An Introduction to Radiation Protection

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Fundamentals

The rise of nuclear medicine as a critical component of clinical care has prompted a concomitant surge in the importance of radiation protection within radiochemistry laboratories, radiopharmacies, and nuclear medicine facilities [1]. The potential harm of ionizing radiation was recognized not long after it was first implemented into medical applications [2, 3]. Overexposure to radiation was the cause of both deterministic (*e.g.* skin injuries) and stochastic (*e.g.* cancer) health problems for early workers. As such, the development of appropriate radiation safety and protection practices began to be formulated for the safe use of ionizing radiation in both the laboratory and the clinic [4].

Key Organizations in the Field of Radiation Protection

The first recommendations on radiation protection were offered in the late 1920s by an international radiation protection group—"The International X-Ray and Radium Protection Committee"—formed in 1928 during the 2nd International Congress of Radiology in Stockholm to respond to the dramatic increase of injuries to radiologists. In 1950, this committee was renamed the "International Commission on Radiological Protection" (ICRP). Today, the ICRP is an independent registered charity consisting of international experts whose aim is to provide recommendations on appropriate standard human protections and to disseminate this information in reports addressing all aspects of protection against ionizing radiation [4, 7–11]. The ICRP bases many of its recommendations on data produced by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), a committee consisting of scientists from different member nations whose role is to assess and report measurements on the effects of exposure to ionizing radiation [5, 6]. Another important organization in this field is the International Atomic Energy Agency (IAEA). Based within the United Nations, the IAEA is an independent intergovernmental organization that promotes safety in the application of nuclear technologies as well as the protection of human health and the environment against ionizing radiation. The IAEA has developed basic safety standards implementing the guidance in the publications of the ICRP [12–14].

National and local authorities typically have specific regulations governing the use and storage of radioactive materials, including those used by radiochemists. Academic, laboratory, and medical facilities develop specific procedures in order to achieve safety results according to their own local governing structure. The overall objective of all of these organizations is to facilitate the beneficial use of radionuclides and to ensure the safe practice of radiochemistry while simultaneously protecting workers, patients, and the public from the detrimental effects of ionizing radiation.

Fundamental Principles of Radiation Protection

At its core, radiation protection is governed by three principles that can be applied in a variety of settings to determine the actions necessary to ensure the health and safety of staff, patients, and the public:

The principle of justification dictates that any decision that alters the radiation exposure to an individual should do more good than harm. In other words, the benefits to individuals and to society from introducing radiation or continuing exposure to radiation must outweigh the harm created by the exposure to the said radiation [4, 15].

The principle of optimization of protection dictates that the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should always be kept *a*s *l*ow *a*s *r*easonably *a*chievable (ALARA), considering both economic and societal factors [4, 15].

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Table 1 Internationally recommended annual dose limits in "planned exposure" situations

Type of limit	Occupational	Public
Effective dose	20 mSv[a]	1 mSv
Equivalent dose to…		
Lens of the eye	20 mSv[b]	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	–

[a]Averaged over defined periods of 5 years with the further provision that the effective dose should not exceed 50 mSv in any single year. Additional restrictions apply to the occupational exposure of women who have declared a pregnancy.
[b]Some countries have suggested an occupational dose limit of 50 mSv for the lens of the eye.

The principle of dose limits dictates that the total dose to any individual from regulated sources in planned exposure situations should not exceed the limits specified by the applicable regulatory bodies. Fundamental differences between the groups of people exposed (the public, workers, radiochemists, students, apprentices, *etc.*) must be taken into account in order to ensure the most appropriate levels of protection. As such, dose constraints—restrictions on prospective doses to individuals—must be employed as part of the practice of radiopharmaceutical chemistry. Table 1 lists the current internationally recommended dose limits for "planned exposure" situations.

Details

Radiation Interactions with Matter

Broadly speaking, the emissions from radionuclides can be classified into two categories: particles and photons (see Chap. 3 for a far more detailed discussion of radioactive decay and emissions). In the context of radiation protection, the manner in which these emissions interact with matter can have important implications, both in terms of their potential to do damage to tissue as well as the shielding and countermeasures necessary to provide proper protection. The interaction between radiation and matter can often result in ionization events within materials, a process that—not surprisingly—depends on both the source of the radiation and the material being irradiated [2, 16]. The "specific ionization"of radioactive particles or photons of radiation is defined as the number of ion pairs produced by them per unit of path length (number of ion pairs cm^{-1}) as they interact with materials. The average energy required for an ionizing radiation to produce a single ion pair in air is about 33.7 eV, while it is 35 eV in water [17]. The energy lost by the incident particle or photon of radiation is described by the term "linear energy transfer" (LET), which is defined as the average energy imparted per unit of path length ($keV\mu m^{-1}$) [18].

Interactions of Particles Charged particles such as alpha particles, beta particles, and positrons interact with materials in ways that depend heavily on their mass, kinetic energy, and charge [3]. Table 2 provides some basic properties of several alpha- and beta-emitting radionuclides. Alpha particles are high-LET emissions (>100 keV μm^{-1}) and usually possess energies of several MeV. They typically travel in straight lines due to their relatively large mass and momentum and have a high specific ionization due to their large positive charge. They deposit most of their energy as they slow down in materials at the end of their range, a point known as the Bragg peak [2]. In air, this distance corresponds to ~3–4 cm, though it is *much* shorter in tissue: about 10–20 μm. Alpha particles are less of a radiation hazard from external exposures because they cannot penetrate through the outermost layer of dead skin—about 70 μm thick—although several alpha-emitting radionuclides also emit photons that require consideration from a radiation protection standpoint. Figure 1 displays the average range of alpha particles of various energies in water, which is often used as a proxy for the range of the particles in tissue. On the other hand, alpha particles can be a significant concern if introduced internally, where they can directly interact with the cells of the mucosa of the breathing airway, the alveoli in the lung, the lining of the gastrointestinal tract, and the surfaces of the bone [19]. As a result, working with alpha-emitting radionuclides requires careful contamination control along with countermeasures to avoid inhalation or ingestion.

Table 2 Selected physical properties of several alpha- and beta-emitting radionuclides

Radionuclide	Half-life	E_{max} (MeV)	Range in water (mm)
Beta (negatron) emitters			
^{3}H	12.5 years	0.019	<0.1
^{14}C	5730 years	0.157	0.3
^{32}P	14.3 days	1.710	8.0
^{35}S	87 days	0.167	0.3
^{89}Sr	50.5 days	1.491	6.6
^{131}I	8 days	0.606	2.2
^{186}Re	3.8 days	1.077	4.3
^{188}Re	16.8 h	1.965	10.0
^{153}Sm	1.9 days	0.702	2.5
^{177}Lu	6.7 days	0.498	1.5
$^{90}Sr/^{90}Y$	28 years	2.284	12.2
Beta (positron) emitters			
^{18}F	110 min	0.634	2.4
^{11}C	20.4 min	0.960	5.0
^{13}N	10 min	1.199	5.4
^{15}O	2 min	1.732	8.2
^{68}Ga	68 min	1.899	9.1
^{82}Rb	75 s	3.356	15.6
Alpha emitters (and progeny)-alpha only			
^{212}Bi	60.5 min	6.090	0.1
^{225}Ac	10 days	5.800	0.1
^{223}Ra	11.43 days	7.590	0.1
^{224}Ra	3.66 days	8.784	0.1
^{226}Ra	1620 years	7.833	<0.1

