ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 28(4), 449-455 (2023) https://doi.org/10.4283/JMAG.2023.28.4.449

Proposal of Hybrid Shielding Method focused on General X-ray Facility Inspection

Young-Seok Ji[1,2], Jo-Ho Kim[1,3], and Man-Seok Han[1,4]*

[1]*Department of Health Medical Science, Graduate School, Kangwon National University, Samcheok 25949, Republic of Korea*
[2]*Department of Radiology, Seoul National University Bundang Hospital, Seongnam 13620, Republic of Korea*
[3]*Department of Radiology, Inje University Sanggye Paik Hospital, Seoul 01757, Republic of Korea*
[4]*Department of Radiological Science, Kangwon National University, Samcheok 25949, Republic of Korea*

(Received 18 October 2023, Received in final form 4 December 2023, Accepted 5 December 2023)

Shielding design of radiation areas requires comprehensive consideration of the environment. However, the current situation is that the thickness of shielding materials is conservatively designed to reduce risk factors, and thickness standards are basically calculated using a formula to estimate the shielding before design. This research proposes a hybrid method for optimal shielding thickness that combines simulation and actual data. Dose conversion factor (DCF) calculated in 1.5 mm lead situation, compared with MCNP and Actual dosimeters (PED, CD-Gam-1), and the lead shielding design of the five types from 0.25 mm lead to 1.25 mm lead was simulated with a 0.25 mm lead interval, and evaluation areas was divided into radiation workers (< 20 mSv/yr) and patients (< 1 mSv/yr) in detail. When applying PED-DCF and CD-Gam-1-DCF, the result was a lead thickness reduction of up to 1.25 mm lead. Therefore, we propose a radiation protection facility inspection method designed in hybrid.

Keywords : Radiation inspection, Shielding design, Monte Carlo simulation, General X-ray, Dosimeter, Radiation protection

1. Introduction

Radiation exposure for medical diagnosis is increasing globally, regardless of developed or developing countries [1, 2], and concerns about radiation exposure are also constantly being raised [3]. The subject of radiation exposure in medical institutions can be divided into patients and radiation-related professions (Radiologists, Radiological technicians, Medical doctors, Nurses, etc.). Since radiation-related professions are exposed to continuous radiation exposure due to work rather than one-time exposure like patients, studies to reduce radiation exposure of radiation workers have been actively reported in the past [4-8].

According to International Commission on Radiological Protection (ICRP) Publication 147 and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2012 Report, cancer caused by radiation at low doses like tens of mGy is interpreted as a Linear non-threshold (LNT) model [9, 10], National Council on Radiation Protection and Measurements (NCRP) Commentary No. 27 also states that they support the LNT model unless practical epidemiological study data are presented [11]. Therefore, radiation-related professions should comply with the As Low As Reasonably Achievable (ALARA) principle and continuously make efforts to minimize the incidence of cancer caused by radiation according to the LNT model.

The major departments of medical institutions that deal with radiation are radiology, radiation oncology, and nuclear medicine, and research on shielding devices and the function of X-ray equipment is being conducted to reduce radiation exposure to radiation workers [4, 6-8]. Above all, the first way to minimize radiation exposure is to design the shielding of the radiation-area to be safe and comply with legal standards. Each country or international organization presents and manages acceptable standards for radiation shielding [11-15], and standards are generally calculated using a formula to estimate the shielding thickness before design or measuring leakage

*Corresponding author: Tel: +82-33-540-3383
Fax: +82-33-540-3389, e-mail: angio7896@naver.com

dose using a dosimeter. Shielding design requires comprehensive consideration of the performance of the radiation-generating device, the size of the radiation-area, and shielding materials. However, the current situation is that the thickness of shielding materials (e.g., Concrete, Lead, etc.) is conservatively and excessively designed to reduce risk factors such as reconstruction. For radiotherapy area using high energy (Mega-electronvolt; MeV), Monte Carlo (MC) codes for optimal design are continuously being studied [16, 17], however research related to general X-ray area that uses relatively low energy (kilo-electronvolt; keV) is lacking.

Therefore, this study proposes a method for selecting the optimal shielding thickness that combines simulation data using MC codes and actual data using suitable dosimeters based on general X-ray area that uses diagnostic energy (keV).

