Estimating the Shielding Requirements for a Newly Planned PET-CT Facility

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ABSTRACT

Positron Emission Tomography (PET) combined with Computed Tomography (CT) is a powerful and very sensitive diagnostic tool that integrates functional and anatomical imaging into one combined scanning system. Positron emission tomography is based on the characteristic way in which positrons annihilate by combining with an electron. This process usually results in the emission of two 511 KeV photons which travel in opposite directions. These 511 KeV annihilation photons are much higher energy than other diagnostic radiations. Because of this high energy of the annihilation radiation, shielding requirements for a PET facility are different from most of the other diagnostic imaging facilities and it's a very important consideration in the design of a PET or PET-CT imaging facility. As a result, significant shielding may be required in floors and ceilings as well as adjacent walls in a PET-CT facility. In this work we present the estimation of the shielding requirements for a newly planned PET-CT facility. Shielding calculations of adjacent walls were presented for both controlled and uncontrolled areas. Formulas were used to calculate the shielding materials following the basic AAPM (American Association of Physicists in Medicine) guidelines. This mathematical analysis of the shielding estimation is very important for a newly planned PET-CT facility. Adequate safe planning with vendor, facility architect and a qualified medical physicist are essential to make a cost effective and safe design while maintaining radiation safety standards with regulatory limits.

Key words: PET-CT, annihilation photons, transmission factors, dose reduction factors.

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INTRODUCTION

PET-CT is one of the most powerful and sensitive diagnostic imaging modality that integrates functional and anatomical imaging into one combined system. All PET tomographs use coincidence detection of the positron electron annihilation photons to acquire the projection data required for reconstruction image. Certain radionuclides decay by spontaneously converting a proton into a neutron and simultaneously emit a positron. After the positron dissipates its kinetic energy as it traverses tissueor other material, it captures an electron. Because the electron and positron are antiparticles, they mutually annihilate, producing two 511 keV photons (1).These 511 KeV annihilation photons are much higher energy than other diagnostic radiations. A PET scanner consists of an array of detectors which are named as ring scanner that are arranged to detect the essentially simultaneous arrival of these two photons. The most useful clinical PET radiopharmaceuticals isF-18 Fluoro-2-deoxyglucose (F-18 FDG).18F-FDG has been shown to have a beneficial impact on patient management and has become an established technique, particularly for the staging of some cancers. The half-life of F-18 is only 110 minutes. Because of the high energy of the annihilation radiation, shielding requirements for a PET-CT facility are different from most of the other diagnostic imaging facilities and it's a very important consideration in the design of a PET-CT imaging facility (2-3). As a result, significant shielding is required in floors and ceilings as well as adjacent walls in a PET-CT facility.

In this work we have presented the estimation of shielding requirements for a newly planned PET-CT facility of the Apollo Hospitals Dhaka. Shielding calculations of adjacent walls were presented for both controlled and uncontrolled areas. Formulas were used to calculate the shielding materials following the basic AAPM (American Association of Physicists in Medicine) guidelines (4).

Basic requirements for a PET-CT facility

The patient preparation room is a requirement for any PET-CT facility and must be included in the radiation safety planning. A busy PET-CT facility should have more than 1 uptake room. This must be considered when performing shielding calculations. After the uptake period, the patient should void to clear the radioactivity that has accumulated in the bladder which is approximately 15-20% of the administered activity and these are excreted within the first two hours (5-6). It is highly recommended that a bathroom be reserved for PET-CT patients. All areas in the vicinity of the PET-CT facility must be considered for shielding calculations including the areas above and below the PET-CT facility as well as the adjacent areas on the same floor. The space location of the facility, power consumption of PET-CT, floor loading capacity and required radiation shielding is the major consideration for site planning. There are several factors affecting the radiation protection as well as shielding calculation for PET-CT facility like number of patients imaged, amount of isotope administered per patient, length of time each patient remains in the department, location of the facility, general environs of the facility etc. It is noticeable that the technical staff who works directly with the PET-CT patients receives the largest doses. The components of this dose include radiation from patient injections, patient positioning and the dose received at the imaging procedure (7-10).

MATERIALS & METHODS

Attenuation with the patient's body

The dose rate from the patient is reduced by a significant factor due to the body absorbs some of the annihilation radiation. A number of papers have been published where direct measurements have been estimated at different directions from the patient (11-18). These published results were normalized for the amount of administered activity of radiotracer and distance from the patients, and were also corrected for radioactive decay back to the administration time. Based on the mean of these values, the AAPM task group recommends using a patient dose rate of 0.092 µSv m^2 /MBq h (3.4 µSv m^2/h/37 MBq) immediately after administration.

