Radiation protection in Nuclear Medicine

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Abstract. In this paper the emerging critical point in Nuclear Medicine radiation protection are presented. Shielding issues regarding cyclotron installations, as well as safe delivery of radionuclides and management of gaseous effluents are addressed. Manipulation of beta and positron emitting radionuclides is also discussed, with reference to the problem of correct assessment of personal dose to the extremities.
In all these cases, the role of Monte Carlo simulation techniques is emphasized, as for contributions in the proper evaluation of the source term and transmission factors in shielding calculation for multi modal PET-CT and SPECT-CT scanners.
Finally, the classification algorithm introduced more than 10 years ago by ICRP Publication 57 is reviewed and possible updates discussed.

KEYWORDS: Radiation Protection; Nuclear Medicine; PET radiopharmaceuticals; beta emitting radionuclides; Monte Carlo techniques; shielding.

1. Introduction

Nuclear Medicine has undergone a process of evolution in the last few years, with the growth of clinical PET, the wide diffusion of cyclotrons for PET radionuclide production, the sudden appearance of multimodal PET-CT and SPECT-CT scanners, the introduction of new molecules for targeted radionuclide therapy, surgical practices using radiotracers, like sentinel limphonode or breast cancer and others.
However, even if a few relevant documents dealing with specific aspects have been published [1], [2], the apparatus of reference documents as regards radiation protection in Nuclear Medicine is still essentially based on the more than 10 years old ICRP Publication 57 [3].
In this paper a review of open issues is attempted and possible lines of evolution of radiation protection in Nuclear Medicine are examined.

2. PET radiopharmaceuticals production

2.1 Cyclotron s site planning and shielding

The number of cyclotrons used in the production of PET radionuclides is dramatically increased all around the world [4]; even if local or regional distribution of the most important radiopharmaceutical ^{18}F-FDG is possible and has been widely adopted, the installation of a cyclotron in a Hospital presents several unique features, like the possibility of use of very sort lived radionuclides (^{11}C, ^{13}N). Cyclotrons have thus become an integral part of Nuclear Medicine equipment in several clinical and research settings.
The NCRP has recently published a relevant Report [1], replacing the aged NCRP51 [5] . The NCRP144 publication, however, deals with all types of protons and particle accelerators, ranging up to multi GeV energies, and the recovery of information for the specific field of relatively low energy accelerators for radionuclide production is not as immediate as wished.
Cyclotrons installed in Hospital institutions are typically compact systems, capable of accelerating H^- ions to an energy in the range of 10 – 20 MeV, and optionally D^- ions up to about 8 - 10 MeV. They

are frequently self shielded, but both in this case and in the general one of a "naked" cyclotron, additional shielding must be provided.
The basic equation for estimation of the expected dose at the target point is based on a reference dose value (at a certain angle, and at a distance of 1 m); in general, H_{ref} will be different at 0° and 90°:

$$H_{expected} = H_{ref} \cdot \frac{U \cdot T}{d^2}$$

The required attenuation factor is then:

$$B_x = \frac{H_{limit}}{H_{expected}}$$

And the number of tenth value layers needed for reaching the objective is:

$$n = \log_{10}\left[\frac{1}{B_x}\right]$$

The shielding thickness calculated should take into account different values for the first and "equilibrium" TVL

