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TLD environmental monitoring of new scanner facilities at the Nuclear Medicine Department of the Taiwan Medical University Hospital

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Abstract.
OBJECTIVE: Single-photon emission computed tomography (SPECT) as well as dual energy X-ray absorptiometry (DXA) scanners were designed in July 2018 at the Nuclear Medicine Department (NM), of the Taiwan Medical University Hospital. These scanners emit substantial X-rays from the target, which are tungsten, iron. Therefore, patients undergoing SPECT and DXA diagnosis, in addition to medical personnel, are exposed to undesirable photon leakage.
METHODS: Following administration of radiopharmaceuticals, patients become radioactive sources; thus, it is necessary to evaluate a possible increase in the environmental gamma exposure rates in the NM as a result of the operation of the new scanners. A three month evaluation of environmental radiation in the NM was performed using the accurate and sensitive TLD-100H approach, which gives an error rate less than 10%.
RESULTS: Detected exposure radiation rates in the NM ranged from 0.12 ± 0.02 to 1.00 ± 0.15 mSv per month, indicating that the imaging room had significantly different radiation rates. The results were compared with previous results, and no significant contribution to the enhancement of environmental gamma radiation was detected, which remained far below the occupational dose recommended by ICRP 60. The minimum detectable dose (MDD) for environmental radiation is also discussed herein to demonstrate the reliability of TLD-100H.
CONCLUSION: Recommendations were sent to the authorities of AEC-ROC to implement actions that could reduce doses at these high-dose locations to meet the ALARA principle.

Keywords: Environmental radiation rates, thermoluminescence dosimeter, SPECT, DXA, Nuclear Medicine Department, minimum detectable dose

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1. Introduction

Nuclear medicine could be widely used in applications for a variety of diagnostic tests and disease treatments, and its use has increased dramatically over the past decade [1–9]. The Nuclear Medicine Department (NM) of Chung Shan Medical University Hospital (CSMUH) at Taichung designed two scanners: The new Single Photon Emission computed tomography, SPECT, 670 DR, Discovery, and the dual energy X-ray absorptiometry, DXA scanner, Hologic, Discovery, and were operated in July 2018. In addition, Positron Emission Tomography with Computed Tomography, PET/CT, Philips GEMINI GXL PET/CT, as well as Single Photon Emission computed tomography accompanied with computed tomography, SPECT/CT, Symbia T2, Siemens, Illinois, USA, were installed at NM in 2007 and 2011, respectively. A few studies evaluating extra environmental radiation dose rates for PET/CT technologists working at PET/CT have been reported in the literature. This study measured the environmental radiation in the NM of the Taiwan Medical University Hospital. The target made of tungsten, iron of these scanners emit substantial X-ray emissions, and the public and patient are therefore exposed to extra radiation within these facilities, although in a much lower dose than environmental background radiation. However, this exposure cannot be ignored for health reasons [1–10]. Furthermore, following administration of radiopharmaceuticals, patients become radioactive sources. When radionuclides decay, γ-rays are emitted into the environment. The radionuclides used in the NM are ^{18}F, ^{67}Ga, ^{99m}Tc, ^{131}I, and ^{201}Tl, the main γ-emission energies are in the range of 80 to 500 keV [5,6,8].

A few photons emitted from these radionuclides can penetrate the reinforced concrete (RC) and lead (Pb) shielding wall, further scattering into the vicinity outside the imaging room. This environmental radiation, however minor, causes health concerns for medical personnel. The controlled area includes four imaging and control rooms, exclusive toilets for patients, three activation boxes, an injection room, and a radioimmunoassay laboratory in the NM.

In addition, CSMUH is in the process of building a new Isotope Therapy Center (ITC), which commenced operation on 1 May 2019. The new ITC, SPECT, and DXA must meet with a limit of 100 mSv per 5 years and 50 mSv per year in the controlled area [1,8,10]. The lack of data about a possible increase in environmental radiation rates in the new scanners also motivated this study. Figure 1 shows a plane view of the basement 1 layout at the CSMUH (including the NM, Radiation Oncology Department, and cyclotron), with all dimensions quoted in centimeters. In addition, the areas are classified into free (uncontrolled) and controlled areas, and the dose restriction levels should be 1 mSv per year and 50 mSv per year, respectively [1,10].

