13

Hazards of Radioisotopes

Radioisotopes, such as ^{14}C and ^{32}P, are unusual forms of elements containing the same number of protons and electrons as the normal form, but a differing number of neutrons. They are less stable than the normal form and decay spontaneously producing radioactivity. The introduction of the use of radioisotopes into biological research was one of the single most significant advances in research within at least the last several decades and possibly during the entire century. As a result of this development, today radioactive biological tracers, radioisotopes, are perhaps the most versatile, comparatively inexpensive, and easily used research tools available in biomedical research. Virtually every important discovery in biochemistry and molecular biology since these tracers were introduced was made using these substances; listing these advances would take pages. Examples of some of the techniques developed with the use of radioisotopes show their versatility and utility: radioimmunoassay; metabolic uptake studies using tracer techniques; autoradiography; exchange kinetics; radiochromatography; and radiometric analysis, to name a few.

However, despite the importance and utility of radioisotopes, their use also has a negative side. Careless or improper use of these substances can pose a significant danger to the user, other laboratory and building occupants, and the environment. Radiation can neither be seen nor felt, nor detected directly by any other sense. Therefore, control of hazards arising from the use of radioisotopes is based upon the careful following of certain procedures, backed up by monitoring and surveying of facilities where radioisotopes are stored and used.

Long before much attention was paid to biological or chemical hazards, and indeed, to many of the other hazards now covered by occupational safety regulations, radiation hazards were covered by federal and state laws. This long history of regulation has resulted in the publication of a very large body of knowledge concerning radiation safety. Despite the fact that much of it is almost 30 years old, many references are still current. Some of these, in fact, are quite good, and will be referred to in this chapter.

In comparing the three main types of hazards found in biomedical laboratories, chemical, biological, and radiological, only radiation has the unique characteristic of ease of detection of its presence: with very few exceptions, the presence of contamination or radiation areas is readily detected by fairly inexpensive equipment, so that steps can be taken to prevent continued exposure or spread of the hazard. Thus, many of the control measures in handling radioisotopes use instruments that can detect radiation.

This chapter is not meant to serve as a handbook for research with radioisotopes. There are many such, and every laboratory should have access to one for sources of chemical and physical data (467, 498) along with a general reference (33, 307, 414). The purpose of this chapter is to introduce the fundamental prin-

S. R. Rayburn, *The Foundations of Laboratory Safety*

ciples of radiation, its measurement, biological effects, sources of natural and artificial radiation, and to discuss the principles of radiation protection. A good understanding of the nature of radioisotopes and their hazards will help the worker to use them safely.

13.1 Characteristics of Ionizing Radiation

What is "ionizing radiation," and why is it hazardous? Ionizing radiation is produced by various physical mechanisms: some radiations are the result of natural processes and others can be created by artificial means. Some sources of radiation are from natural radioactivity, from x-rays, from artificial sources or processes, and from cosmic rays which originate in space (see Section 13.5).

"Radiation" itself is not a single entity or process, caused by a single phenomenon. Ionizing radiation is composed of differing particles, all atomic or subatomic in size, and by electromagnetic radiation (light and radio waves are also electromagnetic radiation). The uniqueness of ionizing radiation lies in its capability to interact with matter, disturbing its atoms by tearing away their electrons. These atoms become *ionized* and hence the term *ionizing radiation.*

There are four types of radiation generally considered when discussing radiation hazards. These are: 1) alpha particles, or helium nuclei; 2) beta particles, or electrons; 3) neutrons; and 4) electromagnetic radiation (gamma rays and x-rays).

Alpha particles, or helium nuclei, are almost always produced by naturally occurring elements having unstable nuclei, such as uranium, radon, thorium, and radium. Artificial transuranic elements are also alpha emitters. These particles are quite massive, since they are composed of two protons and two neutrons, which gives them an atomic mass of 4 atomic mass units (amu). The two protons give the particle a net electrical charge of two (He^{2+}); its high mass and charge allow a considerable number of interactions with surrounding atoms. A high mass and charge are not the only characteristic of the alpha particle. They are also highly energetic; almost all alpha particles have energies ranging from 4 to 9 million electron volts (MeV).*

The very characteristics of alpha radiation that make it so potentially destructive to tissue, i.e., massiveness and charge, also make it the easiest of the ionizing radiations to protect against. Alpha particles have a very short range in air and are easily stopped by a sheet of paper or by the skin. However, should an alpha emitter be ingested, a serious health hazard is created. Since all of the energy of the radiation is deposited in a very small volume, tissue damage will be great. This explains why plutonium, an emitter of high-energy alpha particles, is so toxic when inhaled into the lungs.

Beta particles are composed of unpaired electrons, which are singly charged particles possessing a mass of about 1/7,300 that of the alpha particle. Most beta decay results in emission of **negatrons**, or negatively charged electrons, but some processes produce **positrons**, or positive electrons. Beta particles are produced by naturally occurring isotopes (e.g., tritium or ^{3}H, ^{14}C, ^{40}K), by artificially produced isotopes (e.g., ^{32}P, ^{35}S, ^{45}Ca), and by "mechanical" means (e.g., electron microscopes, accelerators). The range of a beta particle in air or its ability to penetrate matter is directly proportional to its energy and to the density of the substance. As in the case of alpha emitters, beta emitters inside the body pose a significant health hazard, while the ex-

*The electron volt is a measure of the kinetic energy of a nuclear or subnuclear particle or quantum of energy, or a measure of potential energies at the atomic level. It is equal to the amount of energy gained by an electron travelling through a potential field of 1 volt. To place the concept of the amount of energy possessed by an alpha particle into perspective, the average energy of a chemical bond between atoms is 3 eV, while the amount of energy deposited by a typical interaction of alpha particles as well as other ionizing radiation with target atoms (called *primary ionizations*) is as much as 60 eV. Therefore, one interaction can disrupt 20 bonds; a single 4-MeV alpha particle can thus damage as many as 1.3 million molecules with primary ionizations only.

ternal hazard is somewhat greater for high-energy beta emitters than for alpha sources. The energy of beta radiation is less than that of alpha radiation, ranging from a lower limit of about 0.018 MeV to over 3.5 MeV.

Gamma radiation and x-rays

In contrast to the two forms of radiation previously discussed that are composed of atomic particles, this radiation is composed of electromagnetic energy, like light or radio waves, but having a far shorter wave length. Thus this radiation has neither mass nor charge. Gamma radiation is produced by natural radioisotopes (e.g., ^{22}Na, ^{40}K, ^{7}Be), and by many reactor-produced artificial radioisotopes and fission products of atomic reactors and nuclear explosives. X-rays are produced by the slowing down of fast electrons in materials of high atomic number; this is how they are "mechanically" generated in x-ray machines. Some modes of radioactive decay result in capture or ejection of electrons from electron shells close to the nucleus; these processes give rise to the production of x-rays. Gamma rays arise in the nucleus and often accompany the emission of alpha and beta particles.* Since gamma and x-radiation are massless and chargeless, their **specific ionization** (ability to cause ionizations, as we will see later) is lower than alpha or beta radiation; however, they possess long ranges in air and are extremely penetrating and pose a significant internal as well as external hazard. Gamma radiation energy for the more common isotopes ranges from about 0.035 MeV to over 1.5 MeV.

Neutrons, the fourth major type of ionizing radiation, are rarely used in biomedical laboratories. Sources of neutrons are spontaneously fissioning isotopes (e.g., some of the artificial transuranic elements), atomic reactors, accelerators, and from reactions involving the interaction of alpha or gamma radiation on beryllium or certain other elements. Since the study of neutron radiation characteristics is so specialized, and exposure to neutrons is not a common hazard in biomedical research, we will not discuss them further.

*X-radiation and gamma radiation of the same energy are thus identical, differing only in their manner of production.

13.2 Interaction of Radiation with Matter

When a radioactive particle or photon strikes a substance, it is either absorbed by the substance or is scattered. Which one of these happens is determined by the form of the radiation, its energy, and the nature of the substance with which it interacts. Radiation protection is concerned with the effects of *absorption* of the radiation in the substance, because the mechanisms of absorption give rise to particular kinds of biological injury, and a knowledge of the characteristics of the radiation allows the selection of proper shielding.

Energy is transferred from the radiation itself to the absorbing substance by either of the following two mechanisms:

- *Ionization.* All atoms are normally electrically neutral. The atoms of substance become ionized when their *electrons are removed*, leaving the atoms with net positive charges and free electrons.
- *Excitation.* The radiation can interact with the atoms of a substance, raising its energy level from its normal, or *ground* state, to an excited, or unstable state by *displacing electrons* to a higher orbit. This is an important mechanism which allows measurement of radiation by analytical techniques or in personal monitoring, as we will see in Section 13.10.

When atoms of a substance become ionized, an electrical instability is created within that substance. Ionization results in the formation of **ion pairs**, consisting of positively charged atoms and negatively charged free electrons. Different kinds of ionizing radiations have different efficiencies of creating ionizations. The term used to compare the relative efficiencies of the various kinds of radiation at producing ionizations is known as the **specific ionization**. It is defined as the number of ion pairs formed

divided by the path length in centimeters. Specific ionization is directly related to the energy of the radiation, its mass and charge, and the density of the material with which it interacts.

Alpha particles interact with matter by pulling off orbital electrons from atoms as they are deflected by the positively charged nuclei of these atoms. They also can cause excitation of the atoms by pulling orbital electrons into higher orbits. The energy thus deposited in the atoms can break chemical bonds, and secondary ionizations can be caused by production of free electrons and by secondary x-rays produced when the excited atom drops back into the ground state. Alpha particles have very high specific ionizations.

Beta particles are electrons and are far smaller than alpha particles. They are ejected from atoms at velocities far greater than alphas—about 20 to 94 percent of the speed of light for betas possessing energies up to about 1 MeV—but because they are only 1/7,300 as massive as the alpha (5.4×10^{-4} atomic mass units) and have half the charge, interactions with matter occur at less frequent intervals. Thus the specific ionization for beta particles is smaller, and beta particles have a greater range of penetration in matter than alpha particles. Figure 13.1 shows the penetrating ability of beta particles in various common materials. The figure shows that penetrating ability is a direct function of the energy of the particle and the composition of the substance.

High-energy beta particles interact with matter in a unique way. When a high-energy beta particle approaches the nucleus of an atom, electrostatic forces slow and/or deflect it. This change in velocity or bending of the

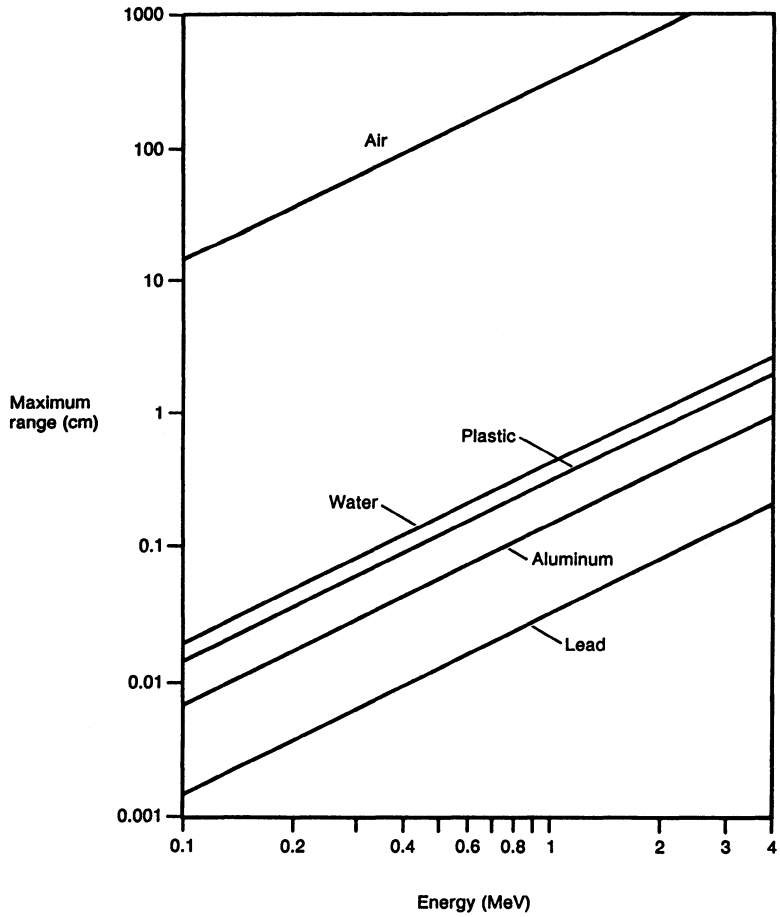

FIGURE 13.1 Penetrating ability of beta radiation. The maximum range of beta particles in various materials expressed as a function of particle energy. Adapted from (467).

particle's path (both are decelerations in the particle's velocity) results in the production of x-rays. These x-rays are termed **bremsstrahlung** (German: "breaking radiation"). Atoms of higher atomic weight are more efficient bremsstrahlung-producers than those of lower atomic weight. This is why beta shielding for isotopes like ^{32}P is made from plastic, rather than from lead.

Since **gamma rays and x-rays** are massless and chargeless, they do not undergo electrostatic interactions with matter and therefore cannot produce ionizations in matter directly. Instead, they interact with atoms to produce electrons that in turn can produce secondary ionizations. The secondary ionizations are extremely penetrating and can severely damage the substance absorbing the radiation. Later in this chapter, we will discuss the effects of these kinds of radiation on biological systems (see Section 13.4). However, before we can discuss biological effects, we must define some of the units used to measure radioactivity and radiation dose.

13.3 Measurement of Radioactivity

There are several different terms used to measure radioactivity: measures of the physical processes including units of the quantity of radioactivity present, units of radiation exposure, and units of radioactive dose. Now we will define these units and see how they are used. Table 13.1 lists the various terms used to measure radioactivity, as well as the kind of measurement for which each term is used.

