. Capture gammas are produced when neutrons are absorbed or captured by nitrogen in the atmosphere and by the nuclei of various weapons materials. These capture reactions are accompanied by the release of secondary gammas. Residual radiation primarily includes gamma rays, beta particles, and alpha particles generated beyond the first minute after detonation. Most of these radiations are produced by the decay of the fission fragments generated by weapon fission processes, but some are activated bomb components and surface materials that are made radioactive by exposure to the intense neutron flux generated by fission and fusion events.

The broad classes of initial radiation and residual radiation come from an analysis of a 20-kt ground burst. The hot fireball produced by this weapon, laden with highly radioactive fission fragments, rises upward through the atmosphere so quickly that, after about 60 seconds, it reaches a height from which the initial radiation can no longer strike the ground. A person on the ground would therefore be safe from the initial radiation after 1 minute. As the yield of the weapon is increased, the fireball rises more quickly, but the 60-second point remains approximately the same. The main hazard from initial radiation is acute, external, whole-body irradiation by neutrons and gamma rays. It is only for very small tactical weapons that the initial radiation is potentially fatal at distances where the blast and thermal effects are survivable (see Figure 1-3). Therefore, significant initial radiation hazards are restricted to the first minute after detonation and to several hundred meters surrounding a small-yield tactical weapon. Conversely, residual, or fallout radiation, covers a wide geographic area and remains a significant biological hazard long after detonation.

Fallout

Residual nuclear radiation from a detonation is defined as radiation that is emitted more than 1 minute after the detonation of the weapon. At this 1-minute point, the fireball for a 20-kiloton-yield weapon will have cooled to the point that it no longer glows and will have risen up to 7 miles into the atmosphere. The convective forces caused by the fireball result in an enormous amount of air and debris being sucked upward. In an airburst, the residual radiation results mostly from the fission products and, to a lesser extent, unused fuel that was not fissioned due to the disassembly (blowing apart) of the core during the detonation. Additionally, there will be activation products formed by the interaction of neutrons with bomb materials such as the case, the shielding, and the neutron reflector. If the fireball touches or is close enough to the earth that materials on the ground are sucked into it, the materials are vaporized and mix with the other materials in the fireball. The debris from a predominately fusion weapon (the ERW mentioned earlier) will not contain the amounts of fission products that a comparable-yield fission weapon will. If the fission yield of the ERW is sufficiently low, most of the residual radiation will be due to neutron interactions in the weapon and the surrounding environment.

The primary hazard of residual radiation is from the creation of fallout particles. Sources of fallout include all those listed in the previous paragraph: fission fragments, unused fuel (uranium, plutonium, and tritium), and activation products. As may be suspected from the previous discussion, an airburst of sufficient height to prevent the introduction of ground-based materials into the fireball will result in far less fallout than a ground or near-ground burst. In Hiroshima and Nagasaki, the bombs were detonated at a height to maximize blast damage and minimize fallout to allow earlier entry into the cities for inspection of the damage. Fallout is categorized as early fallout or late fallout.

Early fallout is radioactive material deposited within the first day after detonation. This fallout is the most significant for the military because it is highly radioactive, geographically concentrated, and local. It tends to consist of larger particles (approximately 0.01–1.0 cm in diameter) usually deposited within a few hundred miles of ground zero. The two largest sources of this early fallout are fission products and activation products formed by neutron interactions. Because the material has had little time to decay, it is initially very radioactive when it falls; however, it tends to decay quite rapidly. An approximation of the decrease in dose rate can be made by using what is referred to as the "seven-ten rule," where for every sevenfold increase in time, the dose rate will decrease by a factor of ten. Using this rule, if you have a dose rate at 1 hour post-detonation of 30 Gy/h, for example, in 7 hours the dose rate will be 3 Gy/h, and in 49 hours (7 × 7) it will be 0.3 Gy/h. This approximation is accurate within about 25% through about 2 weeks post-detonation. There are around 300 isotopes of 36 elements formed from the fission process in a weapon. Most of these are radioactive, decay by beta radiation, and are often accompanied by gamma emissions (Figure 1-4).[4] The biological hazards from early fallout are primarily external, whole-body, gamma-ray irradiation; secondarily external beta-particle irradiation from beta emitters deposited on the skin; and lastly internal irradiation from isotopes that are ingested, injected, or inhaled.

