RPE | Radiation Physics & Engineering
An International Peer-Reviewed Journal
Published by K.N. Toosi University of Technology
http://rpe.kntu.ac.ir
Research Article

Radiation Physics and Engineering 2020; 1(3):37–42
https://doi.org/10.22034/RPE.2020.89330

An analytical and Monte Carlo investigation of the sufficiency of the present shielding of PET/CT imaging system at Tehran's Shariati hospital

Fereshteh Gholami[a,b], Ehsan Alibeigi[a,c], Mojtaba Shamsaei-Zafarghandi[a], Ehsan Nazemi[c,*]

[a] *Faculty of Nuclear Engineering and Physics, Amirkabir University of Technology, Tehran, Iran*
[b] *Department of Radiotherapy, Chamran Hospital, P.O. Box 1693715814, Tehran, Iran*
[c] *Nuclear Science and Technology Research Institute, Tehran, Iran*

HIGHLIGHTS

- Calculation of a present PET/CT installation shielding using simulation and analytical method.
- Comparison of Monte Carlo with analytical method of above PET/CT shielding requirement.
- Showing that present shielding structure is adequate for treating up to four more patients a day.

ABSTRACT

By the rapid development of imaging systems such as PET/CT for diagnosis of cancer, the protection of staff and public has become a main health concern. Due to serious and irreversible harms of ionization radiations, protection of all those who are exposed is the main concern of health issues. The main basis of the calculation of the shielding design in the medical imaging systems is that the absorbed dose should not exceed the allowed limit. In this study, the current shielding status of the PET/CT installations in Tehran's Shariati hospital was investigated using the MCNPX Monte Carlo code to ensure that the dose limits for both the controlled and uncontrolled area are not violated. The proposed simulation method was benchmarked with a validated analytical method. Shariati hospital provides services to four patients every day, leading to a dose rate in the range of 2.6×10^{-6} to 9.35×10^{-3} mSv/week. The minimum dose rate in this range represents the value behind the door of the waiting room (public uncontrolled area), while the maximum in this range corresponds to the value behind the glass of the scanner room (operator controlled area). The simulation results for 8 patients/day in this center showed that the dose rate behind the wall of the injection room will increase from 4.88×10^{-6} mSv/week to 2.81×10^{-2} mSv/week, which is well below the recommended levels. This indicates that the present shielding is adequate for up to four more patients per day.

KEYWORDS

Positron-emission-tomography
Computed-tomography shielding
Dose rate
Monte Carlo method
Analytical method

HISTORY

Received: 28 February 2018
Revised: 21 August 2018
Accepted: 18 September 2018
Published: July 2020

1 Introduction

Positron emission tomography (PET) is promising owing to its ability to capture physiology and acquire critical diagnostic information, unavailable from high-resolution anatomy investigations (Madsen et al., 2006). This technique is considered as a noninvasive diagnostic imaging modality, which utilizes certain radiopharmaceuticals. In this modality, a radionuclide is injected into the patient, and thereby abnormal metabolic activities in the surrounding organs can be examined. As the chemical quantities administered to each patient are minor, the radiopharmaceuticals do not interfere in the process of interest (Coker, 2007). PET cameras are adjusted to detect paired 511 keV photons generated as a result of a positron-electron annihilation event (Powsner and Powsner, 2008).

PET/computed-tomography(CT) is an advanced imaging modality which combines functional PET and structural CT information to examine abnormal metabolic activities within and around an organ by injection of a radionuclide into the patient. A PET/CT scan combines CT and PET scans into one scan, leading to an improvement of the lesion localization and diagnosis accuracy (Mawlawi et al., 2006).