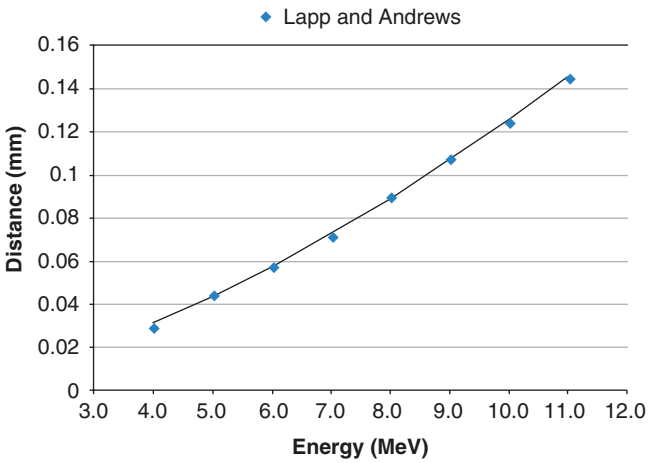

Fig. 1 Range of alpha particles in water ("tissue-equivalent" values)

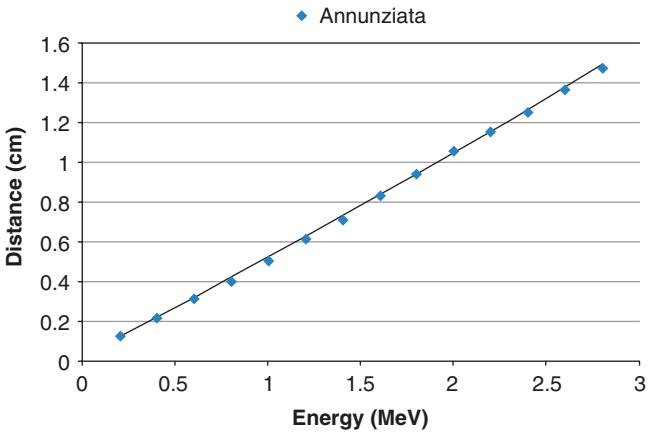

Fig. 2 Range of beta particles in water ("tissue-equivalent" values)

Beta particles and positrons have very low mass and a singular charge. As a result, they are easily deflected during interactions and follow a tortuous trajectory through materials. Beta particles are considered low-LET radiations (<10 keV μm^{-1}) with a much lower specific ionization than alphas. This allows beta particles to travel much greater distances in materials: depending on their energy, a few centimeters to many meters in air and microns to millimeters in soft tissues. Figure 2 displays the average range of beta particles in a tissue-equivalent environment. A deflected (or decelerated) beta particle will also emit a bremsstrahlung photon—typically a low-energy X-ray—that will itself have further interactions in the material. As explained in detail in Chap. 3, when a positron expends all of its energy and comes to a stop, it annihilates with an electron (its antiparticle) and creates two 511 keV photons that travel in opposite directions. These photons also lead to many secondary interactions and therefore require heavy shielding [20, 21]. Depending on their energy, beta particles can represent both an external and an internal radiation exposure hazard.

Interactions of Photons Photons—including gamma rays (from gamma decay, electron capture, or isomeric transition), X-rays (from electron capture), and bremsstrahlung X-rays (from particle interactions)—are electromagnetic radiations. They can cause ionizations as they travel through matter, yet they have no mass and carry no charge. The type of interaction depends heavily on the properties of the material as well as the energy of the photon [2, 3].

At lower photon energies, the photoelectric effect dominates. The photoelectric effect occurs when the photon is completely absorbed, and a tightly bound atomic electron—now called a photoelectron—is ejected with a kinetic energy related to the energy of the incident photon. In addition to this primary ionization, the vacancies in orbital shells are filled immediately, resulting in the emission of additional X-rays and/or Auger electrons. The probability of the photoelectric effect increases with decreasing photon energy and increasing atomic number of the material. The ejected electrons undergo many local ionizing events close to the site of their creation and, therefore, contribute most to the locally absorbed dose.

At medium photon energies, Compton scattering predominates. In Compton scattering, an incident photon transfers some of its energy to—and, as the name suggests, is scattered by—a loosely bound or free electron, the "Compton electron." The scattered photon goes on to create other interactions within the material and can increase the dose rate in the area of the source. The probability of a Compton interaction decreases with energy but is not dependent upon the atomic number of the material. When photons interact with water or soft tissue, the probability for Compton scattering typically predominates. Compton interactions typically result in low-energy absorption and low overall radiation doses to staff.

Internal conversion interactions can occur between a gamma ray emitted from the nucleus of an atom and an orbital electron of that same atom. The gamma ray is completely absorbed, and the orbital electron—the "conversion electron"—is ejected with a kinetic energy that depends upon both the energy of the gamma ray and the binding energy of the electron. As in the photoelectric effect, additional characteristic X-rays and/or Auger electrons can be emitted as the vacancies within various orbitals subsequently refill. These ejected electrons can also undergo many local ionization events close to the site of their creation and, therefore, contribute mostly to the locally absorbed dose. Any deflected or secondary photons carry energy further away from the initial site of interaction and—following subsequent electron-producing interactions—are responsible for the deposition of radiation dose at more distant sites. Higher-energy photons (>1.022 MeV) can also interact with materials by pair production, but the probability of this interaction is rather low and is not a concern in typical radiochemical

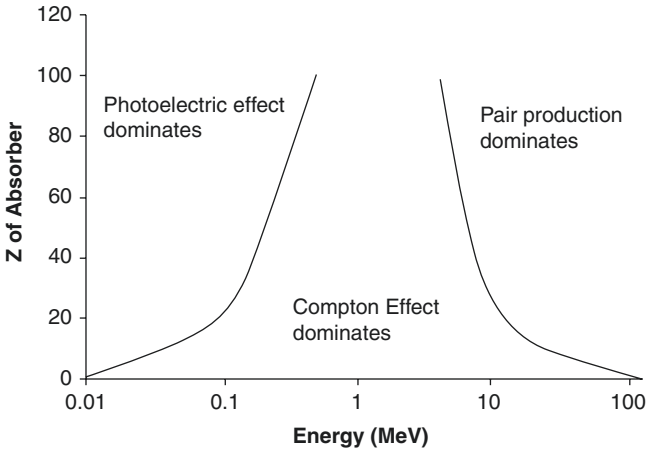

Fig. 3 Major types of interactions between photons and matter at various energy ranges and absorber densities

work. Figure 3 displays an approximation of the energy ranges and types of absorbers for which each of these types of interactions predominate.

Radiation Protection Quantities and Dose Concepts

Exposure Exposure (X) is defined as the sum of all the electrical charges (Q) of one sign produced by photons during primary and secondary ionizations in a given mass (m) of dry air at standard temperature and pressure (STP).

$$X = \frac{Q}{m}$$

The SI unit of exposure is the coulomb per kg (C/kg). The special unit of exposure has historically been called the roentgen (R), defined as 2.58×10^{-4} C kg^{-1} of dry air at STP and only applying to photons less than 3 MeV [17]. The flux of a photon radiation field is defined by the number of photons passing through a cross section of 1 cm^2 at a given distance from the source. In radiochemical applications, the intensity of a photon radiation field is usually represented in terms of the exposure rate (mR h^{-1}) or the effective dose rate (μSv h^{-1}) at a given distance from the source.

