Radiation Protection for Personnel and the Environment

13

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Contents

Learning Objectives

- Understand the fundamental principles of radiation protection applied to the nuclear medicine facilities workers.
- Recognize the importance of a radiation protection culture and implementation of the international basic safety standards with regard to radiation protection of the nuclear medicine staff.
- Define key responsibilities and main issues for ensuring radiation protection of the nuclear medicine staff.
- Identify and learn the main measurement units used in radiation protection.
- Define the main factors for planning/implementing a nuclear medicine facility.
- Identify and manage the main sources of radiation exposure.
- Understand how to manage the solid and liquid waste produced in a nuclear medicine facility.
- Define the classification of working areas and workers.

13.1 General Concepts in Radiation Protection

Nuclear medicine is the medical specialty based on the use of radionuclides administered in the form of unsealed compounds for diagnostic and therapeutic purposes to patients with a wide variety of diseases.

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The extensive use of radioactive compounds, especially in the unsealed form, requires a careful observation of the radiation protection principles both for patients and for personnel. The objectives of radiation protection continue to evolve. While national regulatory bodies are present in almost each country, a reasonably consistent approach can be considered to have general validity and is commonly applied throughout the world: this system is called "system of radiological protection," as defined by the International Commission on Radiological Protection (ICRP) which takes into account the scientific information coming from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [1]. This system will be described in this chapter, paying particular attention to its application to nuclear medicine occupational exposure. Whereas the detailed formulation of the radiation protection principles can be found in the ICRP publications, this chapter describes a concise and simplified summary of these principles.

With its Publication 103 [2], the ICRP recommends a system of radiological protection to cover all possible exposure situations, by considering three possible conditions: (1) planned exposure, (2) emergency exposure, and (3) existing exposure situations. Regarding nuclear medicine, only the first condition can be taken into consideration. In fact, the use of radiation in nuclear medicine is a planned exposure situation under a mandatory regulatory control, for which appropriate authorization from the regulatory body is necessary before starting operations. The so-called potential exposure (accidental spills of radioactive compounds and other incidents in the workplace) can occur, but these remain part of the planned exposure situation, and they must be considered and described, with the corresponding planned solutions, in the application to the regulatory body for authorization.

ICRP defines as a "practice" a planned exposure in a nuclear medicine facility, because "practice" means every situation that can improve/minimize exposure to ionizing radiation by optimizing the operating procedures. Regarding nuclear medicine, ICRP classifies radiation exposure of individuals into three categories:

1. Medical exposure, i.e., exposure occurring in patients treated with radionuclides for diagnosis or therapy and in individuals helping to support and comfort these patients (caretakers)
2. Occupational exposure, i.e., exposure of workers employed in nuclear medicine facilities
3. Public exposure, i.e., exposure incurred by members of the general public (e.g., inadvertent exposure of individuals staying close to the patient after discharge from the nuclear medicine department after having been treated with a radioactive compound, etc.)

Table 13.1 Annual dose limits for workers and public (from ICRP)

	Occupational	Public
Effective dose (mSv)	20	1
Equivalent dose (mSv) to		
Eye lens	20	15
Skin	500	50
Hands and feet	500	

This chapter deals only with occupational exposure, for which ICRP introduced three fundamental radiation protection principles:

1. Justification: any decision that alters the radiation exposure situations should do more good than harm.
2. Optimization of protection: the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable (ALARA), taking into account economic and societal factors.
3. Limitation of doses: the total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits recommended by the ICRP.

All these three principles must be considered in radiation protection of workers (occupational radiation protection). Recommended dose limits are given in Table 13.1 for workers and public. These limits are derived from ICRP 103 [2] (effective and equivalent dose to the skin and hands and feet), from ICRP 118 [3], and from International Atomic Energy Agency (IAEA) [4] documents (for the eye lens).