*Corresponding author: enazemi@aeoi.org.ir

Early PET centers produced F-18 with their special cyclotron designs, owing to the short half-life of F-18. Nowadays, PET scanning is widely used method and it is therefore feasible for regional laboratories to produce radio fluorine for their regional users. Owing to the short 110 min half-life of F-18, it is necessary to have a larger F-18 activity than the value that needs to be administered to a patient. Shielding against high-energy gamma radiation is needed in PET scanning. Conventional wall materials such as hollow concrete, cinder blocks, and gypsum wallboard provide an insufficient protection for these high-energy radiations. For example, the half-value layers (HVLs) for 150 kVp X-rays and 511 keV gamma rays are a 0.3 mm thick Pb with a 22 mm thick concrete and a 5 mm thick Pb with a 98 mm thick concrete, respectively. The walls of the PET suite need an additional lead shielding. Most of the other modalities involve smaller radiation sources such as an X-ray target with a smaller scattering area. In PET, the activity is distributed throughout the body, as the radiation absorbed by the body tissues act as an extended source (Johnson and Birky, 2012).

In this research, the current shielding status of the PET/CT installations in the Tehran's Shariati hospital is investigated using the Monte Carlo N-Particle eXtended (MCNPX) simulation code and is also benchmarked with a validated analytical method. The main purpose of this paper is to ensure that the dose limits for both the controlled and uncontrolled area are not violated and also investigate the capability of this facility for scanning more number of patients per day.

2 Materials and Methods

2.1 Monte Carlo simulation

In this study, the PET/CT facility of the Shariati hospital was simulated using the Monte Carlo N-Particle eXtended (MCNPX) code, which is used for various type of particles such as neutron, photon, electron, etc or coupled neutron/photon/electron transport processes (Pelowitz et al., 2005). The simulation geometry is similar to that used in our previous work (Shamsaei Zafarghandi et al., 2014) and consists of a three-room area: injection room, waiting room, and scanner room. The geometry details of the three parts are illustrated in the sections 2.1.1, 2.1.2, and 2.1.3. In this study, the dose limitations reported by the International Commission on Radiological Protection (ICRP) for controlled and uncontrolled areas of PET/CT facilities for staff and public were used, respectively. In all simulations, the average flux in each cell was calculated using the F4 tally, and converted into a dose rate using the DEn and DFn cards in the input file of the MCNPX code, as the reported dose limitations are expressed by dose rates (Pelowitz et al., 2005). It is worth noting that the photon-fluxtodose-rate conversion factors, utilized in the DEn and DFn cards, were obtained from ICRP-21 (ICRP, 1971). The staying times of the patients in the rooms combined with their activities were considered in all simulations using the FMn card in the input file of the MCNPX code. In addition, the variance reduction method of Russian roulette was implemented in the simulations as the walls are thick.

2.1.1 Injection room

Radioisotopes cannot be produced in the injection room, and the radiotracer is transmitted daily to this room. In Shariati hospital, four scans at intervals of 1 hour are performed every day. The radioisotope arrives to the injection room at 9:00 AM. The amount of radiotracer should be sufficient so that each patient receives 10 mCi. Scans are performed at 10 AM, 11 AM, 12 AM, and 1 PM. Owing to the short half life of fluorodeoxyglucose (18-FDG) ($T_{1/2}$ = 110 min), the amount of radiotracer should be so that the activity be larger than 40 mCi. For the first two patients, the calculation procedures are as follow:

- Patient 1: As the injection of the first patient is performed at 9:00 AM, the injected initial radiotracer activity is $A_1 = A_{01} = 10$ mCi, where A_{01} is the initial activity ($t = 0$).
- Patient 2: The second patient is injected at 10:00 AM. The initial activity at 9:00 AM for the patient 2, A_{02}, needs to be larger than 10 mCi to reduce to the value of 10 mCi at 10:00 AM. Therefore:

$$\begin{aligned} A_2 &= A_{02}\mathrm{e}^{-\lambda t} \\ \rightarrow 10\ \mathrm{mCi} &= A_{02}\exp[(-\ln 2/110\ \mathrm{min})/60\ \mathrm{min}] \\ 10\ \mathrm{mCi} &= A_{02} \times 0.6852305 \\ A_{02} &= 10\ \mathrm{mCi}/0.6852305 = 14.5936\ \mathrm{mCi} \end{aligned} \quad (1)$$

The calculations are the same for other patients. The results of the calculations for all of the patients are presented in Table 1. Total activities in the injection room for 4 and 8 scans at 9:00 AM were calculated to be 77 mCi and 426.17 mCi, respectively,. These values were used as the source power of the injection room in the simulations.