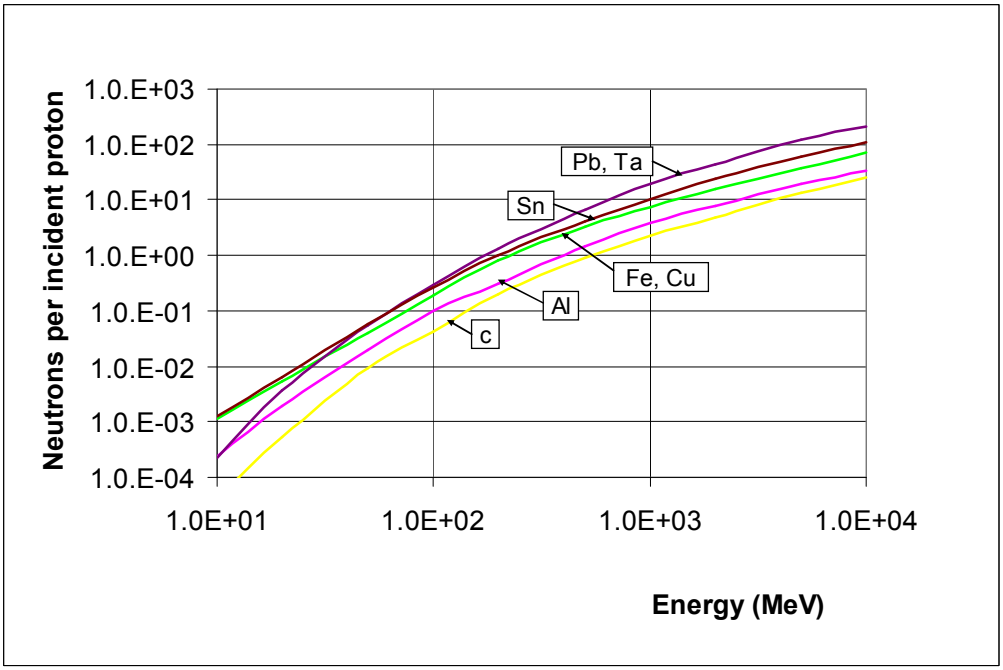
$$S_p = TVL_1 + (n-1) \cdot TVL_n$$

And the final shielding thickness, with the addition of a "safety" HVL, is given by

$$S_{p,s} = S_p + HVL_n$$

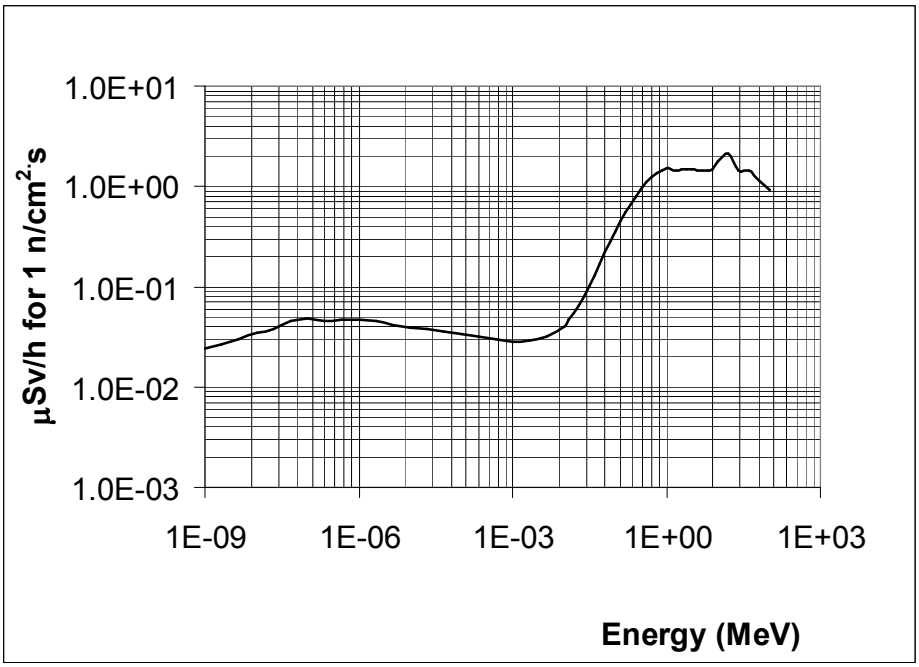
The equations are relatively simple; the complexity is in the choice of the proper parameters, particularly the starting H_{ref} value.