- *Radioactivity.* Radioactive decay is a process governed by statistics. At any given instant of time, each radioactive atom has a measurable probability of decaying. The rate of decay depends upon the number of original atoms present and upon the instantaneous fraction of atoms decaying per unit time, the **decay constant**. Another term used in discussing radioactivity is the **half-life**. This is defined as the amount of time it takes for the quantity of radioactive atoms present to be reduced to half of the original value.
- *Activity.* The **activity** of a radioactive isotope is the instantaneous number of atoms decaying per unit time. It determines the quantity of radioactive material present. The special unit of activity is the **curie**, which is abbreviated "Ci." When this term was first defined, it was based upon the decay rate of 1 gram of radium, which is about 3.7×10^{10} disintegrations per second. Since the curie is a very large quantity, it is customary to express activity in millicuries (mCi) or even smaller units (see Table 13.1). The International Commission on Radiological Units (ICRU), an international scientific standards organization, has adopted a new unit of activity, the **becquerel** as part of the International System of Units (SI). In this system, the becquerel (Bq) is defined as 1 disintegration per second.
- *Exposure.* The ICRU special unit of radiation exposure is the **roentgen** (R). It measures the number of ions liberated in a given mass of air through interaction with gamma or x-radiation. Generation of one ion pair in air requires 34 eV. One roentgen is defined as 2.58×10^{-4} coulomb per kilogram of air (about 1.0 electrostatic unit of charge per cubic centimeter of air) at standard temperature and pressure (20°C, 1 atmosphere). Note that the roentgen is not defined for alpha or beta radiation. It is a measure of *radiation flux*, the amount of radiation impinging upon a material. However, it does not measure the amount of absorbed radiation, which is more important as a measure of biological damage. Ionizations in air are simple to measure with relatively inexpensive equipment, which are generally calibrated to provide measurements in milliroentgens per hour. We will see that absorbed radiation is far more difficult to measure directly.
- *Absorbed dose.* The special unit of absorbed energy, the **rad** (**r**adiation **a**bsorbed **d**ose), is defined as the amount of radiation that transfers 100 ergs of energy per gram of absorbing material. The rad is useful for measuring absorbed energy for any ionizing ra-

TABLE 13.1 Units used to measure radioactivity and radiation

Unit	Value	Symbol	Purpose or use
Activity			
Curie	3.7×10^{10} disintegrations per sec	Ci	Measurement of the total amount of radioactive material in sample. Measurement of the total amount of radioactivity in a given mass, the specific activity, which is usually measured expressed in μCi/millimole
Millicurie	10^{-3}Ci	mCi	
Microcurie	10^{-6} Ci, or 2.22×10^{6} disintegrations per min[1]	μCi	
Nanocurie	10^{-9} Ci	nCi	
Picocurie	10^{-12} Ci	pCi	
Becquerel (SI)[2]	1 disintegration per second	Bq	
Exposure			
Roentgen	2.58×10^{-4} coulomb/kg air	R	Measurement of ionizations in air resulting from the interaction of gamma or x-rays with air molecules. A "radiation flux"
Milliroentgen	10^{-3} R	mR	
Absorbed dose			
Rad	100 erg/gram	rad	Measurement of the amount of energy deposited in a substance for any type of radiation. 1 R in soft muscle deposits about 93 erg/gm
Millirad	10^{-3} rad	mrad	
Gray (SI)	1 joule/kg (100 rad)	Gy	
Dose equivalent			
Rem	rad $\times$ QF[3]	rem	Measurement of relative biological effect of dose for different radiations
Millirem	10^{-3} rem	mrem	
Sievert (SI)	gray $\times$ QF	Sv	

[1]This quantity is used very frequently in radioisotope work.
[2]SI: International System of Units (International Commission on Radiological Units, ICRU).
[3]QF is the quality factor, which is used to take into account the fact that radiations have varying efficiencies of causing damage in biological systems. The QF of x-, γ-, and β-radiation is 1; the QF for α-radiation is 10; the QF of neutrons is 2–20, depending on their energy.

diation, not only for gamma or x-radiation. The rad is far more difficult than the roentgen to measure directly because the unit measures the amount of radiation *absorbed* in a substance, but in radiation protection usage the two quantities (roentgen and rad) are actually fairly close. In soft muscle tissue, a 1-roentgen exposure delivers 93 ergs/gram, and in air, 1 roentgen corresponds to about 86.9 ergs/gram. Because of the difficulty in directly measuring absorbed dose in a substance, without introducing much error we can assume that for most applications 1 roentgen is equivalent to 1 rad, i.e., 1 R = 1 rad.

- *Dose equivalent.* This is a unit of dose that is used mainly by radiation safety professionals. Since all types of radiations do not exhibit the same level of biological damage per unit of energy absorbed, an empirical quantity called the **quality factor** has been developed to allow the addition of doses of different radiation types to obtain a total biologically effective dose. The higher the ionization density of the radiation, the more extensive the biological damage caused per unit of absorbed energy. Thus, x- and gamma rays and most beta radiation possess a quality factor of unity, while alpha and neutron radiations possess far larger quality factors (see

Table 13.1). The special unit of dose equivalent is the **rem**, which stands for **r**oentgen **e**quivalent **m**an. Therefore, for most common radioactive substances used in the biomedical research laboratory emitting gamma, x- or beta radiation, 1 R $\approx$ 1 rad = 1 rem.

13.4 Biological Effects of Radiation

Ionizing radiation causes biological damage by interacting with the molecules of a living organism, causing changes in their structure and function. To understand the effects of radiation in biological systems, we need to examine the physicochemical interactions of the radiation with the biochemistry of the living system.

As we have seen, when radiation (either particulate or electromagnetic) interacts with an atom of a molecule, some of the energy of the radiation is transferred to the atom. The interaction can involve either the nucleus of the atom or the surrounding electron shell. If sufficient energy is absorbed by the atom, or if it is physically changed by the interaction, it can alter the chemical structure of the molecule. This physical change then results in a chemical change that "cascades" into a biological effect. This cascade is shown in Figure 13.2.

Radiation can disturb the sensitive balance of biological systems by causing physiological or morphological changes which interfere with the cell's function or structure, resulting in **somatic damage**, or it can cause **genetic damage** by disturbing the genetic material. The degree of somatic damage to the organism depends on the dose of radiation and the types of tissues which absorb the radiation. In general, cells that are dividing and growing rapidly are the ones that are most sensitive to radiation damage. This is known as the "Law of Bergonié and Tribondeau," which states, "the radiosensitivity of a tissue is directly proportional to the reproductive activity and inversely proportional to the degree of differentiation" (42).

Radiation damage differs from damage resulting from other types of hazards, such as chemical poisoning, because, for certain types of radiation injury, there appears to be no threshold for radiation damage. Figure 13.3 illustrates a hypothetical dose-effect curve for radiation at two different levels and for a chemical agent. A characteristic feature of poisons is that they possess a threshold dose below which no adverse effect is observed. Above the threshold, the effect rapidly becomes quite apparent with doses only slightly greater than the threshold. With radiation doses, the effect gradually increases with dose, and for even very small doses, biological responses can usually still be demonstrated. Depending on organ system and injury, there is no clearly delineated threshold dose in radiation exposure, which is an issue important to radiation biologists as well as to safety personnel.

Another comparison that can be drawn is one comparing the results of consuming a cup of hot tea versus an equivalent amount of x-ray energy taken up in the body. While the energy delivered by the tea will have no adverse effect, the x-radiation dose, which contained an equal amount of energy, will lead after several days to serious illness and probably death. Thus it is not the energy itself that causes the damage but how the energy is deposited in the tissues. In fact, in terms of the mechanism and amount of energy delivered to a biological system, ionizing radiation is the most potent,* being some 50 times more effective than ultraviolet light, and about 10^8 times more effective than cyanide in terms of energy released to produce an equally deadly effect. Since cyanide is a very potent metabolic poison, in radioactivity we are dealing with an extraordinarily potent agent.

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*To appreciate the potency of ionizing radiation on a quantitative basis, we can estimate that a whole body lethal dose of radiation produces ionizations and excitations in tissue affecting about 7.7×10^{15} atoms per gram of tissue; soft tissue is composed of about 8×10^{22} atoms per gram. Therefore, the fraction of affected atoms is about 1×10^{-7}, or only one atom in every 10 million (76, p. 178).

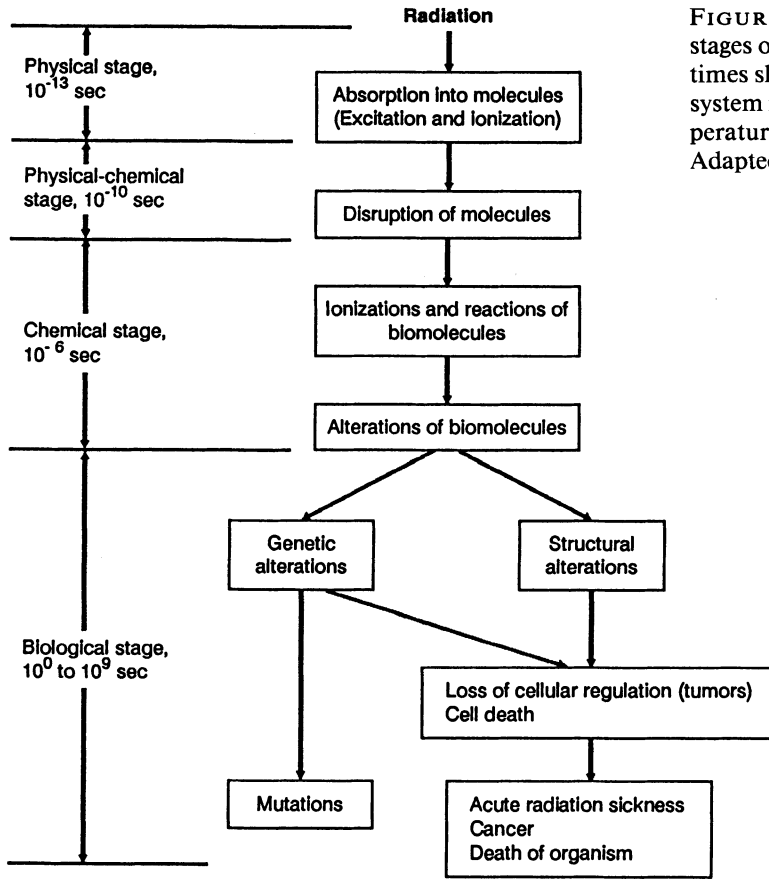

FIGURE 13.2 Temporal stages of radiation action. The times shown depend upon the system irradiated and the temperature during irradiation. Adapted from (119, p. 6).

Variations in radiosensitivity of cells

Table 13.2 illustrates the fact that there is a wide range of radiosensitivity depending on the tissue or organ involved. The most sensitive tissue is the hematopoietic, including the bone marrow, spleen, lymph nodes, and thymus. What factors determine how sensitive a particular tissue is to damage from the effects of radiation? One factor is the degree of differentiation of the cells in the tissue. This and some of the other major factors are discussed below:

- *Degree of differentiation.* The more rapidly a cell multiplies, the greater its susceptibility to radiation damage. Differentiated cells do not multiply, and are not as radiosensitive as cells which are not differentiated. Tissues which have a high cellular turnover rate (blood, epithelial) are more sensitive than those that don't (muscle, nerve).
- *Cellular metabolic levels.* Cells that have a high metabolic rate (producing products such as hormones or enzymes) are sensitive to radiation damage. This damage may not interfere directly with cellular multiplication, but it might interfere with the organism's health. Table 13.2 shows the combined effects of this and the preceding factors.
- *Enzyme levels.* Most cells possess enzyme systems that are capable of repairing some types of radiation damage.
- *Oxygen.* Oxygen is a powerful radiosensitizing agent. All other factors again being equal, cells that have a higher oxygen content are more susceptible to radiation damage than those that do not.

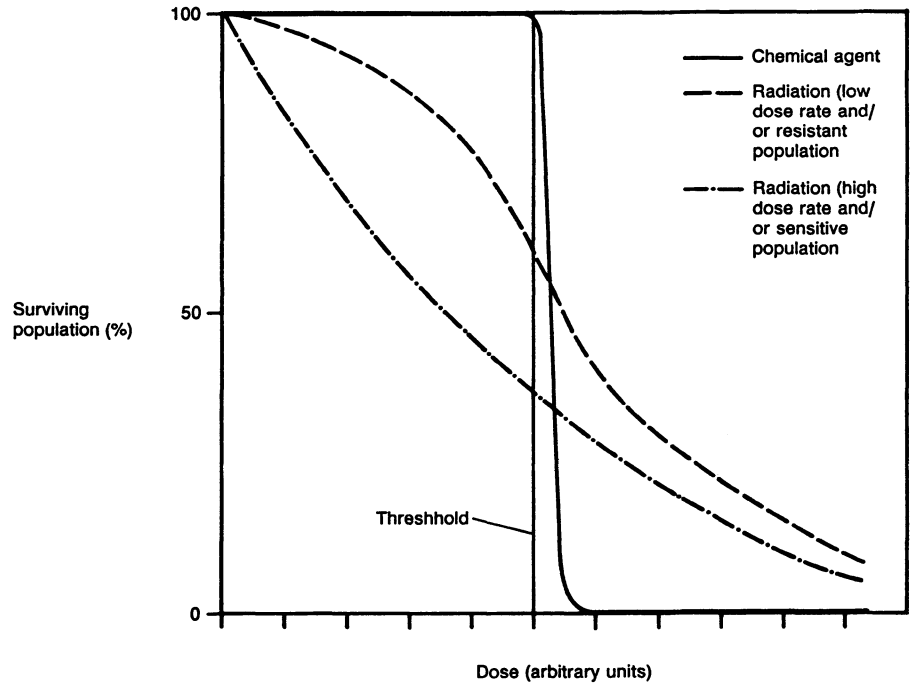

FIGURE 13.3 Dose-effect curves. These curves show the response of a population of microorganisms to ionizing radiation and to a hypothetical chemical agent.

Effects of radiation on organisms

The effect that ionizing radiation has on an organism is a function of several different factors.

- *Total dose.* The total amount of radiation absorbed by the organism is a major factor in the amount of injury sustained.
- *Time.* The time course of radiation exposure, i.e., whether the radiation was received in a single large exposure (acute) or over a relatively long period of time (chronic), is a second major factor.
- *Area absorbing dose.* The third factor is the area of the organism exposed to the radiation, i.e., whole body, partial body, or single organ exposure.

Different organisms have differing radiosensitivities to radiation. The amount of radiation needed to kill an organism is not absolute; it is a statistical phenomenon based upon factors we discussed above. Therefore, average values have been devised to express the amount of acute, whole-body radiation required to kill 50 percent of the exposed population within 30 days of the exposure. This quantity of radiation is called the **lethal dose**, and is written $LD_{50/30}$. Without treatment, the $LD_{50/30}$ for man is about 450 rad, but this is based upon limited evidence and educated estimates. $LD_{50/30}$ data obtained for other species have shown a very wide range of radiosensitivities: 350 rad for dogs, 550 rad for mice, 700 rad for bats, 1,500 rad for tortoises and about 8,000 to 20,000 rad for snails.

