International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011)
Rio de Janeiro, RJ, Brazil, May 8-12, 2011, on CD-ROM, Latin American Section (LAS) / American Nuclear Society (ANS)
ISBN 978-85-63688-00-2

CALCULATION OF SHIELDING AND RADIATION DOSES FOR PET/CT NUCLEAR MEDICINE FACILITY

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ABSTRACT

Positron emission tomography (PET) is a new modality that is gaining use in nuclear medicine. The use of PET and computed tomography (CT) has grown dramatically. Because of the high energy of the annihilation radiation (511 keV), shielding requirements are an important consideration in the design of a PET or PET/CT imaging facility. The goal of nuclear medicine and PET facility shielding design is to keep doses to workers and the public as low as reasonably achievable (ALARA). Design involves: 1. Calculation of doses to occupants of the facility and adjacent regions based on projected layouts, protocols and workflows, and 2. Reduction of doses to ALARA through adjustment of the aforementioned parameters. The radiological evaluation of a PET/CT facility consists of the assessment of the annual effective dose both to workers occupationally exposed, and to members of the public. This assessment takes into account the radionuclides involved, the facility features, the working procedures, the expected number of patients per year, and so on. The objective of the study was to evaluate shielding requirements for a PET/CT to be installed in the department of nuclear medicine of Bangladesh Atomic Energy Commission (BAEC). Minimizing shielding would result in a possible reduction of structural as well as financial burden. Formulas and attenuation coefficients following the basic AAPM guidelines were used to calculate un-attenuated radiation through shielding materials. Doses to all points on the floor plan are calculated based primarily on the AAPM guidelines and include consideration of broad beam attenuation and radionuclide energy and decay. The analysis presented is useful for both, facility designers and regulators.

Key Words: Radiation, shielding, PET, nuclear medicine, ALARA, radionuclides

1. INTRODUCTION

The dramatic increase in the use of PET/CT techniques has given rise to concern regarding the level of radiation exposure of both healthcare staff and patients. The shielding of PET-CT facilities presents special challenges because of the diverse radiation and sources involved [1-5]. Because the 0.511-MeV annihilation photons are more penetrating than lower-energy diagnostic radiation, shielding may be required in floors, ceilings and walls. Among the factors to consider are: i) the radionuclide and its physical properties (i.e. half-life and the abundances and energies of emitted radiations); ii) the administered activity; iii) radiopharmaceutical pharmacokinetics (i.e. uptake and excretion); iv) scan duration; v) CT scan parameters; vi) the workload, that is, the number of patients scanned per week; vii) any existing structural and instrument shielding; viii) the occupancy factor, that is, the fraction of time a point of interest (or "reference point") is occupied by staff, the general public; ix) the point-of-interest distance, that is, the distance from the radiation source to the reference point; and x) the shielding design-goal dose limit for the point of interest.

Fluorine-18 (used to radiolabel fluoro-deoxyglucose (FDG)) and other short-lived PET radiopharmaceuticals will be imaged within one to two hours of injection. To minimize potentially variable muscle uptake of ^{18}F-FDG, the patient should remain sedentary between injection and imaging. Thus, an "uptake room" is required. The design of uptake rooms is often challenging because of space limitations, and shielding is generally required to maintain doses in the adjoining areas below regulatory limits. The PET scanner room will require shielding both because of activity in the patient as well as scattered X-rays from the CT. Exposure to ionizing radiation has the potential to be harmful and, in some cases, even deadly [6-7]. Most commonly, the Linear Non-Threshold (LNT) hypothesis is accepted in the field of radiation safety. The LNT hypothesis simply asserts that health detriment is linearly proportional to radiation dose with no threshold. This brings importance to a concept of radiation safety called ALARA (As Low As Reasonably Achievable). Because results of exposure at low levels are *not* known, the philosophy of ALARA expects that exposure rates be kept as low as possible taking into account social and economic factors. The objective of this work was to calculate radiation dose through shielding materials in the proposed PET/CT facility at BAEC.

