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A Comparative Study of the Construction of Positron Emission Tomography/Computed Tomography Facilities in Three South African Hospitals

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ABSTRACT

Introduction: Development of higher energy modalities such as positron emission tomography/computed tomography (PET/CT), has led to more complex shielding problems. This is due to several factors, such as the radiopharmaceutical relatively high-administered activity, high patient throughput, and high energies of 511 kilo-electron volt (keV) positron annihilation photons. Therefore, this study aimed to compare three different methods used to determine the required shielding thicknesses of PET/CT facilities.

Material and Methods: The required shielding thicknesses for three facilities were determined by using three different shielding methods, i.e. narrow beam, broad beam and Monte Carlo approximation. The design goal was chosen as 6 mSv/year for radiation workers and 1 mSv/year for the public. In addition, occupancy factors (T) were established, and all calculations had a use factor (U) of 1. The workload (W) of facilities and thicknesses of all barriers were then calculated for the three facilities.

Results: For narrow beam approximation the average required thicknesses obtained were 6.16 mm lead, 5.12 cm concrete and 2.95 cm iron. Broad beam approximation required an average of 7.55 mm lead, 8.01 cm concrete and 2.96 cm iron thicknesses. Monte Carlo approximation required 7.62 mm lead, 10.59 cm concrete and 2.94 cm iron thicknesses.

Conclusion: The narrow beam approximation demonstrated the least shielding thickness required for the materials used in this study, which can lead to under-shielding. The broad beam and Monte Carlo approximations demonstrated higher required shielding thickness although there were discrepancies between these two approximations for lead, concrete, and iron.

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Introduction

Increasing application of positron emission tomography/computed tomography (PET/CT) techniques in the clinical environment has given rise to concerns regarding the level of radiation exposure to both radiation workers and the public. This is due to several factors, such as relatively high administered activity, high patient throughput, and high energies of 511 kilo-electron volt (keV) positron annihilation photons [1, 2]. The 511 keV-annihilation photons associated with positron decay are more penetrating than lower-energy diagnostic radiation; therefore, shielding requirements are among important consideration in the design and construction of a PET/CT facility.

The goal of nuclear medicine and PET/CT shielding design is to keep dose exposure to workers and the public as low as reasonably achievable [2- 4]. To minimize the radiation exposure to the workers and public, the International Commission on Radiological Protection recommends that radiation workers and the public should be constrained to dose limits of 20 and 1 mSv/year, respectively [5]. In order to ensure that radiation workers and the public are not exposed to doses over these recommended limits, it is important to establish a design dose limit when calculating the shielding of a PET/CT facility.

There are different shielding design goals for controlled and unrestricted areas. The National Council on Radiation Protection and Measurements (NCRP) recommends shielding design goals of 5 mSv/year for controlled areas and 1 mSv/year for unrestricted areas [6]. The aforementioned constraint would be too costly to maintain for the present study; therefore, a design goal of 6 mSv/y was chosen for the all the calculation in controlled areas. This constraint was presented to the National Regulatory Authority of South Africa, as the directorate of radiation control, deemed "fine" for calculations.

Shielding of PET/CT poses special challenges due to the involvement of radiation sources. There are two

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types of radioactive sources present in the facility, including the patient after being injected with the Fluorine-18-Flouro-2-deoxyglucose (^{18}F-FDG) and actual radionuclide (^{18}F-FDG) located in the hot laboratories (hot-lab) [7, 8]. Due to the fact that ^{18}F-FDG is stored and handled with high initial activity, it is required to carefully consider radiation exposure inside and adjacent to the hot-lab, uptake rooms, hot-toilet, and imaging room. With the exception of the PET/CT imaging room, the hot-lab and uptake rooms are most likely to require additional shielding [9]. Several other factors affect the required level of shielding as follows:

1. The workload (i.e., the number of patients scanned per week and amount of administered activity).
2. The radiopharmaceutical used and its pharmacokinetics (including the duration of the uptake period and its clearance rate).
3. The imaging time
4. The occupancy factor (i.e., fraction of time an individual will spend in an area adjacent to the radiation source).
5. The distance from the radiation source (i.e., hot-lab or radioactive patient) to the point of interest

Effectiveness of shielding depends on radiation, thickness, and type of used shielding material. Materials with higher atomic number and high density are more effective in reducing the intensity of radiation than shielding materials with lower atomic number and lower density. A variety of shielding materials are used to minimize the level of exposure to workers and the public. Lead (with a density of 11.35 g/cm^3), iron (with a density of 3.7 g/cm^3), and concrete (with a density of 2.35 g/cm^3) are the most commonly used materials to shield PET/CT facilities [10].