The inner dimensions of the injection room are $220 \times 360 \times 290$ cm^3 (length × width × height); the thickness of the walls is 36 cm, which consist of two granite tiles with the thickness of 2 cm (one of them is inside the room, and the other one is outside the room), 2 mm thick lead, and 31.8 cm thick concrete. The door of the injection room is $5 \times 100 \times 214$ cm^3 with the thickness of 5 cm, including a 2 cm thick wood and 3 cm thick lead. In this room, the radiotracers for each patient are maintained in a vial with a diameter of 5 cm and height of 6 cm. In simulations, 4 and 8 cylindrical syringes with diameters of 5 cm and heights of 6 cm are used as source.

2.1.2 Waiting room

When the radiotracer is injected, the patient is transferred to the waiting room. The waiting time longs until the radiotracer is collected in the volume of interest. This uptake time varies in different clinics, often in the range of 30 to 90 min. This time is 60 min in this hospital. During this time, 30% of the administered activity is removed from the body. Considered as a radiation source just after the injection, the patient must rest in a relative seclusion.

Table 1: Activities for treatments of 4 and 8 patients per day in Shariati hospital.

Number of scans/day	Patient 1 (mCi)	Patient 2 (mCi)	Patient 3 (mCi)	Patient 4 (mCi)	Patient 5 (mCi)	Patient 6 (mCi)	Patient 7 (mCi)	Patient 8 (mCi)	Total activity (mCi)
4	10	14.59	21.29	31.08	N/A	N/A	N/A	N/A	77
8	10	14.59	21.29	31.08	45.3	66.19	96.06	141.04	426.17

The dimensions of this room are $225 \times 378 \times 290$ cm^3 (inner). The thickness of the walls is 36 cm, consisting of two granite tiles with a thickness of 2 cm (one of them inside the room, and the other outside the room), 2 mm thick lead, and 31.8 cm thick concrete. The room has an electronic door located outside the 36 cm thick wall. The door had dimensions of $214 \times 110 \times 5$ cm^3 (thickness= 5 cm) consisting of lead bricks. Each patient in this room was simulated as a cylinder together with a sphere (as head) filled by water. The total length of this phantom is 172 cm and contains a photon source at 511 keV (Bresnahan and Shrestha, 2012).

2.1.3 Scanner room

The PET/CT is placed in the scanner room. Due to the short half-life of 18-FDG and also 30% removing of the administered activity, the patient should wait 1 hour in the waiting room to reduce the amount of activity less than 10 mCi Reaching to the equilibrium condition of the radionuclide distribution in the body owing to the metabolism of the radionuclide may be needed. The patient can then be moved to the scanning room. The scanning room in this hospital has dimensions of $960 \times 540 \times 290$ cm^3. The thickness of the walls is 38 cm, consisting of two granite tiles with a thickness of 2 cm (one inside the room, and the other one outside the room), 2 mm thick lead and 33.8 cm thick concrete. The scanning room has two doors. One of them, with dimensions of $5 \times 100 \times 214$ cm^3, is opened to the control room. The thickness of the door is 5 cm, consisting of a 3 cm thick lead and 2 cm thick wood. The other door is opened to the hallway, with dimensions of $110 \times 5 \times 214$ cm^3 and thickness of 5 cm, consisting of lead bricks. There is a lead glass between the scanner room and control room, so that the operator in the control room can see the patient. The dimensions of this glass are $205 \times 105 \times 2$ cm^3. 2 cm thickness of the lead glass is equivalent to a lead thickness of 2 mm (Fig. 1).