2. COMPUTATIONAL METHODS

Various aspects of PET shielding design have been addressed in a number of publications [8-10]. The computational methods used were based on the AAPM Task Group 108 report [11]. The mean free path of 511-keV photons in air is around 100 meters and so attenuation of the 511-keV photons through air around the suite was considered to be negligible. The amount of radiation released from the source at each stage is shown in equation 1:

$$R_{Si} = t_{eqv}\, A\Gamma(1-F_B) \qquad \ldots.\ (1)$$

where, R_{S_i} is the radiation released from one source (patient) during one stage; A is the activity of the administered dose, Γ is the specific gamma-ray constant, F_B is the factor that accounts for attenuation within the patient [12] and t_{eqv} is the equivalent time, which accounts for radioactive decay.

An equation was obtained from this curve fit and used to predict the transmission factor for radiation traveling through the various lead thicknesses. Combining transmission factors for each wall, by simple multiplication, resulted in a final factor that accounted for the attenuation of all walls through which the radiation would pass. In case of a multilayer shield, the total transmission factor is obtained as a product of the individual transmission factors (included transmission of the patients, k_{pat})

$$k_{tot} = \prod k_i \qquad \text{....} \quad (2)$$

The thickness of the shielding material required for broad beam for a typical PET/CT facility (Fig. 1) was calculated by following the AAPM Task Group 108 guidelines where Monte Carlo transmission data have been fitted to the model proposed by Archer et al. [9]. The Archers formula is as follows:

$$B=[(1+\frac{\beta}{\alpha})e^{\alpha\gamma x}-\frac{\beta}{\alpha}]^{-\frac{1}{\gamma}} \qquad \text{….} \quad (3)$$

Inverting the above we have

$$x=\ln\{[B^{-\gamma}+(\beta/\alpha)]/[1+(\beta/\alpha)]\}/(\alpha\lambda) \qquad \text{….} \ (4)$$

Where B= transmission factor, x=material thickness and α, β, γ are the fitting parameters (Table 1).

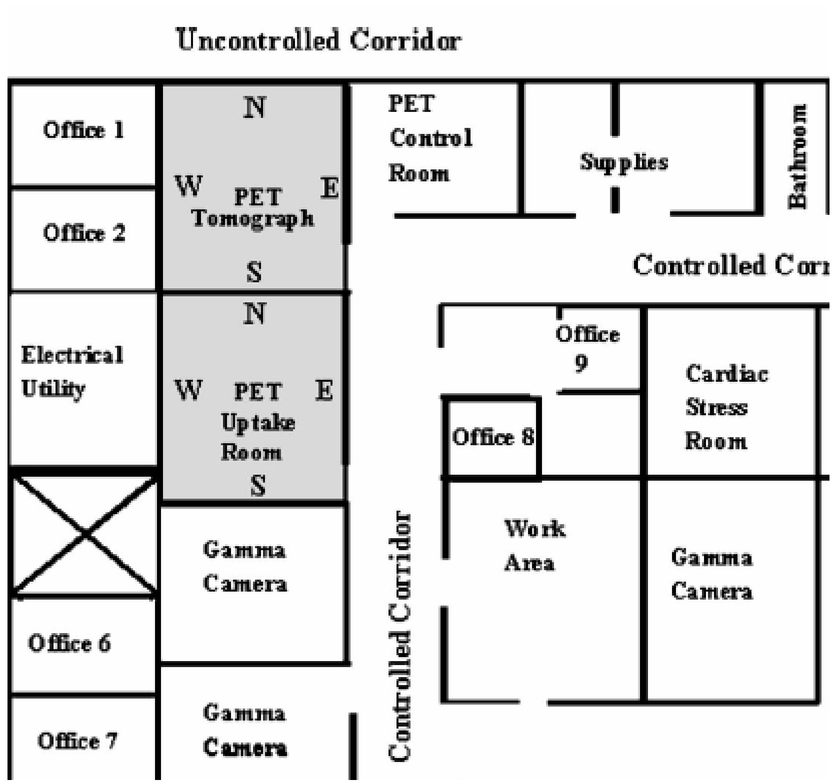

Figure 1. Room layout of a typical PET facility in a nuclear medicine facility.

