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Original Article

Effectiveness of radiation shielding and effective doses of radiological technologists during PET/CT scans at the National Cyclotron and PET Centre, Chulabhorn Hospital: A phantom study

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Abstract

From the Principle of Radiation Protection for workers, radiation shielding is a way to reduce radiation exposure. This study aimed to assess the efficacy of shielding device in reducing effective doses experienced by radiological technologists working in a PET/CT examination room by measuring the equivalent dose with and without shielding device in phantoms using ^{18}F 518 MBq at the National Cyclotron and PET Centre, Chulabhorn Hospital, Thailand. The phantoms were placed at the radiological technologists' working position and nanoDot^{TM} OSL dosimeters were attached at eyes, thyroid, and chest positions for 30 minutes. The experimental results showed that the effective dose measured with and without the radiation shields were 0.249 ± 0.030 mSv and 0.250 ± 0.020 mSv, respectively. Furthermore, data analysis revealed no statistically significant difference ($p > 0.05$) between the two conditions. Hence, it was concluded that the use of radiation shields could not reduce the effective dose.

Keywords: OSL dosimeter, PET/CT, effective dose, lead shield, nanodot

1. Introduction

Nuclear medicine is a branch of radiology in which radioactive substances are used in the diagnosis and treatment of diseases. During diagnosis, radionuclides are administered into the patient's body. The unique property of radionuclides is gamma decay which passes through the body and hits the detector to create diagnostic images. Meanwhile, radionuclides that exhibit alpha and beta decays are used for treatment of diseases. Nowadays, Positron Emission Tomography/ Computed Tomography (PET/CT) is the most popular instrument used in nuclear medicine due to its ability to detect changes at the molecular level as well as organ's functions assessment for further qualitative and quantitative analysis. Therefore, it is an effective tool for rapid lesion detection at the precise location (Townsend, Carney, Yap, & Hall, 2004).

In comparison with other diagnostic instruments in nuclear medicine, examinations using PET/CT can expose patients and radiological technologists to higher radiation doses. Those diagnostic radioactive materials possess the physical property of positron decay, leading to positron annihilation of 2 photons, each with energy of 511 keV, higher than that of gamma decay in the conventional nuclear medicine (Basu *et al*., 2011; Lecchi, Malaspina, & Del Sole, 2016). Furthermore, the International Commission on

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Radiological Protection (ICRP) has stipulated that the effective radiation dose should not exceed 20 mSv per year for practitioners (Stewart *et al*., 2012). In Thailand, the Ministerial Regulation on Radiation Safety 2018 was issued to set standards and monitor the radiation exposure of practitioners according to the Principles of Radiation Protection (American Nuclear Society, 2021). In addition to the distance and duration of work, radiation shielding is another way for monitoring the radiation dose to practitioners, which should not exceed the legal limit, while reducing the chance of exposure to workers (Sisai & Krisanachinda, 2020).

A study by Fujibuchi *et al*., (2010) on the radiation dose received by nuclear medicine practitioners during their practice for ^{18}F-FDG PET examination by measuring the organ absorbed dose of a human phantom (RAN-110), ^{18}F-FDG 380 MBq, using a fluorescence glass dosimeter at 30 and 100 cm from source with lead shield (3 cmPb) and lead apron (0.25 mmPb), revealed that distance could greatly reduce the radiation exposure, while a 3 mmPb shielding device was able to better decrease radiation dose than a lead apron with thickness of only 0.25 mmPb.

Lee *et al*., (2014) investigated the radiation masking efficacy of lead aprons in nuclear medicine by comparing the radiation dose received by operators with and without lead aprons during ^{18}F 370 MBq examination using a Pocket W/R survey meter (Thermo Scientific RadEye G-10) to measure radiation dose at 1 m from the source inside the PET/CT room. It was found that operators with lead aprons were 27% less exposed to radiation than those without. Moreover, the diagnostic radiation measurement of ^{99m}Tc showed that operators with lead aprons were 77% less exposed to radiation than those without. Therefore, a lead apron could significantly reduce the radiation exposure received by operators.

