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Shielding Calculations for Positron Emission Tomography - Computed Tomography Facilities

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1. Introduction

In the last fifteen years, Positron Emission Tomography (PET) - Computer Tomography (CT) has spread rapidly and replaced conventional PET in the field of nuclear medicine. PET-CT allows morphological and functional imaging to be carried out in a single imaging procedure. Integrated PET-CT has been shown to be more accurate for lesion localization and characterization than PET or CT alone, and the results obtained from PET and CT separately and interpreted side by side or following software based fusion of the PET and CT datasets. At the same time, PET-CT scans can result in high patient and staff doses; therefore, careful site planning and shielding of this imaging modality have become challenging issues in the field.

In Mongolia, the introduction of PET-CT facilities is currently being considered in many hospitals. Thus, additional regulatory legislation for nuclear and radiation applications is necessary, for example, in regulating licensee processes and ensuring radiation safety during the operations.

This paper aims to determine appropriate PET-CT shielding designs using numerical formulas and computer code. Since presently there are no PET-CT facilities in Mongolia, contact was made with radiological staff at the Nuclear Medicine Center of the National Cancer Center of Mongolia (NCCM) to get information about facilities where the introduction of PET-CT is being considered.

2. Current status of PET-CT

PET-CT scans allow for more detailed anatomical (CT) and functional (PET) information of a patient, especially with regard to oncology. With attenuation correction performed by the CT component, PET-CT can provide shorter examination times and higher quality images than conventional PET. Recent studies and improvements in PET-CT have led to lower administered dosage and shorter acquisition times as the sensitivity of PET has increased. In addition, there have been many developments in PET-CT's clinical uses, and it is now used in neurology, and cardiology, among other fields, and researchers are currently working on a combination of PET-MRI to improve diagnostic methods. There are, however, still some challenges related to PET-CT staff and patient exposure, radiation shielding, dose assessment, and dose reduction.

3. Regulatory limits

The Nuclear Energy Act of Mongolia regulates dose limits in controlled radiation areas and uncontrolled areas open to members of the public. According to the Act, any nuclear- and radiation-related operations shall ensure that effective dose equivalent in uncontrolled areas does not exceed 1 mSv/year or 20 μSv/h. This implies a weekly dose limit of 20 μSv, which is used to calculate shielding design in uncontrolled areas. The occupational dose limit in controlled areas is 50 mSv/year. Most shielding calculations use a target level of 5 mSv/year in controlled areas to be consistent with ALARA recommendations.

4. Methods and results

For this study, existing numerical formulas and computer simulations were used to design and calculate the amount of shielding needed for the facility. The existing numerical formulas were used to calculate the exposure factor, reduction factor, total dose, and transmission factor, and thereafter the shielding design. For the computer simulations, Monte-Carlo N-Particle Transport Code (MCNP) 6.1 is used. The simulation result is expected to be presented during the conference.

4.1 Calculations

The shielding design can be calculated using numerical formulas. Data to be used in this paper, such as expected workload, occupancy and geometrical dimensions of rooms in the facility, are taken from information provided from radiological staff at NCCM. The dose administered and the workload are assumed to be 15mCi and 9 patients per day, respectively. A plan of the room layout for the PET facility at the existing NCCM building, where PET-CT installation is being considered, is shown in Figure 1. In multi-floor buildings, it is necessary to take into account the areas above and below the PET-CT facility, as well as adjacent areas on the same floor. It is shown in Figure

2. It can be assumed that the patient (the source of the activity) is 1.0 m above the floor. The dose rate is calculated at 0.5 m above the floor for rooms above, at 1.7 m above the floor for rooms below, and at 0.3 m for adjacent rooms on the same level.

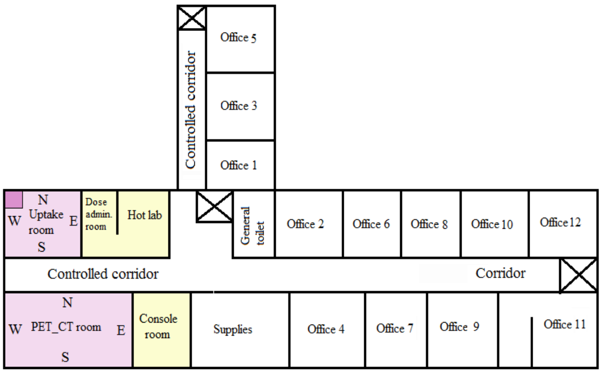

Fig. 1. Considered room layout of PET-CT facility in NCCM. This figure is used in this hand calculation.

4.1.1 Dose rate

The patient injected with the radiotracer is considered as the point source, and complication of physiological redistribution of the radiotracer is neglected. With this assumption, the dose rate (X) per study is not calculated with high accuracy, but it will give a conservative estimation of the dose rate.

$$X = \frac{\Gamma \cdot S}{d^2} \qquad (1)$$

The exposure rate constant is Γ=5.8 R·cm^2/mCi·h, the administrated activity is S=15 mCi, the distance from the point source is d=300 cm, and the calculated dose rate without shielding is 0.976mR/h or 9μSv/h in the PET-CT room.