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Table 1. Fitting parameters for broad beam 511 keV transmission data.

Shielding Material	α (cm^{-1})	β (cm^{-1})	γ
Lead	1.5430	-0.4408	2.136
Concrete	0.1539	-0.1161	2.0752
Steel	0.5704	-0.3063	0.6326

Because PET tracers have short half lives, the dose absorbed per hour is less than the product of the dose rate and the time. The total radiation dose received over a time period t, D(t), is less than the product of the dose rate and time by a factor of:

$$R_t = D(t)/[(D(0) \times t)] = 1.443 \times (T_{1/2}/t) \times [1-\exp(-0.693\ t/T_{1/2})] \quad \ldots.\ (5)$$

For F-18: this corresponds to factors of 0.91, 0.83, and 0.76 for t=30, 60, 90 min, respectively. Total dose at a point d meters from the patient during the uptake time (TU) is 3.0

$$\mu Sv/hour/37MBq \times A_0(MBq) \times TU\ (hours) \times RTU/d^2 \quad \ldots.\ (6)$$

If N_w patients are scanned per week, the total weekly dose is 3.0 μSv/hour/37MBq x A_0(MBq) x TU(hrs) x RTU x N_w/d^2. For an uncontrolled area the NSRC [13-15] limit is 1 mSv/year corresponding to a weekly limit of 20 μSv (2 mrem). Therefore the barrier factor required is:

$$20\ \mu Sv/3.0\ \mu Sv/hour/37MBq \times A_0(MBq) \times TU(hrs) \times R_t \times N_w/d^2$$

$$= 247\ d^2/(TU(hrs) \times R_tTU \times NW \times A_0(MBq)) \quad \ldots.\ (7)$$

Most conservative approach is taken where no shielding from the tomograph is assumed. Method is then similar to that of the uptake area calculation. Because of the delay between the administration of the isotope and the actual imaging, the activity in the patient is decreased by

$$FU = \exp(-0.693 \times TU(min)/110) \text{ where TU is the uptake time} \quad \ldots.\ (8)$$

$$\text{Barrier Factor} = 3.0\ \mu Sv/37\ MBq \times A_0\ (MBq) \times FU \times TI(hrs) \times RTI \times N_w/d^2$$

$$= 247\ d^2/\ (N_W\ TI(hrs) \times RTI \times A_0(MBq) \times FU \quad \ldots.\ (9)$$

Figure 1 shows an example of a PET facility layout that will image 40 patients per week with an average administration of 555 MBq. The uptake time is 1 h and the imaging time is 30 min for each study. Table 2 gives information on the distances from potential sources in the uptake room and PET tomography room to points of interest, along with the target weekly dose values. The required lead shielding for the uptake and scanner rooms is given in Table 3.

Table 2. Typical calculation for a PET Facility. This calculation is based on the following assumptions: 40 patients per week, 555 MBq administration, 1 h uptake, and 30 min imaging time.

Room	Uptake distance (m)	Tomograph distance (m)	Weekly target dose (μSv)	Total dose (μSv)
Office 1	8	3	20	97.2
Office 2	6	3	20	118.2
Office 6	8	7	20	40
Office 7	12	15	20	14.8
Office 9	9	9	20	29..2
Corridor 1	2.5	2.5	100	378.8
Corridor 2	9	4	20	60.2
PET control room	9	2.5	100	122.4
Gamma camera	3	10	100	199

Table 3. Lead shielding requirements for example PET facility (Fig. 1).