It should be noted that the limits on effective dose are for the sum of the effective doses from external exposure in the specified time period and the committed effective dose from intakes of radionuclides in the same period. For adults, the committed effective dose is calculated for a 50-year period after intake, whereas for children it is computed for the period up to reaching 70 years of age; additional restrictions apply to occupational exposure of pregnant women.

Key Learning Points

- Knowledge of the radiation protection system: role of ICRP, UNSCEAR, and IAEA.
- Concept of "practice" as an activity suitable to improve the exposure to ionizing radiations.
- Radiation protection principles: justification, optimization, and limitation of radiation doses.
- Annual limits of radiation dose for workers and public.

13.2 Radiation Protection Units

13.2.1 Average Absorbed Dose

The fundamental quantity to be used in radiation protection is the average absorbed dose D_T in a tissue/organ. It can be expressed by:

$$D_T = \frac{\varepsilon_T}{m_T} \tag{13.1}$$

where ε_T is the total energy imparted to a tissue/organ T and m_T is the mass of that organ. D_T is a physical quantity that can be measured, and its measurement unit in the International System of Units (SI) is called gray (Gy): 1 Gy = 1 J/1 kg.

For low absorbed doses (when stochastic effects occur, a condition that is typical of occupational radiation protection), the biological effects of ionizing radiations depend not only on the absorbed dose but also on the type (and quality) of the particles interacting with the organ/tissue and on the radiosensitivity of the same organ/tissue. In order to take into account these two facts, two radiation protection quantities that cannot be measured directly were introduced: the equivalent dose and the effective dose.

For internal radiation exposure from radionuclides, the equivalent and the effective dose depend also on the biological turnover and retention of the radionuclide. This is taken into account in the committed dose quantities (equivalent and effective).

13.2.2 Equivalent Dose

In radiobiology it is well established and accepted that densely ionizing radiation (e.g., α particles and neutrons) will cause greater damage to a tissue/organ than γ rays and electrons when the target absorbs the same average absorbed dose, D_T. In fact, dense ionization events mean higher probability of inducing irreversible damage to the irradiated organ/tissue.

Thus, the average organ absorbed dose is multiplied by a radiation weighting factor in order to obtain a quantity that more closely reflects the biological effect on the irradiated tissue or organ. This quantity is called the equivalent dose H_T, which is defined as:

$$H_T = w_R D_T \tag{13.2}$$

where w_R is the radiation weighting factor. The w_R factor changes, depending on the type and quality of the radiation interacting with the target. Table 13.2 reports the w_R values for various types and quality of ionizing radiation.

The SI unit of equivalent dose is called sievert (J/kg). Exposure from different types of radiation results in a total equivalent dose that is the sum of the equivalent doses from each type of radiation. It should be noted that H_T cannot be considered as a physical quantity, because it cannot be directly measured. In fact, factor w_R is an empirical factor.

13.2.3 Effective Dose

The probability of stochastic effects depends not only on the equivalent dose but also on radiosensitivity of the organ/tissue irradiated. Radiosensitivity of the organs of the human body is quantified through the tissue weighting factors w_T. W_T represents the relative contribution of an organ or tissue, T, to the total damage due to the stochastic effects resulting from a uniform irradiation of the whole body.

The total tissue-weighted equivalent dose, E, is called effective dose and is defined from the equation:

$$E = \sum w_T H_T \tag{13.3}$$

where the sum is obtained by taking into account all the organs sensitive to the induction of stochastic effects that have absorbed an equivalent dose H_T.

Table 13.3 reports the tissue weighting factors w_T reported in ICRP 103 [2]. Note that the sum $\Sigma w_T = 1$ (as expected, the sum of the probability of damage over the whole body must be 1).

The use of effective dose is useful in radiation protection. In fact, different exposure situations (e.g., internal versus external exposure to different types of radiation) can be combined and result in a single value, the effective dose.