Absorbed Dose Absorbed dose (D) is defined as the mean radiation energy imparted to, transferred to, or deposited in a mass of any material.

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

The unit of absorbed dose was historically called the rad (*r*adiation *a*bsorbed *d*ose), defined as the energy absorption of 100 ergs/g of material (or 0.01 J kg^{-1}). The SI unit of absorbed dose is now the gray (Gy), which corresponds to an absorption of 1 J kg^{-1} [18]. Therefore, 1 Gy = 100 rad. While roentgens are used only for photon exposures, the concept of absorbed dose can be used to measure all types of ionization radiations at all energies. However, one shortcoming of this unit is that it does not take into account the *r*elative *b*iological *e*ffectiveness (RBE) of different types of radiation. The relative amount of biological injury to an irradiated tissue depends on the energy deposited (absorbed dose), the type of radiation (and thus its LET), and the dose rate (*e.g.* acute, fractionated, protracted, or chronic).

Equivalent Dose To account for differing RBEs, the absorbed dose (Gy) can be modified using a radiation-weighting factor (w_R) that depends on the LET distribution of a radiation field. The equivalent dose (H_T) in a tissue is the sum of the product of the absorbed dose in the tissue and the w_R for each of the radiation types [4].

$$H_T = \sum_R w_R D_{T,R}$$

The unit of equivalent dose was historically called the rem (*r*adiation *e*quivalent *m*an). The SI unit is now called the sievert (Sv), and since w_R is dimensionless, the unit for equivalent dose is the same as that for absorbed dose: J kg^{-1}. In water or soft tissue, 1 R is approximately equal to 1 rad and thus about equal to 10 mSv. Newer radiation survey meters often display radiation intensity rate results in terms of μSv h^{-1}. The radiation-weighting factor for photons, gamma rays, X-rays, and beta particles (except those from tritium) is uniform at 1 [4, 22]. The radiation-weighting factor is 2.5 for beta particles emitted from tritium, 2 for protons, and 20 for alpha particles; a range of values can be used for neutrons depending on their energy [4, 22].

Effective Dose The concept of effective dose provides a whole-body equivalent of partial-body exposures and takes organ doses and relative radiation risks into account. The effective dose (E) is the sum of the product of the equivalent dose (H_T) for each organ and the associated tissue-weighting factor (w_T) for that organ [4].

$$E = \sum_T w_T H_T$$

As the tissue-weighting factor is dimensionless as well, the SI unit continues to be the Sv. Table 3 lists the tissue-weighting factors for each organ.

It is often useful to have a sense of the dose rates expected from radioactive sources in order to devise protection schemes or calibrate instruments. The specific gamma constant (Γ) is the dose rate (μSv h^{-1}) from a unit of activity of the source (1 MBq). Table 4 gives the specific gamma con-

Table 3 Tissue-weighting factors (w_T) for each organ

Tissue	w_T
Bone marrow (red), colon, lung, stomach, breast, remainder tissues[a]	0.12
Gonads	0.08
Bladder, esophagus, liver, thyroid	0.04
Bone surface, brain, salivary glands, skin	0.01

[a]Nominal w_T applied to the average dose to 14 "Remainder Tissues": adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix

Table 4 Specific gamma constants (Γ) and approximate external exposure from 1 MBq of typical radionuclides employed in radiopharmaceutical chemistry

Radionuclide	Gamma constant (Γ) at 1 m (μSv h^{-1} MBq^{-1})	Contact with 5 ml syringe (μSv h^{-1})
^{3}H	N/A	<1
^{11}C	0.1596	2930
^{14}C	N/A	<1
^{13}N	0.1596	2930
^{15}O	0.1596	2930
^{18}F	0.1547	2880
^{32}P	N/A	23,900
^{35}S	N/A	<1
^{51}Cr	0.0049	87
^{57}Co	0.027	275
^{60}Co	0.3475	6500
^{67}Ga	0.019	402
^{68}Ga	0.1789	3500
^{89}Sr	N/A	16,400
^{90}Y	N/A	43,500
^{99m}Tc	0.0211	354
^{82}Rb	0.1647	3100
^{111}In	0.0867	1220
^{123}I	0.044	605
^{125}I	0.041	620
^{131}I	0.0613	1130
^{137}Cs	0.0896	1610
^{153}Sm	0.0124	241
^{177}Lu	0.0076	76
^{201}Tl	0.0124	49
^{223}Ra (and progeny)	0.0534	750

stants (μSv h^{-1} MBq^{-1}) at several distances and typical geometries for many radionuclides used in nuclear medicine [17, 23, 24]. The specific gamma constants are provided for point sources, 5 mL syringes, and 10 mL glass vials. Once the dose rate at some distance from a point gamma-ray source is known, the dose rate at other distances can be calculated. This is because the radiation intensity of a given activity (A) is inversely proportional to the square of the distance (r) from the source. This rapid approximation is accurate within about 1% as long as the distance away from the source is at least three times the longest dimension of the source.

$$\frac{H_T}{t} = \frac{\Gamma A}{r^2}, \left(\mu \mathrm{Sv\,h^{-1}}\right)$$

Biological Effects of Radiation

When particles or photons interact with tissue, ionizations events can disrupt the structure of biomolecules in a manner that can kill cells or induce changes in their genetic makeup that can lead to the development of abnormal cell populations [25]. *In vivo* studies in animals and humans (*e.g.* follow-up of individuals after radiation exposure) have helped our understanding of the effects of radiation organisms. Epidemiologic studies of human populations exposed to high levels of radiation—such as the Japanese survivors of the atomic bombs and the emergency responders to the Chernobyl disaster—have provided critical information on the long-term effects of exposure [25, 26]. In general, risks of cancer have been estimated by extrapolating the dose-response data from these epidemiological studies down to the lower doses received by radiation workers, patients, and the public.

Since the mass of most tissues is about 75% water, water forms the main target for radiation within the body. When a water molecule becomes ionized—a process called water radiolysis—the highly reactive free-radical ion H_2O^+ is formed. Two H_2O^+ molecules can react to form the hydroxyl radical ($OH^\bullet$) which can diffuse short distances and oxidatively damage the primary target of radiation in the cell: DNA. This type of interaction is called the "indirect effect" of radiation. This mechanism stands in contrast to the "direct effect," which occurs when ionizing particles damage DNA directly. The indirect effect is the main cause of radiation damage and accounts for about two thirds of the damage to an exposed cell. Both effects can induce DNA lesions such as base damage, single-strand breaks, and double-strand breaks (DSB). It is estimated that a dose of 1 Gy of gamma radiation will induce >1000 incidents of base damage, about 1000 single-strand breaks, and 20–40 DSB per cell [2].

