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Chapter 5

Applied Radiation Protection Physics

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Additional information is available at the end of the chapter

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Abstract

Nuclear medicine is an area where both patients and occupational radiation doses are among the highest in diagnostic imaging modalities today. Therefore, a good understanding and proper application of radiation protection principles are of great importance. Such understanding will allow optimization of practice that will be translated into cost savings for health care administrations worldwide. This chapter will tackle: radiation protection in the routine practice of both diagnostic and therapy applications in nuclear medicine including PET, diagnostic facility design, safety aspects of the common radionuclides used in clinics, the safety of the pregnant and breast feeding patients, radiation effect of exposure to ionizing radiation, and risk estimates. The chapter will discuss the operational radiation safety program requirements applied to Conventional Nuclear Medicine using Gamma Cameras, SPECT/CT, PET/CT, and Radioiodine therapy facilities. The chapter will serve as a quick reference and as a guide to access more detailed information resources available in the scientific literature.

Keywords: radiation protection, safety program, dose limits, physics, PET, SPECT, radionuclide therapy

1. Introduction

Good radiation safety practice in nuclear medicine comprises various components: facility design and construction, local radiation safety rules and procedures, staff training, emergency preparedness, equipment quality assurance, and area and contamination monitoring.

Institutions must develop, document, and implement a radiation protection program covering the scope of practice covered under the license. The use of safety procedures, engineered

controls like automatic injectors, movable, and syringe shields are encouraged and must be applied to ensure the radiation protection of staff and the public. The radiation protection program contents and methods of its implementation must be reviewed on an annual basis or up to 3 years [1].

2. Important physics relations and definitions

There are few physics relations that are needed in the planning phase the facility that we like to summarize under this section of the chapter. First, let us define radiation dose:

absorbed dose (D) denotes the quantity of radiation energy absorbed by matter from ionizing radiation, and is defined by:

$$D = \Delta E/m \tag{1}$$

ΔE is the energy imparted by the ionizing radiation in a volume, and *m* is the mass in that volume.

The dose D is measured in [Gy].

$$1\ Gy = 1\ [Joule/kg].1\ Gy = 100\ rad, 1\ mGy = 0.1\ rad, 1\ mrad = 10\ \mu Gy \tag{2}$$

Radiation exposure measured in Roentgen (R) with 1 R = 0.87 rad (in water or tissue).

How to use the distance effect to estimate dose rates at certain distances from radioactive sources? We remember that radioactive sources in nuclear medicine could be Tc-99m, Rb-82, and F-18 generators, sealed sources used for calibration, I-131 capsules, and the injected patients.

$$\dot{D}_1.{d_1}^2 = \dot{D}_2.{d_2}^2 \tag{3}$$

$\dot{D}$ is the dose rate measured in ($\mu Gy.hr^{-1}$) and d is the distance that is usually in (m).

The second is the radioactive decay equation given by

$$A = A_0.\,Exp\ (-\lambda.t) \tag{4}$$

where A is the the activity of the source most often in (MBq). (1 mCi = 37 MBq), $\lambda = \ln 2/T_{1/2}$, $T_{1/2}$ is the half live of the isotope in units of (time) (sec, min, hrs, or years).

And the third is the relationship between dose and the dose rate

$$D = \dot{D}.t \tag{5}$$

where $\dot{D}$ is the dose rate in ($\mu Gy.hr^{-1}$) and t is the time in (hr).

And the next important relation that is often used is the shielding:

$$I = I_o\, B\,(\mu x).\, Exp\ (-\mu x) \tag{6}$$

where I_o is the incident intensity, B (μx) is the build-up function, μ is the linear attenuation coefficient of the shield in (cm^{-1}) that depends on the material used and the radiation energy, and x is the thickness of the shield in (cm).

Exp (−μx) is the attenuation factor [2].

Radionuclide	Half-life	Emitted radiation	Energy (abundance)*	Gamma dose rate constant in (μGy/hr.m²/GBq)***	Half value layer in lead (mm)**
^{11}C	20.5 min	β^+ (ɣ)	0.39 MeV (100%)	139.3	4.95
^{18}F	109.8 min	β^+ (ɣ)	0.24 MeV (96.9%)	135.1	4.96
^{32}P	14.2 days	β^-	0.695 MeV (100%)	Pure beta emitter	Pure beta emitter
^{51}Cr	27.7 days	ɣ	0.32 MeV (9%)	4.22	1.92
^{57}Co	271.7 days	ɣ	0.122 MeV (86%)	14.11	0.298
^{68}Ga	68 min	β^+ (ɣ)	0.74 MeV (88%)	129	5.12
^{89}Sr	50.5 days	β^-	0.585 MeV (100%)	Pure beta emitter	Pure beta emitter
^{89}Zr	78.4 hrs	β^+ (ɣ) ɣ	0.897 max MeV 22.3%) 0.909 (99%)	123.4*	9.02
^{90}Y	64 hrs	β^-	0.93 MeV (100%)	Pure beta emitter	Pure beta emitter
^{99m}Tc	361.2 min	ɣ	0.140 MeV (89%)	14.1	0.234
^{111}In	67.4 hrs	ɣ	0.172 MeV (89%) 0.247 MeV (94%)	83.13	0.257
^{131}I	8.04 days	β^-, ɣ	0.19 MeV 90%) β^- 364 keV (83%)$ɣ_1$ 0.637 MeV (7%) $ɣ_2$	52.2	2.74
^{133}Xe	5.25 days	β^-, ɣ	0.10 (100%) β^- 0.081 (37%) ɣ	14.33	0.0379
^{153}Sm	1.95 days	β^-, ɣ	0.23 MeV (50%) β^- 0.103 MeV (28%) ɣ	12.2*	0.0876
^{177}Lu	6.73 days	β^-, ɣ	0.15 MeV (79%) β^-_1 0.12 MeV (9%) β^-_2	4.7*	0.542
^{198}Au	2.7 days	β^-, ɣ	0.32 (99%) β^- 0.40 (96%) ɣ	54.54	3.35
^{201}Tl	73 hrs	ɣ, x	0.167 MeV (8%) ɣ 0.070 MeV (74%) x_1 0.080 MeV (20%) x_2	10.22	0.258