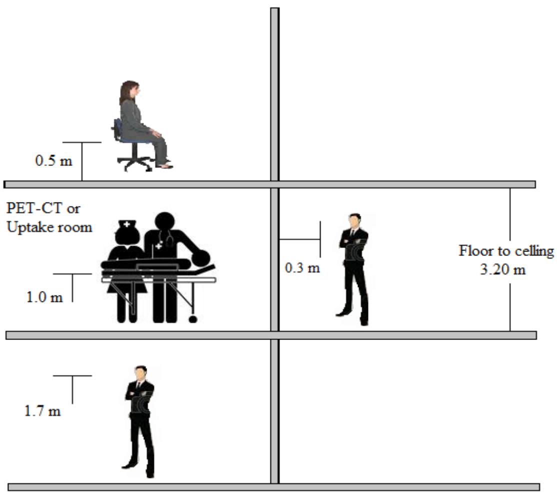

Fig. 2. Distances to be used in shielding calculation

4.1.2 The reduction factor

The total radiation dose received over a period of time tends to be less than the estimated calculation because of the short half-lives of PET radiotracers. This is called the reduction factor (R_t) and can be found using Equation 2.

$$R_t = 1.443\left(T_{\frac{1}{2}} \cdot t_s\right)\left(1 - e^{-0.693\left(\frac{t_s}{T_{\frac{1}{2}}}\right)}\right) \qquad (2)$$

where, $T_{1/2}$=half-life of the radionuclide and t_s=study duration time. For F-18, R_t is calculated as 0.91, 0.87, 0.83, and 0.76 for t_s=30, 45, 60 and 90 min, respectively.

4.1.3 Total weekly dose

The total weekly dose (D) at a point spaced d meters from the patient source during the integration time (t_s) can be determined using Equation 3.

$$D(t_s) = \frac{\Gamma \cdot S \cdot R_t \cdot t_s \cdot F \cdot T \cdot N}{d^2} \qquad (3)$$

where, F=post-administered activity after uptake period, defined by F=exp[-0.693·$T_U/T_{1/2}$], T_U=uptake time, T=occupancy factor, and N=number of patients per week.

4.1.4 Attenuation and transmission of photons

Attenuation of gamma photons in matter is defined with attenuation coefficient μ, its initial intensity I_0, reduced intensity I after passing through the matter and distance d travelled by the radiation.

$$I = I_0 e^{-\mu x} \qquad (4)$$

4.1.5 Calculation results

In the calculation, information about distances from potential source in uptake room and PET-CT room are taken from existing building information of NCCM. Furthermore, some assumptions are made: 45 patients per week, 555 MBq administration, 45 min uptake, and 30 min imaging time. The calculated data on weekly doses and transmission factors are shown in Table I. Based on the transmission value calculated, some cell information is excluded because their transmission factors are above factor 1, so no shielding is required. Using Equation 4, the required barrier thickness is calculated for brick, which is the building material of the NCCM. A rough estimation is presented in Table II.

Table I. Weekly doses calculation for PET-CT facility at NCCM.

	Target dose	Uptake dose	PET-CT dose	Total	Transmission
Room	(μSv)	(μSv)	(μSv)	(μSv)	Factor
Office 1	20	55.5	13.9	69.5	0.288
Office 2	20	35.5	13.9	49.5	0.404
Office 3	20	31.2	8.7	39.9	0.501
Office 4	20	13.9	13.9	27.8	0.719
Office 5	20	16.5	5.4	22.0	0.911
Office 6	20	22.1	8.7	30.8	0.649
Office 8	20	13.9	8.7	22.6	0.886
Corri. 1	100	319.8	126	445	0.225
Control room	100	40.8	126	166	0.602
General toilet	20	40.8	25.9	66.7	0.300

At the NCCM, the existing wall thickness is 12 cm for the inner wall and 51 cm for the outer wall, and 25 cm for the floor. For the rooms above and below the PET-CT location, the dose rate is 108 μSv per week, and the required barrier thickness is 90 cm of brick according to the Equations 3 and 4.

Table II. Required barrier thickness for the rooms of PET-CT facility at NCCM. Existing wall thicknesses are not considered.

Rooms	Barrier thickness, cm	Rooms	Barrier thickness, cm
Office 1	68	Office 6	23
Office 2	49	Office 8	7
Office 3	37	Corridor 1	80
Office 4	18	Control room	27
Office 5	5	General toilet	64

Table II shows that additional shielding is necessary for uptake and PET-CT rooms to ensure radiation doses are within the regulatory limits in the control room, office room 1 and 2, the corridor, and the general toilet. The required lead shielding can be found using Equation 4, which is presented in Table III.

Table III. Required lead shield for PET-CT facility at NCCM.

Walls	Uptake room shielding, lead (mm)	PET-CT room shielding, lead (mm)
N	0	2
E	14	2
S	14	0
W	0	0

4.2 Monte-Carlo N-Particle Transport Code

MCNP code software is used for analyzing nuclear processes. This code is frequently used for estimating radiation shielding calculation. In this study, MCNP 6.1 is used. The simulation result is expected to be presented during the conference.

5. Conclusion

Well-designed facilities do not require additional shielding, which should help cut down overall costs related to PET-CT installation. According to the results of this study, building barrier thicknesses of the NCCM building is not sufficient to keep radiation dose within the limits. To meet the regulatory limits, additional shielding material is necessary.

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