Radiation-induced DNA damage promotes the formation of "unclean" or "complex" breaks that must be excised before being repaired, a process that holds the potential for the loss of genetic material [2]. It is almost certain that the most important—and most lethal—form of radiation-induced DNA damage is the double-strand break (DSB). About half of radiation-induced DSBs are not repaired correctly, and the complexity of these DSBs increases with the density of ionization. As mentioned earlier, this is the primary reason high-LET emitters have higher RBE than radionuclides with low LET. Cells with damaged but improperly repaired DNA may also survive with modified DNA, a process that may lead to delayed cell death, neoplastic cell transformation, and carcinogenesis. The dose rate of the radiation

exposure represents another important variable for DNA damage. More specifically, protracted—rather than acute—exposure to low-LET radiation has a sparing effect on cells and organisms, as there is time to allow the DNA repair mechanisms of the cell to cope with the lesions created by the radiation [26]. This is referred to as the "dose-rate effect." The dose-rate effect is not typically observed for exposure to high-LET particles, because cells hit by a single high-LET particle experience such a large amount of damage that reducing the dose rate has little sparing effect.

Cells often demonstrate different levels sensitivity to radiation-induced damage. Generally speaking, cells tend to be more radiosensitive if they have high rates of division or are undifferentiated. As a result, erythroblasts, epidermal stem cells, and gastrointestinal stem cells are particularly sensitive, while nerve cells and muscle fiber cells are particularly insensitive. There also appears to be a genetic basis for the vulnerability of cells to ionizing radiation. These trends underscore the importance of tissue-weighting factors when evaluating the radiation risks to individual tissues and organs [4].

Health Effects of Radiation

It is convenient to classify the health effects of radiation into two types: tissue reactions and stochastic effects. Tissue reactions—historically referred to as "deterministic effects"—include the damage done to organs or tissues when a sufficiently high number of cells die [8]. In these situations, the dose threshold is the amount of radiation dose delivered before effects are seen. The severity of tissue reactions shows a clear dose-dependent relationship in which higher doses cause more significant effects. Tissue reactions include skin reactions, cataracts, and other injuries. Tissue reactions are categorized as either "early effect" or "late effect" based on whether the effects occur immediately following exposure or after a time delay (sometimes as long as months or years). Two of the most common tissue effects—erythema (reddening of the skin) and epilation (the loss of hair)—are reversible following doses of only a few Gy but become permanent at doses approaching 10 Gy.

Stochastic effects are probabilistic in nature and originate in cells that survive a dose (or doses) of radiation [5]. Stochastic effects generally occur with longtime delays and include cancer, non-cancer diseases (*e.g.* cardiovascular diseases or cerebrovascular diseases), and hereditary effects. According to current models, stochastic effects can originate from a single, mutated cell. Therefore, stochastic effects do not have a dose threshold, and the severity of the effects does not increase with dose. The most significant risk from low-dose radiation exposure is the latent development of cancer. For adult radiation workers, the ICRP have adopted a linear risk coefficient for cancer of 4.1% Sv^{-1} for radiation protection purposes and whole-body doses [4, 11]. For example, if a population of workers were to receive 250 mSv over the course of their employment, they may have about a 1% increased risk of cancer above the background level of cancer expected in a population of unexposed workers. It should be noted that this risk value is highly uncertain (within approximately a factor of about three), and statistically significant increases in risk have not been demonstrated below 100 mSv. That said, the principles of optimization of protection and application of dose limits ensure that personnel doses are managed well below these doses [27].

Detection and Measurement in Radiation Protection

Radiation measurements are central to radiopharmaceutical chemistry and radiation protection, and the basics of radiation detection are covered in Chap. 27. In this section, we will discuss several specific types of instruments that are utilized in radiation protection. Along these lines, radiation surveys are performed to evaluate external radiation fields and check for the radioactive contamination of areas and personnel. There are two basic types of radiation detectors: dose metersand counters [16, 28–30]. Dose meters are designed with an output that is proportional to a dose-related quantity delivered to the detector (μSv h^{-1} or μGy h^{-1}). In contrast, a counter gives an output as a measure of the number of ionization events occurring within the detector (counts per second, cps). In a radiochemistry lab, several radiation survey meters are utilized alongside specialized probes and detectors.

Gas Detectors Detectors such as Geiger-Müller (GM) counters and ion chambers operate by applying a voltage across a gas-filled cavity. Ionizing radiation induces ionization events in the gas, and the electron-ion pairs are separated by the applied electric field. The movement of these charges within the electric field results in a measureable electric current. Gas detectors operate differently depending on both the applied voltage and the filling gas. Geiger-Müller counters are typically operated at high voltage (about 500–1000 V) and utilize a gas with a high atomic number such as neon or argon. In a GM probe, the movement of charges within the high voltage electric field results in a cascade of secondary ionizations from the freed electrons [30]. This amplification process produces a very large, short-term discharge in the entire chamber that is recorded as an individual "count." This cascade effect allows a large amount of current to be collected for a single event, therefore providing high sensitivity albeit with a short dynamic range. GM counters with thin entrance windows are generally sensitive monitors

for the location and measurement of contamination with beta- and gamma-emitting radionuclides. They are rugged instruments with large signal outputs, making them suitable for use with very basic and inexpensive pulse-counting circuitry. However, they tend to overrespond at low energies (in the range of 40–100 keV) by about a factor of five when calibrated for high-energy radiation (such as >600 keV).

Ion chambers, in contrast, are operated at lower voltages so that the incoming radiation releases electrons and the collected charges produce a small electric current. All of the charges created by the ionization events or radiation interactions are recorded to give a measurement, which can then be related to dose or dose rate (*i.e.* the higher the current, the higher the dose rate). Therefore, ionization chambers are often used for routine dosimetry and generally have a very low variation in their energy response [30].

Solid-State Detectors Solid scintillation detectors are made of materials that produce light when exposed to ionizing radiation. Scintillation materials have a characteristic efficiency with which the incident radiation is converted to light. For radiation protection purposes, a sodium iodide crystal activated with thallium—NaI(Tl)—coupled to a photomultiplier tube (PMT) is a common and useful radiation detector. The PMT converts the incident light pulse created by the detector into a measureable electric current. Scintillation detectors are used widely in photon dose-rate meters and in gamma contamination monitors [30]. Scintillation probes fitted with thin entrance windows are also used for monitoring less penetrating emissions, such as low-energy photons, beta particles, and alpha particles. Portable scintillation survey instruments are generally very sensitive.

Wipe Tests When it is necessary to assess small amounts of activity on contaminated surfaces, wipe or swab tests should be performed as indirect survey methods. Wipe tests are also particularly useful, as they allow the user to check if the contamination is removable. In a wipe test, glass fiber disks, paper disks, or cotton-tipped swabs are usually used to wipe surfaces and are then measured with calibrated counting systems [*e.g.* a NaI(Tl) gamma counter or a beta counter]. Wipe tests allow for surface contamination to be estimated in units of activity per wipe area (dpm cm^{-2} or Bq cm^{-2}) after appropriate calibration factors are applied. These calibration factors are functions of the instrument's efficiency for the specified radionuclide, the area wiped, the duration of counting, and the "removal factor" (typically about 10% or so). The frequency with which wipe tests should be conducted depends on the amount of activity used in a laboratory as well as types of manipulations performed. That said, wipe tests should be performed on a weekly or monthly basis.