*Calculated from Ref. [3].
**Taken from Ref. [3].
***From Ref. [4].

Table 1. Radionuclides of interest in diagnostic and therapeutic nuclear medicine. The energy is the average β emission in MeV.

Other important definitions are one relating the shielding material halve (HVL) and tenth value layers (TVL) with μ measured in (cm^{-1}).

$$HVL = \ln\ 2/\mu, \text{and } TVL = \ln\ 10/\mu \tag{7}$$

Another important relationship is the one relating a radioactive source specific Gamma Ray Constant known as r and the dose rate $\dot{D}$

$$\dot{D}\ (t) = r.A\ (t)/d^2 \tag{8}$$

Γ is in ($\mu Gy.hr^{-1}.\ m^2.\ mBq^{-1}$), the activity A at time (t) in (MBq), and the distance d in (m).

And the total dose is the integration of the dose rate over the total time.

$$D = \int \dot{D}.dt \tag{9}$$

The above-mentioned relations are the fundamental ones know as time, distance, and shielding that need to be used in radiation protection applied to nuclear medicine (**Table 1**). There are other useful relations such as:

$$1\ Sv = 100\ rem, 1\ rem = 0.01\ Sv, 1\ mrem = 10\ \mu Sv. \tag{10}$$

3. Nuclear medicine facility design and shielding evaluation

3.1. Typical nuclear medicine department

A typical nuclear medicine facility contains the following rooms or areas: (1) reception area; (2) waiting room; (3) hot lab; (4) imaging room(s); (5) thyroid uptake room; (6) physician office(s); (7) chief technologist office; (8) hallways; and (9) bathroom(s). For regulatory purposes, these areas are considered to be either restricted or unrestricted areas [5].

The following devices are used in typical nuclear medicine hot lab: (1) dose calibrator; (2) fume hood; (3) shielding material (such as lead and leaded glass for use in the hot lab, pigs, syringe holders, syringe shields, aprons, and portable shields); (4) protective clothing (laboratory coats and gloves); (5) radioactive waste storage containers; (6) sealed calibration sources (for dose calibrator, well counter, and gamma camera); (7) survey meters and exposure meters; (8) well counter; (9) whole-body/ring dosimeters; and (10) individual room exhaust systems and activated charcoal gas traps [5].

3.2. Facility general requirements

All rooms, where radioactive materials are used and stored, shall have the appropriate radiation signs posted at the entrance door; gamma camera rooms, dispensing rooms, and hot laboratories are controlled areas, and therefore, access to unauthorized personnel shall be restricted. The hot lab shall be provided with a fume hood with proper exhaust and filters for handling volatile radionuclides. All radionuclides shall be stored in shielded containers.

All containers of radioactive materials shall be labeled with a radiation sign and with the word "Caution: Radioactive Material" with the name of the radionuclide, its chemical form, activity, and expiry date/time if applicable.

The radioactive waste bags/container shall have a label with date of disposal [1].

3.3. Radiation shielding design

Structural shielding should be considered in a busy nuclear medicine facility where large activities are handled and where many patients are waiting and examined. In a PET/CT facility, structural shielding is always necessary and the final design will generally be determined by the PET application because of the high activities used and because of the high energy of the annihilation radiation.

Careful calculations should be performed to ensure the need and construction of the barrier. Such calculations should include not only walls but also the floor and ceiling and must be made by a qualified medical health physicist. Radiation surveys should always be performed to ensure the correctness of the calculations [5].

The shielding design goals in accordance with NCRP 147 standard are as follows.

It is always recommended to pay extra attention when performing initial facility design by assigning the task to a qualified medical health physicist with board certification to perform the shielding calculations and or to review and approve the shielding design. Such action, at the planning stage, is meant to avoid future problems and to save unnecessary cost resulting from redesigning the facility or installing additional structural shielding materials.

The medical physicist should do the following:

1. Specify a maximum activity for all isotopes that are expected to be used in the facility.
2. Select the highest dose rate resulting from the isotope list or add all potential dose rates that might be exposed in the same time inside the hot lab (the hot lab is the storage area of the radioactive sources and materials used clinically in the department).
3. Calculate the expected dose rate ($\dot{D}_1$) at (d_1) = 1 meter from the source for ease of calculation.
4. Evaluate the dose rate ($\dot{D}_0$) at a specific point (d_2) that needs to be protected; this point in space is located normally in adjacent areas and behind the walls (using Eq. (3)).
5. Calculate the dose per week using a realistic number of hours of total exposure time (ET) of the source for a period of a week (using Eq. (5)).