The PET/CT facility (C, C1, R10, and Act1-3) is surrounded by a shielding wall which consists of 30 cm thick RC and 3 mm thick Pb equivalent. RC, Pb are generally the most cost-effective shielding materials to protect against the leakage of γ and X rays [8]. The SPECT/CT facility has a height of 5.3 meters, and the ceiling and ground of each floor are 20 cm thick RC. These walls are 30 cm thick RC and 5 mm thick Pb equivalent, and the walls are also separate in the control rooms (A-D) and the imaging rooms (A1–D1) in this facility. The radioimmunoassay laboratory (E) and injection room (I) are also separated by 30 cm-thick RC walls and 3 mm thick Pb equivalent [1]. A 1.5 m width corridor (R5-8) separates the new ITC and SPECT/CT facilities. Near the NM, the Department of Radiation Oncology (RO, 30 m away from the NM) operates the linear accelerators (Axesse and Elekta Synergy). A self-shielded cyclotron, RDS-111, CTI, is operated 35 meters away from the NM on the same basement floor (B1).

Fourteen staff members of NM, including radiologists, nurses, and medical doctors, contacted the relatives, patients and the public. Table 1 lists the properties of the commonly used radionuclides [6,8].

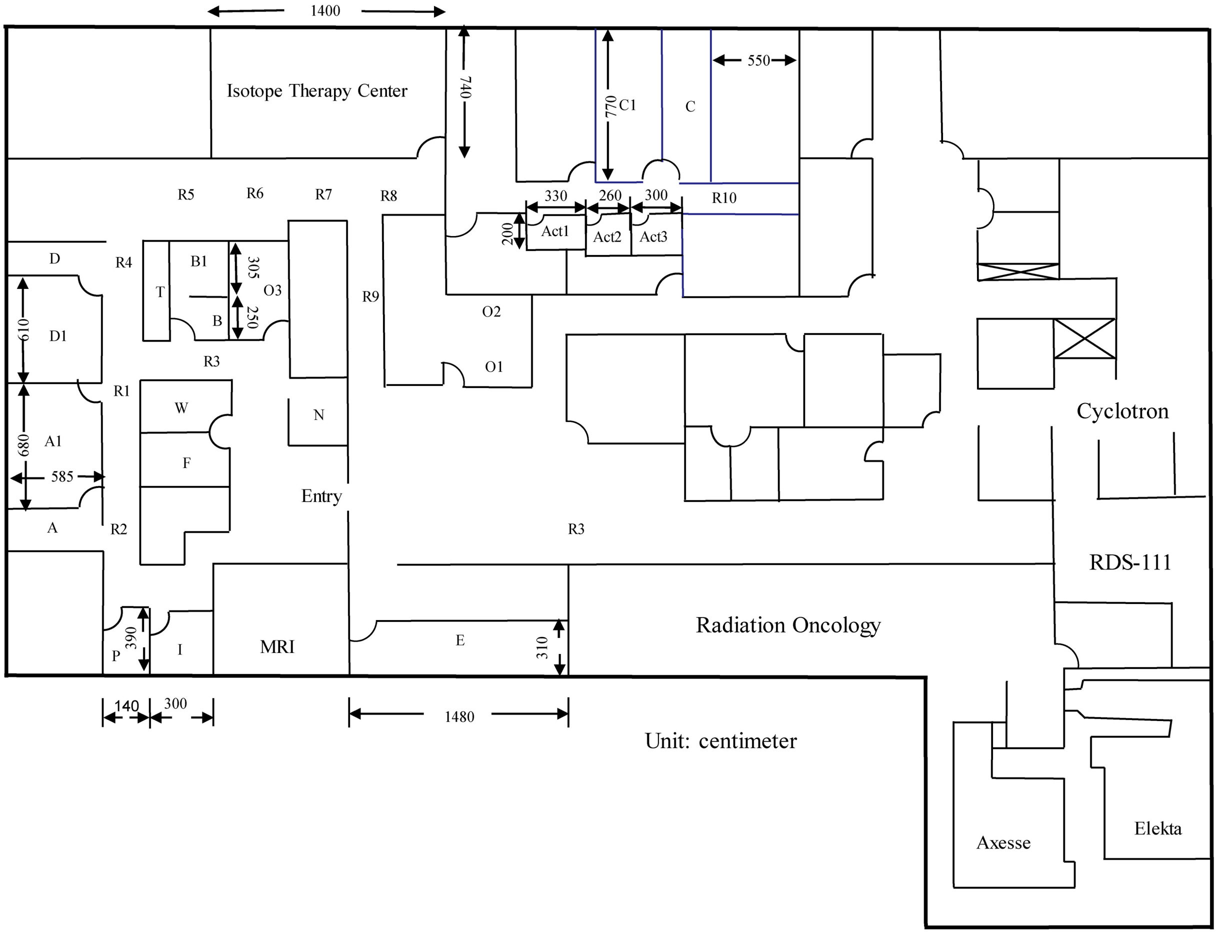

Fig. 1. A layout of basement 1 of at CSMUH, which was included the NM, RO and cyclotron. These locations were labeled with letters from A to T where TLDs were placed. Each point was selected based on its occupation by workers and general individuals. TLDs were suspended at SPECT, DXA, PET/CT and SPECT/CT control rooms (A, B, C, and D) on the walls at one meter height above the floor. In addition, TLDs were tapped at the ceiling directly "O" ring above the scanner in the imaging room (A1, B1, C1, and D1).