Liquid Scintillation Counter A liquid scintillation counter (LSC) is a very common instrument for measuring the results of wipe tests. LSCs use liquid as the counting medium and have a very high counting efficiency due to the mixing of the radioactive samples with the scintillation cocktail. The liquid absorbs the energy from the interaction of the radiation and re-emits this energy as light. The intensity of this pulse of light is directly proportional to the amount of energy deposited in the cocktail. LSCs are especially useful for assessing wipes or swabs containing alpha- or beta- emitting contaminants removed from surfaces and for the evaluation of leakage from radiation sources.

Radiation Dosimetry and Occupation Monitoring

The primary objectives of occupational monitoring are to provide a basis for estimating the actual radiation exposure of workers and to demonstrate compliance with local administrative, legal, regulatory bodies. Radiation monitoring is also useful to test the optimization of operating procedures, to increase the awareness of risk for individuals, and to motivate workers to reduce their own exposure [31]. All workers in radiochemistry must be continuously monitored for whole-body radiation exposure with whole-body dosimeters. In addition, extremity monitoring (with ring or wrist dosimeters) is also needed in cases in which operations could result in significant radiation exposure to the hands or arms, including the elution of generators as well as the preparation, dispensing, and handling of radiopharmaceuticals [23, 24, 32]. In radiopharmaceutical chemistry, external sources are the predominant source of exposure to personnel. Internal exposures can typically be prevented by basic safe-handling practices coupled with proper administrative and engineering controls [23, 24]. From a dosimetry standpoint, gamma radiation is responsible for the majority of the external dose to radiation workers in most cases.

External whole-body monitoring methods include the use of film badges, thermoluminescent dosimetry badges (TLD), pocket dosimeters, electronic dosimeters, optically stimulated luminescence dosimeters (OSL), and solid-state devices. Hand-dose monitoring methods include the use ring or wrist dosimeters with film or TLDs. Some newer electronic detectors also provide a visual readout of both the dose rate and the cumulative dose and are equipped with an audible alarm signal to warn the wearer for radiation levels above a pre-defined threshold. Radiochemists should be provided periodic dosimetry reports and should be made aware of their overall whole-body and hand (or extremity) doses. This enables the ongoing assessment of their radiation dose as well as the opportunity to identify situations that require

improved protection measures. In many situations, extremity monitoring at the base of the index or ring finger of the non-dominant hand is appropriate. However, to determine the best position for the extremity monitoring for a specific individual, the most exposed position on the hand should be determined by individual measurements over a short trial period.

Internal dosimetry techniques are also available in the event of the accidental intake of radioactive materials. In this case, a bioassay is often necessary. The term "bioassay" refers to a procedure for determining the nature and activity of the internal contamination through either *in vivo* measurements or *in vitro* measurements on elimination products (*e.g.* nasal swabs or urine/fecal samples). The route of entry into the body is also an important consideration for determining the means for measurement. Inhalation, ingestion, percutaneous absorption, and wound entry are the most common routes for the intake of radioactive materials. It is common to utilize partial body *in vivo* bioassay counting methods to assess the uptake of radioiodine in the thyroid [i.e., a thyroid counter system using a NaI(Tl) probe detector calibrated to measure the activity of radioiodine in the neck]. "Whole-body" counting—*e.g.* using a gamma camera—is another common method to measure internal contamination in the absence of bodily fluids for testing. Periodic bioassay measurements are typically required when using radioisotopes of iodine or high-activity alpha sources and should be coordinated with radiation protection staff.

Radiation Protection in Radiopharmaceutical Chemistry

Safe Handling of Radioactivity The work performed in radiochemistry labs often involves the use of high amounts of radionuclides, typically up to tens of GBq for short-lived radionuclides. Moreover, procedures require the handling of radiopharmaceuticals very close to the extremities (*e.g.* fingers, hands, and wrists) and the exposure to highly ionizing pure beta emitters and mixed photon/beta emitters. These activities will expose workers to external radiation, the potential for external contamination, and the potential for internal contamination upon accidental intake. It is therefore critically important to ensure the safe handling of radioactivity. The goal of any radiation protection scheme is to optimize protection while facilitating the safe use of radioactive sources and materials. Key considerations in this regard include minimizing the amount of surplus material used in the laboratory, minimizing the time spent by radiation workers near radioactive materials, maximizing the distance between radiation workers and radioactive materials, employing sufficient amounts of shielding, and ensuring careful planning prior to the start of work with radioactive materials.

Time The dose accumulated from external irradiation is directly proportional to the amount of time spent working near the source. Practice and experience are crucial for minimizing the time necessary to perform each step of a radiochemical process. Nonradioactive trial runs are often suggested for gaining practical experience without the possibility of radiation exposure.

Distance One of the most effective strategies in radiation protection is increasing the distance between the worker and the source. With regard to the manual manipulation and handling of radioactive materials, significant reductions in dose can be achieved by using tools with long handles, such as tongs or forceps.

Shielding Although working quickly can reduce radiation exposure, minimizing the time spent manipulating radioactive materials is not sufficient as a lone countermeasure. Indeed, the use of shielding and increasing the distance between the worker and the radioactive source is often more effective than working swiftly. The choice of shielding material depends on the type and energy of the radioactive emission. For gamma rays, a high atomic number material such as lead is very effective for maximum attenuation. Beta radiations are best shielded with low atomic number materials—such as plastic, Plexiglas, or acrylic—that minimize the production of bremsstrahlung X-rays, which are more penetrating than beta particles. When large activities of high-energy beta emitters are used, a mixed shielding strategy using plastic on the inside and lead on the outside is preferred. For gamma radiation, the shielding efficacy of a specific material is expressed by the half-value layer (HVL): the thickness of material needed to reduce the intensity of radiation by a factor of two [29]. Table 5 lists typical HVLs for various shielding materials, and Table 6 includes several commonly used syringe and vial shields.

In general, working behind lead or leaded-glass shields (or in heavily shielded hot cells) and using long-handled tools, shielded vials, and syringe shields can dramatically reduce external exposure during the synthesis, preparation, and formulation of radiopharmaceuticals. Figures 4 and 5 show examples of possible laboratory setups for the proper shielding or beta particles and photons, respectively.

Planning Ahead When synthesizing and manipulating radiopharmaceuticals, it is critical to think about what you are going to do and anticipate possible issues that could pre-

vent the successful completion of the experiment. Some questions that should be considered before beginning an experiment include …What could go wrong? What could distract you during the procedure? Have you reviewed the laboratory protocols for the experiment at hand? Are all the necessary supplies available? Have you checked the relevant instruments and equipment to ensure that they are working correctly? Are your gloves, coat, and shoes properly covering your body? Do you know the location of the closest safety shower and eyewash? Where is your survey meter, and has it been calibrated?