So far, we have calculated the weekly dose expected to be present in an area that requires protection using:

$$D_w\ [\text{mGy/week}] = \dot{D}_0\ [\text{mGy/hr}]^*\ (d_1[\text{m}]/d_2[\text{m}])^{2*}\ \text{ET}\ [\text{hr/week}] \tag{11}$$

The calculated D_w in (mGy/week) is compared with D_L in (mGy/week) from **Table 2** (shielding design goal). The calculated dose rate in the area that needs to be protected is evaluated against the weekly effective dose limits from **Table 2**. The structural shielding is found

Area	Occupational type	Annual effective dose limit (mSv)	Weekly effective dose limit (mSv)
Controlled area	Workers	10	0.2
Uncontrolled area	Public	0.5	0.01

Table 2. Structural shielding design goals.

acceptable if the dose per week is below 0.2 or 0.01 mSv per week for controlled and uncontrolled areas, respectively. For more details, it is recommended to have a copy of NCRP report 147 for frequent consultations and references.

The D_L use must be multiplied by the occupancy factor (OF) in the area that needs to be protected. The following is a list of OF from the NCRP 147 report (**Table 3**).

The linear attenuation coefficient (μ) describes the fraction of a beam of X- or gamma-rays that is absorbed or scattered per unit thickness of the absorber in (cm).

The attenuation factor is calculated as: (AF) = Exp $(-\mu x) = D_L/D_w$, assuming the buildup factor B (μx) = 1, which is valid using the point source approximation. The buildup factor is the factor by which the total value of the quantity being assessed at the point of interest exceeds the value associated with only primary radiation. The total value includes secondary radiations especially scattered radiation.

Then, we have

$$\text{Ln}\,(D_L/D_w) = -\mu x \text{ or } \text{Ln}\,(D_w/D_L) = \mu x \tag{12}$$

Knowing μ depending on (material & energy) from tables [6, 7], we can calculate the required thickness of the shielding material x given by:

$$x\,[\text{cm}] = \text{Ln}\,(D_w/D_L)/\mu\,\left[\text{cm}^{-1}\right] \tag{13}$$

3.4. Shielding survey

An area survey report is always required by the regulatory authorities after structural shielding installation and before routine operations of the facility. The report includes dose rate measurements in various locations behind the installed barriers and an evaluation of the weekly effective

Area	Occupancy factor
X-ray control room, X-ray room, nursing stations, receptionist areas, offices, lab, pharmacies.	1
Patient examination & treatment rooms.	1/2
Corridors, patient rooms, staff rest rooms.	1/5
Public toilet, storage rooms, unattended waiting rooms. Patient holding area.	1/20
Outdoors, parking lots, stairways, elevators, Janitor's closets.	1/40

Table 3. List occupancy factors.

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dose for the controlled and uncontrolled areas when appropriate. The reported results shall confirm the adequacy of the shielding installed.

4. Local rules and regulations

The facility's management must sign the license application and has authority for the radiation protection program. The radiation safety officer is appointed by management and must accept, in writing, responsibility for implementing the radiation protection program. The nuclear medicine physicians are also part of the license and described as authorized users. The licensee must periodically (at least annually) review the radiation protection program content and the efficiency of its implementation [1].

Licensees must provide individual dose monitoring devices: TLD or OSL badges to each of the following staff:

1. Any adult likely to receive an annual external dose >10% of the limits for radiation workers which is 20 mSv per year (e.g., 2 mSv);
2. Minors likely to receive an annual external dose of 1 mSv.
3. Declared pregnant women likely to receive an external dose >1 mSv during an entire pregnancy.
4. Each licensee must conduct operations so that the annual total effective dose equivalent to individual members of the public does not exceed 1 mSv.

5. Quality control (QC) program

When imaging equipment is first installed, a qualified medical physicist performs a set of tests in order to document the equipment performance and to ensure that it meets the agreed technical specifications between the vendor and the hospital. The National Electrical Manufacturers Association (NEMA) in the United States has defined tests that allow equipment performance testing and comparison between different machines and vendors. Quantitative data acquired during the specified tests are gathered and kept for evaluating the equipment performance overtime to detect any deterioration. This helps detecting problems early, since gradual deterioration of performance is detected on the curve even before the performance deteriorates beyond the specifications. Quality control program needs continuous monitoring: if you do not insist on quality control measurements, the QC program will silently die, and image quality will slowly deteriorate [8, 9].

A quality standard requires that QC program for all equipment used in imaging the patients to be performed on a regular basis and documented. There is a major trend worldwide for hospitals to implement a quality management programs (QMP) for all imaging services

provided; such QMP includes a radiation safety program (RPP) aimed to protect patients and staff working in the diagnostic imaging departments.

The QC program must include well counters, dose calibrators, gamma counters, automated dispensing/injection system, and radiation survey meters.

Also, the IAEA basic safety standard (BSS) requires a quality assurance program (QAP) to be part of the facility QMP. Therefore, it is recommend to integrate both RPP and QAP into the facility wider QMP to fulfill the requirements of the Joint Commission International (JCI) for example.