Figure 1 – Yield of neutrons per incident proton on various materials, as a function of energy. Adapted from NCRP144 [1] and IAEA TecRep283 [6].



The data on yield of neutrons per incident proton [1], [6] help to evaluate the source term, together with the conversion factors for neutron dose rate [7], [8].

Figure 2 – Conversion factor for H*(10) as a function of energy [8].



However, spectral information on the emitted neutron beam is necessary as well [9], [10].
Monte Carlo techniques will play an increasing role in the evaluation of specific issues, like transmission of radiation in ducts and labyrinths and activation of structural components and building materials [11].
The IAEA is in course of publishing several technical documents that will be of great help in assisting site planning and safe installation of cyclotrons for biomedical use.

2.2 Safe delivery of radioactivity boluses.

Once the irradiation for the production of a radionuclide is completed, the target material, typically a limited volume of a liquid or gaseous media, has to be delivered to the destination hot cell.
To be safe, the delivery requires that several conditions be verified: a) the delivery line should be tighten; b) the receiving hot cell should be in a safe condition.
As regards the first point, periodical tests of line tightness must be performed, i.e. by pressurizing the line with carrier gas and verifying that the pressure decrease is less than a prescribed threshold (e.g. less than 1 psi in 60 s for a filling pressure of 50 – 60 psi). These tests should be an integral part of radiation protection surveys.
Concerning the second requirement, the hot cells should be equipped with a control system able to communicate to the cyclotron control software the status of the cell (e.g. the status open / closed of the door , of the cell ventilation etc.).

2.3 Cyclotron components maintenance

Routine use of a target determines a slight decrease in production yield and periodical need of cleaning and rebuilding the target, with replacement of the foils and o-rings. Disassembly and cleaning of the target needs several precautions from the radiation protection point of view.
A safe working place for target disassembly should be foreseen in designing a new installation. The target should be disassembled working in an area protected by an L-shaped shield, with a glass lead loaded window; and the highly activated foils should be quickly removed. The target chamber, whose activation is relatively limited, can then be moved to a vented chemical hood, in order to clean the inner surfaces of the target body limiting the risk of personal contamination by powders, aerosols etc.
Contamination by inhalation can potentially happen in all operations regarding the vacuum chamber of a cyclotron; internal ions sources could be a source of contamination due to residuals produced in the discharge in the ion source gas (Tantalum radionuclides); activated powders can be produced by damaged stripping foils, collimators and other items hit by the beam. Proper clothes, gloves and a face mask should be worn by the operators during all maintenance operations.
Apart preventive measures, contamination control techniques specific for metallic radionuclides such as ^{56}Co, ^{57}Co, ^{58}Co, ^{52}Mn and ^{54}Mn should be available.

2.3 Aeriform emissions from synthesis modules.

Synthesis modules can a source of radioactive gases and aerosols [12]. There is a variety modules for the production of different radiopharmaceuticals, and also in the case of the most important one, 18F-FDG, there are several different options.
In very general terms, synthesis modules could present two main points of emission of aeriform radioactive wastes: a) a waste gas outlet, directly connected with the radionuclide collecting vial and the reactor (or reactors). The emission from this outlet is typically of limited volume, but with significant activity; it is then frequently connected to a waste tank, in order to allow controlled release after waiting time. b) a module is typically equipped with a vacuum pump, whose outlet is the second potential source of radioactive wastes; these are frequently characterized by a moderate volume and a limited activity concentration; options for the management of these effluents include a compressing station or a waste delay line, that allows sufficient transit time to get proper decay prior to release.