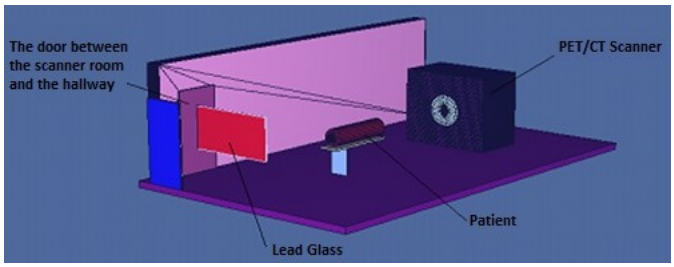

Figure 1: Simulated geometry of the scanner room.

The maximum energy of the Siemens PET/CT unit is 140 kVp (the peak energy of the poly-energetic X-ray spectrum). This energy corresponds to a tenth-value layer (TVL) thickness smaller than 0.95 mm for lead. The F-18 administered to PET/CT patients releases annihilation photons. The energy of these photons is 511 keV. This energy corresponds to a TVL thickness of approximately 16.6 mm. Nevertheless, the TVL is not the only important factor in designing the shield of the suite. For the shielding of the CT portion, fluence rate is another important factor. When the PET/CT suite is designed to shield against 511 keV photons which decay in the patient, it can be assumed that this shielding is adequate for the high fluence rate of the low-energy X-rays deposited from the CT portion of the unit (Coker, 2007). The structural shielding for each area in the PET/CT suite was determined by placing a layer of a material or combination of materials such as lead, concrete, and granite, around the room.

2.2 Benchmarking of the simulation using an analytical method

In order to benchmark the proposed Monte Carlo simulation method, the obtained results from the proposed Monte Carlo method were compared with those of a validated analytical method proposed by Madsen et al. (Madsen et al., 2006) for the estimation of the shielding requirements for PET and PET/CT facilities. It is worthy to mention that the analytical method has been reported only for concrete and lead as the shielding materials of a PET/CT facility. Therefore, we benchmarked the simulation method with the analytical method for the waiting room of the Shariati hospital when the walls of this room contain only concrete or lead for 20 and 40 patients/week. The following is an explanation of the analytical formula proposed by Madson et al. for the waiting room of a PET/CT facility.

The total dose at a given distance from the patient during the uptake time (T_u), administered activity (A_0), and dose reduction factor during the uptake time (R_{tu}) can be calculated by Eq. (3) (Madsen et al., 2006):

$$R_{tu} = 1.443 \times \left(\frac{T_{1/2}}{T_U}\right) \times \left(1 - \exp\left(-0.693\frac{T_U}{T_{1/2}}\right)\right) \quad (2)$$

$$D(T_u) = 0.092\ \mu\text{Sv}(\text{m}^2/\text{MBq} \times \text{h}) \times A_0(\text{MBq}) \times T_u(\text{h}) \times [R_{tu}/d(\text{m})^2] \quad (3)$$

If N_w patients are scanned per week, the transmission factor (B) is calculated by Eq. (4) (Madsen et al., 2006):

$$B = \frac{10.9 \times P \times d(\text{m})^2}{T \times N_w \times A_0(\text{MBq}) \times T_u(\text{h}) \times R_{tu}} \quad (4)$$

where P is the weekly dose limit and T is the occupancy factor. The weekly dose limit P in the United States is considered to be 0.02 mSv/week for uncontrolled

Table 2: Comparison of the dose rates for 4 and 8 scans per day of the PET suite of Shariati hospital.