6. Occupational dose limits

Radiation exposure to staff working in nuclear medicine occurs from radiopharmaceutical dose preparation, injection of the activity to the patients, and escorting and supervising the patient during image acquisition. The application of the three principles in radiation protection allows staff to considerably decrease the level of radiation exposures. Time, distance, and shielding must be applied for good radiation protection practices.

The good news is the administered activities, which are generally low and most of the used radiopharmaceuticals have short half-lives, and the resulting level of radiation exposure, organ doses, and effective doses are low and do not pose high risk to individuals working in nuclear medicine services and also for the patients. However, regulations require that all occupational exposures both external and internal must be assessed and reduced as much as possible the ALARA principle. Therefore, licensees must comply with the following dose limits for occupationally exposed staff (**Table 4**).

Type of limit	Occupational	Public
Effective dose, whole body	20 mSv per year, averaged over defined period of 5 years	1 mSv per year
Lens of the eye	20 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	—

Table 4. Recommended dose limits as per latest ICRP recommendations (ICRP 103, 2007) [10].

7. Radioactive contamination control and spill procedure

The following is a typical spill procedure that can be implemented as part of the radiation protection program:

1. Notify all persons in the area that a spill has occurred.
2. Prevent the spread of contamination by isolating the area and covering the spill, if appropriate, with absorbent paper. If clothing is contaminated, remove that article of clothing

and place in a plastic bag. If an individual is contaminated, rinse contaminated area with water and wash with a mild soap, using gloves.

3. Notify the radiation safety officer or appropriate individual of any unusual circumstances immediately.
4. Wearing gloves, a disposable lab coat, and booties, if necessary, clean up the spill with absorbent paper.
5. Place absorbent paper and all other contaminated disposable material in a labeled radioactive waste bag or container.
6. Survey the area or contaminated individual with an appropriate radiation survey instrument and check for removable contamination. Standard commercial cleaners maybe used to clean most spills involving radioactive materials used in hospitals.
7. If necessary, continue to decontaminate the area or individual until decontamination action no longer result in reduction of the residual activity.
8. If necessary, leave absorbent paper labeled "Caution: Radioactive Material" over the area to prevent loosening of any fixed contamination.
9. Check hands and clothing for self-contamination.
10. Report the incident to the radiation safety officer or appropriate supervisory personnel. If personnel contamination is found, the skin dose will be evaluated [11–13].

8. Ordering receiving and opening radioactive packages

Good practice recommends performing wipe test on every radioactive packaged received, and it is the responsibility of the RSO to perform the test and document the results.

Ordering radioactive material is through licensed/authorized service providers and authorized to transport radioactive materials under national radiation protection regulations. When ordering radioactive materials for extended period of time is also recommended to check the maximum total activity licensed and not to order more than the maximum in order to avoid any license violations or noncompliance. The RSO must authorize each order of radioactive material and must maintain proper database and records as specified in the nuclear medicine license.

Generally, transportation of radioactive sources in any country follows the international atomic energy agency (IAEA) regulations for the safe transport of radioactive materials. The IAEA regulations include details about the shape and the labeling of packages to ensure mechanical and physical safety during the transport including the potential exposure to water and flames [14, 15].

There are three different labels: I–White, II–Yellow, and III–Yellow. In all cases, the radionuclide and its activity should be specified. The label gives some indication of the dose rate D at the surface of the package:

Category I–White $D \leq 0.005$ mSv/h

Category II–Yellow $0.005 < D \leq 0.5$ mSv/h

Category III–Yellow $0.5 < D \leq 2$ mSv/h

9. Radiation surveys and instrument calibration requirements

9.1. Routine area surveys

Regular radiation area monitoring is required by regulations. Records must be kept in file for compliance purposes. Some areas need more attention in Nuclear Medicine Departments such as the radiopharmacy, where the large amount of radioactive materials is manipulated. Therefore, permanent area monitors can be installed and sometimes are required by the national regulators. Area monitors could be scintillation counters or ionization chamber type with audible signal for dose rate monitoring. The radiation area monitoring program is sensitive to potential increase of activity in the radiopharmacy and new added radionuclides to the list of radionuclides used at the department. It also serves as a warning to staff in the case of unshielded radiation source that is exposed in the work area [16].

9.2. Radiation measuring instrument calibration requirements

Regulatory authorities require licensees to have an instrument capable of measuring radiation dose rates in the order of (1–1000 μSv/hr) ready to be used at all times in nuclear medicine departments [1]. Periodic calibration of instrument is a regulatory requirement in most countries. Such calibration must be performed by an authorized center licensed to calibrate radiation detection and measurement instruments for dosimetry and radiation protection purposes.

Records of calibration certificates must be maintained with the RSO, and proper sticker are recommended to be on the surface of the calibrated instrument indicating the validity date of the calibration and the due date of next calibration.

10. Caution signs and posting requirements

Area postings are required by regulations. In most countries, posting requirements are specified as part of the license document called license conditions or as part of the written document that contains the current radiation protection regulations. Copies of such documents must be available at the radiation protection office for consultations when needed.

11. Labeling containers, vials, and syringes

Syringe and vials that contains radioactive materials must be labeled with the isotope, activity, time, date, and technician or radiopharmacist signature at all times when stored or in transit to be administered to the patients for both injections and oral administration routes.