He *et al*., (2017) explored the efficacy of a lead apron with thickness of 0.5 mmPb in masking gamma rays measured by the energy spectra using spectroscopic techniques (HPGe spectrometer model GLP-1695). The results showed that the lead apron could shield the radiation and halved the absorbed radiation for photons with energy below 140 keV. However, the lead apron could not shield the radiation for high-energy photons, such as ^{131}I (356 keV), ^{18}F (511 keV), and ^{137}Cs (662 keV).

In addition, Deb, Jamison, Mong, and U (2015) determined the efficacy of radiation shielding from ^{99m}Tc and ^{131}I by using lead aprons with various thicknesses of 0.25, 0.50, 0.75, 1.00, and 1.25 mmPb at 1, 1.5, and 2.0 m from source with survey meter (Cypher 5000). For ^{99m}Tc, the increasing of lead apron thickness and distance from source resulted in a reduction in radiation exposure by 50%. On the other hand, the increasing of lead apron thickness for ^{131}I and distance from source did not significantly reduce radiation exposure. Furthermore, the shielding efficacy of lead apron with various thicknesses for ^{18}F and ^{124}I at 1 m from source by using Personal Radiation Monitor (Bleeper III model 05-104) was also measured. For ^{18}F, the use of lead aprons with increasing thickness could reduce radiation exposure. Meanwhile, the lead apron with thickness of 0.25 mmPb for ^{124}I could also reduce radiation exposure. However, greater thicknesses increased radiation exposure for operators due to the scattering of Bremsstrahlung radiation. Further studies should be required on the practical application of each radioactive substance.

Currently, there is a higher quantity of radiation dose received by operators due to the increasing use of diagnostic PET/CT at National Cyclotron and PET Scan Centre, Chulabhorn Hospital, Thailand. Thus, this study purposed to assess the efficacy of radiation shielding devices, including lead glasses, thyroid shield, and lead apron, and the effective radiation dose for operators when standing at 30 cm distance from patients in the PET/CT examination room with and without the shielding devices. Also, the suitability and efficiency of radiation shielding devices for radiological technologists was evaluated.

2. Materials and Methods

2.1 Phantom experiment

The efficacy of shielding devices was examined by simulating the measurement of radiation received by operators in the PET/CT (Siemens, Biograph 16) examination room with or without the shielding devices using a Head phantom (Model RS-108T, Alderson Phantoms, USA) and a Lung/Chest phantom (Model RS-111T, Alderson Phantoms, USA) substituted for operators. The optically stimulated luminescence dosimeter (OSL) (Model nanoDot^{TM}) was attached inside and outside the shielding devices with different thickness, namely lead apron of 0.5 mmPb (Model B303M-M), thyroid shield of 0.5 mmPb (Model NST-M1), and lead glasses of 0.75 mmPb (Model Incredibles). Three pieces of OSL were attached at each position as shown in Figure 1.

A PET phantom was filled with ^{18}F 518 MBq as a source of radiation in place of the patient, with radiation measurement of 30 cm distance from the center of the bed for 30 min. as demonstrated in Figure 2. The experiment to measure radiation exposure for the same condition was conducted 3 times. Therefore, 9 values were obtained for each position.

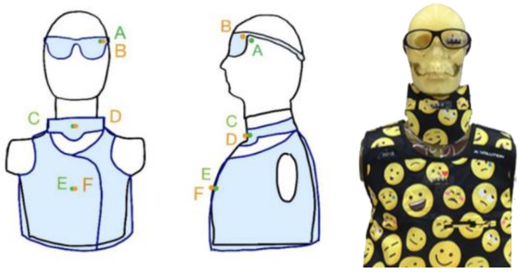

Figure 1. Installation of OSLD Model nanoDot^{TM} at position A, B, C, D, E, and F inside (green) and outside (orange) of the shielding devices on the Head phantom and Lung/chest phantom

Figure 2. Experimental setup

The measured radiation exposure was an equivalent dose in each position, namely the eye area, the eye lens (Hp(3)), thyroid (Hp(0.07)), and chest (Hp(0.07)). The OSLs in units of personal dose equivalent Hp(d) were further calibrated to obtain the effective dose Hp(10), defined as the operational quantity for individual monitoring of personal dose equivalent Hp(d). The depth d reference was 10 mm for strongly penetrating radiation (Protection, 1999).