Table 13.2 w_R factors as reported in ICRP 103

Radiation type	w_R
Photons	1
Electrons, muons	1
Protons	2
Alpha particles, fission fragments, heavy nuclei	20
Neutrons	Energy continuous dependent function

Table 13.3 w_T factors as reported in ICRP 103

Tissue	w_T	Σw_T
Red bone marrow, colon, lung, stomach, breast, remainder tissues	0.12	0.72
Gonads	0.08	0.08
Bladder, esophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04

13.2.4 Committed Dose

When radionuclides are incorporated in the body, the dose absorbed by the body is related to the decay time of the radionuclide. Therefore, another quantity, defined as "committed dose," has been introduced. From a radiation protection point of view, the committed equivalent dose can be expressed by:

$$H_{\mathrm{T}}(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_{\mathrm{T}}(t)\,\mathrm{d}t \tag{13.4}$$

where t_0 is the time of intake and τ is the time of integration. For adult workers $\tau = 50$ years. A committed effective dose can be defined as:

$$E(\tau) = \sum_T w_{\mathrm{T}} H_{\mathrm{T}}(\tau). \tag{13.5}$$

Key Learning Points

- Knowledge of the absorbed dose and its SI unit.
- Knowledge of the radiation protection units (equivalent dose, effective dose, committed equivalent dose, and committed effective dose) and their SI units.

13.3 Radiation Protection in Nuclear Medicine

13.3.1 Introduction

Virtually all the possible procedures in the nuclear medicine facility must be subjected to radiation protection. These procedures are:

- Ordering radionuclides
- Unpacking and checking the shipment
- Storage of radionuclides
- General rules for work in controlled and supervised areas
- Preparation of radiopharmaceuticals
- Personal and workplace monitoring
- Internal transport of radionuclides
- Management of radioactive waste
- Administration of radiopharmaceuticals to patients
- Protection issues in patient examinations and treatments
- Routine cleaning of facilities
- Decontamination procedures
- Care of radioactive patients

Rules must be established and upgraded, under the responsibility of the licensee, by the radiation protection officer, RPO. Radiation protection in a nuclear medicine facility must be strictly linked to the medical activity in the facility. This means that radiation protection in general must consider patients and workers taking into account also economic and social factors.

Almost all countries have their own legislation in radiation protection. The regulatory systems require that any facility has a formal authorization to perform nuclear medicine "practices" from the radiation protection regulatory institutions and that the persons working in nuclear medicine facilities have a specific training in radiation protection.

The requirements to be fulfilled in order to grant such an authorization vary from country to country, but in general they comply with the requirements of the IAEA Basic Safety Standards (BSS). The IAEA BSS system is a set of published practical general recommendations taking into account the ICRP (and UNSCEAR) publications. This system requires that a set of responsibilities and duties be formally assigned to the persons involved in working with radionuclides.

Key Learning Points

- Nuclear medicine procedures are subjected to radiation protection.
- Radiation protection in nuclear medicine requires a specific authorization.
- Such authorization must be granted by the local regulatory body; usually the regulatory rules follow the IAEA BSS publications.
- The person responsible of the activity is the licensee; he/she can delegate some specific activities concerning radiation protection to other persons.
- These persons (medical physicist, radiation protection officer, nuclear medicine specialist, technologist, radiopharmacist) must be specifically educated and trained in radiation protection.

13.3.2 Formal Authorizations and Responsibilities

Before starting the activity, a nuclear medicine facility needs to be formally authorized by the radiation protection regulatory body. The licensee is responsible of the application of what the authorization requires. He/she can decide to assign to other persons (nuclear medicine specialists, medical physicists, technologists, radiopharmacists, radiation protection officers) some specific responsibilities in implementing radiation protection in the nuclear medicine facility.

All the persons having responsibilities must possess the required education level, must be trained, and must have the competence to perform their duties.

A radiation protection program must be adopted; the necessary resources must be given also for the education and training of the personnel working in the facility. An example of radiation protection program can be found in [5].