An average of 300 patients per month were diagnosed in the NM. In addition, 150 patients received 20 mCi (74 MBq) ^{99m}Tc-MDP each and 110 patients received 10 mCi (37 MBq) ^{18}F-FDG each from 1 October to 31 December 2018.

The evaluation of extra environmental radiation dose rates for PET/CT technologists working at PET/CT facilities has been reported in the literature. The present study measured the environmental radiation within the NM of the Taiwan Medical University Hospital.

1.1. PET/CT facility

2-deoxy-2-[^{18}F]-fluoro-d-glucose, ^{18}F-FDG injections must still be prepared manually due to a large number of patients, so extra doses to staff performing the work are unavoidable. The main application of ^{18}F is in PET/CT, administered as ^{18}F-FDG in the injection room (I) to allow glucose cell metabolism that in turn detects tumor processes. PET/CT is considered among the best diagnostic imaging techniques,

Table 1
Properties of commonly used radionuclides at NM of CSMUH [1,6]

Radio-nuclide	Half life	γ-rays (keV)	Abundance (%)	Administered dose (mCi)	Patients per month	Waiting time	First scan time (min)	Waiting time (hr)	Second scan time (min)
^{18}F	110 min	511	194	6–8	110	45–60 min	20	3–4	20
^{67}Ga	78.2 hr	184	20	5	20	1 days	30 (WB) 15 (Organ)	–	–
^{99m}Tc	6.0 hr	140	90	20–25	150	20 min-4 hrs	15	–	–
^{131}I	8.0 day	364	81	2	3	3–7 days	30 (WB) 15 (Organ)	–	–
^{131}I	8.0 day	364	81	29.5	3	7 days	30 (WB) 15 (Thy)	–	–
^{201}Tl	73 hr	167	9.4	2	4	5–10 mins	15	3–6 hrs	15

since it provides both morphological and functional information about the organ. ^{18}F is a positron emitter that has characteristic annihilation photons, 511 keV.

Prior to diagnosis using ^{18}F-FDG, each patient was asked to wait in the activation box (Act 1–3) for 45–60 minutes to ensure thorough distribution. The patient remained in the exclusive toilet (T) for approximately two minutes to empty the bladder before being moved to the imaging room (C1).