2.2 Radiation dosimeter

The OSL calibration was performed by Thailand Institute of Nuclear Technology (TINT) using cylindrical and slab phantoms in terms of Hp(3) and Hp(0.07), respectively. The nanoDot™ dosimeters (Landauer Inc., USA), designed for measuring a small, single point radiation exposure normally worn on a wrist or a finger, were selected in this study. Each dosimeter, 10x10 mm^2 in size and 2 mm thickness, was composed of carbon doped aluminum oxide (Al_2O_3:C) crystal, whose thickness and diameter were 0.3 mm and 7 mm, respectively, sealed in a thin polyester sheet. Measurements were read out by a microStar mobile reader (Landauer Inc., USA). In the luminescence process similar to the optically stimulated luminescence (OSL) or InLight dosimeters, the irradiated dosimeters were stimulated by a visible green light from the light emitting diode (LED). The amount of luminescence was proportional to the absorbed radiation and remained significantly unchanged after the reading. This characteristics enabled nanoDot™ to be read out many times. The effective dose was evaluated by a correction factor between the conversion coefficient of Hp(10) and Hp(0.07) for ICRU-slab as in the following equations:

Figure 3. "nanoDot™" dosimeters and a mobile reader "microStar"

$$E=0.5H_W+0.025H_N \quad (1)$$

Where E is effective dose, H_W is personal dose equivalent at chest under the apron, and H_N is personal dose equivalent at neck outside the apron. (Sudchai, Their rattanakul, Jianklang, & Termsuk, 2015; International Organization for Standardization, 2019).

2.3 Statistical analysis

Data analysis and statistics for experimental results and hypothesis testing was Mann - Whitney U Test, Stata 121SE software. The parameters were presented as mean, standard deviation, probability, Null hypothesis (H_0), and One-tailed alternative hypothesis (H_1) as represented in equations (2) and (3) below:

$$H_0: \mu_1 = \mu_2 \quad (2)$$
$$H_1: \mu_1 < \mu_2 \quad (3)$$

Where μ_1 is the effective dose received by the Radiological Technologists with the shielding device and μ_2 is the effective dose received by the Radiological Technologists without the shielding device.

3. Results and Discussion

The efficacy of radiation shielding devices in reducing radiation exposure was demonstrated by Radiological Technologists working in the PET/CT examination room using nanoDot™ OSL to measure the radioactivity of 518 MBq ^{18}F at the eyes, neck, and chest positions with 9 dosimeters at each position for 30 minutes. The obtained results are shown in Table 1.

The statistical analysis of experimental results was performed with Mann - Whitney U Test, Stata 121SE program, to calculate the statistical difference at 95% confidence of the measured radiation dose with and without radiation shielding devices. The use of shielding devices did not significantly reduce the equivalent dose at different positions. After the equivalent dose for calculation of effective dose (Hp(10)), the results showed the effective doses with and without lead apron were 0.249 ± 0.030 mSv and 0.250 ± 0.020

Table 1. Equivalent dose detected with and without shielding devices.

nanoDot™ (no.)	Equivalent dose (mSv)					
	Eye lens (H_p(3))		Thyroid (H_p(0.07))		Chest (H_p(0.07))	
	w	w/o	w	w/o	w	w/o
1	0.109	0.094	0.159	0.140	0.212	0.191
2	0.087	0.090	0.121	0.111	0.253	0.247
3	0.078	0.109	0.140	0.095	0.232	0.210
4	0.104	0.107	0.133	0.104	0.243	0.227
5	0.101	0.094	0.172	0.152	0.193	0.227
6	0.076	0.072	0.123	0.142	0.271	0.260
7	0.089	0.100	0.133	0.121	0.266	0.242
8	0.107	0.114	0.142	0.095	0.209	0.175
9	0.080	0.100	0.102	0.114	0.211	0.204
mean ± S.D.	0.092 ± 0.013	0.098 ± 0.012	0.136 ± 0.021	0.119 ± 0.021	0.232 ± 0.028	0.220 ± 0.028
p-value	0.401		0.132		0.301	

mSv, respectively, with no statistically significant difference ($p = 0.825$).