13.4 Facility Design

This is a duty/responsibility of the medical physicist, who must take into account the following factors:

- Safety of sources
- Optimization of protection for staff and the general public
- Preventing uncontrolled spread of contamination
- Maintaining low background where most needed
- Fulfillment of national requirements regarding pharmaceutical work

13.4.1 Location and General Layout

In the choice and design of the location of a nuclear medicine facility, the following factors must be addressed: (1) it must be readily accessible, especially for outpatients (who generally constitute the majority of the patients), and (2) it should also be located away from radiotherapy sources and other sources of ionizing radiation (cyclotron), which can interfere with the measuring equipment.

The work areas must be separated from the room where patients who have already been administered with the radiopharmaceutical are waiting for the scan. The uncontrolled spread of contamination must be avoided; therefore, the rooms for preparation of radiopharmaceuticals must be far away as possible from rooms for measurements and from the patients' waiting areas.

The transfer of unsealed sources across the facility must be avoided or reduced as much as possible.

In general, the type of work to be performed and the characteristics and quantities of the sources employed must be considered. Based on this, the need of air changes, shielding of walls, materials used for the walls, floors, and work benches must be examined.

The rooms of the facility must be classified based on the hazard as low, medium, and high hazard areas. The risk of contamination must be reduced as soon as possible also by containing the contamination and cleaning it, using floors and work benches that are impermeable to water and chemicals, easily washable, and resistant. The floor cover should be curved to the wall. The walls should also be easily cleanable. Chairs and beds used in high hazard areas should be easy to decontaminate.

The opportunity to install ventilation systems (fume hood, laminar-flow cabinet, or glove box) must be considered in the rooms where unsealed liquid or gaseous sources are manipulated.

In some cases and in some countries, legislation does not allow the immediate release to the sewer system of aqueous waste produced by the patients treated in the nuclear medicine facility. In this case a dedicated tank system must be designed and used, following the authorizations for the discharge. A separate bathroom for exclusive use by the patients to whom radiopharmaceuticals have been administered is recommended; the waste from this bathroom must be connected to the dedicated tank system—if so indicated in the authorization requirements.

Additional details regarding floor planning and additional topics can be found in the IAEA *Nuclear Medicine Resources Manual* [6].

13.4.2 Storage of Radioactive Sources

The licensee must establish a security system to prevent the loss, unauthorized use, or damage of sources. Radioactive materials can be ordered only by the authorized persons. The sources must be recorded in a document and stocked in dedicated rooms, under the responsibility of the authorized personnel. The regulatory body should promptly be informed in cases of lost or stolen sources.

Possible accidents to the facility must be considered (fire, water flood, earthquake), and the risks due do possible dispersion of radionuclides in the environment must be considered and addressed.

13.4.3 Structural Shielding

A possible shielding of walls, floors, and ceilings must be considered, depending on the type and the quantity of radionuclides used. In a PET/CT facility, structural shielding is always necessary, due to the high energy of the annihilation radiation. Calculation of the degree of shielding required must be performed by a qualified medical physicist adequately trained in radiation protection. Radiation surveys should always be performed to ensure correctness of the calculations.

13.4.4 Workplace Classification

With regard to occupational exposure, the BSS require the classification of workplaces as controlled areas or as supervised areas.

In a controlled area, individuals follow specific protective measures to control radiation exposures. The controlled area

must be clearly identified, and it is convenient to use existing structural boundaries, which should already be considered at the planning stage of a facility.

A supervised area is any area for which occupational exposure conditions are predictable and stable. They are kept under continuous scrutiny, even though specific additional protective measures and safety provisions are not normally needed.

In a nuclear medicine facility, the rooms for preparation, storage (including radioactive waste), and injection of the radiopharmaceuticals are usually classified as controlled areas. Owing to the potential risk of contamination, the imaging rooms and waiting areas for injected patients might also be classified as controlled areas. The area housing a patient to whom therapeutic amounts of activity have been given will also be a controlled area.