12. Determining patient dosages and radiation effects

Because of the low administered activities and short half-lives of radiopharmaceuticals used in diagnostic nuclear medicine practice, the resulting radiation doses (both organ doses in rad and effective dose equivalents in rem) pose extremely low radiation risks.

Concerns about stochastic radiogenic risks have led to NRC regulations for diagnostic nuclear medicine that inherently demand a radiation protection philosophy based on the conservative hypothesis that some risk is associated with even the smallest doses of radiation.

There is no question that exposure of any individual to potential risk, however low, should be minimized if it can be readily avoided or is not accompanied by some benefit. The weighing of risks and benefits, however, is not always based on objective data and calls for personal value judgments, which can vary widely.

Today, after more than a century of careful review of the evidence for radiation effects from the radiation doses associated with diagnostic nuclear medicine, there appears to be little reason for apprehension about either genetic or somatic effects (including thyroid cancer).

13. Risk assessment of the pregnant and breast feeding patient

13.1. Pregnant patients

Pregnancy is not an absolute contraindication to radionuclide studies. If a patient is pregnant, it is imperative to discuss the indications for the study with a departmental medical officer, and the fact that the patient is pregnant must be clearly marked on the consultation form. A smaller than normal activity of radiopharmaceutical may be administered, thereby minimizing radiation to the fetus. There is little risk involved with the use of ^{99m}Tc radiopharmaceuticals, but studies with other radionuclides should be avoided unless clinically justified [16].

If a pregnant patient undergoes a diagnostic nuclear medicine procedure, the embryo/fetus will be exposed to radiation. Typical embryo/fetus radiation doses for more than 80 radiopharmaceuticals have been determined [17].

There should be no concern about radiation exposure below 150 mSv to pregnant patient. Most of the calculated doses to the embryo fetus are below 18 mSv except for ^{67}Ga which is 18 mSv. Radiation doses received from a diagnostic medical imaging procedure are not high enough to cause a spontaneous abortion.

Radioiodine ^{131}I is widely used for therapy of hyperthyroidism and thyroid cancer. Its use is generally contraindicated in pregnancy, as large doses to the fetus and fetal thyroid may result due to the passage of the radioactivity across the placenta.

Ref. [18] has a table showing the injected activity and the corresponding calculated dose to the fetus. Also, ICRP has published two other documents [19, 20] having more information about radiation doses received by the fetus as results of the injection of radiopharmaceuticals to the mother.

13.2. Breast feeding patients

In situations involving the administration of radiopharmaceuticals to women who are lactating, the breastfeeding infant or child will be exposed to radiation through the intake of radioactivity in the milk, as well as external exposure from close proximity to the mother. Radiation doses from the activity ingested by the infant have been estimated for the most common radiopharmaceuticals used in diagnostic nuclear medicine [21].

Many radionuclides may be concentrated in breast milk. This may mean that the patient has to stop breastfeeding for a period of time. Table 8.1 (p. 516) in Ref. [16] gives a guide to the period of time that breast feeding must be interrupted.

In most cases, no interruption in breast feeding was needed to maintain a radiation dose to the infant well below 100 mrem (1 mSv). Only brief interruption (hours to days) of breast feeding was advised for ^{99m}Tc-macroaggregated albumin, ^{99m}Tc pertechnetate, ^{99m}Tc -red blood cells, ^{99m}Tc-white blood cells, ^{123}I-metaiodobenzylguanidine, and ^{201}Tl. Complete cessation was suggested for ^{67}Ga-citrate, ^{123}I sodium iodide, and ^{131}I sodium iodide. The recommendation for ^{123}I was based on a 2.5% contamination with ^{125}I, which is no longer applicable.

14. Diagnostic reference levels (DRLs)

Diagnostic reference levels are published by many countries across the globe for both adult and pediatric patients. Such levels are published and made public by national authorities in radiation protection in medicine.

Establishing DRLs is recommended even at the local level in order to bench mark the practice against well-established ones. Use of the reference levels is a way of optimizing the clinical practice and fulfills quality standard requirement such as JCI and national regulations. **Table 5** contains a list of administered activities for the most common nuclear medicine exams with a range and maximum recommended values when applicable.

Study type	Radiopharmaceutical	Range of administration activity in MBq	Maximum recommended activity in MBq
Bone	Tc-99 m MDP/HDP	730–880	1110 *
Bone marrow	Tc-99 m nanocolloid	360–440	
Brain (perfusion)	Tc-99 m HmPAO	669–814	1110 *
Brain tumors	Tl-201 chloride Tc-99 m MIBI	100–666 122–814	
Breast imaging	Tc_99m-MIBI	832.5–1017	1110 *
Brain (shunt patency)	Tc-99 m DTPA	33.3–40	
Cisternography	Tc-99 m DTPA	166–203	

