Chapter 1

# NUCLEAR EVENTS AND THEIR CONSEQUENCES

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# INTRODUCTION

Radiation damage to human cells was first recognized just 4 months after the reported discovery of X rays by Wilhelm Conrad Roentgen. In 1896, Dr. J. Daniels found that the irradiation of his colleague's skull resulted in loss of hair. Since then, many other biomedical effects of radiation have been described.

The understanding of atomic physics increased rapidly in the early twentieth 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.

Today, more and more countries are developing nuclear weapons, with those in the United States and the Soviet Union achieving the greatest capabilities. One modern American or Soviet submarine carries nuclear weapons that can release energy equivalent to 500 bombs of the size used at Hiroshima in 1945. This vast power is greater than the energy released from all weapons in all previous wars combined. Of course, the extensive use of these nuclear weapons in a confrontation would nullify an effective medical response. Rational minds must continue to recognize this potentially devastating nuclear power and maintain a general peace, as they have for over 40 years.

The deterrent effect of nuclear weapons does not mean that military physicians can ignore the possibility of their use. The most likely situations requiring a medical response are the use of weapons against a deployed naval force, a remote city, or a remote facility; a third-world conflict; a terrorist act; or an accident involving a nuclear weapon.

Military medical preparedness can focus beyond nuclear weapon events. Today, nuclear material is used in medicine, industry, and power generation, bringing increased risk of occupational and accidental exposures. New radiation hazards in space will have to be overcome if successful peacetime and military uses of that frontier are to be realized. 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. In comparison with a conventional explosive weapon, a nuclear weapon's effectiveness is due to its unequalled capacity to liberate a tremendous quantity of energy in a very small space in an extremely short time. 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 or 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 radiations.

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.* 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 = mc2 (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. 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. This means that there is a range of elements for which the neutrons and protons are most tightly bound and, thus, have the most stable nuclear bonds. If nuclei having less stable nuclear bonds can be converted into nuclei having more stable bonds, the system will pass from a state of lesser to greater stability, and energy will be released. This is the energy source of nuclear weapons. The process can occur in two ways: *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 farther 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, being massive and 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 thirty-eight 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, which 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-kiloton-yield weapon used at Hiroshima was a gun-assembled device (1 kiloton, or kt, equals the energy released by detonation of 1,000 tons of TNT, and 1 megaton, or MT, equals 1,000,000 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. 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 multi-megaton weapons in the American and Soviet inventories are fusion weapons, deriving much of their power from the combination of light isotopes of hydrogen (deuterium and tritium) into heavier nuclei lying farther up the curve of binding energy per nucleon. Due to the presence of powerful forces of electrostatic repulsion, initiation of the 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 fission and fusion processes, usually in roughly equal proportions.

An *enhanced radiation weapon,* or neutron bomb, might be produced by altering the design of a standard small-yield fusion weapon to permit the high-energy fusion neutrons to better escape the device. This modification increases the initial production of neutron radiation, reduces the proportion of the weapon's energy expressed in blast and thermal effects, and reduces the amount of residual fallout radiation. Thus, a given total yield produces more biologically damaging neutron radiation, less destruction of materiel from blast and thermal effects, and less residual radiation fallout.

**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. 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, which 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 80% of the original nuclear fuels, which even in a relatively efficient 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 of 1,000,000°C. The intensely hot fireball reradiates thermal energy in the form of electromagnetic radiation at infrared, visible, and ultraviolet frequencies.

At about the same time, the weapon's materials have started to expand supersonically outward, dramatically compressing and heating the surrounding air. This phenomenon, called *case shock,* is the source of the destructive blast wave and further thermal radiations. A unique interaction between the X-ray-heated air and the case-shock-heated air is responsible for the nuclear weapon's characteristic double pulse of thermal output. Added to these blast and thermal effects is the initial nuclear radiation (primarily neutrons and gamma rays) which 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 depicts the typical energy partition for a standard fission or fusion device and the energy partition expected from a typical enhanced-radiation weapon (neutron bomb).

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 shows the range over which the various effects are lethal, as a function of yield. It is noteworthy that 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. A qualitative difference arises from the production of *(a)* initial nuclear radiations from the fission and fusion processes themselves and *(b)* delayed radioactivity from decay of the unstable fission fragment byproducts.