Underestimating and overestimating the required shielding thicknesses during the construction of PET/CT facilities imposes two different kinds of problems. Underestimating results in hazardous environment in terms of ionizing radiation and overestimating results in a safer environment but results in unnecessary high costs for the hospital. In order to prevent underestimating and overestimating construction thicknesses, it is important to apply a safe and cost-effective method to determine the required level of shielding. Several studies have published different methods for the calculation of the required thickness for shielding PET/CT facilities [3, 11, 12]. These methods include the narrow beam approximation, broad beam approximation, and Monte Carlo approximation.

The narrow beam approximation assumes that the radiation source is a point source and neglect scatter radiation. The broad beam approximation assumes that the patient is a point source but takes scatter radiation into consideration. The Monte Carlo approximation assumes that the patient is a static source and takes scatter radiation into consideration [3, 11].

A number of studies have been published regarding the evaluation of the Monte Carlo approximation. The aforementioned studies endorsed the view that the Monte Carlo approximation is an accurate and practical way to determine the required shielding thickness for a PET/CT facility [2, 11, 13, 14]. Therefore, any shielding thickness exceeding the thickness obtained from the Monte Carlo approximation is assumed to be an overestimation and any shielding thickness below the thickness obtained from the Monte Carlo approximation is assumed to be an underestimation.

Given that the financial implications of PET/CT shielding suites can be substantial, it has become increasingly important to optimize the thickness of shielding required for each barrier [15]. Therefore, the present study aimed to retrospectively analyze and compare the construction thicknesses of three PET/CT facilities using three different shielding methods, namely the narrow beam approximation, broad beam approximation, and Monte Carlo approximation.

Materials and Methods

The researchers selected three PET/CT facilities non-randomly and calculated the required shielding retrospectively. To maintain anonymity, pseudo names were given to the three facilities, including Priv1, Gov1, and Gov2. The required shielding thicknesses were calculated for the hot-labs, uptake rooms, and imaging rooms using different shielding methods, namely the Monte Carlo, broad beam, and narrow beam approximations. All the calculations in this study were based on ^{18}F-FDG radionuclide. The unattenuated dose (D_0) was firstly determined through the following formulas:

For the hot-lab:

$$D_{\text{hot-lab}} = \frac{0.143\ \mu Sv m^2 \times A_0 \times T \times 10h/week}{d^2} \quad (1)$$

For the uptake room:

$$D_{\text{uptake}} = \frac{0.092\mu\text{Sv}.m^2/\text{MBq.h} \times A_0 \times N_W \times T \times t_u R_{tu}}{d^2} \quad (2)$$

For the imaging room:

$$D_{\text{imaging room}} = \frac{0.092\ \mu Svm^2/\ MBqh\ N_W A_0 \times T \times 0.85 \times F_U \times t_i R_{t_i}}{d^2} \quad (3)$$

Where $\boldsymbol{N_w}$ is the number of patients imaged per week that was 8 patients per day (for 5 working days), A_0 is the administered activity (370 MBq) of ^{18}F-FDG, which is a long-lived isotope, T is the occupancy factor (i.e., 1, 0.25, and 0.0625 for controlled areas, adjacent corridors, and unoccupied areas, respectively), R_{tu} is the dose reduction factor over the uptake time t_u, R_{ti} is the dose reduction factor over imaging time t_i, $\boldsymbol{F_u}$ is the decay factor, and $\boldsymbol{d}$ is the distance from the radiation source to the point of interest obtained from the architectural drawings for each facility demonstrated in figures 1, 2, and 3.