3. Radiopharmaceuticals manipulation and administration

Production and dispensing of patient's individual doses of radiopharmaceuticals require manual operations that expose operators hands to relatively high radiation doses. This aspect is become more and more important, since relevant radiopharmaceuticals, both for diagnostic and therapeutical use, are labelled with beta emitting radionuclides. This includes PET radionuclides, since positron radiation has sufficient energy to escape from syringes and thin walled containers, and pure beta emitters, like ^{90}Y, or beta – gamma emitting radionuclides as ^{153}Sm or ^{177}Lu, not to mention the widely use ^{131}I.
Most part of personal dosimeter for extremities have only limited response to low energy beta radiation, due to thickness of the envelope or to lack of proper calibration.
Use of less then optimal dosimeters can lead to a significant underestimation of H(0.07).
Research work in modelling manipulation and administration operations with Monte Carlo techniques will be instrumental in the development of proper dosimeters and in making them widely available for proper assessment of operator's extremities and eye lenses dose.
The ORAMED project (http://www.oramed-fp7.eu/), in the framework of the European Union FP7 platform, is an example of multinational co-operative action to promote and undertake reasarch in these fields.

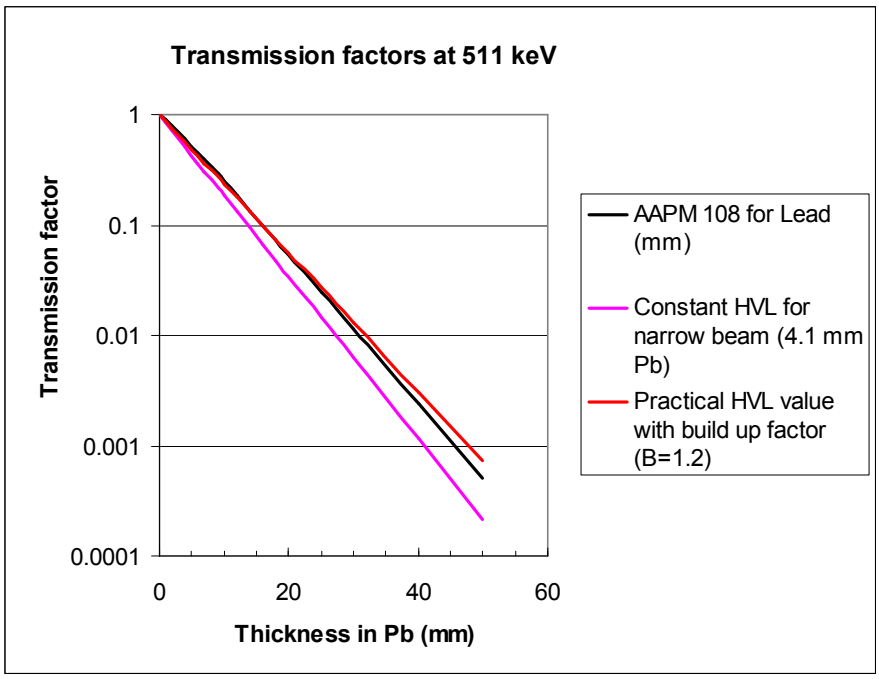
4. Multi modality scanners

PET-CT and SPECT-CT scanners have changed the diagnostic approach in Nuclear Medicine. The integrated information supplied by these kind of equipment has proved to improve the value of diagnostic procedures is a relevant fraction of cases and in several applications [13].

The installation of each single modality is relatively well known, but multi modal scanners have raised new problems and requested a mixing of culture and knowledge on site planning and radiation protection procedures that is not always readily available.

The recent publication of a relevant AAPM report [2] has clarified the situation and supplied valuable help in the design of new installations. It is worth to note that in this case also, Monte Carlo techniques have been useful for evaluation of broad beam transmission data; this approach is, in general, preferable to the classical use of build up factors.

Figure 3 – Comparison of transmission data for 511 keV photons. The use of narrow beam data determines a severe under estimation of transmission, as evaluated by Monte Carlo simulations The use of practical HVL value, including a build up, could give results near to the Monte Carlos method, but a slight under estimation is observed for relatively thin barriers.