### Blast Effects

During the detonation of a standard fission or fusion nuclear device, the rapidly expanding plasma gives rise to a shock or blast that is responsible for dissipating about 50% of the total energy of the weapon. This represents a tremendous amount of energy, even in small, tactical-sized weapons of a few kilotons. 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 blast wave is a wall of compressed air 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 (pounds per square inch) 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 without any visible wounds. In addition, serious abdominal injuries, including hepatic and splenic rupture, may result from a rapid and violent compression of the abdomen.

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.

Although the $LD_{50}$ (lethal dose, or fatal injury, for 50% of cases) from tumbling occurs at about 50 mph, the $LD_{50}$ from impact occurs at about 20-25 mph. The $LD_{50}$ from blast is estimated to occur at 6 psi, due primarily to the force of blast winds. For a small tactical weapon or terrorist device with a yield of 0.5 kt, the range for this level of overpressure would extend to slightly less than 0.5 km. For larger tactical or strategic weapons with yields of 50 and 500 kt, the range for $LD_{50}$ at 6 psi would expand to just under 2 km and just under 4 km, respectively.

Protection from the effects of the blast wave is difficult to achieve because it 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 with feet 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

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 atmosphere, it does not contribute significantly to producing casualties. The second pulse is composed primarily of energy in the infrared and visible portions of the electromagnetic spectrum, 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 a large quantity of thermal energy in a very brief time. This 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. 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, the healing of a flame burn is abnormal because the germinal layer has been damaged.

Since 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. Even clothing will provide some protection from the deposition of thermal energy onto the skin. Since light colors tend to reflect rather than absorb thermal energy, light-colored clothing will offer more protection than dark-colored clothing.

Figure 1-3 shows the range of $LD_{50}$ for burn injury from weapons of different yields. Notice that 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. As the weapon yield increases, the range for burn injury increases much more rapidly than the range for blast injury or radiation injury. This means that burns will always be present 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.

***Eye Injury***. Thermal energy may also cause eye injury. The two types of eye injury that would occur would not burden a medical facility. Flash blindness is a temporary condition that results from a depletion of photopigment from the retinal receptors. This happens when a person indirectly 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 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. It is surprising that retinal burn is no more detrimental to mission accomplishment than is flash blindness.

To protect against injury, the eyes can be closed and shielded after the individual receives warning of a detonation. Using one of the lead-lanthanum-zirconium-titanium goggles that have been developed 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. Initial radiation consists of neutrons and gamma rays produced within the first minute after detonation. Mechanisms for producing initial radiation are *(a)* the generation of neutrons and gamma rays directly from the fission and fusion processes, *(b)* the production of gamma rays through inelastic scatter reactions with elements in the atmosphere surrounding the weapon, and *(c)* the isomeric-decay and neutron-capture gamma rays. 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 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 radiations no longer strike the ground. A person on the ground would therefore be safe from the initial radiations 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. Figure 1-3 shows that 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. 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 fallout covers a wide geographic area and remains a significant biological hazard long after detonation.

***Fallout.*** Our consideration of the origin of radioactive debris begins with a review of the basic nuclear and physical processes that occur as the device detonates. As the fissile material splits, the massive and highly charged fragments carry away 82% of the fission energy, and release it as heat within the bomb components. This transforms the components into an extremely hot plasma. Bremsstrahlung interactions between the electrons and positive ions within this plasma generate an intense source of low-energy X rays, which leave the plasma and interact with the first several meters of air surrounding the weapon. The X rays heat this air to an extremely high temperature and initiate the development of the fireball that is characteristic of nuclear explosions. The rapid outward expansion of weapon material dramatically compresses and heats the air around the weapon (case shock), further contributing to the generation of the fireball. This hot bubble of gas, containing highly radioactive fission fragments and activated weapon material, is the origin of the fallout radiation.

Sources of fallout include *(a)* highly unstable fragments produced by the fissioning of plutonium or uranium, *(b)* roughly 80% of the nuclear fuels that remain unreacted after the weapon has blown itself apart (uranium or plutonium for all weapons, as well as tritium for fusion devices), and *(c)* activation products (weapon components and ground elements made radioactive by exposure to the weapon's intense neutron flux). Another contributor to fallout is *salting*, the inclusion of materials in a weapon that will activate when exposed to the initial neutron flux, thus increasing the amount of residual radioactive isotopes. Because of operational limitations in using a salted weapon, it is expected that this technique will be rarely used. Since the fission fragments produced by the fissioning of uranium or plutonium account for most of the activity in the fallout field, the fusion process is relatively “clean” regarding the production of residual radiation.