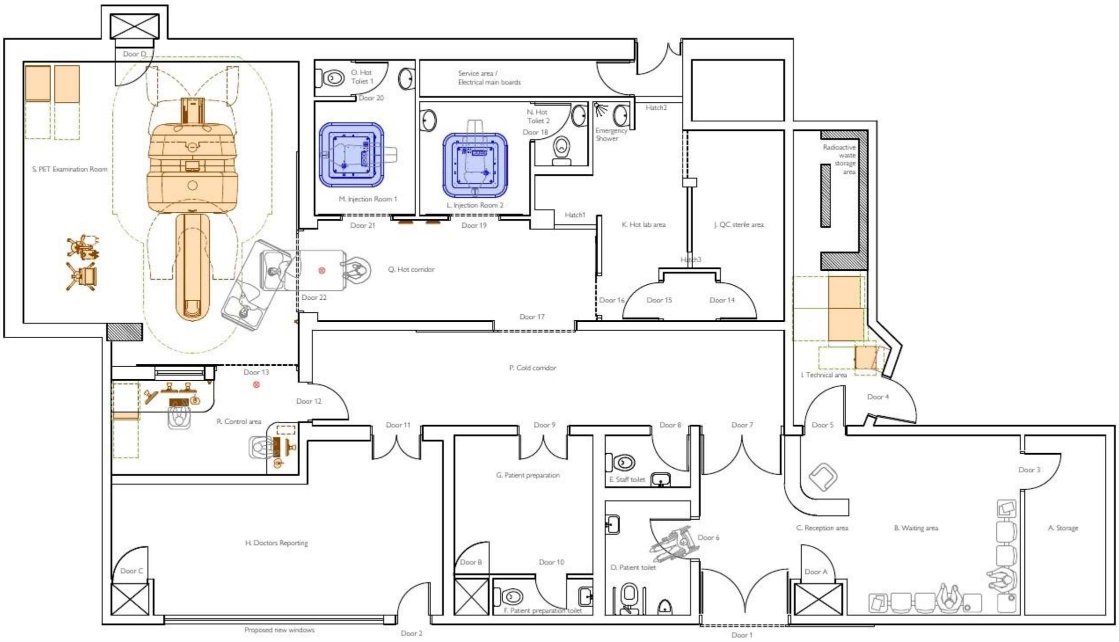

Figure 1. Positron emission tomography/computed tomography room layout for Gov1

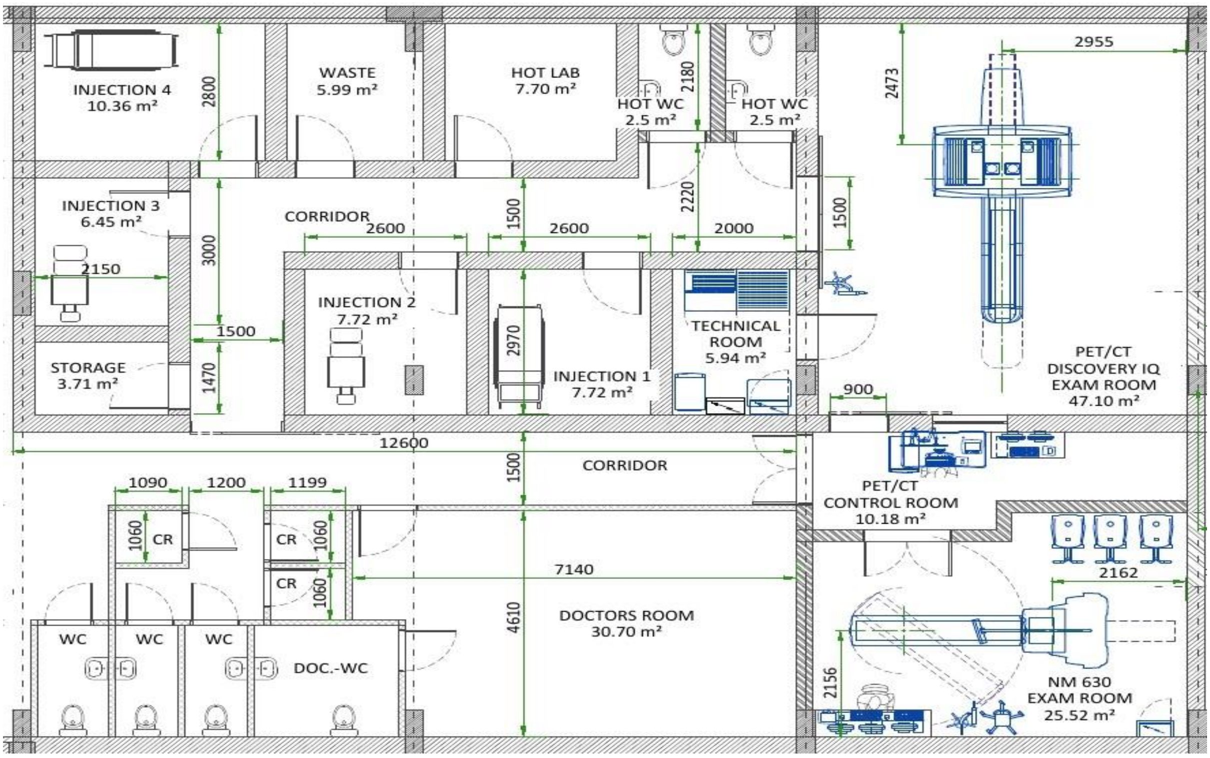

Figure 2. Positron emission tomography/computed tomography room layout for Gov2

The PET/CT layout for Gov.1 consisted of a hot-lab, two uptake rooms placed adjacent to each other, and an imaging room. Hot and cold corridors were used to separate controlled from uncontrolled areas, such as reception area, staff toilets, and waiting area.

