PHILIPS

IQon Spectral CT

True Spectral Imaging

Now, with the IQon Spectral CT,
every scan can be spectral on demand
There's always a way to make life better.

innovation + you

PMP
Review Article
Progress in Medical Physics 33(4), December 2022
https://doi.org/10.14316/pmp.2022.33.4.53
eISSN 2508-4453

Review of Shielding Evaluation Methodology for Facilities Using kV Energy Radiation Generating Devices Based on the NCRP-49 Report

Na Hye Kwon[1,2], Hye Sung Park[3], Taehwan Kim[4,5], Sang Rok Kim[5], Kum Bae Kim[6,7], Jin Sung Kim[1,2,8], Sang Hyoun Choi[6,7], Dong Wook Kim[1,2]

[1]Department of Radiation Oncology, Yonsei Cancer Center, Heavy Ion Therapy Research Institute, Yonsei University College of Medicine, [2]Medical Physics and Biomedical Engineering Lab (MPBEL), Yonsei University College of Medicine, [3]Department of Physics, Yonsei University, [4]Department of Medical Physics, Korea University, [5]Radiation Safety Section, Korea Institute of Radiological and Medical Sciences, [6]Research Team of Radiological Physics & Engineering, Korea Institute of Radiological & Medical Sciences, [7]Department of Radiation Oncology, Korea Institute of Radiological & Medical Sciences, [8]Oncosoft Inc., Seoul, Korea

Received 13 December 2022
Revised 23 December 2022
Accepted 26 December 2022

Corresponding author
Dong Wook Kim
(joocheck@gmail.com)
Tel: 82-2-2228-8115
Fax: 82-2-2227-7823

Corresponding author
Sang Hyoun Choi
(shchoi@kirams.re.kr)
Tel: 82-2-970-1590
Fax: 82-2-970-2412

In this study, we have investigated the shielding evaluation methodology for facilities using kV energy generators. We have collected and analysis of safety evaluation criteria and methodology for overseas facilities using radiation generators. And we investigated the current status of shielding evaluation of domestic industrial radiation generators. According to the statistical data from the Radiation Safety Information System, as of 2022, a total of 7,679 organizations are using radiation generating devices. Among them, 6,299 facilities use these devices for industrial purposes, which accounts for a considerable portion of radiation. The organizations that use these devices evaluate whether the exposure dose for workers and frequent visitors is suitable as per the limit regulated by the Nuclear Safety Act. Moreover, during this process, the safety shields are evaluated at the facilities that use the radiation generating devices. However, the facilities that use radiating devices having energy less than or equal to 6 MV for industrial purposes are still mostly evaluated and analyzed according to the National Council on Radiation Protection and Measurements 49 (NCRP 49) report published in 1976. We have investigated the technical standards of safety management, including the maximum permissible dose and parameters assessment criteria for facilities using radiation generating devices, based on the NCRP 49 and the American National Standards Institute/Health Physics Society N.43.3 reports, which are the representative reports related to radiation shielding management cases overseas.

Keywords: Radiation shielding, Safety, Radiation generator, NCRP 49 report

Introduction

According to the statistical data from the Radiation Safety Information System (RASIS), there are 7,679 organizations using radiation generating devices, where 6,299 of them are South Korean organizations registered for general use and licensing to use these devices for industrial purposes [1]. If the maximum tube voltage is 170 kV or the surface radiation dose rate is higher than 10 μSv/hr, permission must be issued from the Nuclear Safety Commission. 307 domestic industrial organizations have been identified with the permission to use radiation generating devices.

Organizations that use such devices are obliged to be accountable for the safety of the employees or general public entering and leaving the facility and ensure they are not exposed to radiation more than the dose limit [2]. The legal standards for safety evaluation and management of the radiation facilities and workers differ depending on the purpose of application. The standards legally apply differently depending on the dose limit for people entering and exiting the facility, design outside the facility, and finally the management for different generators [3,4]. Such legal standards have a common objective of safe use of the radiation generating devices. According to the guidelines by the Nuclear Safety Commission for the preparation of radiation safety reports, the production, sales, use, and mobility of these devices require an application for permission from the regulatory authority and a radiation safety report [5].

The radiation safety report requires one to specifically describe 13 items under the Nuclear Safety Act, which includes an assessment of whether the exposure dose to workers and frequent visitors is as per the limit stipulated by the Nuclear Safety Act. In this process, the safety shields at the facilities using radiation generating devices must be evaluated. Representative reports that recommend methodologies for assessing safety shields at the facilities include the NCRP 49 report published in 1977 by the National Council on Radiation Protection & Measurements (NCRP) and the American National Standards Institute (ANSI)/Health Physics Society (HPS) 43.3 report published in 2008 [6,7]. The NCRP 49 report sets forth the medical X-ray and gamma-ray shielding methodologies for rays of 10 MeV or less, and the ANSI/HPS N.43.3 report proposes facility guidelines for X-ray generators up to 10 MeV or less for non-medical purposes and for equipment that uses gamma-ray as energy source.