Delayed fallout generally consists of the smaller particles deposited after the first 24 hours. This material is less significant as an immediate hazard to the military because it has a longer time to decay and it is deposited over a wider area. Delayed fallout is almost exclusively an internal hazard due to ingestion of iodine, strontium, and cesium in food and milk. Under certain circumstances, delayed fallout may be distributed worldwide, presenting a widespread long-term health hazard through internalized exposure.

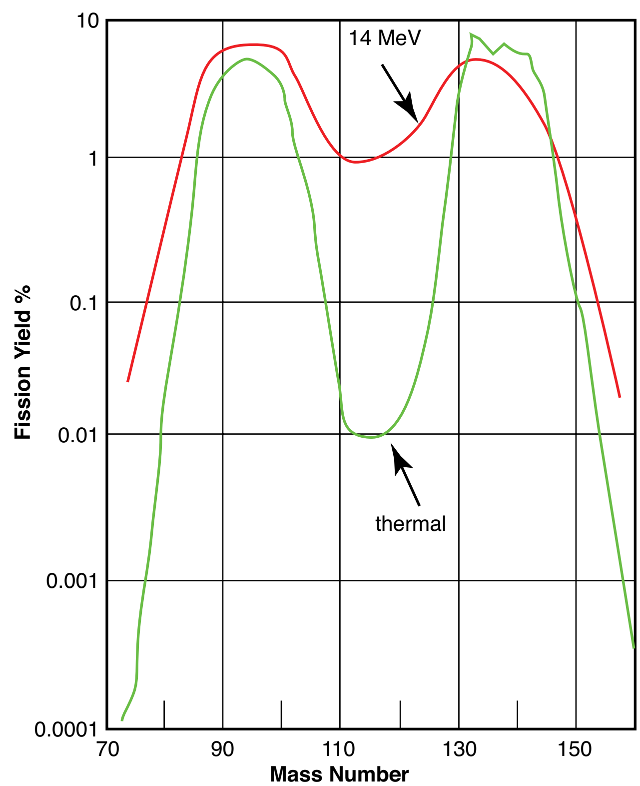

Figure 1-4. Probability curve for the production of radioisotopes due to U-235 fission.

The ultimate deposition of nuclear fallout on the ground is influenced by the physical interactions of the rising fireball with the atmosphere. For a ground, water, or near-surface burst, the interaction of the fireball with ground debris greatly affects the fallout deposition. As the hot gas bubble quickly rises through the atmosphere, it creates and is followed by a strong vacuum directly from below. This generates winds that rush radially inward toward ground zero and upward toward the ascending fireball. These winds can pick up large quantities of dirt and debris from the ground and inject them into the fireball (a process called stem formation). This material, along with any other ground material directly vaporized by a surface burst, then provides condensation centers within the fireball. The gaseous fission fragments condense more quickly on these relatively larger debris particles than they would have otherwise, greatly increasing early local fallout. This fallout is deposited quickly in a concentrated area relatively near ground zero. The activation of surface materials through irradiation of ground elements by the direct neutron flux of a near-surface burst may also increase the local fallout hazard to troops traveling through that area soon after detonation.

In the case of a pure airburst detonation with no secondary ground materials injected into the fireball, the cloud rises and cools and the fission fragment vapors begin to cool and condense at certain temperatures (characteristic of their particular elements). Therefore, because the time for airburst fission-product condensation is delayed and because fission products do not condense on large particles of ground debris, the proportion of fallout activity expressed as early local fallout is greatly reduced.

Characteristics of Fallout and the Prediction of Hazards

The factors that determine the extent of anticipated fallout hazard are as follows:

- The total fission yield (fission fragments are the largest contributor to fallout activity)
- The ratio of energy produced by the fission process versus the fusion process (the higher the fission fraction, the more fission products and consequently the greater the radiological hazard)
- The specific design of the weapon (for example, an ERW will produce proportionately less fallout than an equivalent-yield standard nuclear weapon)
- The altitude of burst (a ground, water, or near-surface detonation produces the greatest early local hazard)
- The composition of surface elements near ground zero in a near-surface burst (accounting for the neutron flux-induced activation potential of surface materials)
- The meteorological conditions (winds and precipitation introduce by far the greatest uncertainties in predicting where and when the fallout will be deposited)
- The time after detonation (the more time allowed for radiological decay, the less the activity of the fallout field)

In terms of absolute quantity of energy from fallout, approximately 10% of the quoted energy yield of a typical fission weapon will be residual radiation; for fusion weapons, it will be approximately 5%.