Radiation sickness

For a more complete understanding of radiation injury, let us consider the effects on humans of acute, high-level doses of ionizing radiation. A dose of radiation less than the $LD_{50/30}$, produces a variety of symptoms depending upon the amount of radiation received. When an individual receives an acute, whole-body radiation dose in excess of a cer-

TABLE 13.2 Relative radiosensitivity of tissues and organs[1]

Radiosensitivity	Tissue or organ	Biological effects[2]
Extremely high	Hematopoeitic tissue: Bone marrow Spleen Lymph nodes Thymus	Almost immediately (<15 min) after a dose of 50 R, white cells die. Red cell population drops after 14–21 days. Symptoms include malaise, anemia, susceptibility to infection.
Very high	Epithelial tissue	Doses of about 100 R will cause somatic death in germinal layers of epithelial tissues. This results in loss of hair, nose bleeding, intestinal malabsorption and diarrhea, sores in mouth, and other epithelial disorders.
Moderately high	Reproductive tissue	Doses of 100 R will reduce fertility, and doses of 200 to 300 R can produce infertility lasting about 12 to 15 months. Irradiation of the gonads leads to somatic changes in the germ cells and can cause mutations in future offspring.
Neutral	Gastrointestinal tissue: Small intestine Colon	Doses of 500 to 1,000 R cause degenerative changes within 30 minutes of exposure. Results of irradiation include impaired enzyme secretion, cellular degeneration and failure of absorption of nutrients, infection, dehydration from diarrhea.
Radioresistant	Vascular tissue: Capillaries Arteries and veins	These tissues have varying sensitivities, but most damage occurs in high dose ranges (600 to 1,500 R). Causes internal bleeding, bruising, nose bleeding, and changes which affect other tissues.
Radioresistant	Calcified (nongrowing) tissue: Bone Teeth	Local doses of 700 to 1,500 R can damage some parts of bone. Regeneration begins after 2–6 weeks.
Radioresistant	Pulmonary tissue: Lungs Bronchii	High doses of 1,000 to 2,000 R causes inflammation. Damage to blood vessels results in edema and hemorrhaging.
Very radioresistant	Muscle and connective tissue	High doses (in excess of 2,000 R) are required before changes in muscle tissue and connective tissue are observed.
Highly radioresistant	Nervous tissue	Massive doses of 3,000 R or greater required to damage nervous tissue. Doses in this range will cause ataxia, loss of motor coordination, and unconsciousness.

[1]One single, acute whole body or local exposure by x or γ radiation.
[2]This table assumes that 1 roentgen (R) = 1 rad.

tain level, certain symptoms tend to predominate, depending on the total dose received. These symptoms collectively are referred to as **radiation sickness**.

Radiation doses of under 80 to 100 rad will probably have no noticeable overt effect. Some changes in the blood count will probably occur, but this is the short-term extent of exposures. At about 100 rad, the threshold for radiation sickness occurs. In the range of 100 rad up to doses exceeding the $LD_{50/30}$, radiation sickness follows a pattern that depends upon the total dose absorbed. Radiation sickness is characterized by an initial period called the **prodromal period**. It lasts for up to two days following exposure and is characterized by nausea, vomiting, and diarrhea, especially for higher doses. An asymptomatic **latent pe-**

riod, lasting from five to 10 days (higher doses) to about two weeks (lower doses), follows. Following the latent period, symptoms of acute radiation sickness begin to be experienced. These are most or all of the following: epilation (hair loss), loss of appetite and malaise, fever (especially for higher doses), sore throat, hemorrhage, purpura (purple rashes caused by subcutaneous bleeding), petechiae (small purplish skin spots, again caused by subcutaneous bleeding), nosebleeds, pallor, diarrhea, and emaciation. Some deaths occur at about the 300-rad level. Survivors are convalescent for about 3 months (300 rad) to 6 months (500 rad).

Doses exceeding 100 rad tend to cause their most immediate and significant damage to certain organ systems: the blood-forming organs, the gastrointestinal system, and the central nervous system. The effect on that organ system predominates in determining the course of radiation sickness. This radiation sickness-organ system relationship is called the **acute radiation syndrome**; some of the actual biological responses to these high-level radiation exposures are shown in Table 13.2.

Delayed effects of radiation

After apparent recovery from an acute radiation exposure, an individual may experience a delayed effect as a result of this acute exposure. However, there is also evidence that *chronic* low-level radiation exposures can also result in delayed effects. Little is known about the etiology of these effects, or if any threshold exposures exist below which delayed effects do not occur, so this is an area of real concern to those who work with radioactive substances on a regular basis. Table 13.3 gives estimates of the risks to humans of various delayed effects of exposure to low-level radiation. Let us briefly look at some of these delayed effects of radiation exposure.

- *Cancer.* The mechanisms of radiation-induced cancer are not understood. Several theories have been advanced to attempt to explain the phenomenon. These include induction of an oncogene or oncogenic provirus (see Section 11.5), radiation-induced loss of cellular growth control leading to tumor formation, or radiation-induced gene transfer-misrepair mutations that may produce tumors (487). The latent period for development of cancer seems to be quite lengthy: 20 years or longer. The most common radiation-linked cancers are leukemia, and cancers of the lung, skin, and bone.
- *Heritable effects.* This is a hypothetical effect, since no cause-effect relationship has been conclusively demonstrated. However, the potential for damage to future offspring cannot be ruled out.
- *Somatic changes.* Certain late effects, such as cataracts, leukopenia (lowering of white blood cell count), and sterility, have been documented.
- *Life span.* Individuals exposed to acute, whole-body radiation early in life will probably have a shortened life span on the order of 1 to 4 days per roentgen of exposure (485, 495). Chronically exposed persons may also have a shortened life span, but there is no data available to support this conjecture.

Until now, we have been discussing the effects of whole-body irradiation exposure. Such exposures are quite uncommon, especially in the biomedical research laboratory setting. Furthermore, protection of a portion of the body from radiation dramatically increases the $LD_{50/30}$; this fact makes it possible to use localized doses of thousands of rad for radiation treatment of certain kinds of tumors.

13.5 Nonoccupational Exposure to Radiation

Radiation is present everywhere. Humans are exposed to sources of ionizing radiation from the earth, from interstellar space, from medical diagnostic procedures, from man-made radiation from power plants or fallout from nuclear-bomb testing, or even from consumer products. This exposure can be classified into the following four categories: naturally occurring radiation, radiation from products of technology, radiation from consumer prod-

TABLE 13.3 Probability of delayed effects from low-level radiation exposure

Delayed effect	Probability of effect occurring	Reference
Cancer		
Bone	4 to 8 × 10^{-6}/70 yr period per rem dose received over 70-yr lifespan (10% of dose is from background radiation)	65, 485
	0.5 × 10^{-6}/rad for age-averaged population and normal life expectancy	99
Leukemia	2 × 10^{-6}/rem exposure per year[1]	63, 95
	21.5 × 10^{-6}/rad for age-averaged population and normal life expectancy	99
Other cancers	<250 × 10^{-6}/70 yr period per rem dose	62
	95 × 10^{-6}/rad for age-averaged population and normal life expectancy	99
Total cancer risk	120 × 10^{-6}/rad for age distribution of U.S. population	99
	160 to 450 × 10^{-6}/rem, lifetime distribution[2]	316
	200 × 10^{-6}/rem, lifetime distribution[2]	233
	150 to 350 × 10^{-6}/rem, lifetime distribution[2]	485
Heritable effects	Doubling dose (double the natural mutation rate) estimated to be 40 rem to entire population for single generation	316
	110 × 10^{-6} eventual cases of genetic disease per rem of exposure	100
Other somatic effects		
Cataracts	Doses in excess of 1,000 rad of x- or gamma radiation required	485, 495
Life span shortening	Approximately 1 to 4 days/roentgen exposure early in life	485, 495
Degeneration of organs	Probably does not exceed cancer incidence	62, 65

[1]Incidence peaks after a latent period that probably varies according to dose.
[2]Corrected from data for premature deaths to account for all cancer instances.

ucts, and radiation from medical devices and diagnosis. Table 13.4 gives the average annual exposure rate in the United States for nonoccupational exposure produced by these sources.

Sources of radiation occurring naturally include **cosmic radiation and terrestrial radiation.** Cosmic radiation is of either galactic origin or solar origin. Cosmic radiation from the sun (solar flares) does not possess sufficient energy to cause a significant dose contribution at ground level. Galactic cosmic rays interact with air molecules, producing a secondary shower of a large variety of subatomic particles and the **cosmogenic nuclides**, ^{7}Be, ^{22}Na, and ^{24}Na, tritium, and ^{14}C. Terrestrial sources of natural radiation are called **primordial radionuclides**: these are the long-lived isotopes that are part of the earth's crust or biosphere. The main constituents of this group of natural radioactive sources are ^{238}U and ^{232}Th, together with their unstable decay products, and ^{40}K.

In addition, almost every mineral contains some radioactive atoms. Minerals are found in construction materials, such as concrete and granite, and contribute to nonoccupational exposure.

Internal doses from natural radionuclides are primarily caused by ingestion or inhalation of compounds containing tritium, ^{14}C, ^{40}K, or daughter products of ^{238}U, and ^{232}Th. ^{222}Rn is a decay product of ^{238}U, whose release from the ground into basements of residences has recently become recognized as a significant health problem in many areas of the northeast and Great Lakes states of the United States. The average annual absorbed dose to the lungs from all natural sources has been estimated to be about 110 millirad/year (485).

A portion of the nonoccupational exposure

TABLE 13.4 Total annual radiation dose from nonoccupational, environmental sources*

Source	Dose (mrem/year)
Medical use	
Diagnosis	77
Dental	1.4
Radiopharmaceuticals	13.6
Total	92
Natural background	
Cosmic	28
Terrestrial	26
Internal	28
Total	82
Technological development	
Fallout	5
Power plant and nuclear industry	<1
Building materials	5
Television sets	0.5
Aircraft travel	0.5
Total	12
Grand total	***186***

*Data compiled for USA population.
Source: (316).

everyone receives is the result of new technology. The term for this form of exposure is **technologically enhanced radiation**. Examples include air travel, nuclear power, fallout, use of natural gas for heating or cooking, or living near a coal-fired power plant.

The use of **consumer products** that contain radioactive sources can contribute to nonoccupational exposures (320). Examples of consumer products incorporating radioactive materials are radioluminescent indicators (timepieces, signs, instrument dials), ionization smoke detectors, anti-static devices, dentistry porcelains, pottery glazes, incandescent gas mantles, and tobacco products. Low levels of radiation are also generated by such sources as color television tubes, but emissions are well controlled and the glass of the picture tube is sufficiently thick to absorb most of this radiation.

The fourth environmental source of radiation is from exposure to **medical diagnostic and therapeutic devices**. X-ray exposures used for medical and dental diagnosis, and therapeutic doses, are additional exposures that add to the individual's total exposure.

13.6 Risk Assessment for Radiation Safety

More than any other laboratory hazard, research involving radioisotopes probably generates the most public concern. In fact, a survey (418) of three lay groups on relative risks of various activities revealed many misconceptions. In the survey, the highest risk rankings were assigned by the public to issues that have had a high public visibility through news media coverage, and nuclear power was ranked first by two of the three groups (its actual ranking was 20 out of 30). This high visibility tends to produce overestimates of risk. Risk perceptions associated with exposure to radiation provide an illustration of the degree of misestimation of the actual level of risk. One study has determined that radiological workers exposed to the industry-wide average of radiation exposure (which is 0.35 rem per year) are among the safest of all industry groupings (425).

The risk of injury resulting from exposure to low levels of radiation or other hazards can be assessed by addressing several questions.

- How is the effect on health influenced by the manner in which the dose is received? The frequency of the dose and its size must be considered.
- Is the effect on health reversible or irreversible?
- Is the effect on health characterized by a single injury which does not progress, or are the effects progressive?
- What relationship exists between the dose, the frequency of biological inactivations (ionizations) and injury? Can any threshold be detected?
- What is the relationship between the injury and personal factors such as age at exposure, physical condition, sex, and genetic susceptibility?
- What is the relationship between the injury and external factors such as exposure to

chemical agents? Are synergistic interactions known or suspected?

As you might expect, answers to many of these questions are difficult, if not impossible, to obtain. There are two possible general types of long-term responses to radiation exposure. One type, probablistic in nature, is based upon the frequency of inactivating ionizations as a function of the dose received; injury probably consists of nonlethal damage to individual cells, and no known threshold exists. The probability of contracting the condition—but not its severity—is dependent upon the dose. Such injuries probably include heritable effects and induction of cancer. A second type of response is deterministic in nature, depending upon both the frequency of biological inactivations and their magnitude as a function of the total dose. Thresholds have been observed in this type of response, which probably results from extensive destruction of cells in affected organs. Here the severity of the condition is proportionate to the radiation dose. Examples of injuries exhibiting a threshold response include sterility, cataract of the eye, and damage to blood-forming organs. Teratogenic effects probably have components of both responses. Any attempt at determining the individual's response to radiation exposure must take into account these injuries and their probabilities, a decidedly difficult undertaking.

To put the level of risks we are talking about into some perspective, let us consider relative shortening of lifespan as a consequence of engaging in various activities or exposures to various risks. Table 13.5 gives this data and allows ranking of risk of lifespan shortening resulting from radiation exposure along with risks from engaging in other activities. This data is most effective if it is used to compare risks between activities and is not as meaningful if individual numbers are used in isolation.

The question of the existence of a threshold dose of radiation required to produce a long-term effect has been argued for over 30 years, since G.B. Lewis first postulated a linear relationship between dose and cancer induction

TABLE 13.5 Reduction of life expectancy

Cause	Days[1]
Being unmarried (male)	3,500
Cigarette smoking (male)	2,250
Heart disease	2,100
Being unmarried (female)	1,600
Being 30% overweight	1,300
Cancer	980
Being 20% overweight	900
Having less than 8th grade education	850
Cigarette smoking (female)	800
Stroke	520
Cigar smoking	330
Dangerous jobs—accidents	300
Pipe smoking	220
Increased food intake—100 cal/day	210
Motor vehicle accidents	207
5 rem per year for 30 years, calculated	150
Pneumonia, influenza	141
Use of alcohol	130
Home accidents	95
Suicide	95
Diabetes	95
Being murdered	90
Misuse of legal drugs	90
Average jobs—accidents	74
Drowning	41
Job with radiation exposure	40
Falls	39
Pedestrian accidents	37
Safest jobs—accidents	30
1 rem per year for 30 years, calculated	30
Fire—burns	27
Use of illicit drugs	24
Poison	18
Suffocation	13
Firearms accidents	11
Natural radiation[2]	8
Poisonous gases	7
Medical x-rays	6
Drinking coffee	6
Use of oral contraceptives	5
Natural disasters, combined	3.5
Drinking diet drinks	2
1 rem occupational dose, calculated	1
Reactor accidents	0.02
Radiation from nuclear industry	0.02
1 mrem occupational dose, calculated	0.001
Periodic Pap test	−4
Smoke alarm in home	−10
Air bags in car	−50
Mobile coronary care units	−125
All safety improvements, 1966–76	−110

[1]Quantitative values only to be used to compare one risk with another rather.
[2]From (316).
Adapted from (97).