Shielding properties

Lead and concrete are the most likely materials to be used for shielding in the PET-CT facility. A variety of attenuation coefficients has been used to estimate transmission requirements for PET-CT facilities.

Table 1. Broadbeam Transmission Factors at 511 keV in lead, concrete, iron.

Transmission Factors			
Thickness[a,b]	Lead	Concrete[c]	Iron
0	1.0000	1.0000	1.0000
1	0.8912	0.9583	0.7484
2	0.7873	0.9088	0.5325
3	0.6905	0.8519	0.3614
4	0.6021	0.7889	0.2353
5	0.5227	0.7218	0.1479
6	0.4522	0.6528	0.0905
7	0.3903	0.5842	0.0542
8	0.3362	0.5180	0.0319
9	0.2892	0.4558	0.0186
10	0.2485	0.3987	0.0107
12	0.1831	0.3008	0.0035
14	0.1347	0.2243	0.0011
16	0.0990	0.1662	0.0004
18	0.0728	0.1227	0.0001
20	0.0535	0.0904	
25	0.0247	0.0419	
30	0.0114	0.0194	
40	0.0024	0.0042	
50	0.0005	0.0009	

[a]Thickness in mm for lead.
[b]Thickness in cm for concrete and iron.
[c]Concrete density = 2.35 g/cm3.

Several publications have been made for the narrow-beam, good geometry attenuation coefficients for lead and concrete. The effective half-value layer of lead for shielding photons of 511 KeV under broad beam conditions has been reported in the range 4.1-5.5 mm. (19-21) and the half value layer has been reported in the range 3.4-4.3 cm for the concrete under narrow beam conditions at 511 KeV corresponding to the difference between normal density concrete (2.35 g/cm3) and low density concrete (1.84 g/cm3) that is commonly used in modern construction. Table-1presents the monte carlo transmission factors for lead, concrete, and iron (4).

Radioactivity Administration-Dose Factors

Due to short half lives of PET tracers, 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 (D_R) and time (t) by a factor of

$$R_T = D_t/(D_R \times t) = 1.443 \times (T_{1/2}/t) \times (1\text{-exp}\,[-0.693\, t/T_{1/2})] \quad \ldots\ldots (1)$$

For F-18, this corresponds dose reduction factors $R_T$are 0.91, 0.83, and 0.76 for *t*=30, 60, and 90 min, respectively.

Uptake (Patient Waiting Area) Room Calculation

Patients undergoing PET-CT scans need to be kept in a quiet resting state prior to imaging to reduce uptake in the skeletal muscles. The total dose $D(T_U)$ at a point d meters from the patient during the uptake time (T_U) in the post dose administration patient's waiting room is

$$D(T_U) = 0.092\ \mu Sv\ m^2/MBq\ h \times A_0\ (MBq) \times T_U\ (h) \times R_{TU}/d(m)^2 \quad \ldots\ldots\ldots (2)$$

If X_w patients are scanned per week, the total weekly dose is

$0.092\ \mu Sv\ m^2/MBq\ h \times X_W \times A_0\ (MBq) \times T_U\ (h) \times R_{TU}/d(m)^2$ Thus, the transmission factor (B) required is

$$B = 10.9 \times P \times d(m)^2 / (T \times X_W \times A_0\ (MBq) \times T_U\ (h) \times R_{TU}) \quad \ldots\ldots\ (3)$$

T is the occupancy factor, A_o is the activity per patient, d is the distance from source to barrier and P is the weekly dose limit in µSv. P= 20 µSv for uncontrolled areas, corresponding to the 1 mSv/year limit to the general public and P=100 µSv for ALARA levels in controlled areas.

Thus, for uncontrolled areas, the transmission factor

$$B = 218 \times d(m)^2 / [T \times X_W \times A_0\ (MBq) \times T_U\ (h) \times R_{TU}]$$

$$= 5.89 \times d(m)^2 / [T \times X_W \times A_0\ (mCi) \times T_U\ (h) \times R_{TU}] \quad \ldots\ldots\ldots (4)$$

And for Controlled areas

$$B = 1090 \times d(m)^2 / [T \times X_W \times A_0\ (MBq) \times T_U\ (h) \times R_{TU}]$$

$$= 29.5 \times d(m)^2 / [T \times X_W \times A_0\ (mC\ i) \times T_U\ (h) \times R_{TU}] \quad \ldots\ldots\ (5)$$

Total patients = 50/week, Post dose admin waiting room =3 and Patients per waiting room in a week = 17.