Table 5 Half-value layers (HVL) of lead for selected radionuclides

Radionuclide	Major photon energies (keV)	HVL Pb (mm)
^{11}C, ^{13}N, ^{15}O	511 (200%)	5.5
^{18}F	511 (194%)	5.5
^{67}Ga	93 (38%), 184, (21%), 300 (17%)	0.86
^{82}Rb	511 (192%), 777 (13%)	13.5
^{99m}Tc	140 (89%)	0.23
^{111}In	23 (68%), 171 (91%), 245 (94%)	0.257
^{123}I	27 (71%), 159 (83%)	0.067
^{125}I	~27–35	0.021
^{131}I	364 (81%)	3.0
^{133}Xe	30 (38%), 81 (37%)	0.2
^{201}Tl	71 (47%), 167 (11%)	0.258

Table 6 Examples of typical syringe and vial shields

Radionuclide	Syringe shield	Vial shield
^{99m}Tc	2 mm tungsten	7 mm lead
^{18}F	8 mm tungsten	25 mm lead
^{90}Y	10 mm plastic or 5 mm tungsten (to reduce associated bremsstrahlung)	10 mm plastic or 5 mm tungsten (to reduce associated bremsstrahlung)

Facility Design The physical facilities of a radiochemistry laboratory must ensure an efficient and safe environment for working with radioactive materials. Design factors to be considered include ensuring the safety of sources, optimizing protections for staff and the general public, preventing the uncontrolled spread of contamination, maintaining low background where most needed, and fulfilling national regulatory requirements for radiochemistry or radiopharmaceutical work [12]. The workplace should be classified based on the type of work performed in each area. "Cold" areas are open to the public, clerical staff, and visitors. No radioactivity should be handled in these nonrestricted areas, and the exposure levels should never exceed 20 μSv h^{-1} and 1 mSv y^{-1}. "Lukewarm" areas such as bioassay facilities and counting rooms can be utilized for procedures involving very low levels of radioactivity (kBq), and "warm" areas can be designated for larger levels of radioactivity (MBq). "Hot" areas—in which high levels (GBq) of radioactivity are handled in shielded containers, hot cells, or other enclosures—should not be used except by trained radiation workers. These "hot" spaces include radiochemistry laboratories, radiopharmacies, "hot labs," and "decay-in-storage" areas.

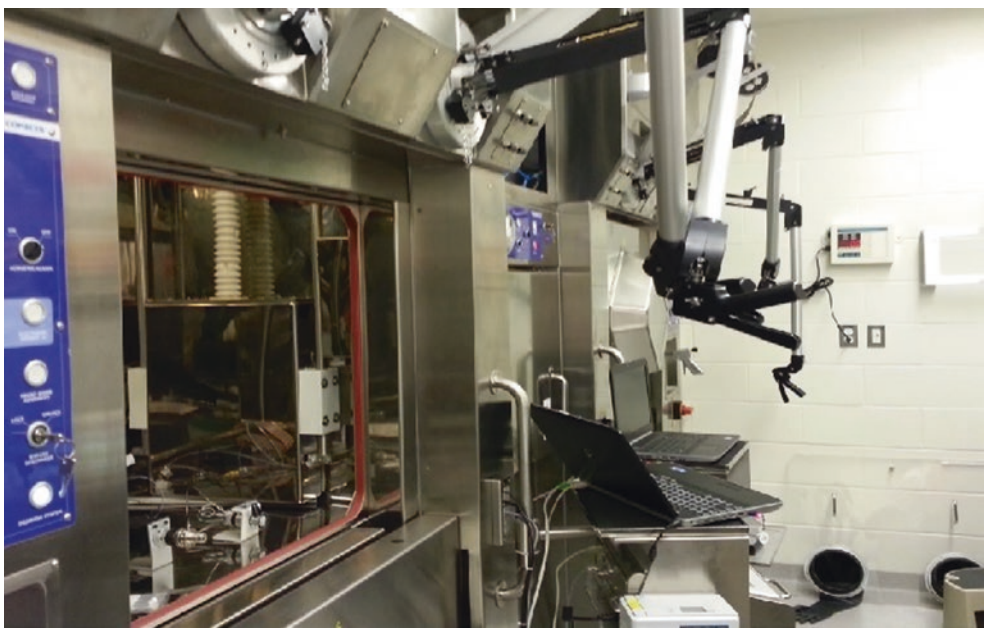

Fig. 4 An example of a standard hot cell and manipulator. This setup is used mainly for high-energy photon emitters such as positron-emitting radionuclides

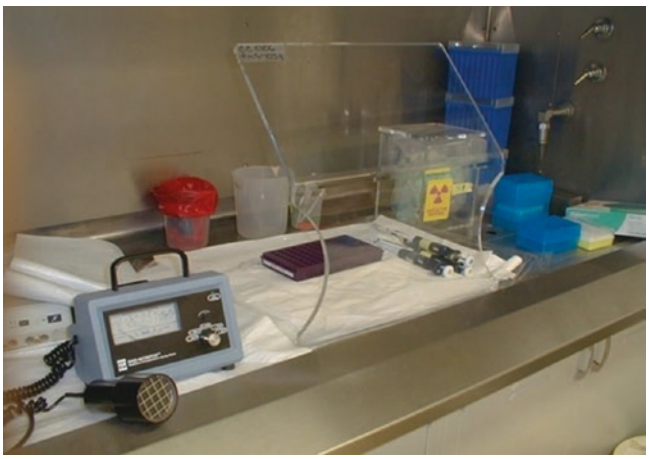

Fig. 5 An acrylic glass setup commonly used for the shielding of beta particles in a laboratory

Control of Radiation Contamination

When working with radioactive materials, it is essential to practice procedures to prevent contamination. Contamination is defined as the presence of radioactive materials in undesirable locations, including surfaces such as countertops and floors as well as body parts such as the skin, hair, face, and hands. In this regard, it is essential to keep areas clean, employ removable and disposable impermeable gloves (two layers can often be helpful), and perform frequent workspace surveys and wipes. The contamination of clothing, skin, or workspace areas should be quickly removed or contained [35]. Table 7 lists beta-emitter dose estimates for the contamination of the skin with various radioactive materials. Please note that these values are for the listed radionuclide only and do not account for equilibria with radioactive daughter products.

Preventing Internal Contamination Small amounts of radioactivity in the body can result in large radiation doses depending on the physical and biological behavior of the radiochemicals. More hazardous internal irradiations arise from radionuclides that emit energetic particles (rather than photons), radioactive substances with longer physical half-lives, and radioactive substances that concentrate in or near radiosensitive tissues (*e.g.* bone marrow, lung, thyroid). The risk of ingesting or inhaling radioactivity is always present during the use of solutions, even if it is low. The main routes through which radionuclides can be internalized are contaminated hands, contaminated skin, accidental wounds incurred during the manipulation of radioactive materials, accidental punctures incurred during the preparation of doses with syringes, and the inhalation of radionuclides vaporized in air [33]. Thankfully, with the exception of liquids containing isotopes of radioiodine [34], the majority of radiopharmaceuticals used in nuclear medicine are non-volatile.