Study type	Radiopharmaceutical	Range of administration activity in MBq	Maximum recommended activity in MBq
Colonic transit	Ga-67 citrate/oral	7–10	
Gallium infection	Ga-67 citrate	166–205	325 **
Gallium tumor	Ga-67 citrate	225–275	325 **
Gastric emptying	Tc-99 m DTPA/colloid	18–37	50 **
GI bleed	Tc-99 m RBC	360–440	1110 *
Hemangioma	Tc-99 m RBC	730–880	925 *
Hepato-biliary	Tc-99 m mebrofenin	166–185	185 *
Leucocytes (WBC)	Tc-99 m HmPAO WBC	200–600	740 *
Leucocytes (Leukoscan)	Tc-99 m sulsemab	660–814	850 *
Liver/spleen	Tc-99 m tin colloid	166–205	222 *
Lung (perfusion)	Tc-99 m MAA	40–150	296 *
Lymphoscintigraphy	Tc-99 m nanocolloid	34–41	120 *
SLNS	Tc-99 m nanocolloid	10–15	120 *
Meckel's diverticulum	Tc-99 m pertechnetate	135–165	450 *
MIBG	I-123 MIBG	360–440	400 *
Octreotide imaging	In-111 octreotide Tc-99 m octreotide	180–220 666–815	222 *
Parathyroid	Tc-99 m MIBI	730–880	925 *
Renal (static)	Tc-99 m DMSA	90–110	170 **
Renogram Tx/native	Tc-99 m DTPA	270–330	540 ***
Renogram Tx/native	Tc-99 m MAG3	150–220	310 **
Spleen	Tc-99 m denatured RBC	90–100	110 *
Thyroid (Tc-99 m) scan	Tc-99 m pertechnetate	90–110	370 *
Thyroid (I-123) scan	I-123 iodide	20.35–16.65	25 *
Testicular scan	Tc-99 m pertechnetate	540–660	940 **
Whole body scan	I-123	166–185	185 *
Whole body scan	I-131 capsules	90–110	185 *
MUGA	Tc-99 m RBC	730–880	1000 **
GFR	Cr-51 EDTA	2–2.5	3.7 ***
PET/CT	^{18}F-fluorodeoxyglucose (FDG)	222–555	650 **

*Ref. [22].
**Ref. [23].
***Ref. [24].

Table 5. Radiopharmaceutical administration activity in adults (weight is 70 kg).

15. Sealed sources inventory and leak testing

Nuclear medicine is a regulated practice in most countries around the world through a rigorous system of licensing and inspections. Most regulations require a biannual inventory and leak testing of all sealed sources used under the practice license.

Sealed sources by nature pose minimum risk of contamination because they are well designed and optimized to prevent leakage; however, they must be tested on a regular basis.

15.1. Inventory requirement

Inventory list will contain the following information: source locations (e.g., hot lab), model number, radionuclide, nominal activity, and the name of the individual who performed the inventory. Inventory records should be maintained for a minimum of 3 years.

Most of the international radiation protection regulations require licensees to notify the regulatory authority in case of loss of any licensed radioactive source or materials. Effort must be deployed in order to recover the lost source or locate them.

15.2. Leak testing requirement

Sealed sources must be wiped in order to detect any removable contamination, must commonly every 6 months or as per license condition requirements.

Cotton swabs or filter or tissue paper can be used to take the wipe sample, and samples must be well identified before proceeding to the sample counting stage to prevent mixing of results.

The person performing the wipe must wear disposable gloves and protective clothing and change the glove after each source in the case of performing wipe testing of multiple sources at the same time and location in order to avoid cross contamination and repeating the wipe testing which may be time consuming.

Counting the wipe samples can be done by using a routine gamma counter, sodium iodide scintillation counter, or by using a Geiger-Muller detector with pancake prop. In case of Geiger or scintillation counter type, the following equation can be used in order to report the results in the proper units.

$$\text{Activity}\ (\text{MBq}) = [\text{wipe}\ (\text{cpm}) - \text{BG}\ (\text{cpm})]/\epsilon\ (\text{cpm/MBq}) \tag{14}$$

where ϵ (cpm/MBq) is the detector efficiency measured in counts per minutes (cpm) per activity in (MBq).

The analysis must be capable of detecting the presence of 185 Bq of radioactive material on the test sample and must be performed by an authorized service provider. An activity of more than 185 Bq on the test sample is considered as leaking source and must be declared to the regulatory authority.

16. Decay in storage and waste management

Radioactive waste from nuclear medicine procedures can be dealt with either by simply storing the waste safely until radioactive decay has reduced the activity to a safe level or possibly by the disposal of low activity waste into the sewage system, if permitted by the local regulatory authority. Long half-life or high activity waste may need long term storage in a suitable storage area.

Technetium-99m waste normally requires storage for only 48 hours, in a plastic bag inside a shielded container. The container should be labeled with the radionuclide and date. Gallium-67, iodine-131, and other longer half-life materials should be placed in a separate labeled and dated plastic bag and stored safely. Sharp items, such as needles, should be separated and placed in a shielded plastic container for safety.

In some countries, the radiation dose rates at the surface of the cleared waste bags and released into normal waste must be measured before disposal. A dose rate limit maybe applied by regulations. Normally, a maximum dose rate of 5μGy/hr. is imposed. Disposable gloves should be worn and caution exercised when handling sharp items. Any labels and radiation symbols should be removed. Radioactive waste should be placed in a locally appropriate waste disposal container, for example, a biological waste bag (since waste, once no radioactive, is usually regarded as biological waste). Placement of waste inside two bags is advisable to minimize the risk of spillage [25].