The workplace must be monitored to check possible contamination of the surfaces. There are two kinds of possible monitoring of the working places: monitoring of exposure and monitoring of contamination. The first one can be performed by using instruments that measure external exposure (dosimeters, ionization chambers, Geiger counters) and the second one by recoiling the contamination on filters (e.g., by smear tests) and then counting them with a spectrometric probe.

Frequency of these measurements must be decided by the medical physicist or the radiation protection officer, based on the work carried out in the facility and on the type and quantity of radionuclides employed.

13.4.5 Waste Management Operations

The management of waste is one of the main issues in the radiation protection of workers and public in a nuclear medicine facility. Usually the radionuclides used in nuclear medicine are short half-life radionuclides; thus, they can be retained in the facility until they decay at the background level, after which they can be released in the environment without hazards for the public.

The contaminated waste can be either solid, liquid, or gaseous. The first principle that a radiation protection program must follow requires that the contaminated waste be reduced as much as possible, in order to avoid the release of radioactivity in the environment. The authorization of a nuclear medicine facility must contain a section concerning the treatment of waste.

Solid waste must be retained in specific containers (available near areas where the waste are generated), segregated in specific locked areas far from the rooms of treatment until their decay under the limits imposed from the regulation authorities. These containers must be clearly identified and labeled, e.g., by listing the radionuclides contained. Specific information on the type and quantity of radionuclides contained and on the external dose rate at a chosen distance from the container must be supplied.

If prescribed by the regulatory system, the liquid waste must be retained in a recoil tank system until the radioactivity concentration reaches the values authorized by the regulatory body. After this period, they can be released into the sewage system of the city.

For some radionuclides (e.g., ^{99}Mo/^{99m}Tc generators), return of the decayed source to the vendor is a good option, especially for long half-life radionuclides.

There must be separate bathrooms for the workers and for the patients.

Key Learning Points

- Knowledge of the main requirements of a nuclear medicine facility project, depending on the work done, on the radionuclides employed, and on their characteristics.
- Knowledge of the main characteristics of the site of waste storage.
- Shielding of the site according to energy (and quantity) of radionuclides employed.
- Classification of the workplaces as controlled areas or supervised areas.
- Solid and liquid waste management.

13.5 Exposure of Workers

Detailed prescriptions on the workers' exposure in a nuclear medicine facility can be found in the IAEA safety guides [7–9], which also include recommendations on how to meet the radiation protection standards. A summary of the relevant issues follows here below.

13.5.1 Sources of Exposure

Occupational exposure to ionizing radiation in nuclear medicine is due to the external irradiation from the unsealed sources and also to the possible introduction into the body (internal exposure) of radioactivity for ingestion or inhalation inside the body.

The precautions against external irradiation depend on the characteristics of the radionuclides employed. In fact, a lead-shielded apron similar to that used in radiology can be a good precaution against external irradiation from lower-energy radionuclides (i.e., ^{99m}Tc), but it is not equally effective as the energy of the photons increases (i.e., ^{131}I).

Similarly, the hazards due to the internal incorporation of radionuclides depend on the decay type (α, β, or γ), on the decay constant, and on the energy of the source incorporated. Furthermore, the biodistribution kinetics of the radionuclide is very important to assess its effect from a radiation protection point of view.

The different activities (from unpacking the sources to administration of the radiopharmaceutical to the patient—as also positioning the patient on the imaging table) contribute to the radiation exposure of the worker. Usually the annual permitted doses are below 6 mSv. They are due mainly to the imaging and preparation-administration procedures. For this reason, it is very important to use adequate shielding for the administration syringes and to work under a fume hood (whenever possible) when preparing the radiopharmaceutical for administration.

Spillage of radioactivity during the procedures must be carefully avoided. If it occurs, the medical physicist and/or the RPO must be immediately alerted. Adequate care must be taken when performing surgical procedures on patients who have been recently treated with radionuclides or when performing autopsy of their corpse (especially after nuclear medicine therapy procedures).

Adequate precautions must be used in cleaning all the surfaces (doors, floor, walls) of a nuclear medicine facility.