An other interesting point, is the consideration needed not only by the equipment, but by the patient itself as a source of radiation. In particular, in busy PET-CT installations, 2 -3 injected patients per scanner should be expected to be present in administration – waiting areas. At a rate of emission of the order of 30 μSv/h at 100 cm per patient, this is clearly a problem that need all the attention of radiation protection professionals, in order to properly plan installations and patient flow.

5. Calssification of Nuclear Medicine departments. The issue of ventilation.

For long time, the Publication 57 of ICRP [3] has been the basis for the classification and the radiation safety design of Nuclear Medicine departments.

This was based on the calculation of a weighted average of the radionuclide activity employed in each room.

Table 1: ICRP 57 radionuclide weighting factors

Class	Radionuclide	Weghting factor
A	^{75}Se, ^{89}Sr, ^{125}I, ^{131}I	100
B	^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{51}Cr, ^{67}Ga, ^{99m}Tc, ^{111}In, ^{114m}In, ^{123}I, ^{201}Tl	1
C	^{3}H, ^{14}C, ^{81m}Kr, ^{127}Xe, ^{133}Xe	0.01

Table 2: ICRP 57 weighting factors for the type of operation

Type of operation or area	Weghting factor
Storage	0.01
Waste handling Scintigraphic counting/imaging when administration is made elsewhere Patient waiting area Patient bed area (diagnostic)	0.1
Local dispensing Radionuclide administration Scintigraphic counting/imaging when administration is made in the same room Radiopharmaceutical preparation, simple Patient bed area (therapeutic)	1.0
Radiopharmaceutical preparation, complex	10

Table 3: ICRP 57 indications on finishing and radiation protection items.

Category of hazard	Floor	Surfaces	Fume cupboard	Room ventilation	Plumbing	First aid
Low	Cleanable	Cleanable	No	Normal facilities	Standard	Washing
Medium	Non-permeable, easily cleanable	Cleanable	Yes	Good	Standard	Washing & decontamination facilities
High	Continuous sheet welded to walls	Cleanable	Yes	Extractor fan	May require special plumbing	Washing & decontamination facilities

While the general scheme of classification remains valid, several update are necessary, taking into account new applications and new knowledge in the field.
First of all, the list of radionuclides considered as typical for Nuclear Medicine applications needs to be updated; not only, in the light of what as been discussed in previous paragraphs, also weighting factors for the type of operation should be reviewed and integrated. But what needs major modification and integration with quantitative information is Table 3, containing indications on

technical and radiation protection design and finishing. In particular, as regards ambient ventilations, a central point in radiation protection for areas at risk of contamination, ICRP 57 indications appear to be vague. In recent years, Technical Committees of the CEN and the European Commission, have developed and introduced a new methodology for calculation of air flow and ventilation in building for non residential use [14], [15]. This methodology, as it is, applies to working and common areas without taking into account specific sources of risk connected to the type of activity.
The flow rate requisite is basically calculated according to the equation

$$q_{tot} = n \cdot q_p + A \cdot q_b \qquad l \cdot s^{-1}$$

were q_{tot} is the total flow rate required ($l \cdot s^{-1}$), q_p is the flow rate required for each of the n person occupying the ambient; the term q_b is the flow rate required to take into account pollutants released in the internal air by the materials of the building itself ($l \cdot s^{-1} \cdot m^{-2}$), and A is the surface of the room considered. The CEN documents supply tables of reference values for the flow rates q_p and q_b, as a function of the specified quality required for the indoor air. The only additional risk factor considered by the European rules is cigarette smoke; in the presence of smoke, a modified version of the above equation applies.
For the quantitative evaluation of the ventilation required in Nuclear Medicine areas it is proposed to adopt an approach similar to the one suggested by CEN for calculation of the ventilation in presence of smoke; this is in the form:

$$q_{tot} = n \cdot q_p + A \cdot q_b + A \cdot q_r$$

Were q_r is the flow rate ($l \cdot s^{-1} \cdot m^{-2}$) requested to account for the risk factor, in particular, the presence of radioactive material. This modality of calculation is not based on a dosimetric criteria, it is simply related to the area of the room / laboratory considered, as a measure of the complexity of the installation, and do not takes into account type and quantity of radionuclides actually employed. However, it can be shown that a proper choice of the values for q_r produces reasonable values for the air exchanges in Nuclear Medicine areas.