(268). Thus it is assumed that the long-term sequelia of radiation exposure fall into two categories: threshold, consisting of carcinogenesis and heritable effects, and nonthreshold, consisting of certain somatic effects, such as cataract production, leukopenia, fertility impairment, and organ damage.

What are the quantitative aspects of risk in low-level radiation exposures? The data are at best uncertain (see Table 13.3), but estimates have been calculated from such human experience as medical x-ray (diagnostic and therapeutic), radiation accidents and inadvertant exposures, data from nuclear tests and from the Japanese experience, and similar sources. Because of the presence of many variables, these data are subject to a wide margin of error. Regulatory agencies have derived limits of exposure based upon a linear dose-response relationship and have assumed that no dose threshold exists. This approach is the most conservative, and will limit the risk to produce the smallest individual risk in all cases (346).

How is the actual incidence of cancer caused by radiation exposure actually related to the total incidence of cancer, and can it be reduced? One study (235) showed that of the total number of cancer fatalities in the United States in 1975 resulting from radiation, only 2.7 percent of the ongoing exposures would result in low-level radiation-induced cancer fatalities. Most arise from natural background radiation or medical exposures. The only significant change that could be made to alter this number is to attempt to modify the incidence of medical exposure. Since most exposures to medical radiation are undertaken to benefit the individual, and presumably other adverse health effects would result as a consequence of withholding the exposure, limiting medical exposures would probably not reduce the total overall mortality.

Finally, no discussion of risk of injury caused by low-level radiation exposure should neglect to mention the many factors that influence individual response to the effect of radiation exposure, or the fact that unknown or poorly understood factors may cloud statistics, thus masking true correlations. Some of these factors include variation of cancer rates according to geographic location and individual race, the so-called "healthy worker effect," calendar year and age variation of cancer mortality, statistical limitations, use of proportional mortality rates, cigarette smoking—cancer correlations, correlations between radiation exposure and other factors that may cause cancer, and others (98). Let us examine some of these factors.

- *Geographical variations.* Different areas of the world have differing background radiation levels resulting from factors like altitude and geology. However, it is difficult to find suitable control groups to measure the actual effect of a higher local background.
- *Healthy worker effect.* Sociologists and occupational health specialists have known for some time about the strong correlation between steady employment in a large organization and good health. This phenomenon has been termed the "healthy worker effect."
- *Chronological variations.* Other factors to be considered include the calendar year used as the base for cancer mortality rates, and the individual age variation at death, which corrects for age-based mortality rates for different diseases.
- *Statistics.* The usual problem with obtaining good statistics for assessing exposure data is the inadequacy of a sample of a population that has had a high enough exposure so that the effect can be observed. The lower the probability of an adverse health effect, the larger the required population size in order to detect the effect at a sufficiently high confidence level.

13.7 Guidelines for Occupational Exposure

Within a few years of the discovery of radiation, the dangers of radiation exposure began to become apparent. As time passed and further information about the biological effects of radiation exposure was discovered, standards-setting organizations, such as the International Council on Radiation Protection (ICRP), were formed to study data on the bi-

ological effects of radiation and to recommend limits for human exposure. These organizations put forward guidelines for people who work with radiation about the maximum amount of exposure that could safely be received, based upon various factors, such as age, duration of exposure, and reproductive status. These guidelines have been accepted by the governments of many nations, including the United States, for occupational exposure to radioactivity. Also, the decision was made to set higher exposure limits for occupationally exposed individuals than the general population. There were several reasons for this decision.

- *Risk vs. benefit.* Individuals receiving occupational exposures accept a small risk which can be balanced against the benefit they gain through employment.
- *Selection of those exposed.* Only selected individuals will be allowed to receive occupational exposures. Medical histories and prior occupational exposure histories should be obtained and maintained; minors and fertile or pregnant women could be excluded from such employment; also, individuals beyond the reproductive age can be preferentially chosen for certain occupations.
- *Limitation of exposure.* The total number of radiation workers is far less than the total population, thus limiting potential damage to the entire human gene pool.

The fact that there is a putative benefit to society from work with radiation (e.g., medicine, research, power generation, etc.) coupled with the desire to limit exposure to a minimum has given rise to the goal of limiting occupational radiation doses to quantities "as low as readily achievable," which is abbreviated as ALARA. Note that this does not mean "as low as possible," since the economic benefits of the use of radiation are considered as well as the individual risks. Therefore, in considering the permissible occupational dose, an attempt is made to limit the occupational dose to as low a level as is possible while also taking into account the social and economic benefits of any remaining dose.

The current occupational dose guidelines were developed in 1957 and have remained basically unchanged since that date. The guidelines were based on the assumption that the greatest danger of occupational exposure results from its heritable effects. Therefore at that time geneticists felt that radiation workers could reasonably receive a total lifetime cumulative dose to the reproductive organs of up to 50 rem by age 30, because by this age statistics showed that over 50 percent of their children will have been born. By age 40, the cumulative dose should be limited to up to 100 rem, since by this age over 90 percent of their children will have been born. Finally, individuals of less than 18 years are not to receive any occupational radiation exposure whatever.

However, these rules would have effectively limited the permissible occupational dose to about 5 rem per year, a level that many researchers felt was too restrictive. In order to satisfy some of these concerns, and to strike a balance between practical limits, benefits to the employer and employee, and concern for future offspring of radiation workers, an age-proration formula was developed by the ICRP. This formula is based on the principle that no occupational exposure is permitted to individuals under 18 years of age, and allows an individual worker to receive up to 3 rem in 13 consecutive weeks, provided that the total accumulated lifetime dose does not exceed $5(N-18)$ rem, where N is the age of the individual. Furthermore, it is expected that the permitted 3-rem per 13-week exposure will be distributed in time as uniformly as possible. Table 13.6 shows radiation exposure limits for both occupational and nonoccupational doses based on current regulatory guidelines. It illustrates that the maximum radiation exposure a worker may receive varies depending on the area of the body that is exposed. Recently, new analyses of the delayed effects on survivors of the bombing of Hiroshima and Nagasaki have detected significant errors in the data on effects of radiation on survivors (367). These new findings will probably result in the reexamination of cancer risks from low

TABLE 13.6 Maximum dose permitted by the U.S. NRC for occupational and nonoccupational exposure*

Area of body exposed	Maximum dose permitted[1]	
	Per calendar quarter	Per year
Occupational exposure		
Whole body[2]	1.25[3]	5
Skin (any portion)	7.50	30
Extremities (hands, forearms, feet, ankles)	18.75	75
Thyroid gland	7.5	30
Major organs (those not listed above)	3.75	15
Fetus (occupationally exposed pregnant woman)		0.5[4, 5]
Nonoccupational exposure		
General public (10% of the permitted maximum occupational dose), in addition to natural and medical sources		0.5

*These are the limits adopted by the Nuclear Regulatory Commission (NRC), Title 10, Part 20, Code of Federal Regulations.
[1]Maximum, in rem
[2]Defined as including any of the following: head and trunk; blood-forming organs; lens of eye; gonads.
[3]A whole body dose of up to 3 rem/quarter is permitted, provided that when added to the accumulated lifetime occupational dose, will not exceed 5(N−18) rem (where N is the age of the individual).
[4]Total during gestation period (472).
[5]Fertile women should be employed in positions where the annual dose is not likely to exceed 2 to 3 rem at a comparatively steady rate to prevent excessive exposure to the fetus before pregnancy is determined.
From (319, 463).

levels of radiation, and may lead to changes in the regulatory guidelines.

Hazards of internal exposure

The goals of radiation protection techniques are two-fold: to minimize exposure to both internal and external sources of radiation. The first goal is based on the fact that radiation-emitting substances that are ingested or otherwise enter the body can be extremely hazardous, far more hazardous then a comparable external exposure. This is true not because the radiation itself is any more damaging when inside the body; the hazard lies in the fact that a very small amount of radioactive material in very close continuous contact with body cells can cause a large amount of local damage. Also, the body tends to concentrate certain chemicals in particular organs: for example, radioiodine will be concentrated in the thyroid, while calcium is concentrated in the bone. Thus, even a very small internal concentration of radionuclide can result in a large dose, and the radioisotope may be difficult or impossible to remove. The depositing of alpha emitters into the lungs by inhalation, for example, will result in lung cancer.

The effective half-life

Radioisotopes may enter the body by inhalation, ingestion, or by passage through the skin via absorption, cuts, punctures, or abrasions. Once an isotope is in the body, the rate of reduction of internal radioactive levels is a function of two different decay processes: physical half-life and biological half-life. We have already discussed the concept of the physical half-life in Section 13.3. Biological half-life is a related concept: it is the amount of time required for the quantity of any substance in the body to decline through excretion to one-half of its initial level. For radioactive substances present in the body these processes combine to produce the **effective half-life**, which will be discussed further in Section 13.9. The use of radiation protection techniques that minimize the possibility of taking isotopes into the body should be stressed in every organization's training and safety policies. These techniques will be discussed in detail in Section 13.9.

13.8 Control of External Exposure

Earlier in this chapter we discussed the concept of ALARA, that is, of limiting exposure to quantities as low as readily achievable. This

concept forms the underlying principle of assessing all exposures to radiation. How does a laboratory worker limit exposure to radiation, when the use of radioisotopes is part of the job? Quite simply, one avoids as much exposure to the material as possible, through control of three primary factors for limiting external exposure: time, distance, and shielding.

Time

The total dose received by an individual is directly related to the length of time that individual is exposed to the radiation and reducing exposure time achieves its greatest significance when working with high-energy sources. The relationship is quite simple:

$$\text{Total dose} = \text{Dose rate} \times \text{Time}$$

Therefore, to limit the total dose received, the exposure time should be reduced as far as possible. By practicing unfamiliar experimental techniques without radioisotopes ("dry runs"), one can limit the exposure while becoming familiar with the protocol. However, do not look at this as license to rush through procedures in order to limit your exposure. First, the low-energy beta emitters—^{14}C, tritium, and ^{35}S—will pose no risk of accumulating a dose provided the source is kept more than several centimeters from the individual's skin; and second, any reduced time gained by rushing will subject the worker to greater risk from accident.

Distance

The propagation of radiation follows the inverse square law. That is, the dose intensity decreases as you move further away from a point source of x- or gamma radiation according to the following relationship: the intensity is proportional to the inverse of the square of the distance, and the intensity is equal to the original intensity divided by the square of the distance.

Since alpha and beta particles have definite maximum ranges in air, the intensity of these radiations decreases rapidly as one moves away from their source, until the maximum range is reached, whereupon the intensity drops to near zero. If the source is not a point source, or if the size of the source is a significant fraction of the distance to where the dose rate is to be measured, then the attenuation of the radiation level is somewhat less than an inverse square relationship. For example, for a linear source, the dose rate I is proportional to the inverse of the distance ($I \propto 1/d$) (24). Calculation of the expected exposure rate of gamma emitters is made possible by using the **specific gamma constant** (symbol Γ) for each radioisotope. This quantity is the exposure rate (R per hour) for one curie of radioisotope at a distance of one meter.

The fact that the intensity drops rapidly as a function of increasing distance is very important in reducing exposure to radiation. The use of tongs or forceps for manipulating a vial of radioactive compound rather than one's hands can reduce the dose to the fingers by a factor of 100 or more for most gamma emitters and for ^{32}P. A separation of 10 centimeters can reduce the dose rate to near zero for low-energy beta emitters, such as ^{14}C or ^{35}S. Another use of distance as a personal protective measure includes the separation of work, storage, and disposal areas from traffic areas or from desks or nonradiation ("clean") work areas. Another technique that can be used is placement of the radioactive material as far from the worker as the space and arrangement of the experiment permits. Clearly, the use of distance as a personal protective technique can be very important in limiting radiation dose.

Shielding

The third major technique for limiting personal radiation dose is the use of shielding. This technique is especially useful when the use of distance as a protective measure is not practical. In fact, the use of shielding is probably the most frequently used technique of reducing exposure. Limiting exposure to alpha and *most* beta radiation is the easiest to achieve through the use of shielding, and as we discussed above, exposure to them can also be limited quite well through the use of distance, making shielding superfluous. However,

while most alpha and beta particles have very short ranges in virtually all materials, certain beta emitters, including ^{32}P, and x- and gamma rays are capable of significant penetration of matter. High-energy beta emitters, of which ^{32}P is the most important, produce secondary x-radiations (bremsstrahlung, see Section 13.2), which in turn can be quite penetrating. Lower energy beta emitters do not produce particles capable of significant penetration of matter. Therefore, beta shields are used for higher energy emitters and are made of materials such as aluminum, lucite, wood, or other materials of low molecular weight which minimize bremsstrahlung production. Beta particles have a definite range in matter depending upon their energy, as Figure 13.1 illustrated. Unlike beta particles, the penetration of gamma and x-rays declines exponentially in matter, and the efficiency of matter in absorbing these radiations is dependent upon the density and the electron density of the absorber. Lead, concrete, and steel are typically used. The attenuation characteristics of x-ray or gamma absorbers allows the determination of the thickness of material required to reduce intensity to half of its initial value. This quantity, lists of which are published in handbooks that contain radiation data, is termed the **half-value layer**. As an example, the half-value layer thickness of lead for ^{131}I is about 3 mm, and of concrete (density = 2.36 g/cm^3), 32 mm. In contrast, the HVL of air for ^{131}I is about 56 meters.

The characteristics of the shielding used in a laboratory should take into account the physical size and total activity of the source, and the nature and energy of its emissions. For alpha and low-energy beta emitters, the use of shielding is usually not necessary. If shielding is needed, its size can be minimized by positioning it close to the source. For small sources the size of the shield required increases as the square of the distance to the source (the inverse square law again). Furthermore, the source will need to be shielded to the rear and to the sides (even if these may be room or fume hood walls) so that someone on the other side of a wall or fume hood is not unnecessarily exposed to radiation. In addition, radiation may scatter and be reflected over or around the shield and can also pass through the lab bench or fume hood work surface and expose the lower portions of the body.

The shielding must be placed so that a balance is struck between accessibility to the work and personal protection, but exposure to the eyes and head must be avoided. Finally, workers must remember that although shielding is the most versatile method of reducing exposure to radiation, it has its disadvantages. These include the expense of the shielding materials, impediments to working with the experimental materials, weight and/or bulk of materials in the work areas, and the potential for contamination of the shielding material.