3.1 Further Discussion / Comments

The experiment to investigate the efficacy of radiation shielding devices was performed by measuring radiation dose received by the phantom at 30 cm distance from the ^{18}F source. The use of shielding device with thickness of 0.5 mmPb did not significantly reduce the radiation dose from ^{18}F. This was consistent with the study of Fujibuchi *et al.,* (2010) and He *et al.,* (2017), which revealed that lead aprons with thicknesses of 0.25 and 0.5 mmPb were not effective to shield high-energy radiation and annihilation radiation (511 keV). Moreover, the study of Braga and Rodrigues (2019) reported that the use of lead aprons to shield ^{18}F-FDG increased radiation dose following the interaction with high energy photon.

Nonetheless, the findings in this experiment were inconsistent with the study by Lee *et al.,* (2014) which found that the use of lead aprons could shield radiation dose at about 27% and reduced the amount of radiation exposure to operators with ^{18}F in the PET/CT examination room. The study of Ahmed, Zimmer, McDonald, and Spies (2007) revealed that lead aprons with thickness of 0.5 mmPb were effective for absorbing low-energy gamma radiation from 99mTc (140keV) up to 82.7% and much higher than that of high-energy gamma radiation from ^{18}F (511 keV) of only 18.2% gamma radiation. The study of Deb *et al.,* (2015) showed that the use of lead aprons with thickness of 0.5 mmPb to shield radiation from ^{18}F could also reduce the amount of radiation exposure to operators. Nonetheless, the inconsistencies might have resulted from the variables in the experiment, such as device for radiation measurement, thickness of shielding materials, types and radiation strength of radioactive substances, duration of radiation measurement, position of shielding device, and distance between the radiation and the phantom. Hence, the thickness of radiation shielding devices should be appropriately considered for the PET/CT examination rooms. The greater thickness of radiation shielding devices was more effective at reducing radiation exposure, compatible to Fujibuchi *et al.,* (2010) and Deb *et al.,* (2015).

The inconsistent results may also be due to the energy response uncertainty measurement of OSLD Model nanoDot^{TM} (3.67%) in this study. The measurement error was approximate and consistent with a study by Nupetch, Awikunprasert, and Pungkun (2018), which examined the radiation dose response of InLight® optically stimulated. It was found that OSL radiation doses, when measured for gamma radiation from radioactive Cs-137 with an energy value close to ^{18}F, had a dose measurement error of less than 5%. Additionally, when considering other factors influencing the measurement uncertainty, such as energy response, angular dependence, linearity response, fading, batch homogeneity, and calibration from SSDL, the measurement error was 16.74% in this study. This was compatible to a study by He *et al.,* (2017), with gamma rays measured by the energy spectra using spectroscopic techniques (HPGe spectrometer model GLP-1695), which had the uncertainty of measurement of 15%.

The thickness of radiation shielding material, type, and intensity of radioactive substances also affected the amount of radiation measurement. From the radiation attenuation theory, the linear attenuation coefficient of gamma rays energy 511 keV for lead: μ=1.827 cm^{-1} (Dell, 1997) showed that a 0.5 mmPb lead coat can attenuate 511 keV of gamma radiation energy only 8.8%. In this study, the 0.5 mmPb lead coat was not able to attenuate the 511 keV gamma radiation exposure from PET assays due to no interactions of high energy photon with lead that may result in additional radiation exposure to workers from wearing lead aprons. Therefore, if there is a necessity or in case of emergency to assist or stay with a patient in PET/CT, the workers could wear lead aprons to reduce the amount of radiation exposure from the CT regardless of additional radiation dose from these reactions. According to a study by Omojola, Akpochafor, Adeneye, and Aniekop (2019), which examined the protective efficacy of lead aprons for X-ray radiation, it was found that the 0.25 mmPb lead aprons were able to reduce energy X-ray doses of 100 kVp up to 70%. Meanwhile, the lead thickness 0.5 mmPb could reduce the X-ray doses of 100 kVp up to 94%. Likewise, a study by Mori, Koshida, Ishigamori, and Matsubara (2014) and Kato *et al.,* (2021) yielded the efficiency of protective aprons, whether lead or Pb-Equivalent, in reducing the X-ray dose exposure of more than 90%.