The Gov2 comprised of a hot-lab, four uptake rooms, and an imaging room. A cold corridor separated the controlled areas from uncontrolled areas, such as the doctor's room.

The Priv1 consisted of a hot-lab, three uptake rooms placed adjacent to each other, and a corridor separating them from the PET/CT imaging room and gamma camera room.

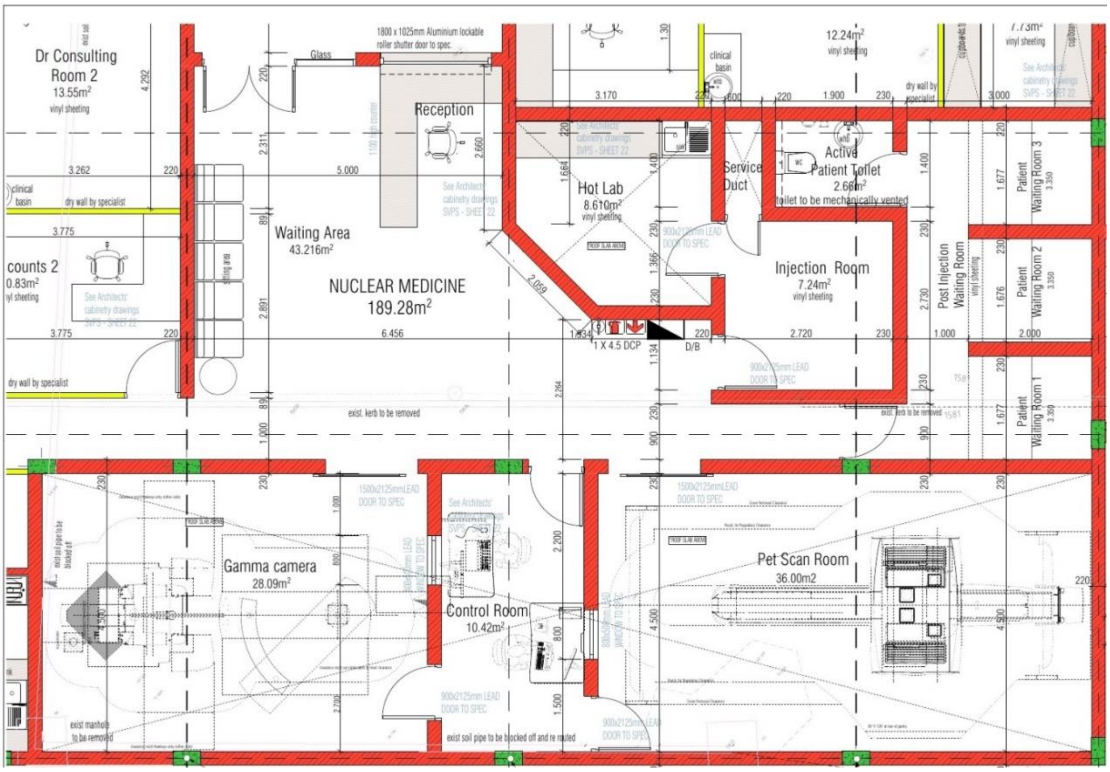

Figure 3. Positron emission tomography/computed tomography room layout for Priv1

The design goals were constrained to 120 µSv/week (6 mSv/year) for radiation staff members with the public shielding design goal remaining at 20 µSv/week (1 mSv/year) for all the facilities. The transmission barrier ratio for each barrier was determined based on the design goal (P), and the calculated unattenuated dose (D_0) was obtained using the following formula:

$$B = \frac{P}{D_0} \tag{4}$$

After obtaining the transmission ratio (B), the required shielding (x) was calculated for the Monte Carlo, broad beam, and narrow beam approximations through the following formulas:

For the Monte Carlo approximation:

$$x = \left(\frac{1}{\alpha\gamma}\right) \ln\left\{\left[B^{-\gamma} + \left(\frac{\beta}{\alpha}\right)\right] \div \left[1 + \left(\frac{\beta}{\alpha}\right)\right]\right\} \tag{5}$$

Where $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ are fittings parameters presented in Table 1, $\boldsymbol{\alpha}$ is the equivalent of an effective attenuation coefficient for equilibrium photon spectrum at large attenuation, $\boldsymbol{\beta}$ is associated with the contribution of photon build-up to the broad beam transmission and its value decreases with an increase in build-up factor, and $\boldsymbol{\gamma}$ describes the change of slope of transmission curves at small thicknesses in which equilibrium photon spectrum has not been attained and its value decreases with increasing energy.