Other control factors

In addition to the primary exposure-limiting factors of time, distance, and shielding, there are some additional factors that are important for enhancing personal safety:

- *Substitution.* Obviously, if it is possible to perform the experiment without the use of radioactive substances, then all exposure is avoided. For example, the ELISA (Enzyme-linked immunosorbant assay) technique has replaced that of RIA (Radioimmuno assay) for many procedures.
- *Containment.* Containment techniques were described in Chapter 10 for working with hazardous biological agents. The same principles also apply to the containment of radioactive materials, through the use of control methods, such as working over absorbent paper in a low-sided tray to control spills, using fume hoods to contain radioactive vapors or aerosols (see Section 12.14), traps to prevent the release of large quantities of radioactive gases or vapors (tritiated water, $^{14}CO_2$, $H^{125}I$, etc.), and protective clothing such as gloves.
- *Radioactivity surveys.* The surveys that the U.S. Nuclear Regulatory Commission (NRC) requires will help to prevent excessive exposure by identifying spills of radioactive materials or radiation from improperly shielded sources (see Section 13.10).

13.9 Control of Internal Exposure

Why should a radioactive substance that is introduced *into* the body be of greater concern than a similar amount of isotope producing an external exposure? Part of the answer is the result of the fact that radiochemicals are important in biological research because they are useful for probing biological function. This means that these substances also can easily move throughout the body no matter whether they were introduced through ingestion, inhalation, absorption through the intact skin, or taken up through cuts, punctures, or abrasions.

There are two major ways in which the uptake of radiochemicals can produce damage. First, the damage the radiation itself causes will result in an injury, and because it is inside the body, the radiation source is in constant and intimate contact with body tissues, thus producing the maximum possible damage. Virtually all of the energy of the ionizing particle or photon is deposited in the surrounding tissues, and since many radionuclides tend to concentrate in specific organs of the body, the potential for significant damage to particular organs is great. Second, the atomic transmutation that results when the radioactive atom decays will alter the chemical nature of the molecule of which that atom is a part, thus resulting in a chemical change. As an example, consider that a ^{14}C atom in DNA decaying to stable ^{14}N could potentially result in a point mutation. This mechanism of injury has been postulated and both discounted (230) and supported (434), but it probably does account for a relatively small amount (about 10 percent) of the damage to the cell (382).

Once a radioactive chemical is introduced into the body, little can be done to speed its removal. Some removal will eventually occur as a result of excretion (urine, feces, perspiration, or expired air) and the activity will diminish as a result of radioactive decay. The **effective half-life** of a radioisotope depends upon both its physical half-life (radioactive decay) and its biological half-life (biological elimination), and is defined as the time required for a radionuclide in the body to be reduced by 50 percent as a result of both radioactive decay and biological elimination, according to the following equation:

$$T_{eff} = (t_r \times t_b)/(t_r + t_b)$$

Where T_{eff} is the effective half-life, t_r is the physical (radiological) half-life, and t_b is the biological half-life.

As we stated earlier, radiochemicals that are taken up into the body will become distributed throughout the body or concentrated in an organ, depending on the chemical specificity of the particular isotope. The organ most likely to suffer the greatest amount of biological damage upon the internal uptake of a radioisotope is referred to as the *critical organ.* This is analogous to the use of the term "critical organ" in reference to toxic chemicals in Section 12.4. The amount of radioactivity in the body of an individual that produces the maximum allowable occupational dose of 5 rem per year (under United States law)* to the critical organ is known as the **body burden** for that isotope. Table 13.7 shows the maximum allowable body burdens for some isotopes commonly used in biological research. Note that isotopes that tend to distribute more or less uniformly throughout the body have a higher permissible body burden (e.g., tritium and ^{14}C), while those that are concentrated in a particular organ have a smaller permissible body burden (e.g., radioiodine). Another major factor determining the size of the permissible body burden is the energy of its radioactive emission. Thus ^{35}S, a low-energy beta emitter that concentrates in a small organ, the testis, has a higher permissible body burden than ^{32}P, a high-energy beta emitter that is concentrated in the bone, which is a far larger organ than the testis and is more dispersed in the body.

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*In the United States, the Nuclear Regulatory Commission (NRC) is responsible for administering the laws and regulations pertaining to radiation exposure, the use of radiation-producing equipment, and all aspects of handling artificially produced radioactive materials. In addition, state laws exist that may further regulate these areas.

TABLE 13.7 Maximum allowable occupational body burdens for selected radioisotopes

Radioisotope	Critical organ	Effective half-life in critical organ (days)	Maximum allowable body burden (μCi)
Tritium (as tritiated water)	Body tissue	12	1,000
^{14}C (as CO_2)	Fat	12	300
^{32}P (soluble)	Bone	14.1	6
^{35}S (soluble)	Testis	76.5	90
^{125}I (soluble)	Thyroid	32	0.57
^{131}I (soluble)	Thyroid	7.6	0.7

Adapted from (231, 498).

Internal exposure to radiation can be controlled through careful laboratory practices and the most important ones are described below. Many of these practices are similar to those used for controlling biological hazards that were covered in Chapter 11. This is because many of the principles that apply to control of biohazards also apply to control of internal radiation exposure.

- *Contain materials.* Be certain the radioactive material is well contained. Utilize proper methods to avoid production or release of gases or vapors, such as working in fume hoods, using drip trays lined with absorbent paper, and wearing gloves and other protective clothing as the procedure dictates. Keep in mind the ideas of primary and secondary barriers (see Section 10.1).
- *Limit quantities.* Use only the minimum amount of radiochemicals required for the experiment. Return stock radiochemicals to storage areas as soon as possible, thereby reducing the chances of a large spill and a major decontamination problem should an accident occur.
- *Follow procedures.* Always follow established laboratory protocol. Use designated work areas, proper equipment, proper protective equipment, and appropriate experimental techniques. Perform the required contamination monitoring after completion of the work and at the appropriate intervals in the laboratory. These principles will be covered in the following section.

13.10 Use of Monitoring and Surveying Devices

Personal monitoring devices

Control of radiation exposure is achieved primarily through the careful handling of radioactive materials and the use of proper procedures. However, the principles of ALARA, quantities as low as readily achievable (see Section 13.7), do allow for the worker to become exposed to small, but finite, doses. To avoid exposure to doses that exceed the U.S. Nuclear Regulatory Commission (NRC) guidelines, and to detect unanticipated or accidental exposure, personal monitoring devices must be used (Figure 13.4). However, a dosimeter is not meant to "protect" or "warn" a worker; rather, it is intended to measure the amount of radiation to which the person has been exposed. There are three basic types of personal monitoring devices, or dosimeters: the pocket dosimeter, the thermoluminescent dosimeter (TLD), and the film badge. The first one is rarely used in the biomedical laboratory, while the other two are commonly used there.

In the U.S., the use of a dosimeter is required by the NRC if it is likely that a laboratory worker may become exposed during any calendar quarter to a dose greater than that listed in Table 13.8. However, users of low- to medium-energy beta emitters (e.g., tritium, ^{14}C, ^{35}S) need not wear a dosimeter as none will respond to the radiations of these materials. The dosimeter record must become a permanent and legal part of the radiation

FIGURE 13.4 Individual dosimeters. These are some of the devices used to measure the exposure dose received by a worker. Front, ring dosimeter; second row, dosimeter film; third row, film badge holders—empty, open, and loaded with film; back row, pocket dosimeter and charger/reader.

TABLE 13.8 Minimum dose that requires personal monitoring

Area of body exposed	Dose (mrem)[1]
Whole body (head and trunk),[2] blood-forming organs, gonads, or lens of eye[3]	300
Extremities[4] (hands, forearms, feet, ankles)	4,700
Skin of whole body	1,875
Radiation area[2] where dose rate per hour equals or exceeds	100

[1]If the dose received during a calendar quarter is likely to be greater than the value shown the worker must wear a dosimeter.
[2]Use whole-body film badge or TLD badge.
[3]Use film or TLD badge clipped to goggles; alternatively, a whole-body badge can be clipped to the collar under certain conditions.
[4]Use TLD ring for hands. Turn clip inward (toward palm) for work with ^{32}P.

worker's occupational exposure record. The three types of dosimeters are described below:

- *Pocket dosimeter.* These devices are about the size of a pen and are carried in a shirt or lab coat pocket, and are of primary use in high radiation areas (e.g., x-ray machines, gamma sources). They are essentially ionization detectors and need a separate device to recharge (reset the indicator to zero), or in some cases, also to read the device. Pocket dosimeters are only sensitive to x-rays or gamma rays and not to beta particles, and do not produce a permanent record of the exposure reading. They are also subject to inaccuracy resulting from discharge leakage and mechanical shocks, but they do provide a rapid indication of dose received, especially if the unit is direct-reading (on a scale viewed by looking through the tube much like a telescope).
- *Thermoluminescent dosimeter (TLD).* Widely used for external dose monitoring, these devices consist of a small chip or a small quantity of powder. TLDs work on the principal of excitation of the atoms in the crystal: the energy deposited in the crystal by the incident radiation is released as light when the crystal is heated (see Section 13.2). The quantity of released light is measured and the dose calculated. The TLD chip is placed in a ring to be worn on a finger or holder which can be worn elsewhere, such as clipped to the frame of safety glasses. TLDs are most frequently used in conjunction with a film badge: the badge is used to record total whole-body exposure, and the TLD records the exposure to the extremity. The advantages of the TLD are its small size, a response to radiation that is energy-independent over a wide range, an ability to respond to a wide range of dose rates and total doses, and a low sensitivity to humidity and heat. On the other hand, TLDs are susceptible to error if damaged or contaminated with foreign matter, and the act of reading the TLD destroys the exposure information so that no permanent primary record of the dose is preserved for reinterpretation or further analysis.

- *Film badge.* The film badge is extremely versatile, is inexpensive, is sensitive to a wide range of doses and dose rates, and can measure most of the different types of radiation reasonably well. Identification of radiations is accomplished through the use of filters of different materials that are placed on both sides of the film. Their function is to differentially absorb energy from the incident radiation, thus allowing the film to be used to determine the type and energy of the radiation to which it was exposed. Because the film is not destroyed when the exposure information is determined, it can become a permanent record of the exposure and can be referred to and reread at a later date. The disadvantages of the film badge include a sensitivity to heat and humidity, a limited wear period (generally 30 days) caused by alterations in the latent image as the film ages, and a response that is dependent upon the radiation energy, which is most apparent for low-energy radiations.

There has been much discussion about the proper place(s) to wear a whole-body dosimeter, such as the film badge. Places suggested have included at the collar, chest level, and waist level, both inside any protective apron or outside of it. Arguments have been made supporting all points of view. Some situations may require that multiple dosimeters be worn. However, the most important point to remember is that radiation workers must be educated in the use of these dosimeters, and the radiation safety department or office must establish clearly defined standards to be followed at the facility to ensure that all users of radiation are wearing and handling their dosimeters in a proper and uniform fashion. In the United States, some states specify the location(s) that dosimeter(s) are to be worn, and certain NRC regulations cover the need for wearing multiple dosimeters.

Measurement of *internal* absorption of radioisotopes is more difficult and less direct. The method used depends upon the chemical nature of the isotope and how it is eliminated from the body. Most common isotopes, such as tritium or ^{32}P, are eliminated in the urine and therefore the urine can be analyzed to determine the total quantity of isotope present in the body. Radioiodines, which are gamma emitters, are concentrated in the thyroid, so an exposure can be detected by placing a gamma probe over the thyroid to obtain a total count. However, dealing with individual cases of internal radiation exposure is a matter that should be left to the institution's radiation protection officer or health physicist.

Instruments for surveying radioactivity

Unlike most biological and many chemical hazards, which usually do not present any outward sign of danger, all radioactive materials have a characteristic trait: radioactive emissions. Since these emissions usually can be detected by instruments, spills or contamination from these substances can be located as long as the amount is sufficiently high. The only major exception to this is tritium contamination, since its energy of emission is too low to be detected by portable instruments. Its presence can only be indirectly detected, and then only if the contamination is removable, as we will see later in this section.

It is necessary to choose monitoring equipment with care, since not all equipment is equally efficient at detecting all types of radiation. There are three basic types of **portable radiation surveying instruments** (Figure 13.5).

- *Geiger-Mueller instruments.* Of all the surveying instruments, the ratemeter equipped with a G-M probe is the most popular, and models that can be equipped with other specialized probes are the most versatile. With the proper probe, this detector is capable of responding to medium- and high-energy beta particles (tritium cannot be detected) with varying efficiencies (sensitivities), and can detect medium- to high-energy gamma radiation as well. The best probe for contamination surveys is the so-called "pancake" probe with a thin window (window density thickness of about 1 milligram per square

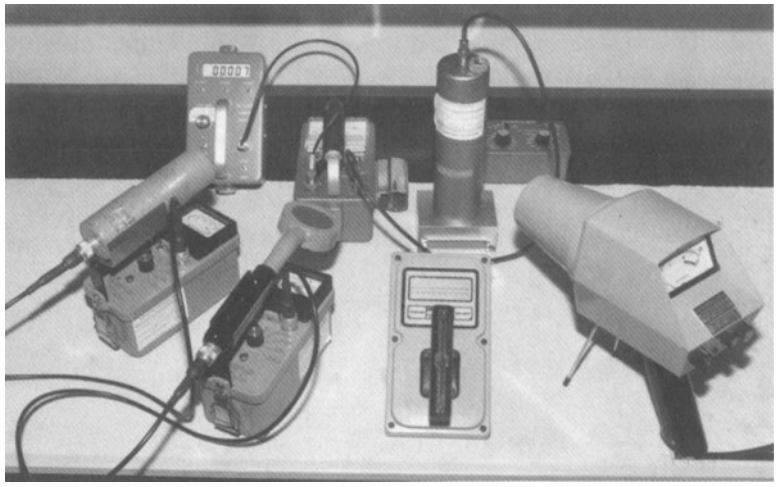

FIGURE 13.5 Monitoring and surveying instruments. These are used to detect spills and stray radiation. Front row, from left: ratemeter with low-energy gamma probe; ratemeter with pancake probe for beta detection; survey meter for gamma and high-energy beta; area-survey meter for detecting gamma and x-ray radiation fields. Back row: alpha detection probe; ratemeter with scalar.

centimeter).* Unless it is calibrated for the particular energy of the radiation being monitored, this instrument will only give an approximation of the radiation exposure rates present. These instruments usually receive hard usage in the laboratory; thus they must be properly calibrated at least every six months by a radiation safety professional to be certain that the instrument is working. The "check source" affixed to some instruments is *not* a calibration source!