RADIOLOGICAL WEAPONS

The use of a radiological weapon as a weapon of terrorism is a distinct possibility. This would likely take the form of either a radiation exposure device or an RDD. There are at least three potential difficulties with using radiation sources as weapons. First, a large enough dose must be absorbed by an individual to cause radiation sickness. This would take a relatively large and energetic source and most likely a fairly long contact time. A source placed in a container that people merely walk by is not likely to produce a sufficient dose to be medically detectable, let alone to cause radiation-induced symptoms. Secondly, because the potential dose received by the person who puts the device together or transports it may be extremely high, the viable options of sources that could be used are limited. Thirdly, dispersed radioactive material from even a very large dirty bomb is unlikely to be concentrated enough (other than right at the scene of the explosion) to cause a high enough dose rate to cause radiation sickness.

Radiological Exposure Device

A radiological exposure device is simply a radioactive source placed in an area where it would irradiate unsuspecting persons. It would be difficult to handle a large enough source to cause injury unless the source was placed where people stay in the same location for some length of time. This also tends to limit the number of potential victims and therefore is not a likely choice for those trying to irradiate vast numbers. This type of source is only an external irradiation hazard.

Radiation Dispersal Device

The classic definition of an RDD is a radiation source wrapped with explosives and detonated to cause a spread of radioactive material. However, this is not the only way to disperse radioactive material. Any device that aerosolizes a liquid or powdered radioactive source may also be used to spread contamination. This can be something as simple as a spray bottle used to spray the material on surfaces where it will be touched or otherwise picked up and spread by unsuspecting individuals, or as commonplace as a truck with a sprayer or a crop-dusting aircraft with hundreds of pounds of material.

Radionuclide	Half-life	Typical Activity	Use
Cobalt-60	5 years	15,000 Ci	Cancer therapy
Cesium-137	30 years	1.5×10^6 Ci 10 mCi	Food irradiation Medical source
Iridium-192	74 days	150 Ci 1 mCi	Industrial radiography Medical source
Plutonium-238	88 years	Varies	Satellite power source
Strontium-90	29 years	40,000 Ci	Radio-thermal generator
Iodine-131	8 days	0.15 Ci	Cancer therapy
Americium-241	432 years	5×10^{-6} Ci	Smoke detectors

Figure 1-5. Possible sources of radiological material for terrorist use.

Potential Radioactive Sources

Legal acquisition of most highly radioactive sources is regulated by federal and state laws requiring licensing of the user and some level of oversight, which depends on the source type and strength. Several common radionuclides are possible sources for use as RDDs (Figure 1-5). Cesium-137, usually in the form of cesium chloride, is commonly used in industry and medicine. It is often sealed in a steel pellet or button and found in teletherapy units, brachytherapy sources, and industrial sources, and sources of over 1,000,000 curies are not uncommon. Cesium emits high-energy gamma radiation and has a half-life of 30 years. Cesium chloride is a salt that can be easily dispersed or dissolved in liquid. In the United States, the Nuclear Regulatory Commission has taken steps to minimize the amount and increase the security of cesium chloride held by licensees because of the potential for it to be used in a terrorist weapon.

Cobalt-60 is used in medical teletherapy units and industrial irradiators. It is commonly found as metallic rods, ribbons, or pellets and emits two high-energy gamma rays. It has a half-life of 5.27 years and is found in sources ranging in strength up to several thousands of curies. Iridium-192 is an industrial radiography and brachytherapy source that is usually in metallic form. It emits high-energy beta particles and several mid- to high-energy gammas. Due to its relatively short half-life (74 days) and the fact that iridium sources are usually fairly small (150 curies or less), it is more likely to be used for a radiological exposure device than a dispersal type of device.

Strontium-90 is a pure beta emitter that releases a very high-energy beta particle. It is used in radiothermal generators, particularly in eastern Europe and Russia. These devices are used to provide power, often in remote areas without electric lines. Strontium is in the form of a ceramic matrix in quantities of tens of thousands of curies. These devices have been responsible for several deaths when unknowing individuals find them and use them to keep warm.

MEDICAL CONSEQUENCES OF NUCLEAR WEAPONS

When preparing for the consequences of nuclear weapons during the Cold War, planners worried about "hardening" (protecting from the detrimental effects of radiation) the electronics and mechanical systems of equipment needed to pursue a conflict. During this same time, the Armed Forces Radiobiology Research Institute and others spent an enormous amount of time, energy, and resources on determining how "hard" the operators of these systems were and how to protect them and allow them to not only survive, but also to function effectively when subjected to doses of radiation that would ordinarily be incapacitating. This also provided data useful to planners and commanders who need to know what the performance decrement to their personnel will be at various doses. The $LD_{50/60}$ (lethal dose to 50% of the population within 60 days) for ionizing radiation at greater than 0.10 Gy/h is around 4.10 Gy with minimal treatment.