Area	Thickness	Type of area	Dose rate for 20 scans/week (mSv/week)	Dose rate for 40 scans/week (mSv/week)
Wall of injection room	4 cm (granite) + 2 mm (lead) + 31.8 cm (concrete)	Controlled area	4.84×10^{-3}	2.81×10^{-2}
Door of injection room	2 cm (wood) + 3 cm (lead)	Controlled area	3.07×10^{-3}	2.40×10^{-2}
Wall of waiting room	4 cm (granite) + 2 mm (lead) + 31.8 cm (concrete)	Uncontrolled area	4.04×10^{-4}	8.11×10^{-4}
Door of waiting room	5 cm (lead)	Uncontrolled area	2.67×10^{-6}	4.88×10^{-6}
Wall of scanner room	4 cm (granite) + 2 mm (lead) + 33.8 cm (concrete)	Uncontrolled area	5.25×10^{-5}	1.06×10^{-4}
Door of scanner room and hallway	5 cm (lead)	Uncontrolled area	2.33×10^{-4}	4.65×10^{-4}
Lead glass of scanner room	2 cm (lead glass)	Controlled area	9.35×10^{-3}	1.87×10^{-2}

area, compared with P= 0.1 mSv/week for as-low-as-reasonably-achievable (ALARA) levels in controlled area, and 1 mSv/year limit to the general public (Madsen et al., 2006). Using the transmission factor, the required shielding and corresponding dose rate can be determined.

For the waiting room of the Shariati hospital, the transmission factor B was calculated using Eq. (4) and data in Ref. (Archer et al., 1983). The parameters T, d, A_0, N_w, and T_u with the values of 1, 1.6 m, 370 MBq, 20 patients/week, and 1 hour, respectively, were substituted in Eq. (4). Using these parameters, the transmission factor was calculated to be $B = 0.09086$, which suggests a 16.35 mm thick lead or 19.35 cm thick concrete as the required shields for the waiting room. By using the same procedure for 40 patients/week, the results show that a 20.9 mm thick lead or 24 cm thick concrete are required as shields. Furthermore, the lead and concrete shields with the obtained thicknesses from the analytical method were employed in the input file of the MCNPX code (explained in Sec. 2.1.2) for the waiting room, and the dose rate behind the wall of the waiting room was estimated.

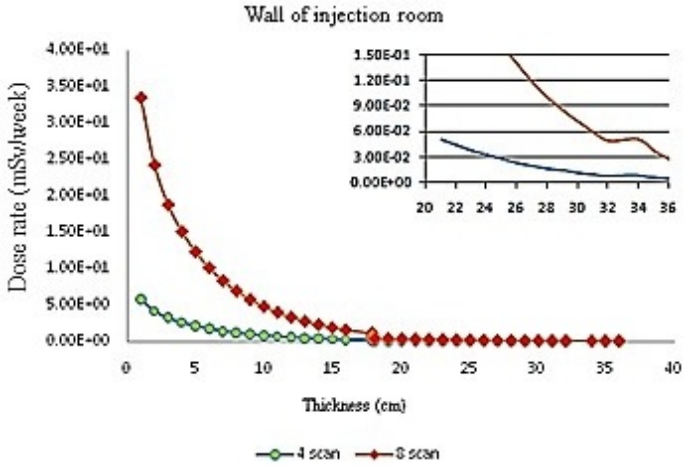

Figure 2: Comparison of the dose rates outside the walls of the injection room for 4 and 8 scans.