Walls	Uptake room shielding (mm Pb)	Tomograph shielding (mm Pb)
N	0	0
E	5	3
S	5	0
W	2	12.1

The PET tomograph can provide a substantial reduction of the dose rate at some of the walls. This depends on the actual geometry and placement of the tomograph in the room (Fig. 2). Because the 511 keV annihilation radiations are so penetrating, it is necessary to consider uncontrolled areas above and below the PET facility as well as those adjacent on the same level. The figure 5 shows generally accepted source and target distances that apply in these cases. Typically, one assumes that the patient (source of the activity) is 1 meter above the floor. The dose rate is calculated at 0.5 meters above the floor for rooms above the source and at 1.7 meters above the floor for rooms below the source.

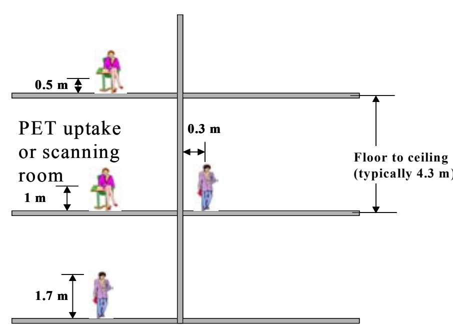

Figure 2. This figure illustrates the generally accepted source and target distances used for floor, ceiling and wall barrier calculations.

3. RESULTS AND DISCUSSION

Dose calculations were performed utilizing PET shielding requirements as recommended by AAPM Task Group 108. Shielding requirements were calculated based on the following parameters: 370 MBq (10mCi) FDG/patient; 10 patients/week; 60 minute uptake time/patient; and 40 minutes of imaging time/patient. Occupancy factor and regulatory requirements of 20 μSv/wk in unrestricted areas and 100 μSv/wk in restricted areas were utilized. Shielding calculations were performed for seven specific restricted and ancillary areas: two unrestricted hallways, three unrestricted offices, one restricted hallway, and an unrestricted office area above PET facility. Calculated radiation levels in five defined unrestricted areas were: 14.0 μSv/wk, 11.4 μSv/wk, 8.7 μSv/wk, 25.2 μSv/wk, and 12.6 μSv/wk for hallway one, hallway two, office one, office two, and office three, respectively. Calculated radiation level above PET facility was 19.4 μSv/wk due to shielding from concrete ceiling/floor. Radiation levels in unrestricted areas were below regulatory requirements of 20 μSv/wk. Calculated radiation level in the restricted hallway was 92.3 μSv/wk which was below regulatory requirements of 100 μSv/wk. Under NSRC Rules, the facility must be shielded so that the effective dose equivalent in uncontrolled areas does not exceed 1 mSv/year or 20 μSv in any 1 h. The 1 mSv/year limit implies a weekly dose limit of 20 μSv, and this limit becomes the determining factor for shielding calculations in uncontrolled areas. The occupational dose limit in controlled areas is 20 mSv/year. Most shielding calculations use a target level of 5 mSv/year in controlled areas to be consistent with ALARA recommendations. Radiation levels in all areas specified were below regulatory requirements. The shielding considerations for the CT portion of the PET/CT systems are substantially the same as they would be for any CT installations. The shielding requirements for a PET facility are different from those of most other diagnostic imaging facilities. This is due to the high energy of the annihilation radiation and the fact that the patient is a constant source of radiation throughout the procedure. Meeting the regulatory limits for uncontrolled areas can be an expensive proposition. Careful planning with the equipment vendor, facility architect, and a qualified medical physicist is necessary to produce a cost-effective design while maintaining radiation safety standards [13-15]. Further study will be performed by using a patient phantom and Monte Carlo simulation.

ACKNOWLEDGEMENT

The authors are thankful to Dr. Kamila Afroz of Institute of Nuclear Medicine and Ultrasound, Prof. M. A. Zaman of Northern University, Mr. S. M. Iqubal and Dr. A. F. M. Kibria of Bangladesh Atomic Energy Commission for their support. The authors are grateful to Dr. F. U. Ahmad, Chairman, Bangladesh Atomic Energy Commission for his encouragement and interest in this work.

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