2. Materials and Methods

2.1. General X-ray Equipment and Shielding Construction

The X-ray equipment (Discovery XR656; General Electric [GE] Healthcare, Chicago, USA) used in the study was manufactured in May 2012, introduced as clinical equipment in June 2012, and is still in use. The equipment has been inspected by the evaluation center every three years from the date of initial installation and was recently approved for performance inspection in 2018. The radiation shielding facility was designed with a 1.5 mm lead to comply with the radiation shielding acceptance standard, which is South Korea's legal standard for radiation defense facilities, and was first approved as a shielding facility in 2012.

2.2. Simulation Study Design

Monte Carlo N-Particle Transport Code (MCNP6 ver.1.0, Los Alamos National Security) was used as a MC codes program [16, 17]. For X-ray area simulation for geometry design, the first measurement was performed using hospital drawings, and the second detailed measurement was performed using the construction tapeline. Representative materials and densities studied were Patient-table (Carbon-amorphous [2.0 g/cm^3], Steel medium carbon [7.872 g/cm^3]), Lead-glass (6.22 g/cm^3), Lead-door (11.35 g/cm^3), Wall-bucky (11.35 g/cm^3), Phantom (Size: 30·30·20 cm, Polycarbonate [1.2 g/cm^3]), and Lead-wall (11.35 g/cm^3), and x, y, and z-axis code work

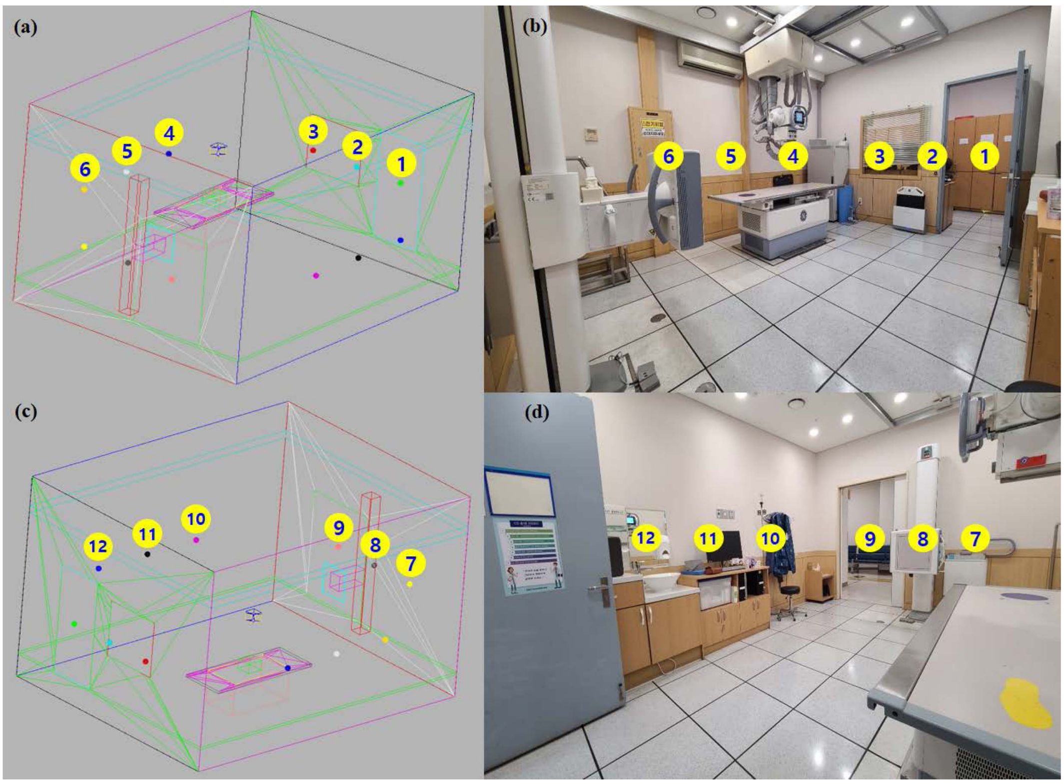

Fig. 1. (Color online) Actual X-ray room and floor plan using MCNP. (a) Measurement points on floor plan from 1-site to 6-site, (b) Actual measurement points from 1-site to 6-site, (c) Measurement points on floor plan from 7-site to 12-site, (d) Actual measurement points from 7-site to 12-site.