Table 4: proposed data of reference for the quantitative calculation of ventilation requirements in Nuclear Medicine departments.

Type of room	Typical range of occupancy (m^2/person)	Default value of occupancy (m^2/person)	Range of air flow rate q_p (l/sec.persona)	Default value of air flow rate q_p (l/sec.person)	Range of air flow for buiding emissions q_b ($l/sec \cdot m^2$)	Default value of air flow for building emissions q_b ($l/sec \cdot m^2$)	Range air flow rate for risk factor q_r (l/sec.m2)	Default air flow rate for risk factor q_r (l/sec.m2)
Diagnostic room	20 - 25	24	5 - 15	10	1.0 - 2.0	2.0	1.0 - 2.0	2.0
Control room	5 - 10	7	5 - 15	10	1.0 - 2.0	2.0	1.0 - 2.0	1.0
Laboratory	5 - 10	7	20 - 40	30	4.0 - 6.0	5.0	4.0 - 6.0	5.0
Wastes storage	20 - 25	24	5 - 15	10	1.0 - 2.0	2.0	1.0 - 2.0	2.0
"Hot" waiting room	1.5 - 2.5	2	10 - 15	12	4.0 - 6.0	5.0	0.0 - 1.0	0.0
Patient room	5 - 10	7	10 - 15	12	1.0 - 2.0	2.0	1.0 - 2.0	2.0

This method of calculation has is strength in its simplicity; its goal it is not to prospectively evaluate the upper limit of inhalation by workers in a indoor ambient. This will be almost impossible, taking into account the huge variability of operational situations, mixtures of radionuclides and in sight of both normal operation and potential accidents. Instead, this straightforward calculation method makes possible for the expert in radiation protection to produce quantitative specification for the ventilation system in Nuclear Medicine department, that can be used unambiguously by the HVAC designer, by simply adding a safety overestimation on the required air flow.

4. Training

Training of staff in Nuclear Medicine should be a component of the programme on radiation protection. The extent of training and the subjects to be considered should be adapted to the particular needs of the different health professional involved. However, it is felt that too much variability exits in different countries, ranging from few hours of on job training, to dedicated university courses. There is need for harmonization [16], [17] and proper planning of the acquisition and maintenance of competences [18], providing not only initial training, but also refresher and updating course and also periodic review and update of the training program itself. Multimedia technologies and the Internet can play a fundamental role in this process; an excellent example is given by the IAEA publications data base and web sites like http://rpop.iaea.org/RPOP .

5. Conclusions

In conclusion, several progresses take place in Nuclear Medicine during the last few years. The number of installed cyclotron is greatly increased, and is still growing all around the world, in order to fulfil the increasing need of ^{18}F and other PET radionuclides. This process has determined the need of updating and improving safety and protection in PET centres, to allow for safe synthesis and dispensing of radiopharmaceuticals.
Diagnostic procedures are now performed with multimodal PET-CT scanners, which require specific site planning and shielding. The experience grown in these years has then lead to the publication of detailed guidelines, that will be an example for similar needs as regards SPECT-CT scanners, that are now becoming more and more diffused.
Classification and radiation protection design of Nuclear Medicine departments is still based on reference documents like ICRP Publication 57 [ICRP57], that is now more than 10 years old and need review, in particular as regards specifications for the ventilation.
Finally, training maintains a crucial role in radiation protection; appropriate programs for health professionals involved in Nuclear Medicine practice should be developed, periodically reviewed and upgraded and should be considered an integral part of the radiation protection programme.

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