The patient was positioned on the PET/CT camera bed of the facility (C1) for the transmission scan. The PET/CT scans took 20 minutes and were performed twice in each patient. The second scan was performed almost 3–4 hour after the first, and the patient was asked to wait in the activation box during the interval. PET/CT scans took 20 minutes in the PET/CT imaging room (C1), and the patient spent more time inside the PET/CT facility. Finally, the patient could leave the NM of CSMUH.

1.2. SPECT/CT facility

Consequently, new occupational radiation safety problems had to be resolved. The most widely used radionuclide in the NM is ^{99m}Tc, not only in the acquisition of heart and skeletal images but also those of the bladder, liver and lungs. Patients can also be diagnosed using ^{99m}Tc-methylene diphosphate (^{99m}Tc-MDP), which emits 140 keV photons during an SPECT/CT scan [6]. Moreover, ^{67}Ga is the main radionuclide used to diagnose inflammatory diseases. In addition, ^{201}Tl is used to obtain myocardial images. ^{131}I can be used in the diagnosis as well as treatment of the thyroid gland.

The thyroid uptake and whole-body retention of ^{131}I were measured by SPECT. Regions of interest could be drawn over the thyroid organ on the each scan. Patient whole-body scanning was connected and the NaI (Tl) detector was positioned at fixed distances of 5 cm from the body. An approximate 30 minute acquisition time yielded whole-body scintigraphy images in the imaging room (A1) [4].

Additionally, prior to SPECT/CT scans using ^{99m}Tc-MDP, the injection took 30–60 seconds in the injection room (I). In the waiting room (W) and in the consultation room (F), each patient was asked to wait about 20 minutes to four hours prior to meeting with a medical doctor, respectively. The administered activities of ^{201}Tl and ^{69}Ga range from 3 to 5 mCi (11.8 to 18.5 MBq).

In this study, thermoluminescence dosimetry (TLD) was used to measure environmental radiation among the NM areas. This high energy radiation poses different radiation hazard problems. Therefore, it became necessary to evaluate a possible increase in environmental radiation rates due to the operation of the new ITC, SPECT, and DXA. Special attention is necessary to optimize radiation safety among these facilities of NM to minimize environmental radiation for the safety of personnel and the public.

2. Materials and methods

2.1. TLD-100 system

TLD-100H has been widely used to detect environmental radiation, since it indicates long-term accumulation during the last 30 years [7]. The TLD-100H was composed of LiF: Mg, Cu, P, 3.2 × 3.2 × 0.9 mm^3. The Harshaw 3500 reader could be used to measure irradiated TLDs. These chips automatically fall under the one month survey [7]. In addition, a highly sensitive TLD-100H was used to map the photon leakage dose rate within the NM of Lin Hsin Hospital during the Fukushima nuclear plant accident. Three TLDs were put in one bag to eliminate the fluctuation in the TLD-100H; thus, 120 TLDs could represent 40 measurement locations by reusable TLDs.

The TLDs were calibrated using known activities, 10 mCi (37 MBq) ^{131}I capsule (Global Medical Solutions Taiwan, Ltd., Taiwan). First, the ion chamber [PTW Farmer chamber type 30013 (0.6 cm^3 made by Best Medical Com., USA)] was placed at 0.5–6 meters away from the ^{131}I source and exposed to earn radiation rates. Second, the TLDs were irradiated with this source for 62 hours.

2.2. Statistical analysis and weighting factor

In order to compare the fluctuations of the TLDs, three TLDs were put in one bag, so that 120 TLDs could be represent 40 measured locations. To ensure batch homogeneity, the sensitivity of each TLD (S_i) was described as:

$$S_i = \frac{R_i - \overline{R}}{\overline{R}} \times 100\% \tag{1}$$

where S_i is the sensitivity of the ith TLD; R_i is the reading on the ith TLD in this bag, and $\overline{R}$ is the average of all TLD readings.