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, geo-graphically 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. Because the material has had little time to decay, it is radiologically very active. The biological hazards from early fallout are external whole-body gamma-ray irradiation from gamma emitters deposited on the ground; external beta-particle irradiation from beta emitters deposited on the skin; and internal beta-particle irradiation from beta- emitting 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. Under certain circumstances, delayed fallout may be distributed worldwide, presenting a long-term health hazard, primarily through internalized exposure.

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 or near-surface burst, the interaction of the fireball with ground debris also 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. For a near-surface burst, 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. Thus, a ground or near-surface detonation is the most significant fallout hazard to the military. 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:

- The total fission yield (fission fragments are the largest contributor to fallout activity)

- The ratio of energy produced in a fusion weapon, by fission process versus 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 enhanced radiation weapon will produce proportionately less fallout than an equivalent-yield standard nuclear weapon)

- The altitude of burst (a ground 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 decay radiation; for fusion weapons, it will be approximately 5%.

The elemental distribution of fission fragments is almost independent of whether the fissile material is plutonium or uranium. In each case, approximately 38 different chemical elements are produced, consisting of about 300 separate radionuclides. Thus, the chemical and radiological characteristics of the fallout field are extremely complex and, in practice, are amenable only to empirical analysis. The fission fragments are highly unstable and decay primarily by emitting gamma rays and beta particles. Activated weapon materials and ground elements, as well as unspent tritium from a fusion weapon, will decay by the same means. The unspent uranium and plutonium from fission processes decay by emitting alpha particles, which are a hazard primarily if they are inhaled. The immediate detection of fallout radiation is not possible with the physical senses, so appropriate instruments must be used. However, the heavy early, local fallout material is usually visible as a dust-like deposit that may look like a film on shiny surfaces. These visible particles are the most hazardous component of fallout.

## MEDICAL CONSEQUENCES OF NUCLEAR WEAPONS

Military planners are concerned with the effect of nuclear weapons on the human component of operational systems. It is futile to harden machinery to large amounts of radiation if the human operator is incapacitated by relatively small doses. Radiobiology research can help reduce the logistical drain on medical resources caused by large numbers of severely injured casualties. Targeting and contingency planning depend on knowing radiation effects on military personnel.

**The Chernobyl Accident**

Unlike controlled radiotherapy, radiation associated with weapon detonations or accidents can result in uncontrolled and usually unpredictable exposures, which make radioprotective measures difficult. As seen in the 1986 accident in Chernobyl, USSR, *dosimetry* (measurement of radiation dose) is also difficult. Physical dosimeters, if available, may be lost during a nuclear event or may record cumulative doses with no information on dose rate. Furthermore, dosimeters provide point data rather than whole-body data. Biological dosimetry is also imperfect, and the time-consuming tests of lymphocyte depletion and cytogenetic damage (such as those used for Chernobyl victims) give different results. Dosimetry with uncontrolled exposures is complicated by two other factors with which military physicians may have to cope.

One is the uneven distribution of exposures on a victim due to shielding. Thus, pockets of critical cells that are necessary to regenerate affected tissues may survive, even if some parts of the body receive very high doses of radiation. 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.

Another complication of dosimetry in accidents or warfare is that other injuries, such as burns or mechanical trauma, can be superimposed on radiation injuries. The prognosis for these combined injuries is much graver than for radiation injuries alone, so combined injuries must be carefully considered during *triage* (sorting of casualties). It is estimated that 65%-70% of weapon-related injuries will be combined injuries, with burns and radiation being the most common combination (Table 1-1).

Burns and radiation effects were the most common injuries seen in seriously injured victims of the Chernobyl disaster. Thousands of medical and paramedical personnel were available for the relatively small number of patients at Chernobyl, but this will not be the case in military situations. If a nuclear weapon is detonated, physicians will have to adapt to mass-casualty management techniques, which require simplified and standardized care.

Today, scientists are exploiting the tremendous advances in biotechnology—the new knowledge and techniques in gene regulation, immunology, neurobiology, and related sciences—and will soon develop significant protection for the human body from the consequences of radiation exposure and associated injuries.

## Nature of Radiation Injuries

Almost every major organ system can be affected by radiation exposure, and management in a nuclear accident or warfare will require the coordinated efforts of physicians, allied health professionals, and health-physics personnel.