After calculate the transmission factor; using the Table1 to find the shielding requirement.

PET-CT room and other associate room's dimension were showed in Table 2.

Table 2: PET –CT and associated Room dimension

Sl No.	ROOM Name	Dimension (meter)
1.	PET-CT scanning room	5.5 X 8.0
2.	PET-CT control room	2.3 X 7.1
3.	Attendance waiting room	4.8 X 2.5
4.	Dose Admin Room	2.4 X 2.6
5.	Radioactive waste storage	2.4 X 1.8
6.	Decontamination Room	2.2 X 1.8
7.	Hot Lab	3.2 X 2.6
8.	Post Dose Admin Waiting -1	2.75 X 2.48
9.	Post Dose Admin Waiting -2	2.75 X 2.3
10.	Post Dose Admin Waiting -3	2.5 X 2.3
11.	Patient Toilet	1.5 X 1.35
12.	Medical Physicist Room	3.1 X 2.5
13.	Technologist Room	4.3 X 2.15
14.	UPS and Battery Room	5.9 X 3.7
15.	Reporting room	4.8 X 3.5

Imaging room calculation

The delay required by the uptake phase between the administration of the radiopharmaceutical and the ctual imaging, the activity in the patient is decreased by

$F_U = \exp[-0.693 \times T_U (min) / 110]$ …… (6)

Where T_U is the uptake time. The decay factor for F-18 at 1 h F_U is equal to exp(−0.693 x 60/110)=0.68. Generally the patient will void prior to imaging, removing approximately 15% of the administered activity and thereby decreasing the dose rate by 0.85. The weekly dose at a distance *d* from the source is calculated as

$0.092\ \mu Sv\ m^2/MBq\ h \times X_W \times A_0 (MBq) \times 0.85 \times F_U \times t_I (h) \times R_{tI}/d(m)^2$ …….. (7)

The transmission factor is given as

$B = 10.9 \times P \times d(m^2) / [T \times X_W \times A_o(MBq) \times 0.85 \times F_U t_I(h) \times R_t]$ ………… (8)

Thus, the transmission factor for uncontrolled areas is

$B = 256 \times d(m^2) / [T \times X_W \times A_o(MBq) \times F_U \times t_I(h) \times R_{tI}]$ …………. (9)

And, for controlled areas at ALARA levels

$B = 1280 \times d(m^2) / [T \times X_W \times A_o(MBq) \times F_U x t_I(h) \times R_{tI}]$ ………… (10)

After calculate the transmission factor; using the Table1 to find the shielding requirement.

Calculation for rooms above the PET-CT unit

Because the 511 KeV annihilation photons are so penetrating, it is necessary to consider uncontrolled areas above and below the PET-CT facility as well as those adjacent on the same level. Figure 1 shows generally accepted source and target distances that apply in these cases. Typically, one assumes that the patient (source of the activity) is 1 m above the floor. The dose rate is calculated at 0.5 m above the floor for rooms above the source.

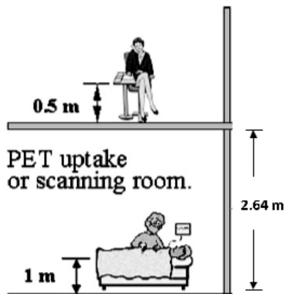

Figure 1: Distance estimation above the PET-CT unit (Modified schematic diagram from AAPM guideline)

Above the PET-CT Unit	Room height =2.64 m, bed height from floor =1m Roof height from the source = 2.64 −1= 1.64 m Distance from source to target = 1.64 + 0.5 =2.14 m

The weekly dose of post dose patients waiting room at a distance *d* from the source is calculated as

$0.092\ \mu Sv\ m^2/MBq\ h \times X_W \times A_0 (MBq) \times t_U (h) \times R_{TU}/d(m)^2$ The weekly dose of PET-CT imaging room at a distance *d* from the source is calculated as

$0.092\ \mu Sv\ m^2/MBq\ h \times X_W \times A_0 (MBq) \times 0.85 \times F_U \times t_I (h) \times R_{tI}/d(m)^2$ After calculate the transmission factor; using the Table1 to find the shielding requirement.