These radiation rates can be evaluated from various measured locations under the same conditions. The weighted mean (R_w) of R is expressed by [11]:

$$R_w = \frac{\sum W_i R_i}{\sum W_i} \tag{2}$$

Standard error (σ_i) of the ith TLD (R_i) can be expressed as [11]:

$$\sigma_i = \sqrt{R_i} \tag{3}$$

The weighting factor (W_i) of ith TLD is derived from standard error (σ_i), as:

$$W_i = \frac{1}{\sigma^2} \tag{4}$$

The weighted standard error of each bag $\sigma_{(A_w)}$ is given by:

$$\sigma_{(A_w)} = \frac{1}{\sqrt{W_i}} \tag{5}$$

2.3. Surveying environmental radiation at the NM center

To evaluate environmental radiation, TLD was randomly suspended at one meter above the floor to represent exposure doses for a person standing among the NM [10]. The measurements were taken for a one month survey and were repeated three times from 1 October to 31 December 2018. Two bags (six TLDs) were used to monitor the environmental radiation rates in Taichung, 750 meters and 3000 meters away from NM, respectively, which were labeled TC1 and TC2. Four bags (12 TLDs) were used to monitor background radiation in the low background lab of CSMU [3,7]. The results for each bag were averaged. The fluctuations, calibration, and counting statistics of the Harshaw 3500 reader for the calibrated TLD-100H were within 10% [7,12].

3. Results and discussion

3.1. TLD-100H calibration

The irradiated TLD chips were read by Harshaw 3500 reader automatically on the following reading cycle. First, TLD is pre-heating temperature 135°C. Second, pre-heating time is 10 sec, and holding 1 s. Third, then acquisition temperature is 240°C at linear heating rate 10°C/s. The acquisition time is 23 s. Before irradiation, the TLD-100H was heated up to 240°C for 10 min in a furnace 47900 [3,7]. The Y (mSv) = 0.0078 × x (nC) −0.1304 is the conversion factor of TLD-100H. In addition, R^2, the square of the correlation coefficient, was equal to 0.9998. The TLD approach was chosen due to its high sensitivity and easy availability for environmental measurements due to a high published R^2 value [3,7].

3.2. Environmental radiation

The TLDs measurements among the SPECT, DXA, PET/CT, and SPECT/CT facilities show a huge gradient that environmental radiation rates varied from 0.15 ± 0.04 to 1.00 ± 0.15 mSv per month, corresponding to the dataset of 40 measured points. All measurement data were not only obtained at one meter above the floor but also on the ceiling above the "O" ring of the scanners.

From the SPECT imaging room (A1), an explicit photon dose rate of 0.90 ± 0.15 mSv per month was measured, which is 5.88 times those measured at the nurse station (N) (0.16 ± 0.04 mSv per month). Hence, these imaging rooms (A1–D1) are classified as "hot" areas, with maintenance access only as absolutely necessary. Thus, RC/Pb equivalent walls can suppress extra radiation leakage. The high X-ray field and 364 keV show that the public and staff must be careful to avoid extra radiation during SPECT operations.

Following the three month survey, the average environmental radiation in the vicinity of the ceiling "O" ring of the SPECT ranged from 0.28 ± 0.04 to 0.90 ± 0.15 mSv per month in the SPECT imaging room (A1). The dose rate decreased markedly with increasing distance from the gantry head of the 670 DR Discovery.

The highest environmental radiation rates came from patient ^{18}F-FDG as well as X-ray leakage from the PET/CT facility, because the measured environmental radiation was approximated from the background radiation in the activation rooms (Act1-3), and in our low background lab were far from these facilities (Fig. 1). Furthermore, the effectiveness of the RC/Pb in the PET/CT control room (C) was 0.90/0.15 = 6.00.

Table 2 lists the environmental radiation in the NM at the 40 measured points. The highest radiation was obtained in the imaging room of the SPECT/CT facility (D1). The individual environmental radiation at points in D1 ranged from 0.76 ± 0.12 to 1.00 ± 0.15 mSv per month.