For the broad beam approximation:

$$x = \left(\frac{1}{B}\right) \times TVL \tag{6}$$

Where *TVL* is the tenth-value layer thickness of the material presented in Table 2.

For the narrow beam approximation:

$$x = \left(\frac{1}{B}\right) \times HVL \tag{7}$$

Where *HVL* is the half-value layer thickness of the material presented in Table 2.

Table 1. Monte Carlo fitting parameters [3]

Shielding material	α (cm^{-})	β (cm^{-})	γ
Lead	1.7772	-0.5228	0.5457
Concrete	0.539	-0.1161	2.0752
Iron	0.5704	-0.3063	0.6326

Table 2. Broad beam approximation TVL and narrow beam approximation HVL [3]

	Thickness (cm)	
Shielding material	TVL	HVL
Lead	1.66	0.41
Concrete	17.6	3.40
Iron	6.5	1.95

TVL: Tenth-Value layer
HVL: Half-Value layer

The Tenth value layer (TVL) is the amount of shielding thickness required to reduce the radiation intensity to one-tenth of its initials value. The Half value layer (HVL) is the amount of shielding thickness required to reduce the radiation intensity to half of its initial value. Lead, concrete, and iron are materials used for shielding gamma radiation.

Results

The thicknesses obtained using the Monte Carlo, broad beam, and narrow beam approximations for the hot-labs, uptake rooms, and imaging rooms in the three facilities are depicted in figure 4, 5, and 6.

A comparison of the obtained construction shielding thicknesses versus barrier transmission ratios for lead, concrete, and iron are illustrated in figures 7, 8, and 9.

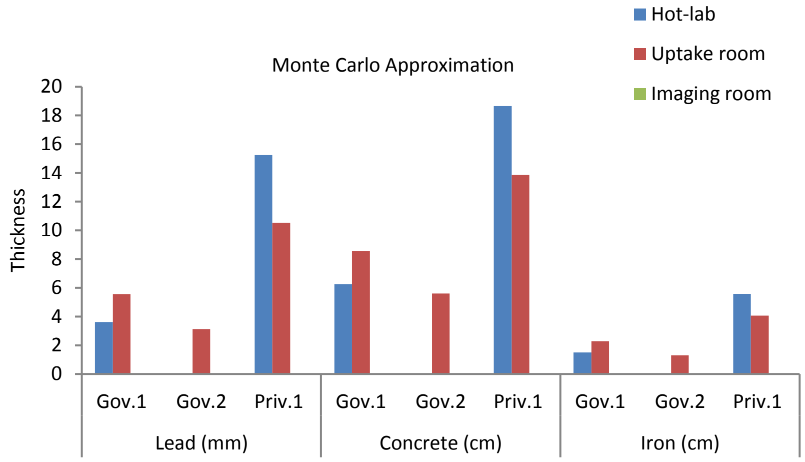

Figure 4. Thicknesses obtained from the hot-labs, uptake rooms, and imaging rooms of Gov1, Gov2, and Priv1 using Monte Carlo approximation

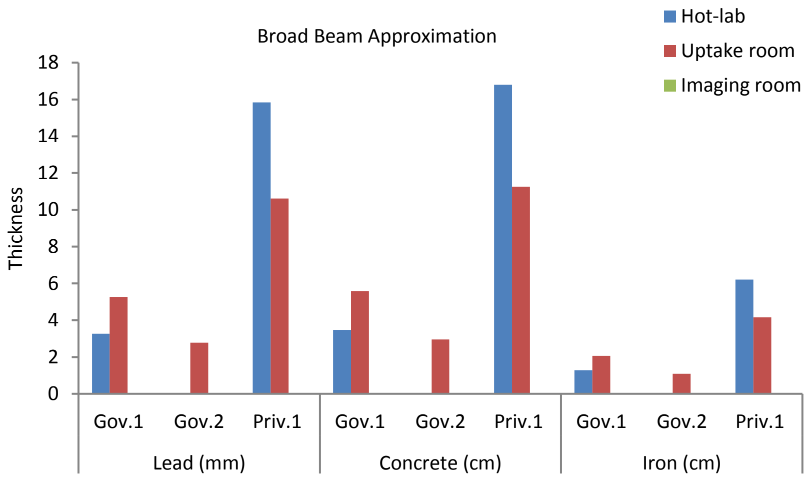

Figure 5. Thicknesses obtained from the hot-labs, uptake rooms, and imaging rooms of Gov1, Gov2, and Priv1 using broad beam approximation