Table 7 Half-life and dose rates for skin exposure of selected medical radionuclides

Radionuclide	Half-life	mGy min^{-1} MBq^{-1} cm^2
^{3}H	12.5 years	<0.1
^{11}C	20 min	38.1
^{14}C	5730 years	5.5
^{13}N	10 min	41.2
^{15}O	2 min	48.2
^{18}F	110 min	34.2
^{32}P	14.3 days	40.0
^{35}S	87 days	5.9
^{51}Cr	27.7 days	0.25
^{57}Co	271 days	1.3
^{60}Co	5.27 years	18.8
^{67}Ga	78.3 h	5.0
^{68}Ga	68 min	36.1
^{89}Sr	50 days	38.1
^{90}Y	2.7 days	40.0
^{99}Mo/^{99m}Tc	6.0 h	31.7
^{111}In	2.81 days	6.3
^{123}I	13.2 h	6.1
^{125}I	60 days	2.5
^{131}I	8.02 days	28.5
^{137}Cs	30.17 years	26.6
^{177}Lu	6.73 days	23.5
^{201}Tl	73 h	4.4
^{223}Ra	11.4 days	10.5
^{226}Ra	1620 years	0.8

Nevertheless, the use of a shielded fume hood (or vented biosafety cabinet) for the manipulation of radiopharmaceuticals is recommended to lower the risk of the inadvertent inhalation of radionuclides.

Radiation Protection in Practice

Radiochemistry facilities typically operate under a radioactive materials license from the local regulatory agency for radiation protection and as such need to implement a detailed documented radiation protection program [13, 23]. A radiation safety officer (RSO) is typically in charge of all aspects of radiation protection. The RSO is usually a health physicist, medical physicist, physician, radiopharmacist, or a nuclear medicine technologist with appropriate credentials based on local legal requirements. A second level of oversight is provided by the radiation safety committee (RSC), a group of individuals from the facility that oversees the operation and implementation of the radiation protection program. The members of this RSC typically include the RSO, administrators, radiochemistry supervision personnel, nurses, physicians, and other "users" (radiochemists, radiopharmacists, nuclear medicine technologists, *etc.*). The RSC meets periodically to review ongoing activities under the program as well as opportunities for improvements. The RSC reviews and approves changes to the radiation protection program, confirms that all new procedures are imple-

Fig. 6 Radiation safety training is crucial for all staff members who use—or come into contact with—radioactive materials

mented safely, investigates and reports radiation safety problems, and ensures the practice of radiation safety and ALARAguidelines.

Radiopharmaceutical chemistry—especially in the context of clinical nuclear medicine—is often performed in accordance with a quality management program (QMP) and under good manufacturing practice (GMP) and good laboratory practice (GLP) protocols. The specifics of these programs should be documented by, taught to, and well understood by each radiochemist. All radiation workers must be formally trained in both radiochemical techniques and radiation protection, including all aspects of regulatory compliance [36, 37]. Such training should be performed upon the hiring of new workers and periodically thereafter as a refresher for even long-serving personnel (Fig. 6).

Safe Practices(Rules) for Radiochemistry Laboratories Radiochemistry laboratories and work areas need to develop standardized laboratory rules for safe practice. We earnestly recommend that these rules include the following suggestions [23, 24, 32]:

- Only individuals who have completed radiation safety training should use radioactive materials.
- The relevant chemical, radiation, and handling hazard precautions and safety protocols should be reviewed prior to any experiment or procedure.
- Only approved radionuclides—and approved quantities of said radionuclides—may be ordered, and receipts should be kept and filed for each order.
- An up-to-date inventory of all radioactive materials should be kept.
- Radioactive materials should be stored to minimize dose rates in work areas. Photon- and high-energy beta emitters should be shielded such that the dose rate at 30 cm is <20 μSv h^{-1} in low-traffic areas and <2 μSv h^{-1} in high traffic areas.
- Radioactive sources must be handled in designated areas, labeled with radioactive warning signs (*e.g.* "Caution: Radioactive Material"), and enclosed in containment vessels with appropriate shielding.
- Secondary containment should be provided in order to limit spills and facilitate their rapid cleanup.
- Food and beverages should not be present in work areas, and refrigerators, hot plates, or ovens that are used for radioactive materials should not be used for food.
- No eating or drinking should be allowed in areas in which radionuclides are used.
- Well-ventilated work areas should be set up in rooms with frequent air changes and negative pressure with respect to the outside. Fume hoods should be used when working with volatile materials (*e.g.* the radioisotopes of iodine, ^{35}S) or alpha-emitting radionuclides.
- Work areas should be kept as clean as possible; plastic-backed absorbent pads or trays should be used to cover work areas and replaced when necessary.
- Pipetting by mouth should be prohibited.
- Long-handled tools should be used whenever practical, and manipulators should be used with high-activity sources.
- Dosimeters—whole body, wrist, and/or ring—should be worn as assigned.
- When practical, syringe and vial shields should be utilized to transfer or manipulate radioactive sources.
- A calibrated survey meter should be kept nearby when using radioactive materials; radiation workers should survey themselves and their workstations frequently.
- A Geiger-Müller counter should be used to detect beta-emitting radionuclides, and a NaI(Tl) counter should be used to detect photon-emitting radionuclides.
- Impervious shoes, a lab coat, and safety glasses should be worn whenever radioactive materials are being handled. Disposable impermeable gloves must be worn and replaced frequently. Generally, common items in the lab such as scissors, tape dispensers, phones, *etc.* should not be handled while wearing gloves that were used with radioactive materials. If these items must be handled with gloves that could be contaminated, they should be designated as "possibly contaminated" and should not be handled with bare hands.
- Reagents should be opened and dispersed behind a splash shield and adequate shielding.
- Capped tubes should be used in centrifuges and agitators to prevent contamination.
- Individual containers should be labeled before placing them in storage.
- Bench covers should be changed between experiments to avoid cross-contamination.
- Glassware, instruments, and central facility appliances should be surveyed frequently and decontaminated before use.

- Waste should be segregated into appropriately shielding containers that are differentiated for short and long half-life radionuclides. All disposals should be logged in a detailed inventory.
- Injuries or personnel contamination should be reported immediately to supervisors and radiation protection staff according to local protocols.
- Work surfaces should be regularly monitored for contamination using radiation survey meters. Whenever unsealed sources are used, wipe or swab tests should be performed to check for contamination.
- At the end of each experiment or procedure, hands, lab clothes, and shoes should be checked for contamination before leaving the work area.

Receipt of Radioactive Packages The receipt of packages containing radioactive materials is regulated by the licensing agency, and local specific regulations must be consulted [38]. Generally, packages must be externally monitored (for dose rate), and an assessment of external contamination levels (dpm cm^{-2} or Bq cm^{-2}) must be performed within 3 h of their arrival. The records of these monitoring procedures and wipe tests must be kept for a minimum of 3 years. Packages that exceed regulator-specified exposure or contamination levels must be reported to both the delivery carrier and the licensing agency. After receipt, radioactive materials need to be appropriately stored and secured to prevent theft or accidental removal.

Radioactive Waste In many cases, waste contaminated with radionuclides with half-lives shorter than 120 days can be allowed to "decay-in-storage" before disposal along with nonradioactive waste (or medical waste as appropriate). Shielded waste containers—such as those in Fig. 7—may be needed for proper containment during decay-in-storage. If radioactive waste cannot be properly stored for decay, it can be disposed of through a licensed waste broker or contractor. Depending on the local license, some small amounts of liquid radioactive waste may be released into the sanitary sewer provided that required monthly average concentrations do not exceed licensing limits. Radiation protection staff should always be consulted on the specifics of handling, storing, and disposing radioactive waste.