- *Scintillation probes.* To increase the efficiency of detection of gamma radiation, ratemeters equipped with detectors that use a sodium iodide crystal doped with thallium as a scintillator are available. For lower gamma energies, a probe with a thin crystal is needed; a thick crystal is used in probes for detecting higher gamma energies. The crystal scintillator responds to radiation by emitting a photon of light whenever an atom in the crystal undergoes an *excitation* (see Section 13.2) followed by a return to the ground state. An electronic circuit measures these photon emissions and converts them to counts. Use of scintillation probes can increase detecting efficiencies by a factor of ten over the G-M probe, and many instruments can accommodate both types of probes. However, the sodium iodide crystals are fragile, and the probes cannot withstand rough handling. Since these instruments are more sensitive than the G-M detectors, periodic calibration is extremely important.
- *Ionization detectors.* These instruments are primarily used for area surveys of radiation levels. Their low sensitivity to beta and low-energy gamma radiation makes them unsuitable for contamination surveys. They do have an energy-independent response for x- and gamma radiation over a wide latitude of radiation energies, so these instruments are useful for radiation area surveys near sources, x-ray machines, etc.

Nonportable radiation-measuring equipment is also used in biomedical laboratories for detecting radiation in area surveys. This equipment is normally used for analytical purposes in research, but their high sensitivity and ability to discriminate between isotope emissions makes these instruments important for contamination surveys. There are three basic types of analytical devices.

- *Gas-flow instruments.* These instruments operate on the same principle as the Geiger-Mueller instrument discussed above. One

*The density thickness is the mass per unit area for a material of given thickness, and is usually expressed in units of mg/cm^2. For a material of density ρ (g/cm^3), the range of a given radiation in the material in mg/cm^2 is equal to $1{,}000 \times \rho \times$ the range of the radiation in centimeters.

type, known as a *ratemeter* because it measures counting rates, is equipped with a G-M detector which is either fitted with a thin window or is windowless. Counting gas ("Q-gas," 98 percent helium and 1.3 percent butane) is fed into the detector to act as a source of ions to enhance radiation detection. G-M counting is very sensitive for alpha and beta particles, and a windowless detector is quite efficient at detecting the low-energy tritium beta particle. The *proportional counter* operates in a fashion similar to the G-M detector, but at a lower electrical potential. Operation at a lower potential does not permit detection of low-energy beta particles with good sensitivity, but does allow discrimination between the energies of beta particles from different beta emitters. Thus the proportional counter can permit the identification of unknown radioactive emissions, a useful property for contamination surveys.

- *Liquid scintillation spectrometers.* Also known as *liquid scintillation counters*, these instruments are in widespread use in biomedical laboratories. They possess high efficiencies at detecting low-energy beta emissions, and the electronic spectrometer can be adjusted to identify counts resulting primarily from a selected isotope. Thus these units can also be used to identify unknown contaminants. They operate on the principle similar to the scintillation probe, except a liquid scintillator solution is used in place of a crystal detector.
- *Gamma scintillation spectrometers.* Liquid scintillation counters do not have good responses to high-energy gamma emissions, a result of the relatively low density of the liquid scintillation mixture. This shortcoming is addressed in the design of the *gamma counter*, which employs a sodium iodide crystal as the scintillation detector in much the same fashion as the hand-held scintillation probe discussed above. This device is more sensitive, and is provided with discrimination circuitry which allows the energy spectra of the gamma radiation to be measured, thus permitting identification of unknown contaminants.

Table 13.9 lists some of the various kinds of radioactive isotopes commonly found in biomedical laboratories and identifies the type of instrument that is most effective for detection of their emissions in monitoring and area surveys.

Contamination limits

Everyone who uses radioactive materials in research has a major responsibility to check for the presence of contamination in the work area after each experiment is completed. In addition, the entire laboratory must be surveyed at periodic intervals, the length of which is dictated by the isotopes used, the frequency of use, and their total activity. The purpose of the survey is to locate areas of radioactive contamination. Contamination can be either removable or fixed (nonremovable). Removable contamination is radioactivity that can be transferred from a surface to a smear test paper by rubbing with moderate pressure. Fixed contamination is radioactivity that remains

TABLE 13.9 Capabilities of surveying instruments

Radiation and isotope type	Portable instrument	Nonportable instrument
Low-energy beta, ^{3}H		4, 5
Medium-energy beta, ^{14}C, ^{35}S, ^{45}Ca	1*	4, 6
High-energy beta, ^{32}P	1, 2	4, 6
Low-energy gamma and x-ray, ^{125}I, ^{51}Cr	2	4, 7
Medium- to high-energy gamma, ^{131}I, ^{22}Na	3	7

*Instrument identification numbers correspond to those shown above:
1. Ratemeter with end window or pancake G-M probe
2. Ratemeter with thin sodium iodide-thallium scintillation probe
3. Ratemeter with thick sodium iodide-thallium scintillation probe
4. Liquid scintillation counter
5. Gas flow ratemeter with open window G-M probe
6. Gas flow proportional counter with closed window
7. Gamma spectrometer with scintillation or semiconductor detector (gamma counter)
Only the instrument(s) most effective at detecting given emissions is shown.

after repeated attempts to significantly reduce the contamination level fail (473).

Table 13.10 lists NRC guidelines for the maximum allowable quantities of radioactive contamination on surfaces and areas. Obviously, it is advisable to keep the actual contamination levels lower than these values. The radiation safety official at the reader's institution can give further specific details about the institution's policies on laboratory contamination.

The usual method for determining the presence of **removable contamination** is the "wipe test." A small disk of filter paper about 3 centimeters in diameter, either dry or moistened with an appropriate solvent, is wiped in a zigzag pattern over a predefined area of about 100 square centimeters, taking care not to touch the wiped surface with the bare hand. Wetting the disk may enhance its capacity to pick up contamination. The disks are coded to correspond to the specific sections of the work areas of the laboratory that have been wipe-tested, and are placed in counting vials. The vials are prepared for counting, and counted in either a **liquid scintillation counter** or gas-flow counter for beta and low-energy gamma emitters, or an analytical gamma counter for high-energy gamma sources (see Table 13.9 for details of these nonportable instruments). The counting results produced by these instruments are converted to total disintegrations per minute (dpm), where needed, and are analyzed and a copy of the results is retained to meet the required record-keeping purposes. Removable contamination on surfaces of laboratories where access is not restricted to radiation workers for medium- and high-energy beta emitters and gamma emitters should not exceed 220 dpm/100 cm^2; for low-energy beta or gamma emitters this value is 2,200 dpm/100 cm^2 (473). The presence of removable contamination is a warning that there is potential for internal uptake of radioactive materials, and may indicate careless or sloppy work with radioisotopes.

TABLE 13.10 Contamination limits for surfaces

	Contamination limits[1,2]					
	Alpha emissions		Beta/gamma emissions[3]			
			All but "low risk"		"Low risk"	
Area or body part	Removable	Fixed	Removable	Fixed	Removable	Fixed
Restricted area[4]						
Maximum surface contamination[5]	220	1,100	2,200	11,000	22,000	110,000
Protective clothing worn only in these areas	220	0	2,200	0	22,000	0
Unrestricted area						
Maximum surface contamination[5]	22	110	220	1,100	2,200	11,000
Personal clothing worn outside restricted areas	22	0	220	0	2,200	0
Skin[6]	220	0	220	0	2,200	0

[1]Units are dpm/100 cm^2 of surface area.

[2]Limits shown are guideline limits. License holders or applicants may propose and justify higher limits to the NRC if need exists.

[3]"Low risk" nuclides include ^{14}C, ^{3}H, ^{35}S, and others whose beta energies are less than 0.2 MeV maximum, whose photon energies are less than 0.1 R/h at 1 meter per curie, and whose permissible concentration in air is greater than 10^{-6} μCi/ml.

[4]"Restricted areas" are areas whose entry is restricted to protect individuals from unnecessary exposure to ionizing radiation.

[5]Averaging is acceptable over nonliving surface areas of up to 300 cm^2 or, for floors, walls, and ceiling, 100 cm^2.

[6]Averaging is acceptable over 100 cm^2 or, for the hands, over the whole area of the hand, nominally 300 cm^2.

Adapted from (473).

Fixed contamination obviously cannot be detected in this manner. If the emission from the contaminated area can be detected by a hand-held, thin-end-window detector with reasonable medium-energy beta efficiencies, and decontamination procedures have been tried, then the contamination is considered to be nonremovable or fixed. The NRC permits levels of fixed contamination on facility surfaces only, of up to five times the permitted levels of removable contamination (473). Fixed tritium contamination cannot be detected, but if removable tritium is found, the area probably needs additional decontamination to be safe. If attempts to clean the contaminated area fail to work, then the area should be covered with bench liner and the radiation safety official consulted for advice.

13.11 The Factors for Safe Use of Isotopes

Many of the laboratory techniques that are recommended or required to be used in radioisotope laboratories are simply an extension of good laboratory practices, and are also applicable to research with biological or chemical hazards. These techniques are primarily designed to help minimize exposure to both internal and external radiation in order to reach the goal of ALARA, exposure as low as readily achievable (see Section 13.7).

Sometimes it is handy to have a rough idea of the relative hazard of a particular radiochemical, or the approximate dose for an isotope is needed, but the necessary tables are not available to do the calculations. There are some generalizations that can be made about beta and gamma radiations that are actually fairly accurate, and may be used as rules of thumb for quick estimates. These are given in Table 13.11.

Radiotoxicity

Some of the factors that must be considered for safe work with isotopes include the isotope's activity and quantity, its chemical form,

TABLE 13.11 Guidelines for safe radioisotope handling

Characteristics of beta radiation

- Beta particles must possess an energy of at least 70 KeV to penetrate the nominal protective layer of the skin (7 mg/cm^2 or 0.07 mm).
- The average beta particle energy of a beta emitter is approximately one-third of the maximum energy.
- The range of beta particles in air is about 3.7 meters/MeV. (Maximum range of ^{32}P beta is 1.71 MeV $\times$3.7 m/MeV $\approx$ 6.3 m.)
- The dose rate in rad per hour produced in a solution of a beta emitter is 1.12 EC/ρ, where E is the average beta energy per disintegration in MeV, C is the concentration in μCi/cm^3, and ρ is the density of the solution in g/cm^3. The dose rate at the surface of the solution is one-half this value. (For ^{32}P, average energy of approximately 0.7 MeV, the dose rate from 1 μCi/cm^3, in water, is 0.78 rad/hr.)
- The surface dose rate through the nominal protective layer of skin (7 mg/cm^2) from a thin uniform deposit of 1 μCi/cm^2 is about 9 rad/hour for beta energies above about 0.6 MeV. Note that in a thin layer, the beta dose rate exceeds the gamma dose rate, for equal energies of emission, by about a factor of 100.
- For a point source of beta radiation (neglecting self- and air absorption) of activity A millicuries, the dose rate at 1 cm is approximately equal to A $\times$ 200 rad/hour and varies only slightly with beta energy. Dose rate for 1 mCi ^{32}P at 1 cm is approximately 200 rad/hour.

Characteristics of gamma radiation

- For a point-source gamma emitter with photon energies between 0.07 and 4 MeV, the exposure rate (mR/hr)within $\pm$20% at 30 cm is 6 $\times$ A $\times$ E $\times$ n, where A is the activity in millicuries; E, the energy in MeV; and n, the number of gammas per disintegration.
- The dose rate to tissue in rad per hour in an infinite medium uniformly contaminated by a gamma emitter is 2.12 EC/ρ, where C is the specific activity in microcuries per cubic centimeter, E is the average gamma energy per disintegration in MeV, and ρ is the density of the medium. At the surface of a large body, the dose rate is about half of this.

Decay rates

- The activity of any radionuclide is reduced to less than 1% after 7 half-lives have elapsed (i.e., 2^{-7} = 0.8%).
- For a material with a half-life greater than six days, the decrease in activity in 24 hours will be less than 10%.

and how it will be used in the procedure. Also, the isotope's particular hazards and its relative radiotoxicity must be considered. Radiotoxicity is a function of the chemical and biochemical characteristics of the isotope (how it is distributed in the body and its biological half-life), the energy and type of radioactive emission(s), and its physical half-life. Those isotopes that present a serious internal hazard if they are introduced into the body are rated as having a very high or high toxicity, whereas those that are less of a hazard are classified in the moderate or low categories. None of the isotopes commonly used in biomedical research are classified as being *very* highly radiotoxic. Table 13.12 lists some isotopes that are often used in biological research, ranking them by radiotoxicity.

Role of physical properties of laboratories

In addition to the isotope's relative radiotoxicity, another important factor in determining the maximum level of radioactivity that may safely be used is the physical characteristics of the laboratory facility, such as whether the walls and floors are porous or nonporous. For this purpose laboratories can be classified into the following three classes: (low-level) good chemical laboratory, (average-level) radioisotope laboratory, and high-level radioisotope laboratory. The physical characteristics that are typical of each of these kinds of laboratories are shown in Table 13.13.

Table 13.14 shows the relationship between these two factors—radiotoxicity and laboratory characteristics—and lists the range of radioactivity that may safely be used in a given class of laboratory. Further information on industrial hygiene requirements for handling radioisotopes be found in (61).

Safety practices in radioisotope laboratories

Safety guidelines and practices for working with radioisotopes can be classified in six different categories:

TABLE 13.12 Radiotoxicity and physical characteristics of commonly used isotopes

Radiotoxicity	Isotope[1]	Physical half-life	Radiation emitted	Energy of radiation[2] (MeV)	Average energy[3] (MeV)	Emission frequency[4] (%)
High	^{45}Ca	164 d	Beta	0.254	0.077	
High	^{125}I	60 d	Gamma	0.035		7
			X-ray[5]	0.027–0.032		136
			Internal conversion electron	—	0.022	
High	^{131}I	8.06 d	Beta	0.61	0.188	
			Gamma	0.364 0.638		8
Moderate	^{32}P	14.3 d	Beta	1.71	0.70	
Moderate	^{35}S	87 d	Beta	0.167	0.049	
Slight	^{3}H	12.3 y	Beta	0.018	0.006	
Slight	^{14}C	5,730 y	Beta	0.156	0.050	

[1]Isotopes are ranked by atomic weight within each toxicity classification.
[2]Maximum energy of beta particle (E_{max}) or energy of photon emission.
[3]Average energy of beta particles.
[4]Percent of disintegrations resulting in emission of an x-ray or gamma ray photon.
[5]From electron capture and internal conversion.

TABLE 13.13 Physical characteristics of radioisotope laboratories

Characteristic	Class of laboratory		
	Good chemical	Radioisotope	High-level
Design of facility	Standard	Standard	Chosen by expert
Walls	Nonabsorbent	Washable, hard, nonporous	Chosen by expert
Floor	Standard, avoid cracks	Nonporous, no corners or cracks	Chosen by expert
Working surfaces and areas	Nonabsorbent, covered with disposable absorbent material	Nonporous, cover with absorbent materials	Glove boxes or other enclosed systems, nonporous surfaces
Sinks	Yes, nonporous	Nonporous, food or elbow-operated taps	Special design
Storage facilities	Special cabinets and/or designated refrigerators	Specially designed ventilated facilities	Special design for particular hazard
Protective clothing	Standard lab coats, kept closed	Clearly identifiable and appropriate	Clearly identifiable and appropriate
Emergency facilities	No particular requirement	Should be available during work with unsealed sources	Should be available during work with unsealed sources

Compiled from (229).