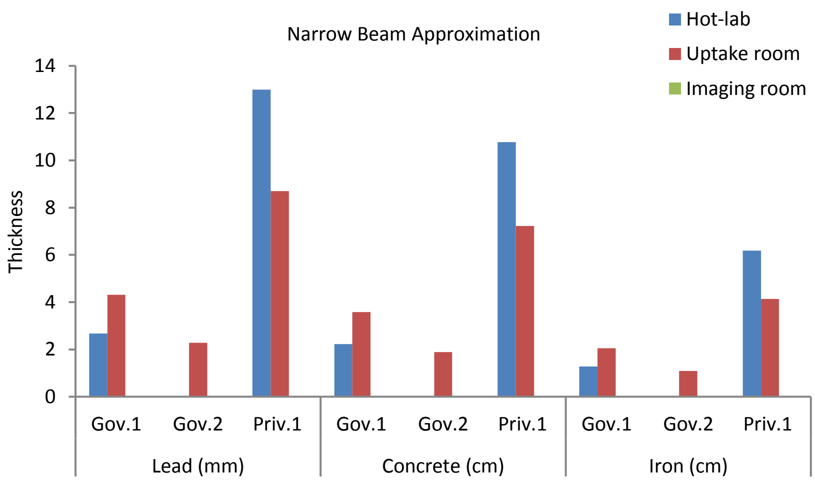

Figure 6. Thicknesses obtained from the hot-labs, uptake rooms, and imaging rooms of Gov1, Gov2, and Priv1 using narrow beam approximation

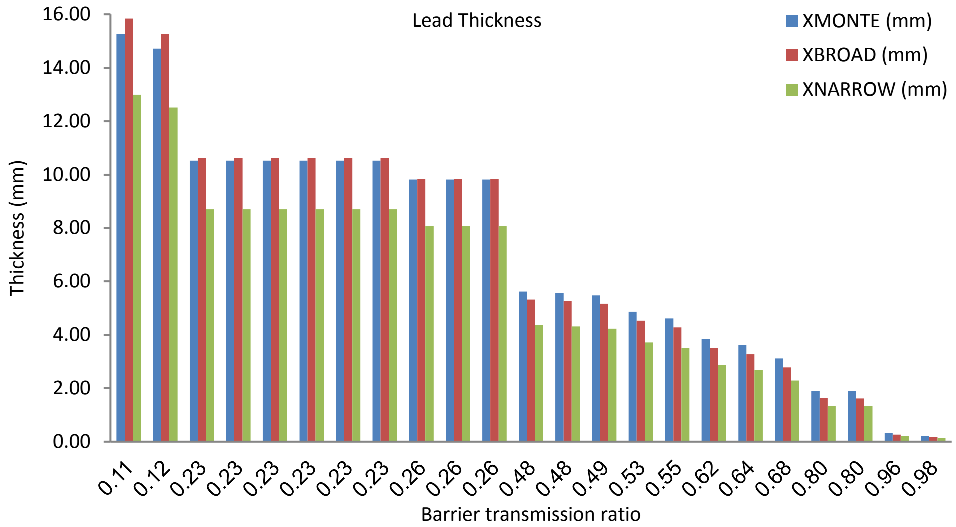

Figure 7. Barrier transmission ratios and lead thicknesses obtained from the Monte Carlo approximation, broad beam approximation, and narrow beam approximation

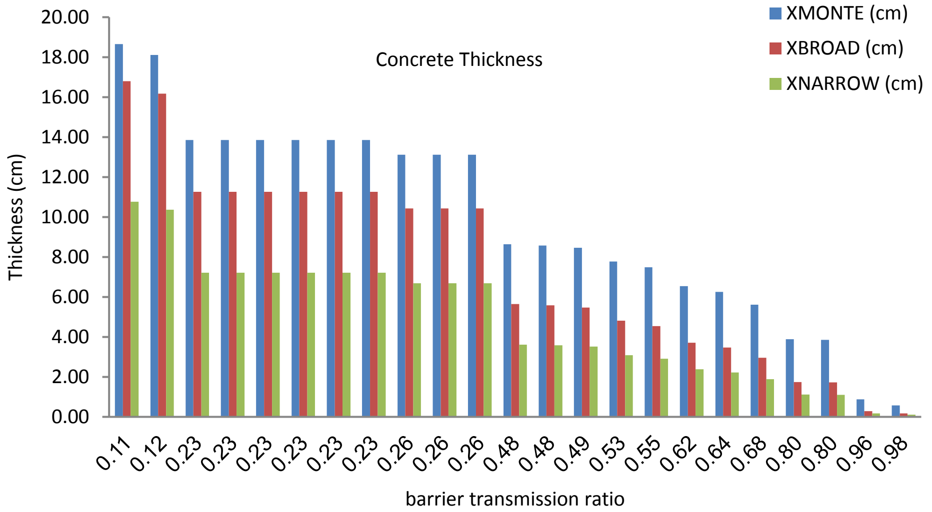

Figure 8. Barrier transmission ratios and concrete thicknesses obtained from the Monte Carlo approximation, broad beam approximation, and narrow beam approximation