was performed referring to the construction tapeline and the manufacturer's manual for the size of each material. The X-ray spectrum used in the code was the Spectrum Processor (IPEM Report 78) [18], and it was implemented at 120 kVp, which was used when the first shielding facility was approved. In the case of the detector (r = 5 cm, 0.0012 g/cm^3), 12-site measurement points were set, 3 per lead wall, in a counterclockwise direction, with the external entrance door to the console area of the X-ray room set as 1-site (Fig. 1). History cutoff (NPS) minimized the error to 5E+8, and tally type was calculated in units of MeV/g using F6:pl. The final X-ray spectrum energy (mSv) was calculated by first multiplying the charge amount by 6.25E+17 and by 1.6E-7 ([J/eV]·[eV/MeV]·[g/kg]) for unit conversion to calculate 100 mAs (250 mA, 0.4 sec) (Fig. 2).

2.3. Actual measurement data analysis

For actual measurements, a personal electronic dosimeter (PED; Tracerco, Billingham, United Kingdom) and a leakage dosimeter (CD-Gam-1; PEHA med. Geräte GmbH, Hesse, Germany) were used for comparative analysis (Fig. 2). The PED dosimeter is generally attached to the chest area of radiation-related professions for measuring personal radiation dose, same as an optically stimulated luminescent dosimeter or thermo-luminescent dosimeter, and the CD-Gam-1 dosimeter is generally a device focused on measuring leakage dosimetry, such as shielding of radiation facilities. Calibration of both dosimeters was carried out in February 2023. Dosimeter was defined as the average value of 15 irradiations under 12-site measurement points and dose conditions (120 kVp, 100 mAs), identical to the simulation study design (Fig. 1).

2.4. Annual dose (AD) at 1.5 mm lead situation

AD was calculated with the actual results under the 1.5 mm lead conditions designed at the time of calculation was used and the imaging time per patient was 1/6 (hr/patients), the working value was 2 (people per group), and the number of patients per year at the hospital was 23,019 (patients/yr) [Eq. (1)].