TABLE 13.14 Maximum levels of radioisotope activity for various types of laboratories

Radiotoxicity of isotope[3]	Maximum activity of radioisotope (mCi) that may be used in:[1, 2]		
	Good chemical laboratory	Radioisotope laboratory	High-level laboratory
High	< 0.1	0.1–100	> 100
Moderate	< 1	1–1,000	> 1,000
Slight	<10	10–10,000	>10,000

[1]General features of these laboratories can be found in Table 13.13.
[2]Modifying factors can be applied to these quantities depending on the type of work involved. The following factors have been suggested:

Procedure	Modifying factor
Storage of stock solutions	× 100
Simple wet operations (pipetting, pouring, etc.)	× 10
Normal chemical reactions and operations	× 1
Complex wet operations with high spill or aerosol production risk	× 0.1
Simple dry operations	× 0.1
Dry operations involving a risk of dust production	× 0.01

[3]See Table 13.12 for radiotoxicity levels of selected isotopes.
Compiled from (229).

1. Personal hygiene practices
2. Protective practices
3. Monitoring and surveying practices
4. Labeling, storage, and record-keeping practices
5. Receiving and disposal procedures
6. Training procedures

Each of these subjects is covered in detail in the next several pages. All laboratory workers who work with radioisotopes should know and observe all the pertinent rules in order to preserve the health and safety of the occupants of the laboratory and even of the building. In addition, strict observance of these rules will

improve the quality of the work done and will reduce the quantity of radioisotopes used to the minimum level.

Personal hygiene practices

Many of these rules are similar or identical to those discussed in Chapter 3.

- Eating, smoking, drinking, or applying cosmetics is prohibited in the laboratory.
- Do not store food, beverages, or eating utensils in the laboratory.
- Mouth pipetting is not allowed. Appropriate pipetting aids must be used.
- No mouth operations are permitted. This includes licking labels. Use only selfadhesive labels. Mouth glassblowing is also not permitted.
- Wash hands thoroughly and monitor hands upon removal of gloves both after completion of work with radioisotopes and also before leaving the laboratory. Pay particular attention to the nails, between the fingers, and around the outer edges of the hands.
- Report all accidents involving radioactive materials to your supervisor and to the radiation safety office.
- Do not touch common surfaces or objects, such as door knobs, refrigerator handles, telephone receivers, or light switches, with gloved hands that have been used to handle radioisotopes. Either remove the gloves and wash first, or use a paper towel interposed between the hand and the object to guard against the spread of contamination.
- A worker who has an open skin wound below the wrist, whether protected or not by a bandage, should not work with radioactive substances without first receiving medical approval. Tiny breaks in the glove and perspiring hands can allow internal uptake of radiochemicals. Also, some forms of radioiodine can penetrate an intact glove.

Protective practices

The following list of **protective practices** summarizes some of the information given earlier in this chapter (see Section 13.8).

- Utilize the principles of time, distance, and shielding to reduce exposure.
- Always wear appropriate protective clothing, such as gloves, eye protection, lab coat, and shoe covers (see Chapter 2). Do not wear protective clothing used for radioactive work outside the laboratory.
- When removing gloves that have been used to handle radioisotopes, be certain not to touch the outside of the gloves with the bare hand. See Section 3.2 for instructions for the safe removal of gloves.
- Wash contaminated gloves before removing them.
- Confine work with radioactive substances to designated areas. Conduct work with liquids in an impervious tray lined with absorbent paper with a plastic backing to contain leaks or spills. Treat used absorbent paper as radioactive waste.
- To prevent the spread or release of volatile isotopes or radioactive gases, vapors, or dusts into laboratory air, conduct such operations in a fume hood or glove box. In fact, unless the safety of working on an open bench can be demonstrated, always use containment practices.
- Consider using a "dry" run without the radioisotope for new protocols or procedures, or where the potential for a significant exposure exists, to detect any problems that may arise (see Section 13.7).
- Utilize remote handling tools if exposure to high levels of beta or gamma radiation to the hands may be possible.
- Avoid the use of containers, glassware, or equipment having sharp edges when working with radioisotopes.

Monitoring and surveying practices

- Wear the appropriate personal monitoring devices, or dosimeters.
- Have the appropriate radiation monitoring equipment on hand and in use during all procedures involving the use of radioisotopes.
- Perform local contamination surveys after the completion of every use of radioisotopes

and survey the laboratory, including storage areas, waste disposal areas, and common areas at periodic intervals dictated by the isotopes used and their level of activity. Record the results of such surveys in a logbook kept for this purpose (see labeling, storage and record-keeping practices below).
- Survey hands, clothing, and shoes for contamination with a portable instrument (if appropriate for the isotope used) before leaving the laboratory and at periodic intervals during the work.

Labeling, storage, and record-keeping practices

- Appropriate caution signs should be posted in all laboratories used for radioisotope work or storage (see Appendix 3).
- Label all storage cabinets, refrigerators, fume hoods, glove boxes, or other areas used for storage or work with radioisotopes with the appropriate caution sign(s).
- All radioisotope working areas must be marked with the appropriate caution sign(s).
- Label all containers used to hold radioactive materials with a "Caution—Radioactive Material" label. Include information about identity of the isotope, its activity, and assay date.
- Radioactive waste containers should have tags showing the isotope, activity, and date the isotope was discarded, and other information. See Figure 13.6 for a sample format.
- Maintain complete records of laboratory use of radioisotopes, including contamination surveys, worker dosimetry reports, shipment receipts, waste disposal, and radiochemical inventory in a laboratory radioisotope logbook.
- Store radioisotopes in locations specially designated and assigned for this purpose only. Provide appropriate shielding. Consider that back scattering of radiation and/or penetration of walls or cabinets can occur, and physically check to be certain this is minimal.
- The storage location for radioisotopes should be secure against unauthorized access and only those individuals authorized to work with these materials should be permitted to remove them.
- Storage locations for radioactive isotopes should be inspected regularly, inventoried periodically, and checked for contamination according to the required schedule.
- Radioisotopes that are quite volatile or capable of releasing radioactive gas must be stored in an area that can be mechanically vented to the open air before the area is entered.
- Store bottles containing radioactive liquids in containers large enough to hold the entire contents of the bottle should leakage occur.
- Store radiochemicals at the lowest practical molar specific activity. Since radioisotopes undergo radioactive decay with time, some of the energy released during decay is absorbed by the radiochemical. This energy absorption, together with the chemical alteration of the decayed atom, causes eventual chemical decomposition of the radiochemical and reduces its useful life. Storage at a low molar specific activity reduces the amount of absorbed energy and extends the useful life of the preparation.
- Reanalyze stored radiochemicals just before use to determine if the substance is still useful.
- When withdrawing stock solution, use sterile technique and/or add a bacteriostatic agent to the stock solution if possible to avoid microbial decomposition.
- Storing radiochemicals in a purified aromatic solvent, if appropriate, to reduce chemical decomposition. If benzene is used as the solvent, store just above freezing. If the radiochemical must be stored in an aqueous solution, add 2 percent to 10 percent ethanol to the substance to scavenge free radicals (140).
- The choice of optimum storage temperatures for aqueous solutions depends on the radiochemical. Store ^{32}P, ^{14}C, and ^{35}S-containing radiochemicals at as low a temperature as possible. However, store high-molar specific activity ^{14}C-amino acids at 2°C with ethanol (140).

CAUTION

RADIOACTIVE MATERIAL

Nº 2600

RADIOACTIVE WASTE TAG 2600

INSTRUCTIONS: Place different isotopes in separate containers: only ^{3}H and ^{14}C can be mixed together in a single container. Complete both sides of the tag. Refer to the Hazardous Waste Disposal Document for more detailed instructions. Call 2-3 days in advance of the desired pick up date.

Isotope	Activity (mCi)	Date	Initials
Total Activity	mCi	For ^{3}H and ^{14}C mixed wastes, total the isotopes separately	
Total Activity	mCi		

MICHICAN STATE UNIVERSITY
OFFICE OF RADIATION, CHEMICAL & BIOLOGICAL SAFETY

MSU is an Affirmative Action/Equal Opportunity Institution

Chemical & Biohazardous Waste Manifest

General Description (Check All That Apply):

☐ Liquid	☐ Solid	☐ Halogenated Solvent
☐ Toxic	☐ Carcinogenic	☐ Organic Solvent
☐ Aqueous	☐ Volatile	☐ Non-toxic
☐ Igniteable	☐ Corrosive	☐ Reactive
☐ Microspheres	☐ Scintillation vials	☐ Animal
☐ Infectious	☐ Autoclaved	☐ Sharps

Waste Characterization: Identify and estimate the concentration of all solvents and HAZARDOUS solutes e.g., percent, ppm, molarity.

Components	Concentration

Container weight or volume: _____

Project Leader _____ Lab Address _____

_____ Phone Number _____

(Signed: Certified Radiation Worker)

For Office Use Only

0-17794

FIGURE 13.6 Radioactive waste disposal tag. Left, front of tag; right, back of tag. (Courtesy of Michigan State University.)

Under optimal storage conditions, typical decomposition rates for selected radioisotopes are: tritium and ^{14}C, about 1–3 percent per year; ^{35}S, about 2–3 percent per year; ^{32}P, 1–2 percent per week; and ^{125}I, about 5 percent per month (140). Information pertaining to specific radiochemicals can be obtained from the vendor.

Receiving and disposal procedures

- Inspect all shipments of radioactive materials. Wear disposable gloves for handling the container and survey packaging (as appropriate) for contamination. (If contamination is found, notify the radiation safety office.) If the radiochemical is potentially volatile, open the package in a fume hood.
- Check the shipment to ascertain the actual activity of the radiochemical as shipped. Errors happen: orders for microcuries may have been read as millicuries, or someone may simply make a mistake.
- Dispose of the shipping carton after marking out or removing the radioactive warning label. Dispose of contaminated packaging materials in the radioactive waste.
- Store radioactive waste in sealed, labeled containers. For liquid waste use double containers or place the container in a deep pan

that can contain the entire contents of the primary waste container in case of a leak or rupture.
- Segregate radioactive waste on the basis of its half-life if local waste program requires such segregation. This can allow savings in waste removal costs by allowing shorter-lived isotopes to decay on-site.

Training

- Do not permit untrained individuals to work with radioisotopes. All radiation workers must receive training in basic radiation safety principles and in handling techniques appropriate for the isotopes they will be using.
- All new radiation workers must be closely supervised and work in the physical presence of an experienced worker until the new worker is fully trained in appropriate procedures.
- Review pertinent safety practices frequently. This is especially important before using a new radioisotope or procedure.

13.12 Safety Procedures for Tritium, ^{32}P, and Radioiodine

There are three commonly used radioisotopes that pose definite hazards if improperly handled or have unique characteristics or hazards associated with their use. This section contains detailed procedures and precautions for the use of tritium, ^{32}P, and radioiodine (^{125}I and ^{131}I).

Tritium is an emitter of low-energy beta particles. Therefore, there is no significant external radiation hazard associated with the use of this isotope. Users of tritium exclusively do not need a film badge dosimeter. Most research with tritium involves amounts ranging from one microcurie to 10 millicuries per experiment. If the process does not involve volatile compounds or aerosol-producing procedures, handling quantities of over one millicurie usually presents little difficulty. For higher levels of total activity, and even for lower levels of high-specific-activity tritium solutions, physical properties such as vapor pressure allow airborne tritium to reach measurable levels. Furthermore, tritiated water is easily absorbed by inhalation and through intact skin; gaseous tritium is readily converted to HTO (tritiated water) upon inhalation, where it equilibrates with body water within three to five hours. Tritium therefore can present difficult problems for internal radiation protection. The following additional precautions should be taken when working with large quantities of tritium, or when the chances for production of gaseous or vaporized tritium are present.

- Use a glove bag or dry box inside a fume hood to work with curie levels of tritium. Pass exhaust air from the glove bag or dry box through a prefilter and tritium trap (e.g., a water bubbler). The tritium concentration exhausted through the fume hood should not exceed 0.2 microcuries per cubic meter.
- Open stock solutions of curie quantities of tritium only in a glove bag or dry box to avoid inhalation of tritium vapors that build up during storage.
- Wear double gloves; if exposure of arms to tritium-filled air can occur, also wear arm shields.
- Frost and condensation that develops on the exterior of storage containers or in the interior of freezers or refrigerators will become contaminated under normal conditions of use. Include checks of refrigerator and freezer frost and condensate in the contamination survey of the laboratory.
- Use disposable labware for all procedures involving high levels of tritium. Seal used labware in plastic bags and place into radioactive waste containers. This will minimize the buildup of tritium vapors in the open waste.
- Since surface contamination and airborne tritium levels are hard to avoid when large quantities of tritium are used, special procedures for monitoring and surveying should be employed. 1) Perform wipe tests using glass fiber filter paper. Wear gloves and handle filter paper with forceps or tongs. Do not

contaminate gloves or the outside of the counting vials by allowing the filter paper to touch these surfaces. 2) Monitor airborne tritium levels by sampling air in the worker's breathing zone with either a fixed air sampler or a body-worn device. Consult with your radiation safety office for details on proper procedure. 3) Survey fume hood exhausts to determine whether government regulations regarding release of tritium to unrestricted areas are being met. The radiation safety office can assist you with this requirement.

- Under U.S. law, users of large quantities of tritium (100-mCi-tritiated water or gas or 10-mCi-tritiated organic compounds or greater) must have urine assays to determine internal tritium uptake. Assays are performed within two days of single uses, and weekly for routine uses of these quantities. Tritium has an average biological half-life of about ten days; this fact and the results of the assay can allow back-calculation of the concentration of tritium to which the individual was exposed. Details of procedure can be found in (337).