When the United States dropped atomic weapons on Hiroshima and Nagasaki, no one had much experience treating radiation injuries, and certainly not in the setting of a mass casualty situation where tens of thousands of individuals were exposed. As was discussed previously, radiation injury is not the only effect from a nuclear weapon, or even an explosive RDD. Many individuals will also suffer burns and trauma, which is termed "combined injury." These combined injuries have a synergistic effect where a less-than-lethal dose of radiation, when combined with a normally nonlethal injury, becomes a potentially fatal combination. In Hiroshima and Nagasaki, when the magnitude of the numbers of people with radiation exposure and injuries, including burns, was combined with the nearly complete destruction of the medical infrastructure, not to mention the preexisting lack of medical equipment due to the war effort, survival became problematic at even relatively low doses. Even in the 21st century, if medical centers are damaged or destroyed and local medical providers are dead or injured, the situation could initially be much like Japan in August of 1945 (Figure 1-6). With somewhere between 4,000 and 9,000 individuals exposed to a survivable dose but also suffering burns and trauma, the medical system would be immediately overwhelmed and victims would need to be transported out of the area of the blast and fallout to have a chance at survival. As the size of the weapon increases—or if a weapon is used on a major city with a high population density—the number of casualties increases, as does the distance from ground zero in which there will be survivors who will require medical treatment.

Some additional confounders are that doses to individuals will not be uniform, nor is there likely to be good dosimetry information immediately available. An individual on one side of a wall in a building is likely to receive a very different dose than a person on the other side of the wall standing in the street. A partial-body irradiation can have drastically different effects than a whole-body irradiation of the same total dose. A personal dosimeter does not cover the entire body and may be exposed to more or less than the majority of a person's body, resulting in unreliable measurements. Unless an electronic dosimeter is worn, no information about dose rate will be recorded. Dose rate has a dramatic influence on what constitutes a lethal dose of radiation.

The Chernobyl Accident

In 1986 when the reactor in Chernobyl, Union of Soviet Socialist Republics (now independent Ukraine) exploded and burned, many individuals were exposed to a combined field of neutron, gamma, and strong beta radiations. Measuring this type of radiation dose is difficult because the different types of radiation have a wide range of quality factors. Quality factors refer to a radiation's effectiveness at causing biological damage. They range from 1 to 20, depending on the energy and type of radiation. What this means is that an absorbed dose of 1 rad (0.01 Gy) can be an effective dose to the body of anywhere from 1 to 20 rem (0.01–0.2 Sv), depending on the radiation involved. Biological dosimetry is a useful tool to help estimate dose, but at the time of Chernobyl, it was very time consuming and often gave conflicting results. Since that time, many advances have been made using automated assays to look at dicentric chromosome aberrations and translocations to estimate dose.

Bone-marrow transplants were generally unsuccessful in Chernobyl victims, partially because of the survival of some host stem cells in the bone marrow; as surviving marrow was regenerated, it rejected the transplanted marrow cells. Since 1986, we have learned to determine if there are any surviving cells

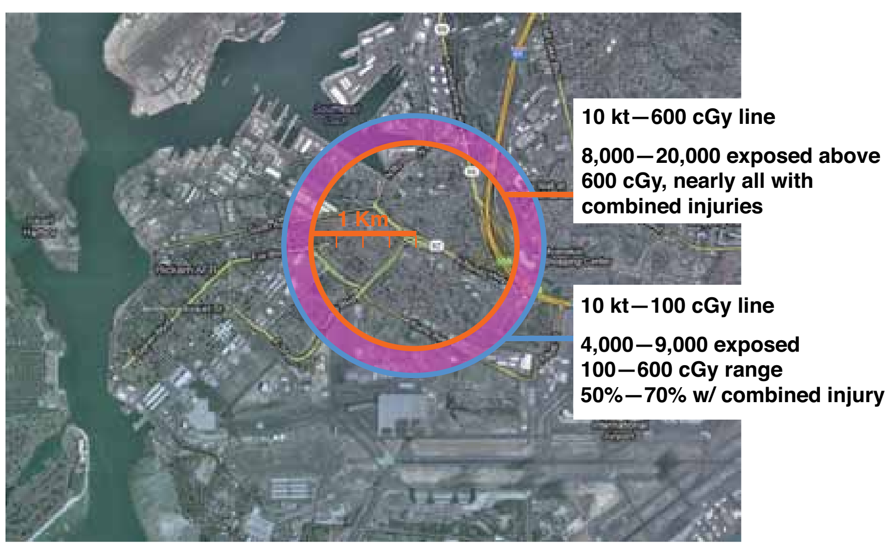

Figure 1-6. Initial radiation effects for a 10-kt yield nuclear weapon. Map: copyright Google, CyberCity 3D, Inc/3D Travel Inc, Digital Globe, GeoEye, US Geological Survey; 2011.