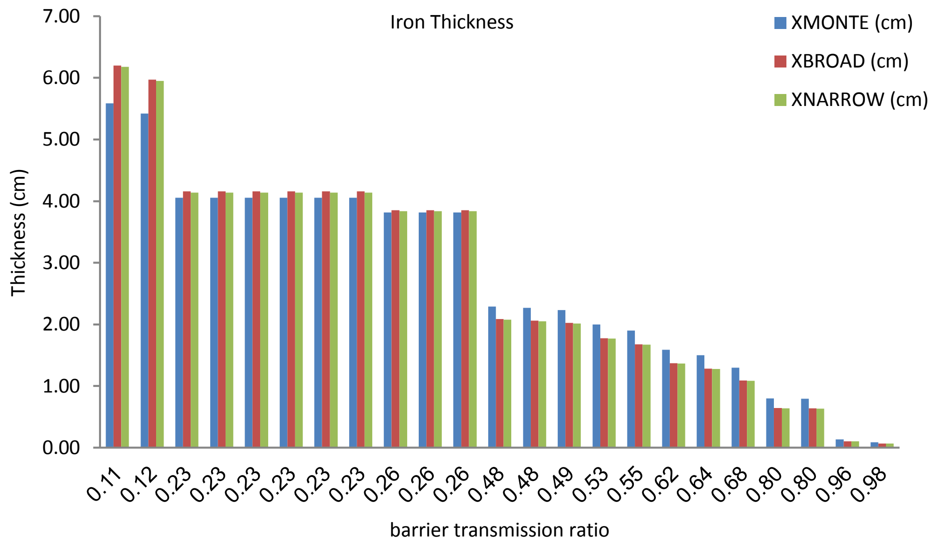

Figure 9. Barrier transmission ratios and iron thicknesses obtained from the Monte Carlo approximation, broad beam approximation, and narrow beam approximation

Discussion

Required shielding for hot laboratories

Figures 4, 5, and 6 depict that Priv1 required the highest level of shielding for hot-lab, compared to Gov1 and Gov2 because the barriers in Priv1 were adjacent to the reception area as illustrated in Figure 3 with very high occupancy. The receptionist and patient's accompanying family members are always seated in this area. This area is also a "high traffic volume area" as people are always present there. Hot-lab of Gov2 required no shielding since all its barriers were adjacent to controlled corridors (only accessible to staff and patients) and unoccupied rooms with very low occupancy factors as illustrated in Figure 2.

Hot-lab of Gov1 was adjacent to a corridor accessible to both radiation workers and non-radiation workers as depicted in Figure 1; therefore, shielding was required there. All three hot-labs were quite spacious with the reported measurements of 7.5, 7.7, and 8.61 m^2 in Gov1, Gov2, and Priv1, respectively. The required size for a hot-lab is 6 m^2 according to the National Regulatory [16].

Required shielding for uptake rooms

Again Priv1 required a higher level of shielding, compared to Gov1 and Gov2 as depicted in figures 4, 5, and 6 due to the short barrier distances of Priv1 and its adjacency to a busy radiation oncology unit. The measured area for an uptake room in Priv1 was 1.67 m^2. Uptake room of Gov2 again had the lowest level of required shielding, since this was a specious area (with the rooms at least 7 m^2 in size) and adjacent to controlled corridors and unoccupied rooms. Uptake rooms of Gov1 required the second-highest level of shielding due to its adjacency to corridors accessible to all.

Required shielding for imaging rooms

All the imaging rooms were larger, compared to other areas, such as the hot-labs and uptake rooms. The three imaging rooms were measured at 27, 26, and 36 m^2 in Gov1, Gov2, and Priv1, respectively. Resulting in longer source to barrier distances, this along with the decay of the ^{18}F-FDG significantly reduced the required shielding. All the barriers in the imaging room required no shielding except for the ceiling in Priv1 with a busy oncology ward and high occupancy above it.

Required thicknesses of construction materials for shielding hot laboratories, uptake rooms, and imaging rooms

The required lead thickness for the hot-labs obtained using the broad beam approximation was 0.35 mm lower for Gov1 and 0.59 mm higher for Priv1, compared to the thicknesses obtained from the Monte Carlo approximation. The narrow beam approximation required 0.94 mm lower lead thickness for Gov1 and 2.26 mm lower lead thickness for Priv1, compared to the thicknesses obtained from the Monte Carlo approximation.