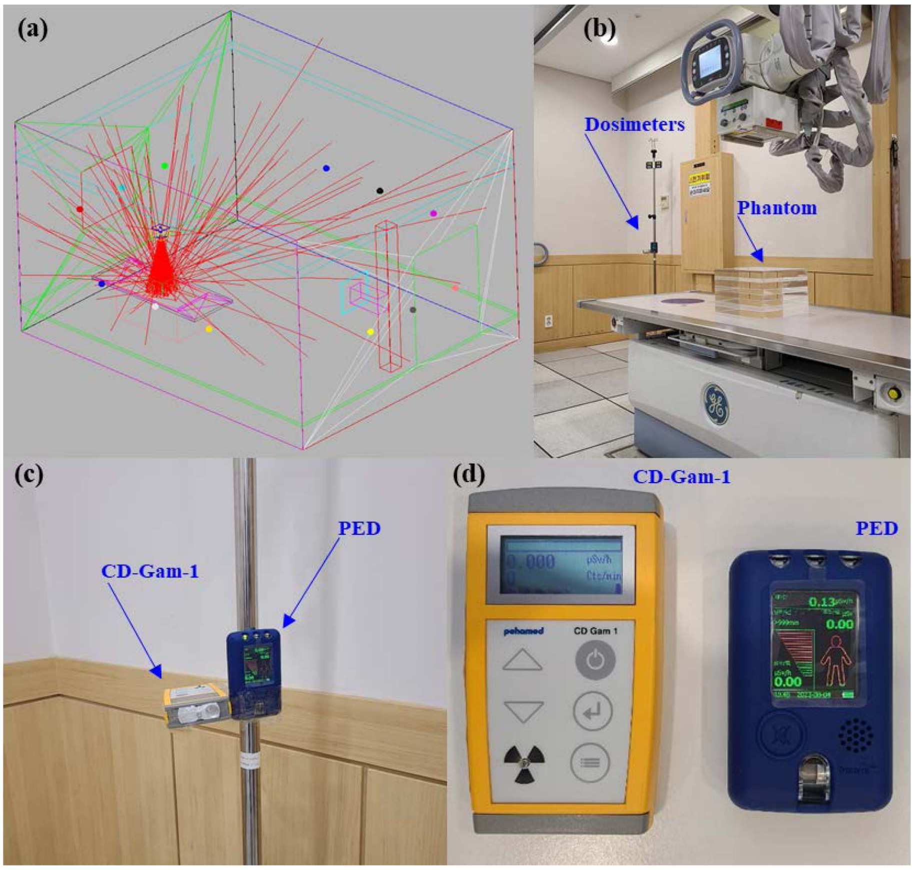

Fig. 2. (Color online) X-ray energy using MCNP and actual measurement dosimeters. (a) Visualized X-ray and scattered particles in floor plan, (b) Actual measurement devices and experiment situation, (c) Zoom in on dosimeters, (d) Leakage dosimeter (CD-Gam-1) and personal electronic dosimeter (PED).

Annual Dose = Actual results · 1/6 · 1/2 · Number of patients per year (1)

2.5. Dose Conversion Factor (DCF)

DCF was calculated using actual results and simulation results from 1-site to 12-site, based on the 1.5 mm lead thickness used in the actual design [Eq. (2)].

Dose Conversion Factor (DCF) = Actual results/ Simulation results (2)

2.6. AD based on Simulation and Actual Data

The design of the five types of shielding from 0.25 mm lead to 1.25 mm lead was simulated with a 0.25 mm lead interval, and the X-ray tube and measurement environment in each situation were the same. Occupational Annual Dose (OAD) and Public Annual Dose (PAD) were calculated using the simulation results, DCF, Working value, Number of patients per year, and Maximum exposure times per patient [Eq. (3), Eq. (4)]. OAD measured from 1-site to 3-site was based on 20 mSv/yr as the actual resident area of radiation workers, and PAD measured in the examination waiting area (from 7-site to 9-site) and patient locker room (from 4-site to 6-site, and from 10-site to 12-site) was evaluated based on 1 mSv/yr.

Occupational Annual Dose (mSv/yr) = Simulation results · Dose Conversion Factor (DCF) · Working value · Number of patients per year (3)

Public Annual Dose (mSv/yr) = Simulation results · Dose Conversion Factor (DCF) · Maximum exposure times per patients (4)

2.7. Statistical analysis

SPSS version 20 (IBM, Armonk, New York) was used for the actual measurement data of PED and CD-Gam-1 dosimeters. First, the normality test was applied, and the difference in the actual data in each zone from 1-site to 12-site was statistically significant when it was less than 0.05 using the Mann-Whitney test.

3. Results

3.1. AD based on Actual data at 1.5 mm lead situation

The AD of PED and CD-Gam-1 dosimeter was 0.623 (±0.02) mSv/yr and 6.147 (±0.04) mSv/yr, respectively at 1-site, 0.701 (±0.01) mSv/yr and 7.448 (±0.09) mSv/yr, respectively at 2-site, 0.778 (±0.01) mSv/yr and 11.325 (±0.04) mSv/yr, respectively at 3-site, 5.158 (±0.03) mSv/yr and 21.459 (±0.64) mSv/yr, respectively at 4-site, 2.619 (±0.07) mSv/yr and 13.054 (±0.26) mSv/yr, respectively at 5-site, 1.477(±0.11) mSv/yr and 5.819(±0.09) mSv/yr, respectively at 6-site, 0.693(±0.01) mSv/yr and 5.057(±0.06) mSv/yr, respectively at 7-site, 0.307(±0.01) mSv/yr and 2.509(±0.13) mSv/yr, respectively at 8-site, 0.615(±0.01) mSv/yr and 4.963(±0.08) mSv/yr, respectively at 9-site, 0.532(±0.01) mSv/yr and 4.628(±0.13) mSv/yr, respectively at 10-site, 0.6(±0.01) mSv/yr and 5.151(±0.03) mSv/yr, respectively at 11-site, 0.65(±0.01) mSv/yr and 5.301(±0.03) respectively at 12-site (Fig. 3), and the difference in AAD of PED and CD-Gam-1 from 1-site to 12-site was statistically significant (All P<0.001).