RESULTS

Shielding requirements have been calculated for PET-CT imaging rooms and the most important post dose administrated patient's waiting rooms. The transmission factors have been calculated from the equation and the shielding requirements have been estimated from the table (Table 1) of broadbeam transmission factors at 511 KeV in lead, concrete and iron. The broad beam transmission factors table was mentioned in AAPM guideline. The shielding requirement for the walls of PET-CT room was found almost from 2 to 10 cm concrete (equivalent ~1-7 mm lead) and for the patient waiting rooms, the shielding requirement was found 20 to 23 cm concrete (equiva-lent ~16-19 mm lead). The details of the shielding requirements have been showed at the Table 3, 4, 5 and 6. Shielding requirement was found higher in the post dose administrated patient waiting rooms than PET-CT imaging room due to the room size and the more time of patients stay after administration dose in patient's waiting rooms. We proposed the PET-CT scan room and the post dose administrated patient waiting rooms concrete thickness more than 25 cm which were more safer.

Table 3: Estimating Shielding requirements for Post dose Admin waiting rooms

Area	Direction	Distance d in m	Rt Dose reduction factor	Result Transmission factor	Shielding requirement from Table1	
					Concrete (cm)	Lead (mm)
Post dose Admin waiting -1	E	1.24	0.83	0.080256	21	17
	W	1.24	0.83	0.080256	21	17
	N	1.375	0.83	0.098683	20	16
	S	1.375	0.83	0.098683	20	16
Post dose Admin waiting -2	E	1.15	0.83	0.069029	23	19
	W	1.15	0.83	0.069029	23	19
	N	1.375	0.83	0.098683	20	16
	S	1.375	0.83	0.098683	20	16
Post dose Admin waiting -3	E	1.15	0.83	0.069029	23	19
	W	1.15	0.83	0.069029	23	19
	N	1.25	0.83	0.081556	21	17
	S	1.25	0.83	0.081556	21	17

For Occupancy factor T= 1, the transmission factor in uncontrolled area 20µSv/Total weekly dose

Table 4: Estimating Shielding requirements for PET-CT room

Area	Direction	Distance d in m	R_{tl}(Dose reduction factor)	Total Weekly dose in µSv	Transmission factor	Shielding requirement from Table1	
						Concrete (cm)	Lead (mm)
PET-CT Scan Room	E	4	0.91	22.38	0.89	2	1
	W	4	0.91	22.38	0.89	2	1
	N	2.75	0.91	47.35	0.42	10	7
	S	2.75	0.91	47.35	0.42	10	7

Table 5: Calculation for above the post dose waiting room

Area	Distance d in m	R_t (Dose reduction factor)	Total Weekly dose in µSv	Transmission factor	Shielding requirement from Table1	
					Concrete (cm)	Iron (cm)
Post dose scan room	2.14	0.83	83.903	0.238	14	4

Table 6: Calculation for above the PET-CT room

Area	Distance d in m	Uptake time decay factor	R_{tl} (Dose reduction factor)	Total Weekly dose in µSv	Transmission factor	Shielding requirement from Table1	
						Concrete (cm)	Iron (cm)
PET-CT Scan/Imaging room	2.14	0.68	0.91	78.192	0.256	14	4

The PET-CT unit is placed in the basement of the hospital. So, it is not required to calculate the shielding requirement below the PET-CT unit.

DISCUSSION

Considering the dose rates and transmission factors of PET radionuclides suggest that, when PET-CT scanning is introduced, some additional shielding is likely to be required within the facility so that staff and members of the public are protected. Planning for a new PET-CT facility should carefully consider the constraints associated with the local regulatory limits. Uncontrolled areas with high occupancy should be placed as far from the PET uptake and imaging rooms as possible. Also, the placement of the door must be carefully considered to avoid the expense with installing a door with extensive lead shielding. The shielding requirements for this planned PET-CT unit were found <25 cm concrete in the all walls. The builders proposed the concrete thickness more than 30 cm for whole PET-CT facility which were more safer. The PET-CT unit was already established with fulfillment of these shielding requirements. The shielding required in the walls for the CT system alone (ignoring the PET component) will have only a modest shielding effect for the 511 KeV annihilation radiation. For example, 1.6 mm of lead provide a transmission factor of only 0.81 for the annihilation radiation. Because the HVL of the CT x-rays is so much smaller than that for 511 keV annihilation radiation; a room that is shielded to meet the general public levels for PET (1 mSv/year) is no need additional shielding for the CT component.

CONCLUSION

The shielding requirements for a PET-CT 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. The mathematical analysis of the shielding estimation is very important for a newly planned PET-CT facility. The shielding calculation is a regulatory requirement to establish a PET-CT facility in Bangladesh. A PET-CT facility is required different design require-ment than conventional nuclear medicine department and is more likely to involve additional radiation shielding. Adequate safe planning with vendor, facility architect and a qualified medical physicist are essential to make a cost effective and safe design maintaining radiation safety standards and radiation doses to staff and the public can be kept to acceptable limits.

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