17. Safety instructions for workers

17.1. General safety procedures

1. Wear laboratory coats in areas where radioactive materials are present.
2. Wear disposable gloves at all times when handling radioactive materials.
3. Monitor hands and body for radioactive contamination before leaving the area.
4. Use syringe and vial shields as necessary.
5. Do not eat, drink, smoke, apply cosmetics, or store food in any area where licensed materials are stored or used.
6. If required, wear personnel monitoring devices (e.g., whole body and/or ring badge) at all times when in areas where radioactive materials are used or stored. When not being worn to monitor occupational dose, these devices must be stored in a low-background area.
7. Dispose the radioactive waste only in designated, labeled, and properly shielded receptacles located in a secured (e.g., locked) area.
8. Appropriately label all containers, vials, and syringes containing radioactive materials. When not in use, place these in shielded containers (e.g., lead pigs) or behind appropriate lead shielding in a secured area if not under constant surveillance and control.

9. Store all sealed sources (e.g., flood sources and dose calibrator check sources, if needed) in shielded containers in a secured area when not in use.

10. Before administering dosages to patients, determine and record activity (based on either decay correction or dose calibrator measurement, whichever method is selected for use). The administered activity must be ±10% of the prescribed activity.

11. Know what steps to take and who to contact (e.g., radiation safety officer) in the event of radiation incidents (such as unsealed material spills or a leaking sealed source), improper operation of radiation safety equipment, or theft/loss of licensed material.

17.2. Radiopharmaceutical therapy safety procedures

Radionuclide therapy presents relatively few hazards to staff and patients, but there are a number of common principles of radiation safety that have to be observed.

Staff caring for or working with patients who have received therapy with radionuclides may be required to follow safe working practices, according to the type of therapy. These are listed in Section 5.2. (IAEA, 2006) [16], we are going to summarize the most important aspects in the mentioned reference here below.

The most common safety procedures include the following: during the pre-therapy stage, testing the female patient for pregnancy is important, and advice to the physician and to the patient can be done by the qualified medical physicist certified in medical health physics or in health physics.

On the admission day for the therapy as inpatient treatment at the hospital, physician guidelines, administrative protocol, advice to nursing staff, and preparation of patient room must be done.

During the therapy days stay at the hospital, control of radioactive waste including urine, contaminated syringes, cotton swabs, and other items must be controlled. Control of visitors, patient, and local environment must be monitored.

At the discharge time, information to the patients must be given and advice on future pregnancies. The patient should be given a discharge card listing the radionuclide and activity administered the activity on discharge and any necessary precautions.

Table 6 includes the discharge criteria that can be applied in the absence of national or local regulations:

Radionuclide	Remaining activity in (GBq)	Measured dose rate in (μGy/hr)
I-131	1.2	70
Re-186	28	150
Re-188	29	200
Sm-153	26	300

Table 6. Radioactive patient discharge limits.

17.3. Emergency department safety procedures

The emergency room (ER) in the medical city should be prepared to assist in an incident with contaminated wounds, and the staff in ER shall be made familiar with radiation decontamination procedures. Such information is available in documents such as references [26, 27]. Let us review the general guidelines to be applied in case of emergencies involving radioactive materials: accidents or incidents such as radioactive spills, skin contamination, traffic accidents, loss of radioactive materials, and use of radiological dispersal devices; in most cases are not life threatening situations. The hazard from radiation exposure to emergency attending staff is little. Therefore, the patient must be treated first and immediately with no consideration of the level of contamination. The patient life must be saved first. Injured patients may be covered with disposable material to prevent any spread of contamination into the hospital facilities. Safe decontamination procedures can be initiated later after the patient has been stabilized.

The basic radiation protection methods of increasing the distance from the radiation source, reducing the time spent close to the source, and use shielding martial between the person and the source can be done when possible. In the current situation, the contaminated patient body is the radiation source.

Personal protective equipment such as gloves, masks, and shoe cover must be used when working on a contaminated injured patient. Counting the amount of contamination on the skin can be done using appropriate radiation detector. Clean the contaminated area by going to the nearest sink, wash with mild soap, and cool to warm water.

Wiping the contaminated area with a filter paper and counting the activity removed on that piece of paper will indicate the amount of activity that can be removed while performing the physical decontamination while a close survey of the contaminated area will give an indication of the total contamination both fixed and removable.

In the case of suspected internal contamination through open skin wounds, inhalation or ingestion of radioactive substances, it may be necessary to take urine samples or performing thyroid uptake counting, the evaluation of internal contamination must be dose by an experienced health physicist (**Table 7**).

Radiation type	Sample isotopes	Survey type	Detector to be used
alpha	Am-241, Po-210, Pu-239 Ra-226, U-238	Direct survey or Wipe test	Proportional counter or Zinc sulfide ZnS scintillator
low energy beta	C-14, H-3, S-35, Pu-241	Wipe test	Proportional counter or Liquid Scintillation counter
Medium energy beta	I-131, P-32, Sr-90	Direct survey or Wipe test	Geiger, Proportional or Liquid Scintillation counters
Low erergy gamma	Am-241, I-125, I-129	Direct survey or Wipe test	Thin NaI scintillator
Medium to high energy gamma	Co-20, Cs-137, I-131, Ir-192,	Direct survey or Wipe test	Geiger counter or Thick NaI scintillator

Table 7. A list of types of radiation detectors and their potential use.