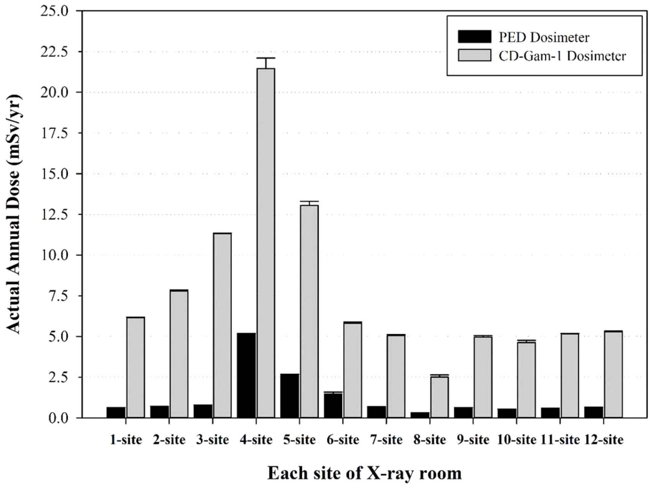

Fig. 3. Actual annual dose based on Actual data at 1.5 mm lead situation using leakage dosimeter (CD-Gam-1) and personal electronic dosimeter (PED).

3.2. DCF results based on PED and CD-Gam-1 dosimeter

PED-DCF from 1-site to 12-site was 1.69E-01, 2.02, 1.11E-01, 1.47, 4.62E-01, 1.89E-01, 2.69E-01, 1.62E-03, 1.53E-03, 6.6E-03, 2.82E-02, and 3.47E-01, respectively, and CD-Gam-1-DCF from 1-site to 12-site was calculated as 1.67, 2.24E+01, 1.62, 6.1, 2.31, 7.43E-01, 1.96, 1.33E-02, 1.24E-02, 5.74E-02, 2.42E-01, and 2.83, respectively (Table 1).

3.3. OAD from 0.25 mm lead to 1.25 mm lead situation

For 0.25 mm lead, AVG-OAD with PED-DCF and CD-Gam-1-DCF was 41.078 (±35.98) mSv/yr and 538.198 (±515.33) mSv/yr, respectively. For 0.5 mm lead, AVG-OAD with PED-DCF and CD-Gam-1-DCF was 9.897 (±8.79) mSv/yr and 130.687 (±130.03) mSv/yr, respectively. For 0.75 mm lead, AVG-OAD with PED-DCF and CD-Gam-1-DCF was 3.786 (±3.29) mSv/yr and 50.101

Table 1. DCF results at each site from 1-site to 12-site in 1.5 mm lead situations using PED and CD-Gam-1 dosimeters.

Measurement sites	Simulation and actual data			DCF value results	
	Simulation	PED	CD-Gam-1	PED-DCF	CD-Gam-1-DCF
1-site	3.2E-04	5.41E-05	5.34E-04	1.69E-01	1.67
2-site	3.02E-05	6.09E-05	6.76E-04	2.02	2.24E+01
3-site	6.09E-04	6.76E-05	9.84E-04	1.11E-01	1.62
4-site	3.06E-04	4.48E-04	1.86E-03	1.47	6.10
5-site	4.92E-04	2.28E-04	1.13E-03	4.62E-01	2.31
6-site	6.8E-04	1.28E-04	5.06E-04	1.89E-01	7.43E-01
7-site	2.24E-04	6.02E-05	4.39E-04	2.69E-01	1.96
8-site	1.64E-02	2.67E-05	2.18E-04	1.62E-03	1.33E-02
9-site	3.49E-02	5.34E-05	4.31E-04	1.53E-03	1.24E-02
10-site	7E-03	4.62E-05	4.02E-04	6.6E-03	5.74E-02
11-site	1.85E-03	5.21E-05	4.48E-04	2.82E-02	2.42E-01
12-site	1.63E-04	5.64E-05	4.61E-04	3.47E-01	2.83

DCF: Dose conversion factor.

Table 2. Simulation and actual annual dose using PED and CD-Gam-1 dosimeters from 0.25 mm lead to 1.5 mm lead situations.