For the uptake rooms, the Monte Carlo approximation required at least 0.30 mm higher lead thickness for both Gov1 and Gov2, compared to the thicknesses obtained from the broad beam approximation. The narrow beam approximation required 1.25 mm lower lead thickness for Gov1, 0.84 mm lower lead thickness for Gov2, and 1.83 mm lower lead thickness for Priv1, compared to the thicknesses obtained from the Monte Carlo approximation.

For iron, the required thicknesses obtained from all the three approximations were statistically similar and only different with a few millimeters. The reason for this could be due to the lack of available literature regarding iron shielding in PET/CT facilities. The Monte Carlo approximation required a higher level of thickness than both narrow and broad beam approximations.

Comparison of Approximations

Figure 7 illustrated that in low barrier transmission ratio region between 0.11 and 0.26, the broad beam approximation required a higher level of lead shielding thickness than the Monte Carlo approximation. This was reversed for a higher barrier transmission ratio between 0.98 and 0.48. For barrier transmission ratios between 0.40 and 0.25, both the broad beam and Monte Carlo approximations estimated similar levels of lead shielding thicknesses.

Implying that at higher radiation intensities, the broad beam approximation overestimates the required level of lead shielding leading to overspending during construction. This finding is in agreement with the results published in the literature, which reported that there is a very small difference up to 10 mm between the lead thicknesses obtained from the broad beam approximation and the lead thicknesses obtained from the Monte Carlo approximation.

With increasing the thickness higher than 10 mm, the broad beam approximation overestimated the level of shielding required, compared to the Monte Carlo approximation [3]. The lead thicknesses obtained from the narrow beam approximation were statistically lower, compared to the lead thicknesses obtained from both broad beam and Monte Carlo approximations. This is because the narrow beam approximation does not consider any scatter radiation; therefore, it underestimated the required level of shielding.

Figure 8 depicts concrete thickness as a function of barrier transmission ratio for both narrow beam and broad beam approximations with lower levels of required thicknesses, compared to the Monte Carlo approximation. This result is in agreement with the published literature, which reported that between 0-25 cm, the narrow and broad beam approximations underestimate the required level of shielding, compared to the Monte Carlo approximation [3]. This finding implies that the construction thicknesses determined from either the narrow beam approximation or broad beam approximation might not be sufficient to ensure that radiation workers and the public are not exposed to high radiation doses.

The Monte Carlo approximation, between 0.11-0.26 barrier transmission ratios, had the lowest level of required thicknesses, compared to both narrow beam and broad beam approximations as illustrated in Figure 9. For barrier transmission ratios above 0.48, the Monte Carlo approximated higher levels of thickness, compared to those by both the narrow beam and the broad beam approximations. This finding is also in agreement with the published literature, which reported that above 5 cm, the broad beam approximation overestimates the required level of shielding thickness for iron [3].

Taking discussion into consideration, the following recommendations were made by the authors:

- Group the hot-lab and uptake rooms together while constructing a PET/CT facility and label them as “hot areas”. Place these “hot areas” adjacent to low-occupancy areas and classify them as controlled areas to which only radiation workers and patients have access.
- Build a hot-lab with a size of 6 m^2 that will require a minimum of 1.00 mm of lead, 2.16 cm of concrete, or 0.38 cm of iron shielding thickness.
- Build an uptake room size of 6.24m^2 that will require a minimum of 1.00 mm of lead, 2.34 cm concrete, or 0.42 cm iron shielding thickness.
- Build an imaging room size of 25 m^2 that will require a minimum of 2.50 mm lead, 12.40 m concrete, or 1.60 cm iron shielding thickness for the Computed Tomography (CT) component.
- If space is not a limiting factor include “hot and cold corridors”.

The three facilities compared in this study were reported with no space constraints; therefore, the above-mentioned recommendations and discussions hold true.

Conclusion

Importance of low-occupancy adjacent areas for hot-labs and uptake rooms cannot be overexpressed in this study. It is very important that all shielding designs of hot-labs and uptake rooms consider low-occupancy adjacent areas. This was not the case for Priv1 that required a higher level of shielding than those of the other two facilities. The narrow beam approximation underestimated the shielding levels required for lead, concrete, and iron; therefore, using this method for the calculation of the required shielding level will be unsafe for radiation workers and the public. The broad beam approximation underestimated the shielding level of thickness required for concrete and overestimated the level of shielding required for iron. Use of this method will lead to shielding errors. It is recommended to apply the Monte Carlo approximation for all shielding requirements of PET/CT. It can be concluded that the Monte Carlo approximation is a golden standard for the determination of the required construction thickness for a safe and well-shielded PET/CT facility.

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