18. Radioiodine therapy and patient release criteria

Radioiodine therapy is one of the most common methods used in radionuclides therapies worldwide; therefore we have included this section to summarize the most important radiation safety aspects related to this treatment for both the patient and the hospital staff caring for the patients. In the literature, there are a lot of references covering all aspects of radioiodine therapy.

This section will consider a summary of applicable requirements for patient accommodation (design requirements including shielding), as well as radiation safety procedures necessary for safe practice.

18.1. General safety principles

Doors of rooms that are occupied by patients undergoing radioiodine therapy shall be posted with the appropriate radiation sign. These rooms are also considered as controlled areas during the stay of the patients, and therefore access shall be restricted to members of the public. A specially designed room/ward is required for radionuclide therapy if therapeutic dose of I-131 is to be administered; bed shields shall be available in the rooms of patients undergoing radioiodine therapy.

A nonporous, easily decontaminated floor and wall surfaces with covered junctions to make cleaning easier;

A dedicated shower and toilet, the toilet draining directly to the main sewer or to a system of radiation waste disposal, depending on local regulatory requirements.

A physical barrier to entry: a simple door may be sufficient; moveable lead shields to minimize nursing exposure.

The possible installation of a remote patient monitoring system (video); door signs prohibiting entry by pregnant women, children, and other persons without permission, giving a time limit for approved visitors.

It is not allowed to remove anything from the room without clearance and requiring the use of protective clothing in the room. Rubbish must be kept within the suite until dealt with by a physicist. A designated place to keep supplies of disposable gloves and gowns, and possibly overshoes, outside the room shall be made available; storage within the room for collection and temporary storage of waste.

The patients are advised to have adequate hydration and voiding frequently and flushing the toilet twice after each voiding. Patient comfort should be catered for by radio, television and/or videotape facilities as well as a comfortable (but easily decontaminated) chair. Disposable sheets, blankets, and eating utensils should be provided. When the patient is ready for discharge, all the patient's belongings must be checked for radioactive contamination and stored or washed separately as necessary.

No member of staff should enter the therapy room without wearing a personal radiation monitor. Persons entering the room should put on plastic aprons, gloves, and shoes. As the

barrier is crossed on leaving the room, this protective clothing must be removed and placed in the disposal bag provided [5].

18.2. Patient release criteria

After hospitalization, the patient undergoing radioiodine therapy treatment is released from the hospital to normal life at home and work. Regulators across the world developed release criteria for the patient to fulfill before his release from the confinement in the hospital. The aim of the regulation is to protect the patient family members and the general public from unnecessary exposure to radiation while living in the same area with the released radioiodine therapy patient.

There is no solid agreement on the patient release criteria among countries in the world today; **Table 8** summarizes the current release criteria applied in the majority of countries.

Release criteria 1 in the table is based on the administered activity; if the patient receive less than 110 MBq, he or she are automatically released from hospital like any other diagnostic nuclear medicine exam using other radiopharmaceutical than I-131. Criteria number 2 is based on the remaining activity in the patient's body upon release; such activity is estimated based on measurements by the hospital radiation protection staff or the RSO. Criteria number 3 is based on the direct dose rate measurement at 1 meter from the patient using a calibrated instrument. The last criteria number 4 is used in the United States where licensee may release a patient if dose calculations using patient-specific parameters, which are less conservative than the conservative assumptions, show that the potential total effective dose equivalent to any individual would be not greater than 5 mSv [28].

Release criteria		Applicable activity or dose rate limit
1.	Administered activity	1110 MBq
2.	Retained activity	1110 MBq
3.	Measured dose rate	Less than 70 μSv/hr
4.	patient specific calculation	Dose to family members less than 5 mSv

Table 8. Summary of radioiodine patient release criteria in the world.

19. Incidents and misadministration

A variety of incidents may occur in nuclear medicine practice which can result in the inadvertent radiation exposure of a patient, a member of the public or a staff member. These include according to reference [29]:

- Misadministration means giving the radiopharmaceutical to the wrong patient.
- Giving the wrong radiopharmaceutical or wrong activity to the patient.
- Unjustified examination of pregnant or lactating female patients.

- Use the wrong route of administration, which includes complete extravascular injections that can result in very high absorbed exposure at the injection site especially if the volume is small, the activity is high, and the radiopharmaceutical has a long retention time.
- The definition of wrong activity should be made locally. In general, a variation of ±25% from the prescribed activity is regarded as acceptable in diagnostic applications.

What primary actions should be taken in case of a misadministration?

- Immediately use all available means to minimize any adverse effects;
- Inform responsible nuclear medicine physician;
- Inform patient and referring physician;
- Calculate dose;
- Indicate corrective measures;
- Implement measures;
- Submit report to the head of the department, to the radiation protection committee and, if required, to the regulatory authority;
- Inform all staff of the accident/incident and the corrective measures implemented.

20. Conclusion

In this chapter, we have attempted to include the necessary information needed by radiation safety officer or medical physicist responsible for the radiation protection of the nuclear medicine department. The chapter may also serve as a guide for clinicians with an overall responsibility of the radiation safety program and the licensing of the facility. The chapter includes links to more comprehensive references in radiation protection applied to nuclear medicine.

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