Radiation Measured Points	0.25 mm lead		0.5 mm lead		0.75 mm lead		1.0 mm lead		1.25 mm lead	
	PED based	CD-Gam-1 based	PED based	CD-Gam-1 based	PED based	CD-Gam-1 based	PED based	CD-Gam-1 based	PED based	CD-Gam-1 based
	Annual dose (Units: mSv/yr)									
1-site	1.468	14.491	0.778	7.68	0.671	6.625	0.649	6.409	0.631	6.227
2-site	50.041	555.379	10.599	117.632	3.457	38.364	1.055	11.711	0.969	10.755
3-site	71.724	1044.723	18.313	266.748	7.23	105.314	3.129	45.577	1.434	20.882
4-site	0.549	2.283	0.147	0.61	0.051	0.212	0.021	0.087	0.011	0.045
5-site	0.285	1.421	0.068	0.338	0.024	0.121	0.011	0.056	0.005	0.024
6-site	0.102	0.401	0.029	0.113	0.011	0.042	0.005	0.019	0.003	0.01
7-site	0.01	0.076	0.001	0.009	0.001	0.005	0.001	0.005	0.001	0.005
8-site	0	0.003	0	0.002	0	0.002	0	0.002	0	0.002
9-site	0.001	0.009	0.001	0.006	0.001	0.005	0.001	0.004	0.001	0.004
10-site	0.052	0.456	0.014	0.118	0.005	0.043	0.002	0.017	0.001	0.008
11-site	0.088	0.758	0.022	0.187	0.007	0.057	0.002	0.021	0.001	0.009
12-site	0.174	1.423	0.031	0.250	0.009	0.070	0.002	0.018	0.001	0.007
AVG-OAD	41.078	538.198	9.897	130.687	3.786	50.101	1.611	21.232	1.011	12.621
(< 20 mSv/yr)	Fail	Fail	Pass	Fail	Pass	Fail	Pass	Fail	Pass	
AVG-PAD	0.14	0.759	0.035	0.181	0.012	0.062	0.005	0.025	0.002	0.013
(< 1 mSv/yr)	Pass		Pass		Pass		Pass		Pass	

OAD: Occupational annual dose, PAD: Public annual dose, DCF: Dose conversion factor, Annual dose is defined as '0 mSv/yr' when it is less than '0.0005 mSv/yr'.

(±50.38) mSv/yr, respectively. For 1.0 mm lead, AVG-OAD with PED-DCF and CD-Gam-1-DCF was 1.611 (±1.33) mSv/yr and 21.232 (±21.25) mSv/yr, respectively. For 1.25 mm lead, AVG-OAD with PED-DCF and CD-Gam-1-DCF was 1.011 (±0.4) mSv/yr and 12.621 (±7.5) mSv/yr, respectively (Table 2) (Fig. 4).

3.4. PAD from 0.25 mm lead to 1.25 mm lead situation

For 0.25 mm lead, AVG-PAD with PED-DCF and CD-Gam-1-DCF was 0.14 (±0.18) mSv/yr and 0.759 (±0.79) mSv/yr, respectively. For 0.5 mm lead, AVG-PAD with PED-DCF and CD-Gam-1-DCF was 0.035 (±0.05) mSv/yr and 0.181 (±0.2) mSv/yr, respectively. For 0.75 mm lead, AVG-PAD with PED-DCF and CD-Gam-1-DCF