^{32}P produces the most energetic beta particle of any isotope used in biomedical research. It has sufficient energy to penetrate the outer layers of the skin and expose living tissue; it can also penetrate the eye to expose the retina. Its high energy can also create secondary x-rays (bremsstrahlung) which are also fairly penetrating. Basic external radiation protection for ^{32}P consists of shielding. The use of distance can also minimize the dose to the skin (Table 13.15). Intake of ^{32}P is almost always via ingestion since most compounds are not volatile and are not absorbed through the intact skin. ^{32}P as phosphate tends to be concentrated in the bone. Almost 70 percent of ingested ^{32}P is excreted within two days of ingestion (232). Ten microcuries of ^{32}P in the bone will give a dose of 5 rem, so care is important in avoiding ingestion. The following precautions should be taken when working with this radioisotope:

- Open and inspect all shipments of ^{32}P in a radioisotope hood before placing the container(s) in storage.
- Safety glasses or goggles, which always should be worn in the laboratory, also provide additional protection against beta radiation. This is important when quantities of one millicurie or more are in use. The incident dose to the eyes is reduced by one-half with plastic goggles.
- Always wear gloves when handling it.
- Use forceps or tongs when handling it to reduce exposure of the extremities.
- Wash and survey hands after use.
- Take special care to avoid producing aerosols during operations such as centrifuging, etc.
- Very high exposure rates are possible when handling high-specific-activity solutions of ^{32}P. The surface dose rate for 1 mCi in 1 ml is 780 rad/hr (see Table 13.15), which creates the potential for an excessive and unnecessary radiation dose to the hands and face when handling uncovered vessels. Never place your hand or any other part of your body over open, unshielded containers containing large quantities of high-specific-activity isotopes.
- Store stock solution in shielding which minimizes production of bremsstrahlung. Place low-density materials, such as lucite or plexiglas, close to the source followed by lead or iron as necessary. Quantities of ^{32}P greater than 0.5 millicuries can be stored in lucite surrounded by lead (1 cm lucite and 1.5 mm lead with a 4-cm-diameter opening works well).
- Use working shields of lucite or plexiglas 1 cm thick. Be certain the shield is tall enough

TABLE 13.15 Exposure of the skin from a ^{32}P source

Distance from 1-mCi source (cm)[a]	Dose per cm^2 of skin (rad/hr)[b]
10	0.8
1	200
0.1	575
0 (contact with surface)	740
0 (1 μCi on 1 cm^2 of skin)	9

[a]For a volume of 1 ml. Internal (self-) absorption in source is included.

[b]Dose is calculated as being delivered to the basal layers of the epidermis (living tissue) whose density is assumed to equal 1. Attenuation effects in air assumed to be minimal at these distances and are neglected.

to protect the face and eyes. If the procedure or apparatus permits, placing a shield close to the source can minimize the size of the shield.

- Lead aprons must *not* be worn when using ^{32}P, since large quantities of bremsstrahlung will be produced. A vinyl apron that stops up to 99 percent of the beta particles has been described (387).
- Workers who handle solutions of 10 microcuries or more must wear whole-body film badges or TLD badges (see Section 13.10). Those working with quantities of 0.5 millicuries or more should wear ring dosimeters as well. The finger ring must be worn with the TLD chip turned *towards* the palm of the hand. For evaluation of eye doses, a TLD badge may be clipped to the safety glasses, or worn at chest or collar level.
- Internal uptake of isotopes can be checked by urine counting in a liquid scintillation counter according to the procedures detailed in (232).
- Routine surveys for contamination should be performed on a weekly basis. Since the primary route of entry of ^{32}P into the body is by ingestion, it is crucial to keep contamination to a minimum to reduce the chance of finger and hand contamination which can result in ingestion. Survey with an end-window G-M meter. Check hands, feet, and working area during and after each use. Count wipes in a liquid scintillation system. Decontaminate and resurvey any area having removable activity exceeding twice background. Record the results of these surveys.
- Store ^{32}P waste in clearly marked areas, away from personnel, behind suitable shielding to reduce beta and bremsstrahlung radiation. Since most biological procedures result in disposal of 100 mCi or more per waste container, the risk from radiation exposure from waste is great. Liquid containers should be placed in deep plastic tubs to contain the liquid in the event of leaks. If lead must be used as part of the shielding, it should be the outermost layer of shielding to minimize bremsstrahlung.
- Some institutions may elect to reduce disposal costs by storing ^{32}P wastes until decay to background occurs. The waste must not be released to the environment until the concentration of isotope in the container has decayed to less than twice background. Assay by removing and counting aliquots to determine when release can be made.

^{125}I and ^{131}I are the two isotopes of iodine used in biological research. Both are gamma emitters and ^{131}I also emits a moderately energetic beta particle. These isotopes are of special concern because the body concentrates iodine—approximately 30 percent of the total free iodine in the body—in one small organ, the thyroid gland. The biological residence time for stable iodine in the thyroid is approximately 100 days. With the physical half-life of ^{125}I and ^{131}I at 60 days and 8 days respectively, a significant fraction of the energy of these isotopes could be delivered to thyroid tissue before appreciable excretion occurs. Because of the differences in energy of the respective radiations, in fact, both isotopes deliver approximately the same dose: about 5 rem per microcurie to the thyroid. This represents a very high internal dose, and extreme care must be taken to avoid internal radioiodine uptake.

Because of this very great hazard, NRC regulations for radioiodines in the work environment are especially stringent. For example, the limits for ^{125}I in air are 5×10^{-3} microcuries per cubic meter for restricted (work) areas, and 8×10^{-5} microcuries per cubic meter for unrestricted areas. The following special techniques and procedures are recommended to help control exposure to radiations from radioiodine.

- Free iodine in solution has a very high vapor pressure. In solutions of pH 11 or greater containing iodine, iodine is always present in the air above the solution. Acidic solutions actually drive the iodine out of solution and into vapor. Elemental iodine sublimes to vapor readily and free iodine is easily taken into the body by inhalation or absorption through the skin. Any chemical technique that produces free iodine as a reaction by-product is therefore extremely hazardous. Among such techniques are iodine-labeling

reactions using solutions of sodium iodide at the millicurie level. Their widespread use makes control of reaction conditions and containment particularly important. Contamination of laboratory air and surfaces will definitely occur unless stringent control measures are followed (294).

- Users of radioiodine should receive specialized training particularly oriented towards the hazards posed by these radioisotopes. Many radioisotope users are unaware of the unique hazards of radioiodine and are thus at risk for internal uptake (359).
- Open radioiodine shipments in an operating fume hood and inspect the container(s) before placement in storage. Many of the chemical forms of radioiodine as shipped are volatile, and breakage during shipment and release of vapors upon opening can present a serious hazard.
- The packaging in which radioiodine is shipped is not adequate for shielding for purposes of storage in the laboratory. Adequate storage shielding must be provided for laboratory storage.
- Fume hoods used to handle radioiodines must have a face velocity of at least 0.63 meters per second (125 feet per minute) and be checked by the radiation safety office and receive certification for this use. All work with radioiodine must take place in a certified hood.
- Opening a vial of radioiodine can result in the release of a significant quantity of iodine vapor. Try to control this by obtaining radioiodine stocks in vials with needle septa. Withdrawals can be made using a microsyringe and needle. Additions can be done by piercing the septum with a vent needle (which for quantities exceeding 1 mCi can be fitted with an activated charcoal filter) and adding reagents through the septum with a second needle. If it is necessary to open the stock container, first purge the air above the solution by forcing it through an activated charcoal trap (this can be a syringe barrel fitted with a needle and filled with activated charcoal).
- Opening vials and performing other operations can produce aerosols containing as much as 2×10^{-3} microcurie per droplet. All liquid operations must be performed in containment.
- Wear disposable gloves (double gloves are advisable) and change them frequently. Some forms of iodine can penetrate the glove if they remain in prolonged contact. Wear a long-sleeved lab coat, and pull inner glove cuffs over the lab coat sleeves. Monitor and change outer gloves frequently or change gloves and monitor and wash hands between changes.
- Users of more than one millicurie of radioiodine per procedure should work in a dry box with activated charcoal filtration in a certified fume hood. If this procedure is followed, the hood need not be reserved exclusively for radioiodine work.
- Direct handling of high-level sources should be discouraged. Use forceps, tongs, or other remote handling equipment. The dose rate at the outside of a glass vial containing several millicuries of ^{125}I in a concentrated solution is on the order of a few rem per hour.
- Shield experimental set-ups and waste using sheet lead and lead glass. Also use shielding to prevent eye and face exposure. Proper shielding for ^{125}I is relatively easy to arrange, while ^{131}I requires much more shielding (see below).
- Surveys for airborne activity are required for laboratories where radioiodine is used. The surveys should cover working areas and fume hood duct discharges. Check the efficiency of vapor entrainment at the fume hood face by collecting air samples from the operator's breathing zone using an activated charcoal sampling trap. Your radiation safety office can assist you or perform this service.
- Wear a whole body film or TLD badge dosimeter. Users handling one millicurie or more at one time should also use a TLD ring dosimeter, and should have bioassays conducted by urinalysis or thyroid counting. Urinalysis procedures are essentially the same as those used for tritium (232). Actually, film dosimetry and urinalysis are not as sensitive in measuring doses from ^{125}I as thyroid counting (252). Thyroid counts should be performed on the day of iodina-

tion and on the two following days after use of radioiodine, or monthly for routine users of concentrations of 10 mCi or more during one week (252). Users of less than 1 mCi per week need thyroid checks at less frequent intervals. A properly calibrated sodium iodide scintillation probe connected to an analyzer is utilized for this rapid and accurate assay method. This service is generally provided by the radiation safety office.

- Conduct area surveys and wipe tests after each use and daily if using 5 millicuries or greater per day and weekly if using less. Use a G-M probe or portable sodium iodide crystal scintillation probe for surveys and count wipes in a gamma counter or liquid scintillation counter (see Section 13.10). The contamination limit for iodine is 500 dpm/100 cm^2.
- Monitor hands, clothing, shoes, and work area after completion of work with radioiodine. The recommended instrument for ^{125}I is a thin sodium iodide crystal probe and for ^{131}I a pancake G-M probe. The unit must be at the workstation and turned on during all use of radioiodine. If any significant contamination is detected during contamination surveys, clean the area with sodium thiosulfate solution. Contact the radiation safety office for any instance of human contamination.
- Store waste radioiodine in the fume hood, taking care not to disrupt airflow in the hood (see Section 12.14). Use deep plastic tubs to contain any spills. Keep the pH of waste liquids between 8 and 11. Seal solid wastes in plastic bags to reduce release of vapors to the environment. If required by institutional policy, segregate ^{131}I and ^{125}I wastes to facilitate on-site decay.
- Drums used to store radioiodine wastes must be kept in well-ventilated areas, away from occupied areas. Shielding may be necessary to prevent exposure if radiation levels are high. The radiation level at one meter per curie for ^{125}I is 0.07 R/hr and for ^{131}I is 0.22 R/hr. A lead sheet of 1.5 mm will reduce the radiation intensity from ^{125}I by a factor of approximately 1,000 and 1 cm of lead will reduce the dose rate from ^{131}I by a factor of 30.

It is also possible to saturate the thyroid with stable iodine to block the uptake of radioiodine. However, this procedure should be avoided unless recommended by a physician, because self-administration of iodine for this purpose may easily result in a dangerous overdose. It is better, however, to follow the proper procedures for handling ^{125}I and ^{131}I; this will minimize exposure.

13.13 Decontamination

Accidental spills or careless work will result in the need to decontaminate a working surface, the floor, equipment, or personnel. If a spill should occur, follow the procedures detailed in Appendix 1. If personnel are contaminated, but do not require immediate medical attention, have the individual remove all contaminated clothing and wash contaminated skin first with water and then with a mild soap and water. Survey the affected area and repeat washing and resurveying until contamination levels are reduced to levels less than 100 dpm/100 cm^2. More detailed information on personnel, area, and equipment decontamination is given in (229, 318, 467).

13.14 Radioactive Waste Disposal

Chapter 7 covers procedures for handling and disposal of laboratory waste. However, there are some specific points pertaining to radioactive waste disposal that must be remembered when planning laboratory operations and procedures. Although specific disposal suggestions for ^{32}P and radioiodine were given in Section 13.12, this section contains some general recommendations designed to minimize hazards and exposure to radiation from radioactive wastes.

- *Keep waste disposal areas clean and secure.* Custodial employees must not handle or

empty any containers from these areas, and, if possible, they should be restricted from entering waste storage areas. Access to waste areas must be at least as restricted as access to other areas where radioisotopes are stored.

- *Separate solid and liquid wastes.* Radioactive wastes must be separated into solids (absolutely no liquids are permitted) and liquids. Liquid wastes must be kept separate according to chemical reactivity. For example, do not mix wastes containing acids with liquids containing bases, and do not mix aqueous liquids with organic liquids. Keep flammable organic solvent radioactive wastes in safety cans. Animal carcasses and liquid scintillation vials are also kept separate.
- *Segregate wastes by half-life.* Short-lived wastes, such as ^{32}P and ^{131}I, should be segregated from longer-lived wastes, such as ^{35}S and ^{125}I. Such segregation will make it possible to store these isotopes until they have decayed to background levels. Keep careful permanent records of initial activities and dates, and survey the waste before it is released to the environment. Further segregate ^{14}C and tritium wastes for removal off-site by a commercial waste service.
- *Keep nonradioactive wastes out of the radioactive waste container.* This will keep waste storage volumes low and disposal costs down.
- *Prevent volatile or powdered wastes from dispersing.* Package all radioactive powders or volatile liquids into sealed containers in a fume hood to avoid dispersing contaminants to the environment.
- *Package "sharps" to prevent puncture of waste liners.* Pipets and other sharp objects should be packaged to prevent their puncturing the inner plastic liner of a solid waste container.
- *Prevent decomposition of contaminated biological waste.* Biological wastes, such as animal carcasses and necropsy wastes, should be disposed of with a sufficient amount of preservative to prevent decomposition, and enough absorbent to soak up residual fluids.
- *Separate "low-level" wastes from other radioactive wastes.* In the U.S., federal law provides exemption of certain low-level wastes from regulatory controls. Under Title 10 of the Code of Federal Regulations, Part 20.303 (abbreviated 10 CFR 20.303), quantities of tritium and ^{14}C possessing activities less than 0.05 microcurie per gram may be discharged into the sanitary sewer; small amounts of other radioisotopes may also be disposed of into the sanitary sewer if the limits of 10 CFR 20.303 are not exceeded. Furthermore, animal carcasses and scintillation vials containing less than 0.05 microcurie per gram of tritium or ^{14}C may be classified as nonradioactive waste under 10 CFR 20.306. If workers take advantage of these provisions of federal law for low-level waste disposal, they must maintain accurate records to document that the waste that was disposed of was within the limits of these sections.
- *Record the contents of each waste container.* Each radioactive waste container must have a record of the identity of radioisotope(s), the activity, and the date (see Figure 13.6). For short-lived isotopes, the date should be the date of assay of the activity, which should be very close to the disposal date.
- *Prepare wastes for shipping according to U.S. Department of Transportation (DOT) regulations.* Final preparation for waste transport involves packing of solid wastes into DOT-approved shipping containers lined with plastic, and absorption of liquids into twice the amount of absorbent needed to absorb that volume of liquid in a DOT-approved shipping container.