Shielding ranged from 0.13 ± 0.02 to 0.90 ± 0.15 mSv per month by the CR/Pb shield in the SPECT/CT control room (D). The radiation rates among radioimmunoassay laboratory (E), corridor

Table 2
Environmental radiation (mSvper month) measured at the NM from Oct. 1st to Dec. 31st, 2018

Locations	Area classification*	Environmental radiation
SPECT facility	A	
SPECT control room (A)	A	0.12 ± 0.02
SPECT imaging room (A1)	A	0.28 ± 0.04–0.90 ± 0.15
Corridor (R1)	A	0.15 ± 0.02
Corridor (R2)	A	0.15 ± 0.03
DXA facility	A	
Control area (B)	A	0.12 ± 0.02
Treatment area (B1)	A	0.16 ± 0.03
Corridor (R3)	A	0.16 ± 0.03
PET/CT facility	A	
PET/CT control room (C)	A	0.15 ± 0.02
PET/CT imaging room (C1)	A	0.32 ± 0.05–0.40 ± 0.06
Corridor (R10)	A	0.16 ± 0.03
SPECT/CT facility	A	
SPECT/CT control room (D)	A	0.13 ± 0.02
SPECT/CT imaging room (D1)	A	0.76 ± 0.12–1.00 ± 0.15
Corridor (R4)	A	0.16 ± 0.03
Activation box (Act 1)	A	0.14 ± 0.03
Activation box (Act 2)	A	0.15 ± 0.02
Activation box (Act 3)	A	0.16 ± 0.02
Radioimmunoassay laboratory (E)	A	0.13 ± 0.02
Consultation room (F)	B	0.15 ± 0.03
Injection room (I)	A	0.18 ± 0.02
Nursing station (N)	B	0.16 ± 0.04
Medical office (O1)	B	0.14 ± 0.03
Medical office (O2)	B	0.15 ± 0.02
Medical office (O3)	B	0.14 ± 0.03
Waiting room (W)	B	0.16 ± 0.04
Toilet (T)	A	0.16 ± 0.04
Taichung (TC1)	B	0.17 ± 0.02
Taichung (TC2)	B	0.13 ± 0.03

*A: Controlled, B: Free.

(R1-10), consultation room (F), and the nurse station (N) ranged from 0.13 ± 0.02 to 0.19 ± 0.03 mSv per month. Staff, patients, and relatives in these locations were not at significant hazard of exposure. This is primarily due to the fact that RC/Pb effectively attenuates penetrating photons. The estimated radiation reasonably agrees with that in TC1 and TC2. The environmental radiation in the PET/CT facility on the upper floor surface which is immediately above C1 and on the lower floor of basement 2 which is below C1 were 0.14 ± 0.03 and 0.15 ± 0.04 mSv per month, respectively. This is in accordance with published data, and the ambient doses determined herein must meet the local radiation protection regulations. The highest evaluated values are far lower than the occupational dose limit for controlled areas, as those are 50 mSv per year and 100 mSv per 5 years [4,13]. Comparisons with previous data show no main public health impact at the Taiwan Medical University Hospital. No significant contributions were measured.

3.3. *Minimum detectable dose (MDD) of TLD method*

The values of radiation rates have a confidence level of 95% and were evaluated by the minimum detectable dose (MDD). When the environmental radiation rates were measured at several points at the same distance, the average environmental radiation rate at these points was used. All measurements were performed three times. These TLDs were subsequently counted and analyzed to evaluate the distribution

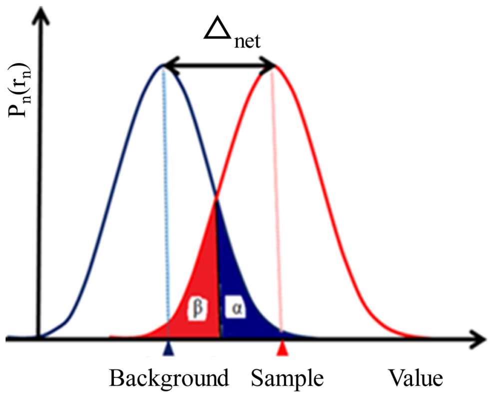

Fig. 2. Both peak A or B corresponded to nearly the same gross count. The gross count is equal to background count (B) adds net count (Δ_{net}) which is written in the region of interest, ROI.