Due to our phantom experiment, it was easy to control variables, such as constant dose ^{18}F-FDG activity, fixed measurement time, and distance for dose measurement of 30 cm with fixed dose rate of 0.35 µ/hr. In this study, there were higher effective radiation doses of 249 µSv with lead apron when compared to the safety threshold of radiation workers of not exceeding 80 µSv per day. In practice, radiological technologists rotate into different rooms. They do not perform routine positions and duties in rooms at all the time. Thus, their radiation exposure doses are within the specified safe range. Moreover, the estimate of radiation exposure doses by radiological technologists depends on a number of variables, such as amount of administered radiation to each patient, which is based on body weight. Therefore, our results could not report the actual amount of radiation dose exposure, which should require further study.

However, the use of radiation shielding to reduce radiation exposure to workers in the PET/CT room is only one alternative. In actual practice, workers can reduce the length of time and increase the distance in contact with patients towards the least amount of radiation exposure.

4. Conclusions

The shielding devices with thickness of 0.5 mmPb could not reduce the effective dose in operators while standing at the distance of 30 cm. away from patients, with statistically significance at 95% confidence level. Therefore, reducing time and increasing the distance of contact with patients should be recommended.

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References

Ahmed, S., Zimmer, A., McDonald, N., & Spies, S. (2007). The effectiveness of lead aprons in reducing radiation exposures from specific radionuclides. *Journal of Nuclear Medicine, 48*(supplement 2), 470P. Retrieved from https://jnm.snm journals.org/ content/48/supplement_2/470P.4

American Nuclear Society. (2021, July 18). Protecting against exposure. Retrieved from http://nuclearconnect.org/ know-nuclear/science/protecting

Basu, S., Kwee, T. C., Surti, S., Akin, E. A., Yoo, D., & Alavi, A. (2011). Fundamentals of PET and PET/CT imaging. *Annals of the New York Academy of Sciences, 1228*(1), 1-18. doi:10.1111/j.1749-6632. 2011.06077.x

Braga, N. R., & Rodrigues, A. S. (2019). Study of absorbed radiation dose in an occupationally exposed individual in PET-CT services. *Revista Brasileira de Fisica Medica* (*Online*), *13*(2), 35-42. Retrieved from http://www.rbfm.org.br/rbfm/article/view/455/ v13n2p35-42

Deb, P., Jamison, R., Mong, L., & U, P. (2015). An evaluation of the shielding effectiveness of lead aprons used in clinics for protection against ionising radiation from novel radioisotopes. *Radiation Protection Dosimetry, 165*(1-4), 443-447. doi:10.1093/rpd/ ncv065

Dell, M. A. (1997). Radiation safety review for 511-keV emitters in nuclear medicine. *Journal of Nuclear Medicine Technology*, *25*(1), 12-17. Retrieved from https://tech.snmjournals.org/content/jnmt/25/1/12.fu ll.pdf

Fujibuchi, T., Iimori, T., Isobe, T., Masuda, Y., Uchida, Y., Matsubayashi, F., & Sakae, T. (2010). Measurement of absorbed doses in organs of medical staff at 18F-FDG pet examination. *Radiological Physics and Technology*, *3*(1), 34-39. doi:10.1007/s12194-009-0073-2