13.5.2 Justification, Optimization, and Dose Limitation

All the procedures must be justified, taking into account the principle that workers have not benefitted from their own radiation exposure. Justification of the procedures is thus important for both the patients and the workers. The risks in radiation work must be contained; however, they should not be greater than for any other works in a hospital setting.

When justified, a procedure must be optimized, trying to administer to patients the minimum possible activity compatible with the diagnostic/therapeutic value of the procedure performed. Such optimization requires the use of shielding (when possible), but also a certain limitation of the time and distance from the patient.

The doses reported above must be considered as maximum limits of exposure. The effective dose absorbed must be further reduced under these limits as much as possible.

Although the facility design, the use of adequate shielding barriers and coats, and good functioning of the fume hoods are very important in the radiation protection of workers, a training program and the education of workers can strongly help in implementing an effective radiation protection of the facility.

While the licensee and employer have the main responsibility regarding limitation of the exposures, the workers have the responsibility to follow strictly the radiation protection rules given and to use properly the instruments, tools, and devices that are supplied to them for radiation protection/radiation measuring purposes.

13.5.3 Pregnant Workers

The dose limits for unborn children are usually the same as the public; thus, this limit must be applied also for the pregnant workers. Therefore, the possibility to remove the pregnant worker from her workplace in nuclear medicine must be seriously taken into consideration, especially due to the possibility, in these facilities, of internal contamination.

13.5.4 Protective Clothing

Protective clothing (gloves, lead-shielded aprons, glasses, shoes or overshoes, caps, masks for aseptic work) must be available to the workers in the facility. The usefulness and opportunity to use the protective clothing depend on the works being carried out and on the characteristics of the radionuclides employed. This is especially true for the lead-shielded aprons that can be very effective for non-high-energy radionuclides.

13.5.5 Personal Monitoring

A personal and environmental monitoring program must be assured under the supervision of the medical physicist and/or the RPO. The responsibility to assure the monitoring program is of the licensee and the employer.

The RPO will decide which workers will be involved in the program (which includes monitoring of external and internal exposure) and what is the most adequate monitoring frequency. Usually the workers involved in the program are persons who routinely work in nuclear medicine, including nurses.

Monitoring of external exposure usually implies the use of dosimeters capable to measure and retain the external radiation exposure. Thermoluminescent (TL) dosimeters are currently used to this purpose.

Monitoring of the possible intake of radionuclides (internal contamination) is rarely performed; such programs are usually implemented in those facilities where large amounts of ^{131}I-iodide for the treatment of thyroid disease are used. Monitoring of internal contamination due to ^{131}I implies the use of an external probe to evaluate the activity present in thyroid. Based on this measurement, the committed effective dose can be calculated as described in ICRP 78 [10].

13.5.6 Local Rules and Supervision

After reaching a specific agreement with the workers (usually through designated representatives), the employer and licensee must:

- Establish written local rules and procedures necessary to ensure adequate levels of protection and safety for workers and other persons.
- Include in the local rules and procedures the values of any relevant investigation level or authorized level and the procedure to be followed in the event that any such value is exceeded.
- Establish local rules and procedures, the protective measures, and safety provisions known to those workers to whom they apply and to other persons who may be affected by them.
- Ensure that work involving occupational exposure is adequately supervised and take all reasonable steps to ensure that the rules, procedures, protective measures, and safety provisions are observed.

All the procedures possible in the nuclear medicine facility (as listed above under the "Introduction" section) must be subjected to radiation protection. The rules must be established and upgraded, under the responsibility of the licensee, by the RPO.

Key Learning Points

- Knowledge of the main sources of radiation exposure in nuclear medicine.
- Relevance of the physical and chemical characteristics of the radionuclides employed.
- Observation of the principles of radiation protection: justification, optimization, and limitation of doses for workers employed in nuclear medicine.
- What to do with pregnant workers.
- Monitoring program of doses for workers: external and internal irradiation.
- Duties and responsibilities of the employer and licensee.

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