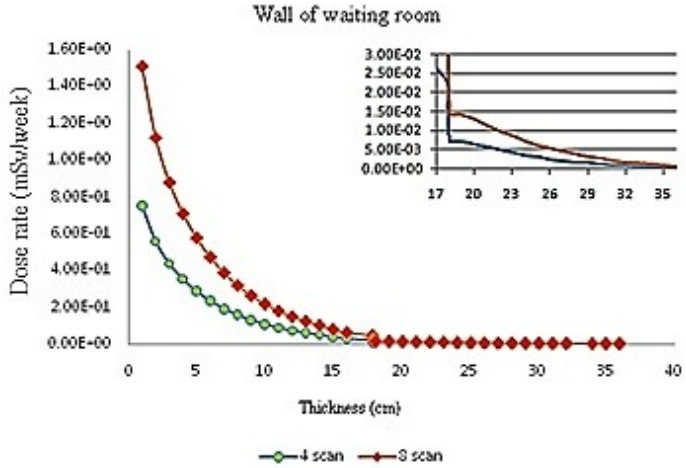

Figure 3: Comparison of the dose rates outside the walls of waiting room for 4 and 8 scans.

3 Results and discussion

In the present study, the PET/CT facility consisting of a three-room area (injection room, waiting room, and scanner room for 4 and 8 scans per day) was simulated using the MCNPX code. The results are presented in Table 2.

Figure 2 shows a comparison between the dose rates outside the injection room walls for 4 and 8 scans per day. The dose rates, when the thickness of the walls is 1 cm, are 5.75 mSv/week for 4 scans per day and 33.4 mSv/week for 8 scans per day. By increasing the thickness to 15 cm, the dose rates decrease to 3.22×10^{-1} mSv/week and 1.87 mSv/week, respectively.

Figure 3 shows a comparison of the dose rates outside the waiting room walls for 4 and 8 scans per day. By increasing the thickness of the walls to 1 cm, the dose rates for 4 and 8 scans per day are 7.54×10^{-1} mSv/week and 1.51 mSv/week, respectively. By increasing the thickness of the wall to 15 cm, the dose rates decrease to 3.90×10^{-2} mSv/week and 7.86×10^{-2} mSv/week, respectively. Figure 4 presents a comparison between the dose rates outside the walls of the scanner room for 4 and 8 scans. The degree of the dose reduction with the increase of the wall thickness

of the scanner room is lower than those of the injection and waiting rooms. In addition, as shown in Figs. 2 to 4, the dose rate around the thickness of 17 cm exhibits a larger decrease compared to those of the other regions, which is due to the existence of a 2 mm thick lead sheet in the concrete shield at this thickness.

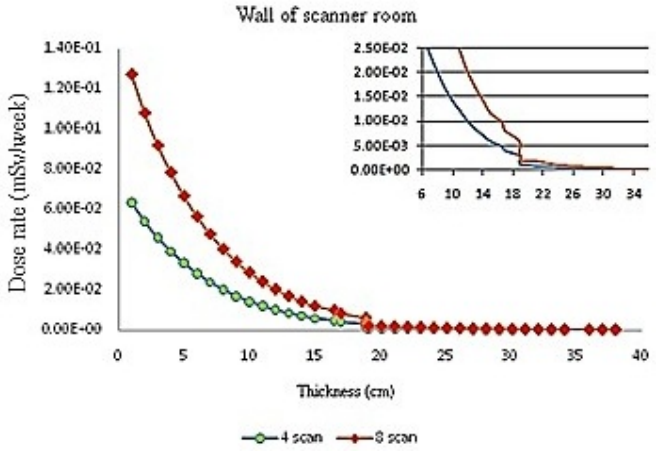

Figure 4: Comparison of the dose rates outside the walls of scanner room for 4 and 8 scans.

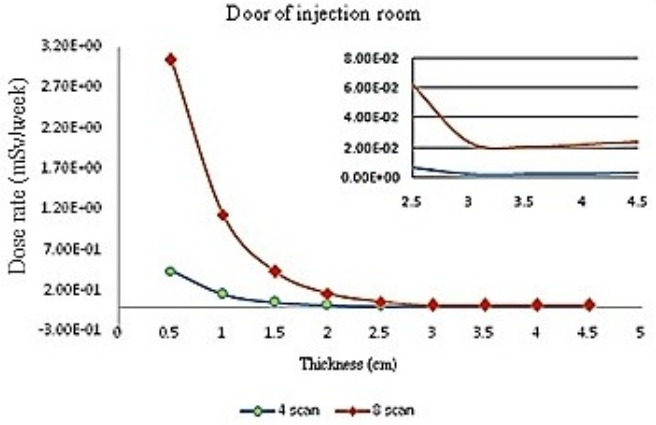

Figure 5: Comparison of the dose rates outside the door of injection room for 4 and 8 scans.