A nuclear device detonated over a major city will cause tremendous numbers of casualties. The day after the detonation, 45,000 dead and 90,000 injured were counted in Hiroshima. Modern weapons would result in a much larger number of casualties. As the number of persons killed immediately due to blast and thermal injuries increases, so does the number of individuals at some distance from the epicenter who have serious but potentially survivable injuries. Therefore, an understanding of these injuries is extremely important to preserve human life and ensure the success of military operations.

Damage to the human body by ionizing radiation is caused by the deposition of energy. This is true for both electromagnetic radiation (such as X rays and gamma rays) and particulate radiation (such as beta particles, which are high-speed electrons, or neutrons). This energy deposition results in reactive chemical products, including free radicals (such as the hydroxide radical). These free radicals can further combine with body chemicals, primarily water, to form reactive species (such as hydrogen peroxide). These elements then combine with cellular components to cause damage. The primary targets of damage within the cell are deoxyribonucleic acid (which can be attacked not only by reactive chemical products but also by direct effects of the radiation itself), cellular and nuclear membranes, and enzymes.

The amount of damage sustained is a function of the radiation's quality, dose, and dose rate, and of the individual cell's sensitivity. The higher the dose, or the greater the deposition of radiation energy, the greater the damage expected. *Quality* refers to particular types of radiation (such as gamma radiation or neutron radiation) and their relative abilities to damage humans. Neutrons seem to be more effective in producing organism death, and gamma rays appear to be more effective in inducing performance decrement. 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 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 (CNS).

The irradiation of cells has both acute and delayed effects (Table 1-2). 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 destruction of the bone marrow, dehydration and electrolyte imbalance due to denudation of the epithelial lining of the intestine, and slow healing of wounds. Delayed effects include cancer and nonspecific life shortening. Eventually, either the organism dies, or regeneration and recovery occur.

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* (ETI), 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. Performance decrement may be due to lesions other than those associated with the lethal consequences of radiation injury to cells. This hypothesis might be significant in the development of practical radioprotectants.

**Acute Radiation Syndrome and Associated Subsyndromes**

With increasing doses of radiation, changes take place in body tissues or organs, some of which are life threatening. The symptoms that appear soon after radiation exposure are called the *acute radiation syndrome* (ARS). This large category may be broken down into the *hematopoietic, gastrointestinal,* and *neurovascular subsyndromes* (Figure 1-4).

The hematopoietic subsyndrome is seen within two weeks after biologically significant radiation doses of 1.0-2.5 grays (Gy). This damage to the body's blood-forming organs, specifically to the bone marrow, can lead to suppressed production of white blood cells and platelets, which in turn leads to increased susceptibility to infection and uncontrolled bleeding. Treatment consists of administering platelets and preventing infection during the time required for bone-marrow repair. Much research is directed toward finding means to enhance the repair or replacement of this tissue.

The gastrointestinal subsyndrome appears within a week or two after exposure to higher doses, which are sometimes survivable. After this exposure, crypt cells in the epithelial lining of the intestine are destroyed. This leads to excessive fluid loss and imbalance of electrolytes within the body, which may result in loss of the intestinal wall. Treatment focuses on preventing fluid loss and on balancing electrolytes during the time required for gastrointestinal repair.

The neurovascular subsyndrome appears within a few days after much higher doses of radiation, and consists of irreversible damage to the CNS. There is no treatment, other than making the patient as comfortable as possible.

**Combined Injury**

ARS and its medical effects are significantly complicated when radiation injury is combined with conventional blast trauma or thermal burn injuries. The following data show that the insult to the body from combined radiation and conventional injuries is much more severe than it would be from a single injury.

In Figure 1-5, the percent of mortality in rats that received an $LD_{50}$ burn is compared to the percent of mortality when this insult was combined with sublethal to minimally lethal doses of radiation. Rats receiving 1.0 or 2.5 Gy of radiation alone had no mortality, while those receiving 5.0 Gy alone had about 20% mortality. Animals that received an $LD_{50}$ burn and 1.0 Gy of radiation (which by itself was not lethal) had increased mortality up to 70%. Animals that received 2.5 Gy of radiation in combination with an $LD_{50}$ burn had mortality approaching 95%. Those that received an $LD_{50}$ burn and an $LD_{20}$ irradiation with 5.0 Gy showed 100% mortality. Thus, radiation combines synergistically with either burn or blast injuries to increase lethality.[1]

## REFERENCE

1. Alpen, E. L. and Sheline, G. E. 1954. The combined effects of thermal burns and whole-body X-radiation on survival time and mortality. *Ann. Surg.* 140: 113-118.

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