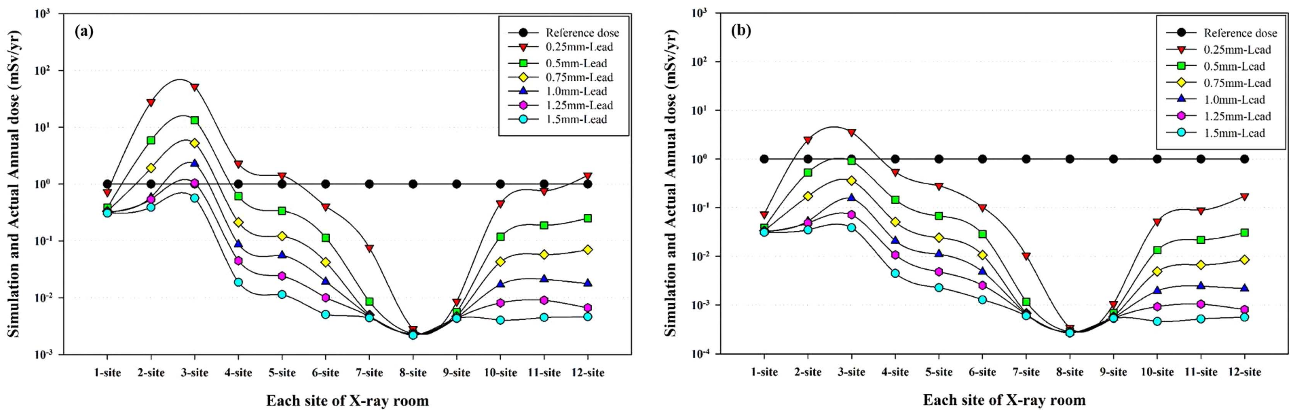

Fig. 4. (Color online) Simulation annual dose based on dose conversion factor (DCF) from 0.25 mm lead to 1.5 mm lead situation. (a) Evaluation of simulation annual dose (CD-Gam-1-DCF) based on reference dose (< 20 mSv/yr or < 1 mSv/yr), (b) Evaluation of simulation annual dose (PED-DCF) based on reference dose (< 20 mSv/yr or < 1 mSv/yr).

was 0.012 (±0.02) mSv/yr and 0.062 (±0.07) mSv/yr, respectively. For 1.0 mm lead, AVG-PAD with PED-DCF and CD-Gam-1-DCF was 0.005 (±0.01) mSv/yr and 0.025 (±0.03) mSv/yr, respectively. For 1.25 mm lead, AVG-PAD with PED-DCF and CD-Gam-1-DCF was 0.002 (±0.01) mSv/yr and 0.013 (±0.01) mSv/yr, respectively (Table 2) (Fig. 4).

4. Discussion

This study is the first study to calculate DCF using simulation results and actual results under the already designed 1.5 mm lead conditions and propose the optimal lead thickness, considering the dose limit by simulating design conditions from 0.25 mm lead to 1.25 mm lead, which are practically impossible to implement.

Managing radiation shielding facilities controls the radiation dose outside the imaging room and prevents radiation damage to radiation workers and the general public who reside or pass by the outside of the imaging room. In South Korea, leakage dose is measured using a radiation dosimeter, barometer, and thermometer, and OAD is considered suitable when it is below 2.58E-5 C/kg (100 mR/wk), and PAD is considered suitable when it is below 2.58E-6 C/kg (10mR/wk) [15]. In addition, conservative shielding is performed using a minimum of 1.5 mm lead according to Korean laws so that general radiation shielding facilities are designed based on 1.5 mm lead without considering factors such as radiation equipment type or area size. NCRP Report No. 147 is a representative guidebook on defense facilities that many countries adopt or modify to suit their local requirements. In addition to providing a calculation formula to calculate the thickness of each shielding material (e.g., lead, concrete, steel), considering distance to the occupied area, occupancy factors, workload distribution, use factor, and so on, it also provides a more detailed thickness calculation by dividing the primary and secondary barriers according to the X-ray irradiation direction, and it is perceived to be suitable if OAD is less than 5 mGy/yr and PAD is less than 1 mGy/yr [12]. However, NCRP Report No. 147 is also regarded to be far from suggesting the optimal shielding method because it relies on conservative calculation formulas. Therefore, in this study, we attempted to propose the optimal shielding thickness as a standard unit for radiation dose (mSv/yr) by fusing simulation data reflecting the diversity of radiation areas and actual data.

The PED and CD-Gam-1 dosimeter used for actual data are dosimetry devices actively used in actual clinical studies and research [4]. PED and CD-Gam-1 were calculated based on DCF as DCF represents the difference between simulation and actual data under 1.5 mm lead, which is the same defense facility shielding condition, so the most accurate ratio between simulation and actual data can be measured. In areas from 1-site to 5-site, where scattered radiation is greatly affected, PED-DCF averaged 0.735 times, and CD-Gam-1-DCF averaged 5.801 times. In areas from 7-site to 12-site, which are less affected by scattered radiation, PED-DCF averaged 0.109 times, and CD-Gam-1-DCF averaged 0.852 times. In other words, the dosimeter with a small difference from the simulation data in total sites was PED, which showed an average DCF of 0.422 times, but in accordance with the ALARA principle, the adoption of CD-Gam-1-DCF, which showed an average of 3.327 times should also be considered in conservative terms. The reason for the differences between dosimetry equipment is the target of the equipment. This is because PED is a target for a personal dosimeter, and CD-Gam-1 is for measuring leakage doses from radiation facilities.