prior to transplant. If so, we can use newer, much more accurate immune compatibility testing and new antirejection drugs to minimize the incidence of rejection. Also, in 1986 granulocyte colony-stimulating factor was approved for use and there have been other new treatments developed since that help the body produce new granulocytes and stem cells. If there is a surviving fraction of stem cells, these treatments can they stimulate them to produce more cells, making a marrow transplant unnecessary.

A number of the personnel injured at Chernobyl sustained burns as well as radiation exposure. Of the 237 individuals hospitalized in the first 72 hours of the accident, 134 of whom suffered from acute radiation syndrome (ARS), 28 died within 4 months from radiation and thermal burns. Over 2,000 medical personnel were on scene to treat those who were hospitalized (around a 10-to-1 ratio). This ratio would be implausible in the event of a modern nuclear weapons incident. Only about 10%–15% of the victims at Chernobyl suffered combined injury. In a nuclear attack, it is estimated that up to 70% of victims would have combined injury (Table 1-1).[5] The nature of these injuries, as well as their numbers, will require that a mass casualty approach be taken.

Nature of Radiation Injuries

Ionizing radiation deposits energy in the materials within which it interacts. In the case of the human body, this energy deposition occurs within the cells. The body is made up mostly of water and radiation interacts with water molecules, dissociating them into free radicals such as free hydrogen atoms and hydroxyls, which can then go on to form other reactive species, like hydrogen peroxide. Both the free radicals and radiation directly attack targets in the cells. Deoxyribonucleic acid (DNA) is the primary target of lethality, although recent research shows that damage to proteins within the cells can be a major contributor to biological damage. Several single-strand DNA breaks occur every day in our bodies. Almost all of these are recognized and corrected by the body's repair mechanisms. When we are exposed to large amounts of radiation at high dose rates, these repair mechanisms are overwhelmed and the damage cannot be repaired. This leads to cell death, which affects tissues that make up organ systems, which in turn make up major portions of the body. The amount of damage sustained is a direct function of the radiation's quality, dose, and dose rate, and of the individual cell's sensitivity. In general, the more quickly a dose of radiation is delivered to the body, the more severe the consequences. The most sensitive cells are those that tend to divide rapidly, such as the bone-marrow stem cells and the cells lining the crypts of the gastrointestinal tract. Less sensitivity is exhibited by cells that divide more slowly or not at all, such as cells in the central nervous system and muscle cells.

The irradiation of cells has both acute and delayed effects. Acute effects involve cell death, cell injury, and the release of disruptive mediators within the cell, which can lead to performance decrements. Other acute effects are infection and uncontrolled bleeding due to bone marrow destruction, dehydration and electrolyte imbalance due to denuding of the epithelial lining of the intestine, and slow wound healing. Delayed effects include cancer and hereditary effects.

Military attention is focused primarily on acute effects because they are of the most immediate concern to the tactical military commander. Performance decrement occurs within minutes or hours after relatively low exposures to radiation. It includes a phenomenon called early transient incapacitation, a temporary inability to perform physically or cognitively demanding tasks. This inability can be accompanied by hypotension, emesis, or diarrhea. A pilot or a soldier in a nuclear/biological/chemical protective suit could be critically affected by a symptom like emesis, since the suits are only designed to protect the wearer from inhalation or contamination and do not protect against penetrating radiation.

TABLE 1-1

PREDICTED DISTRIBUTION OF INJURIES SUSTAINED FROM A NUCLEAR DETONATION

Injury Types	Percentage of Total Injuries
Radiation only	15
Burn only	15
Wound only	3
Irradiation, burns, and wounds	17
Irradiation and burns	40
Irradiation and wounds	5
Wounds and burns	5
Combined injury total	67

Adapted from US Department of the Army. *Treatment of Nuclear and Radiological Casualties*. Washington, DC: DA; 2001. Field Manual 4-02.283. Table 3-1.