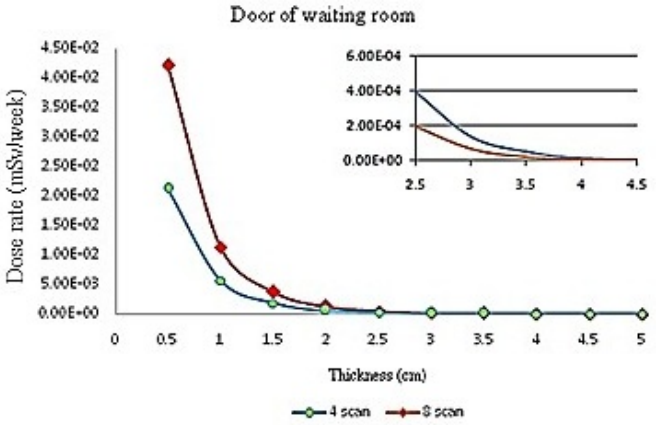

Figure 6: Comparison of the dose rates outside the door of waiting room for 4 and 8 scans.

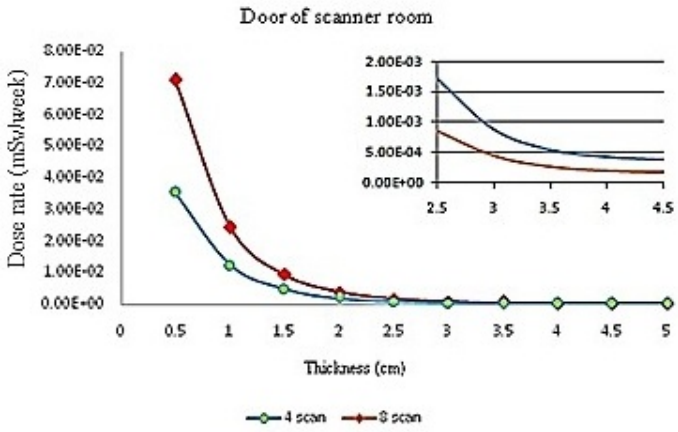

Figure 7: Comparison of the dose rates outside the door of scanner room for 4 and 8 scans.

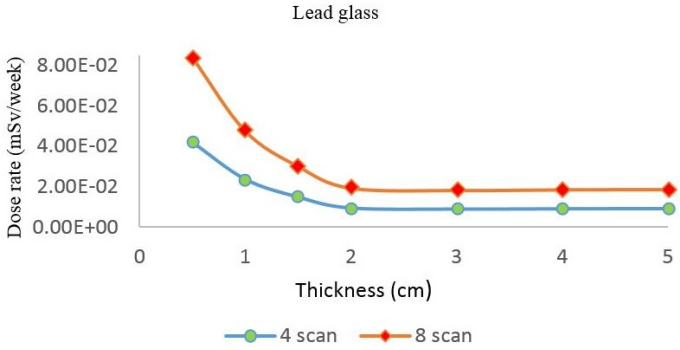

Figure 8: Comparison of the dose rates outside the lead glass for 4 and 8 scans.

Figures 5 to 8 show comparisons of the dose rates corresponding to 4 and 8 scans outside the doors of the injection room, waiting room, scanner room, and lead glass in the scanner room, respectively.