Three measurement points were configured for each lead wall, and more detailed lead thickness can be used if the annual dose limits (20 mSv/yr, or 1 mSv/yr) standard for each point is applied. When applying 0.25 mm lead, OAD, and PAD at 1-site, 6-site, 7-site, 8-site, 9-site, 10-site, and 11-site satisfied the annual dose limits for both PED and CD-Gam-1. When applying 0.5 mm lead, AD based on PED satisfied annual dose limits at total sites, and AD based on CD-Gam-1 satisfied annual dose limits at all sites except 2-site and 3-site. Therefore, if a detailed design for each measurement point is possible, it would be efficient to apply 0.5 mm lead (2 measurement points), and 0.25 mm lead (10 measurement points) for AD based on PED and 1.5 mm lead (1 measurement point), 1.0 mm lead (1 measurement point), 0.5 mm lead (3 measurement point), and 0.25 mm lead (7 measurement points) for AD based on CD-Gam-1. If measurement points are classified in more detail using simulation data and actual data, a more natural curved thickness structure can be designed.

The limitations of this study are as follows: First, DCF is the result of the simulation analysis and the actual result value in the case of 1.5 mm lead. Since it is impractical to calculate DCF for lead thicknesses other than 1.5 mm lead, the most accurate DCF for comparing actual data and simulation data is 1.5 mm lead. Second, dosimeters can only be measured in mSv units. The dose standards of South Korea and NCRP Report No. 147 are presented in mR and mGy units, respectively [12, 15]. However, we decided that the mSv unit was more necessary for further use as the annual dose limit of an optically stimulated luminescent dosimeter or thermoluminescent dosimeter is in mSv units, and the annual dose limit in ICRP Publication 139 is also in mSv units [19]. In addition, the reliability of the data was improved by using two types of dosimetry equipment that focused on personal and leakage doses.

5. Conclusion

Based on annual dose limits (OAD < 20 mSv/yr, PAD < 1 mSv/yr), when applying PED-DCF centered on the personal dose, a design of 0.5 mm lead (-1.0 mm thickness) and 0.25 mm lead (-1.25 mm thickness) can be proposed in the OAD and PAD areas, respectively. when CD-Gam-1-DCF with leakage dose is applied, a design of 1.5 mm lead (No change) and 0.5 mm lead (-1.0 mm thickness) can be proposed in the OAD and PAD areas, respectively. Therefore, we propose an advanced inspection method that combines actual and simulation data.

References

[1] United Nations, Sources and Effects of Ionizing Radiation, UNSCEAR (2000).
[2] Ann. ICRP, Radiological Protection in Medicine, ICRP (2007).
[3] E. Karavas, World J. Methodol. **12**, 264 (2022).
[4] Y. S. Ji, J. Vasc. Interv. Radiol. **33**, 225 (2022).
[5] M. Rehani, Br J. Radiol. **94**, 126 (2021).
[6] M. Takenaka, Br J. Radiol. **94**, 1126 (2021).
[7] Y. J. Chang, Korean J. Pain. **27**, 162 (2014).
[8] N. Sakai, Eur. Radiol. **29**, 985 (2019).
[9] Ann. ICRP, Use of Dose Quantities in Radiological Protection, ICRP (2021).
[10] United Nations, Effects and Risks of Ionizing Radiation, UNSCEAR (2018).
[11] R. E. Shore, Implications of Recent Epidemiologic Studies for the Linear Nonthreshold Model and Radiation Protection, NCRP (2018).
[12] National Committee on Radiation Protection, Structural Shielding Design for Medical X-ray Imaging Facilities, NCRP (2004).
[13] Health Canada, Radiation protection in radiology-large facilities: safety procedures for the installation, use and control of x-ray equipment in large medical radiological facilities-Safety Code 35, Government of Canada (2008).
[14] C. J. Martin, Radiat Prot Dosimetry. **165**, 376 (2015).
[15] Korea Ministry of Food and Drug Safety, Radiation facility protection and inspection guidelines, MFDS (2012).
[16] J. L. Wang, NUCL SCI TECH. **31**, 1 (2020).
[17] A. Y. Chen, Appl Radiat Isot. **66**, 28 (2008).
[18] S. Evans, J. Radiol. Prot. **18**, 026 (1998).
[19] Ann. ICRP, Occupational Radiological Protection in Interventional Procedures, ICRP (2018).