of environmental radiation within the NM. Many of the detected points of environmental radiation rates were uncertain because the corresponding photon doses were under the MDD [12,14]. The net counts (Δ_{net}) of the MDD values in the evaluation of the glow curve were obtained using a Harshaw 3500 reader. The Δ_{net} has significant meaning, k_α is the standard deviation of the net count rate which is given as a single-tail area of α. k_β is the standard deviation with an area β to the left tail. B presents the gross background count. In the statistical results, either α or β is equal to 0.025, which implies the 95% confidence level. Therefore, k_α and k_β were both equal to 1.96. Δ_{net} and can be simplified to Eq. (6) [14].

$$\Delta_{net} = \sqrt{B}\left(k_\alpha + \frac{k_\alpha^2}{2\sqrt{B}} + k_\beta\sqrt{1 + \frac{k_\alpha}{\sqrt{B}} + \frac{k_\alpha^2}{4B}}\right) \tag{6}$$

$K_\alpha = 1.645$; $K_\beta = 1.645$; $B =$ Gross background count

$$\mathrm{MDD} = B + \Delta_{net} \tag{7}$$

Accordingly, the Δ_{net} for fulfilling the criteria of MDD increases with the background counts. Figure 2 indicates the probability density of the gross background count as well as the Δ_{net} in identifying the measured radiation rates written from a Harshaw 3500 counter. Either peak A or B correspond to nearly the same gross count (gross count is equal to background count adds Δ_{net} which is written in the region of interest, ROI). Additionally, the data obtained from peak B is more reliable than that from peak A.

The derived measurements could be re-evaluated to obtain these MDD. A total of 82 of 120 analyzed results to identify radiation from the TLDs failed, due to the 95% confidence level. The unqualified glow curves from the TLDs were mostly around the free and controlled areas within the NM, indicating that only a negligible amount of γ-rays were emitted from the radiopharmaceuticals (^{18}F, ^{67}Ga, ^{99m}Tc, ^{131}I, and ^{201}Tl) within patients and from the scanners in the NM.

3.4. Environmental radiation for personnel

The “hot” points in the radiology personnel control rooms were near the PET/CT control room (A). The extra environmental radiation rates a year for a radiologist who was stationed in the control room (B) of the PET/CT facility was:

$$0.15\ \text{mSvper month} \times 12\ \text{mo/yr} = 1.8\ \text{mSv} \tag{8}$$

This extra radiation dose rate is far lower than that of the annual limit of 50 mSv per year recommended by the ICRP 60 [10]. The results show that the RC/Pb shielding can adequately protect hospital personnel. Hence, the penetrating photons cause no health concerns for medical personnel in the CSMUH during the operation of these scanners. However, due to the ALARA principle, the actual extra radiation in the vicinity outside the NM is worth measuring in future work.

4. Conclusion

In July 2018, the CSMUH built new SPECT and DXA facilities, and the new ITC began operation in May 2019. Therefore, it was necessary to calculate the extra radiation. Evaluation of exposure rates indicates that the environmental radiation rates among the NM range from 0.12 ± 0.02 to 1.00 ± 0.15 mSv per month during a three month survey, which is in agreement with the annual maximum dose reported elsewhere. However, the wall, consisting of RC and Pb, between the free and controlled area adequately protects the public during the operation of these scanners. TLD have been established as a valuable and useful dosimetry system for the assessment of environmental radiation. It can be concluded that at present, these scanners do not contribute to an increase of environmental radiation. These findings can be adopted by medical centers to identify radioactive hotspots and develop precautionary measures for radiation protection.

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Conflict of interest

None to report.

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