The obtained dose rates are reported in Table 3. The results reveal that the relative error between the analytical and Monte Carlo methods is smaller than 4.5%, which confirms the validity of our Monte Carlo simulations. However, in 2007 A.L. Coker (Coker, 2007) found that while the obtained results from analytical method are very close to those of experimental measurements, the results corresponding to MCNPX simulations are not. This difference in their results can be due to large statistical errors in MCNPX calculations; While most of documents recommend that the error corresponding to MCNPX simulations should be less than 5%, they have reported the results of their simulations with a relative error of 0.1.

4 Conclusions

The PET/CT facility in the Shariati hospital, which consists of three areas including an injection room, a waiting room, and a scanner room was simulated using the MCNPX Monte Carlo code. The dose rate was calculated in different area of this facility for scanning of 4 and 8 persons per day, in order to investigate the capability of its present

Table 3: Comparison of the obtained results from the analytical and Monte Carlo methods for the dose rates outside the wall of the Shariati hospital's waiting room of the uncontrolled area.

Number of scans per week	Material	Thickness (cm)	Dose rate in the analytical method (mSv/week)	Dose rate obtained from the simulation method (mSv/week)	Relative error (%)
20	Concrete	19.35	0.02	0.0201	0.5
	Lead	16.35	0.02	0.0209	4.5
40	Concrete	24.2	0.02	0.0197	1.5
	Lead	20.9	0.02	0.0201	0.5

shielding. In addition, the proposed Monte Carlo simulation method was benchmarked with a validated analytical method proposed in the literature for the waiting room of the Shariati hospital when the wall of this room was filled only with concrete or lead for 20 and 40 patients/week. The obtained dose rates calculated behind the wall of the Shariati hospital's waiting room corresponding to the Monte Carlo simulations were compared with those of analytical methods. The relative difference between them was estimated to be smaller than 4.5%, which confirm the validity of our simulations. The validated simulation results indicated that the Shariati hospital may improve its facilities and increase the number of scans up to 8 persons per day without need to additional shielding. The weekly dose rate that each operator receives for 8 scans per day will be smaller than 0.1 mSv/week. For the uncontrolled area, the dose rate for the same number of scans was 25 times lower than the permitted level, providing a desirable safety for the staff and general public in the hospital.

Acknowledgement

We thank all of the staff of the Shariati hospital's PET/CT suite, particularly Dr. Geramifar, who helped us in this study.

References

Archer, B. R., Thornby, J., and Bushong, S. C. (1983). Diagnostic X-ray shielding design based on an empirical model of photon attenuation. *Health physics*, 44(5):507–517.

Bresnahan, M. E. and Shrestha, B. (2012). Potential shielding for a positron emission tomography (PET) suite. *Journal of Biomedical Graphics and Computing*, 2(1):89.

Coker, A. L. (2007). *PET/CT shielding design comparisons*. PhD thesis, Texas A&M University.

ICRP (1971). Committee 3 Task Group, P. Grande and MC ORiordan, chairman,Data for Against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15, ICRP-21, International Commission on Radiological Protection.

Johnson, T. E. and Birky, B. K. (2012). *Health physics and radiological health*. Lippincott Williams & Wilkins.

Madsen, M. T., Anderson, J. A., Halama, J. R., et al. (2006). AAPM task group 108: PET and PET/CT shielding requirements. *Medical Physics*, 33(1):4–15.

Mawlawi, O., Pan, T., and Macapinlac, H. A. (2006). PET/CT imaging techniques, considerations, and artifacts. *Journal of Thoracic Imaging*, 21(2):99–110.

Pelowitz, D. B. et al. (2005). MCNPXTM user's manual. *Los Alamos National Laboratory, Los Alamos*.

Powsner, R. A. and Powsner, E. R. (2008). *Essential nuclear medicine physics*. John Wiley & Sons.

Shamsaei Zafarghandi, M. et al. (2014). Study the shielding for PET/CT imaging installations of Shariati hospital of Tehran with Monte Carlo code. *Iranian Journal of Radiation Safety and Measurement*, 2(2):13–20.