Acute Radiation Syndrome and Associated Subsyndromes

At whole-body or significant partial-body doses around 1 Gy (100 rem) and above, a combination of clinical signs and symptoms occur, which are referred to as ARS. The key mechanisms in the pathophysiology of ARS are depletion of cell lines and microvascular injury.

ARS has four distinct phases or stages, starting with the prodromal phase. During this phase, histamines and other disruptive mediators from free radical effects are released due to cell damage and causing nausea, vomiting, diarrhea, malaise, and, in severe cases, loss of consciousness. Prodromal symptoms can start within minutes, hours, or days after exposure. The time of onset as well as the severity and duration of these symptoms depends on the dose received. Following the prodromal phase is the latent period. During this period, which may last up to 3 to 4 weeks, the patient feels better and appears to recover as symptoms wane. The respite is only temporary; however, and is followed by the manifest illness phase in which the patient is immunocompromised and must be aggressively managed (see Chapter 2). If the patient survives the manifest illness phase, the individual enters the fourth and final phase: recovery.

There are three subsyndromes associated with ARS that are dependent on the total dose received. At the lower end of the spectrum is hematopoietic syndrome, which is seen with doses of around 1 to 5 Gy. The onset of the prodromal symptoms is 3 to 16 hours and they last for less than 48 hours. The prodromal symptoms of the hematological syndrome are characterized by nausea, vomiting, malaise, anorexia, and possibly diarrhea. As the patient enters the latent period, mild weakness becomes the only symptom and will remain for 3 to 4 weeks. If the dose is greater than 3 Gy, there will be epilation or hair loss at around 2 weeks. Manifest illness with bone marrow suppression, infection, and hemorrhage will develop at around 3 to 5 weeks.

The middle subsyndrome is referred to as gastrointestinal subsyndrome and occurs after exposure to around 6 Gy or more. In an unsupported patient with a dose of 6 to 9 Gy, death will occur in 2 to 3 weeks; at greater than 9 Gy, it will occur as early as 1 week after exposure. The prodromal phase for gastrointestinal subsyndrome occurs within 1 to 4 hours and will feature severe nausea and vomiting, possibly watery diarrhea, weakness, and fever. Combat effectiveness will be seriously degraded in the service member with gastrointestinal subsyndrome. A latent period featuring weakness and malaise will last from 5 to 7 days, followed by manifest illness with a return to the prodromal symptoms plus bloody diarrhea, sepsis due to loss of the blood barrier in the intestines, fluid and electrolyte imbalance, shock, and death. At these doses, the intestinal crypt cells are destroyed. As the mature cell layer sloughs off as part of its normal life cycle, there will be no replacement cells to take its place and thus no barrier to keep the intestinal bacteria where they are supposed to be.[6]

Cerebrovascular subsyndrome occurs at around 20 Gy and is always fatal. The prodromal symptoms are erythema, a burning sensation (blush from the endothelial injury and cell breakdown products), vomiting and diarrhea in 30 minutes or less, loss of balance, confusion, and loss of consciousness. The latent period only lasts a few hours and often features euphoria, which is quickly followed by manifest illness. This stage will have severe central nervous system signs due to endothelial cell injury in the brain, unstable blood pressure, respiratory distress, coma, and death.

Combined Injury

ARS and its medical effects are significantly complicated when radiation injury is combined with conventional blast trauma or thermal burn injuries. As has been previously discussed, this combined injury can significantly lower the dose at which fatality occurs. This will lead to significant complications in the treatment strategies employed, and means that there cannot be a "one-treatment-fits-all" mentality for radiation victims. Different doses and confounders will require a very personalized and labor-intensive strategy of treatment.

SUMMARY

Although the Cold War ended many years ago, vast arsenals of nuclear weapons, as well as huge stockpiles of weapons-grade nuclear material, still exist. The number of nations that possess nuclear weapons is at an all-time high, while still more appear to be attempting to join their ranks. In addition to nuclear weapons, the United States is now very concerned with the potential use of radiological weapons such as RDDs. US troops now operate in areas where they may come into contact with abandoned or hidden radiation sources, or may be deliberately targeted with these materials. Our ability to successfully treat radiological casualties has been enhanced by continued research and the availability of new drugs; however, to be successful, treatment must be started soon after exposure by medical personnel who understand the specialized treatment required. US military medical personnel must understand how to treat radiological and nuclear injuries. The country should never underestimate an enemy and assume that they will not use every option available to them against it, including nuclear or radiological weapons.

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