Transporting Radioactive Material During the transport of radioactive materials, the risk of accidents, spills, and the loss of material increases. As a result, strict controls are legally enforced during transportation. Most local regulatory requirements include special training and certification for packaging and transporting radioactive materials. The containers used for transport are designed to minimize the risk

Fig. 7 A lead-shielded waste container used for the storage and disposal of photon emitters such as positron-emitting radionuclides

of damage to the source, to contain any spillage of the radioactive material, and to minimize the radiation exposure to any person handling or coming into contact with the container. Each package needs to be adequately labeled (as required by local regulatory agencies) so that it can be identified by anyone who has to handle it. Labels also bring awareness to hazards in the event of an accidental breach of the packaging. Packages should be easily and safely handled, properly secured during transport, capable of withstanding mechanical impacts and vibration, and have surfaces that can be easily decontaminated.

Radiation Emergencies Most accidents involving radioactive materials can be avoided if all laboratory personnel follow the recommended procedures for safe handling. However, radiochemists must be thoroughly familiar with the emergency procedures of the facility as well as the location of all safety devices in the event of an accident [39]. All radioactive materials in the laboratory that are not immediately in use should be stored in a manner that will safeguard against the possible accidental spread of radioactive material in the event of a major disaster (fires, floods, *etc.*). Spills of radioactive materials can often result in unnecessary exposure and therefore should be properly addressed immediately. Minor spills of radioactivity (up to several kBq) can be addressed by warning other workers and decontaminating the area. Major spills of radioactivity (over 100 MBq) should be addressed by

stopping the spill (if possible), warning other radiation workers, preventing access to the area, and calling the radiation protection staff for assistance with cleanup and decontamination.

Decontaminating Personnel In the event of a life threatening or major injury, precedence should be given to health over exposure concerns. If clothing is contaminated, the contaminated items should be removed to reduce the exposure to the skin and minimize the spread of contamination. The contaminated area should be surveyed quickly to assess the initial general area of contamination. The affected area(s) should be washed using only mild soap and water (and perhaps a soft bristled brush) rinsing away from the body. The washing should proceed toward the center of the contamination so as to avoid enlarging the contaminated area. Stiff brushes and other abrasive items should be avoided, and particular attention should be paid to creases in the skin, the fingernails, and the spaces between the fingers and thumbs. The contaminated areas should be resurveyed after washing to check for reductions in contamination levels, and this washing process should be repeated as long as contamination levels are being reduced or until the skin starts to become irritated. The local radiation protection staff members should be notified so that they can assess the level of contamination remaining and decide if further decontamination procedures are required.

Radiation Protection During Pregnancy Studies have shown that the unborn child is sensitive to high doses of ionizing radiation, particularly during the first 3 months of gestation [40]. As a result, additional controls must be implemented in order to protect pregnant staff and their fetuses from the hazards of ionizing radiation. As soon as a pregnant woman informs her employers of her pregnancy, the protection to the conceptus (*i.e.* the embryo during the earliest stage of pregnancy) must be comparable with that provided for members of the public [41]. The conditions of employment of the pregnant woman must subsequently be adjusted such that the dose to the conceptus will be ALARA and that it will be unlikely to exceed 1 mSv during the remainder of the pregnancy [42]. It is not risky for pregnant staff to work in a radiochemistry laboratory as long as practical measures are implemented to avoid accidental high-dose situations, and there is reasonable assurance that the dose to the conceptus is kept below 1 mSv [13]. Often, work practices can be arranged to allow for the continuation of routine work, but certain radiochemistry procedures—*e.g.* work with volatile radioiodinated compounds [34] or work involving a significant risk of bodily contamination—should be reassigned during pregnancy to ensure that the dose to the conceptus remains ALARA [42].

Tricks of the Trade

Rules of Thumb for Radiation Protection

- Practice ALARA in all situations. Minimize time, maximize distance, utilize shielding, and plan ahead.
- Laboratory gloves minimize the skin dose from beta emitters.
- Consider utilizing two layers of gloves.
- Change gloves frequently, and avoid touching "clean" areas or your skin.
- After five hand-washes with water and soap, only about 2% of the initial activity typically remains on the surface of the skin.
- Use protective goggles or glasses.
- For quick radiation protection purposes, the skin dose per activity per unit area can be roughly approximated as 1 mSv h^{-1} per Bq cm^{-2}. More specific factors based on individual radionuclides are listed in Table 7.
- Syringe shields reduce extremity doses by about 50–85% for ^{99m}Tc and about 25% for positron-emitting radionuclides.
- It requires a beta particle of at least 70 keV to penetrate the protective 0.07 mm thick layer of the skin.
- It requires an alpha particle of at least 7.5 MeV to penetrate the protective 0.07 mm thick layer of skin.
- The activity of any radionuclide is reduced to <1% after seven half-lives. For decay-in-storage, waste should be held for a minimum of ten half-lives before surveying for residual activity and disposal.
- In case of a spill of radioactive materials, practice the SWIM principle: *s*urvey, *w*arn, *i*solate, *m*itigate. In case of a major spill, contact radiation protection staff for assistance.
- Surfaces measuring >100 cps above background with a Geiger-Müller probe should be considered contaminated [43].
- Surface wipes measuring >2200 dpm cm^{-2} for beta emitters or >220 dpm cm^{-2} for alpha emitters should be considered contaminated.

Example Laboratory Audit Checklist

Radiochemists should make arrangements for periodic reviews of their protocols and work areas (at least annually) in order to systematically appraise their radiation protection programs [44]. The purpose of such audits is to ensure the optimization of their protection programs and to take corrective actions when and where necessary. The results of any review or audit of radiation protection should be documented, and follow-up actions should be highlighted to

ensure their implementation. A checklist can be helpful for such periodic assessments. Examples of items to be reviewed during an audit could include the following:

- Workers are knowledgeable and properly trained to work with the radioactive materials present. Documentation of their training is available.
- Workers are aware of emergency procedures and proper ways to respond to a spill of radioactive material.
- Radioactive warning signs (*e.g.* "Caution: Radioactive Material") are posted and visible in all locations that contain radioactive materials.
- ALARA principles are adhered to in the laboratory. This may include using items such as long-handled tools, proper shielding, bioassay tests, ventilated hoods, and hot cells.
- Proper radiation detection instrumentation is present to detect and/or quantify radioactive materials in the laboratory. These instruments are fully functional and calibrated properly.
- Regular contamination survey results, inventory and waste logs, and shipment receipts are maintained and easily accessible.
- Workers are wearing dosimeters when working with radioactive materials and are returning them in a timely manner for processing.
- No food or drinks are being stored or consumed in the workplace.

The Bottom Line

- All work performed with radioactive materials must be justified and beneficial, have an optimized approach for ALARA guidelines, and be performed according to all relevant federal, state, and local dose limitations.
- While long-term health effects have not been statistically demonstrated below 100 mSv, it is important to practice ALARA guidelines to limit possible deleterious biological effects.
- Shielding requirements, handling precautions, and survey instrumentation can vary greatly for different radionuclides. Always prepare carefully before working with a new type of radioactive material.
- In the event of personal contamination, quickly locate and clean the source of the contamination on the skin. Make sure not to irritate the affected area, and contact radiation protection staff for assistance.
- Proper surveying, documentation, work practices, and communication when using radioactive materials can help prevent most radiation safety problems.

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