He, X., Zhao, R., Rong, L., Yao, K., Chen, S., & Wei, B. (2017). Answers to if the lead aprons are really helpful in nuclear medicine from the perspective of spectroscopy. *Radiation Protection Dosimetry*, *174*(4), 558-564. doi:10.1093/rpd/ncw255

International Organization for Standardization. (2019). Radiological protection-X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy-Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence. ISO. Retrieved from https://www.iso. org/standard/66874.html

Kato, M., Chida, K., Munehisa, M., Sato, T., Inaba, Y., Suzuki, M., & Zuguchi, M. (2021). Non-lead protective aprons for the protection of interventional radiology physicians from radiation exposure in clinical settings: An initial study. *Diagnostics*, *11* (9), 1613. doi:10.3390/diagnostics11091613

Lecchi, M., Malaspina, S., & Del Sole, A. (2016). Effective and equivalent dose minimization for personnel in PET procedures: how far are we from the goal?. *European Journal of Nuclear Medicine and Molecular Imaging*, *43*(13), 2279-2282. doi:10. 1007/s00259-016-3513-3

Lee, S. W., Kim, S. H., Ji, B. G., Lee, D. W., Kim, J. S., Kim, G. M., ... & Lee, I. S. (2014). A Consideration of Apron's Shielding in Nuclear Medicine Working Environment. *The Korean Journal of Nuclear Medicine Technology*, *18*(1), 110-114. Retrieved from https://www.koreascience.or.kr/article/JAKO 201428638840645.page

Mori, H., Koshida, K., Ishigamori, O., & Matsubara, K. (2014). Evaluation of the effectiveness of X-ray protective aprons in experimental and practical fields. *Radiological Physics and Technology*, *7*(1), 158-166. doi:10.1007/s12194-013-0246-x

Nupetch, S., Awikunprasert, P., & Pungkun, V. (2018). Radiation dose response of InLight® optically stimulated luminescence (OSL) dosimeter. *The Thai Journal of Radiological Technology, 43*(1), 36-43. Retrieved from https://he02.tci-thaijo.org/index. php/tjrt/article/view/246331

Omojola, A. D., Akpochafor, M. O., Adeneye, S. O., & Aniekop, U. P. (2019). Radiographic assessment of protective aprons and dose simulation to personnel. *Journal of Radiation and Cancer Research*, *10*(2), 117. doi: 10.4103/jrcr.jrcr_14_19

Protection, O. R. (1999). *IAEA Safety Standards Series No*. *GSG-7*, IAEA, Vienna. Retrieved from https:// www-pub.iaea.org/MTCD/publications/PDF/PUB 1785_web.pdf

Sisai, S., & Krisanachinda, A. (2020, March). Measurement of the whole body, eye lens and extremity occupational doses in nuclear medicine staff at King Chulalongkorn Memorial Hospital. *Journal of Physics*: *Conference Series* (Volume 1505, No. 1, p. 012045). IOP Publishing. doi:10.1088/1742-6596/ 1505/1/012045

Stewart, F. A., Akleyev, A. V., Hauer-Jensen, M., Hendry, J. H., Kleiman, N. J., Macvittie, T. J., ... & Wallace, W. H. (2012). ICRP publication 118: ICRP statement on tissue reactions and early and late effects of radiation in normal tissues and organs–threshold doses for tissue reactions in a radiation protection context. *Annals of the ICRP*, *41*(1-2), 1-322. doi:10.1016/j.icrp.2012.02.001

Sudchai, W., Thierrattanakul, S., Jianklang, S., & Termsuk, C. (2015). Nanodot dosimeter for extremity monitoring service in Thailand. *Proceedings of the Fourth Asian and Oceanic Congress on Radiation Protection*. Retrieved from http://www.jhps.or.jp/ AOARP/Congress_files/AOCRP-4_Proceedings_15 0708.pdf

Townsend, D. W., Carney, J. P., Yap, J. T., & Hall, N. C. (2004). PET/CT today and tomorrow. *Journal of Nuclear Medicine, 45*(1 supplement), 4S-14S. Retrieved from https://jnm.snmjournals.org/content/ 45/1_suppl/4S