Although nearly 50 years have passed since its publication, the NCRP 49 report continues to be the guideline for the domestic industrial organizations to perform shielding evaluation; thus, it is necessary to update the guideline to the latest recommended standards for reviewing and evaluating the safety shield. In this study, we have investigated the technical standards for safety management, such as the maximum permissible dose and parameter assessment criteria for facilities using radiation generating devices overseas based on NCRP 49 and ANSI/HPS N.43.3 reports that are the representatives for overseas shielding management. In addition, we have analyzed the methodology of calculating the shielding rate of the facilities and tried to identify the status of shielding evaluation through investigating filters.

Collection and Analysis of Safety Evaluation Criteria and Methodology Data for Overseas Facilities Using Radiation Generators

1. Analysis of the major factors in shielding evaluation based on the overseas shielding design evaluation report

Based on the NCRP 49 and ANSI/HPS N.43.3 reports, we have summarized and compared the key factors used for shielding evaluation for facilities using radiation generating devices. A total of six factors, the maximum permissible dose, workload, use and occupancy factors, half-value layer/tenth-value layer (HVL/TVL), and attenuation curve were investigated for the evaluation criteria of the radiating devices and technical standards for safety management.

1) Maximum permissible dose equivalent (MPD)

The maximum permissible dose is equivalent to the upper limit of the radiation exposure dose, which is the sum of the doses from external and internal exposures. It refers to the standard dose that must be satisfied when calculating and evaluating the shielding effect. Table 1 [6-8] compares the maximum permissible dose for each report for people entering the radiation control and public areas. For the workers entering and leaving the radiation control area, the NCRP 49 report separately sets out the annual and weekly permissible doses for the whole body (gonads, bone marrow, eyes) exposure; however, the ANSI/HPS N.43.3 report divides the body into four main parts and suggests the permissible doses, where the dose must not exceed 50 mSv per year for head and body.

The NCRP 49 report recommends annual permissible dose for four body parts, including 50 mSv for red bone marrow, lens, and whole body, 150 mSv for skin, 750 mSv

Table 1. Comparison of maximum allowable dose by report according to management area

Classification/report	NCRP 49 [6]		ANSI/HPS N.43.3 [7]	NCRP 151 [8]	
Radiation control area	50 mSv/y	1 mSv/wk	50 mSv/y Head, torso, arms, above the elbow or knee	5 mSv/y	0.1 mSv/wk
General area	5 mSv/y	0.1 mSv/wk	1 mSv/y	1 mSv/y	0.02 mSv/wk

ANSI, American National Standards Institute; HPS, Health Physics Society; NCRP, National Council on Radiation Protection & Measurements.

for hands, and 300 mSv for forearm. The ANSI/HPS N.43.3 report recommends an annual permissible dose of 150 mSv for the lens, 500 mSv for hand/elbow/foot/knee, and 500 mSv for skin/other areas. The two reports recommend the maximum allowable doses for different body parts, with the same annual permissible dose of 50 mSv, but the NCRP 49 report also suggests the weekly permissible dose. The permissible dose for people entering the public area is presented in Table 1 [6-8]. Different permissible doses are recommended in each report. Depending on the reports published later, the numbers in the report tend to be conservative.

2) Workload (W)

The NCRP 49 and the ANSI/HPS N.43.3 reports commonly define the amount of radiation measured at 1 m distance from the source in the case of the industrial radiation generating devices of less than 4 MV. For X-ray equipment operating at less than 4 MV, the workload is expressed as workload per week [mA•min/week]. Workload is defined as the product of weekly operation time (t), the time the equipment was run at the facility, and current (I), where the working time is calculated based on 8 hours per day, 5 days in a week, and 50 weeks in a year.

Since the workload applied in the shielding design is the value expected before the actual facility is in operation, it was recommended to take a conservative approach in the actual shielding design. To conservatively evaluate the radiation dose from the radiation generated by accelerators, it is recommended to take the maximum accelerator performance provided by the manufacturer as the evaluation criterion. Similar conservative approach is also recommended for adopting the maximum irradiation surface area, the maximum dose rate, and the maximum energy generated by the accelerator.

Table 2. Comparison of use factors by area in radiation use facilities

Classification/report	NCRP 49 [6]	ANSI/HPS N.43.3 [7]
Floor	1	1
Wall	1/4	1/4 to 1
Ceiling	Less than 1/4	1/4

ANSI, American National Standards Institute; HPS, Health Physics Society; NCRP, National Council on Radiation Protection & Measurements.

3) Use factor (U)

The use factor is defined as the degree to which the workload is dispersed. It refers to the ratio of time that the X-rays emitted during the operation of the radiation generating devices are directed towards the point of interest. When evaluating the industrial devices that do not have a fixed direction of irradiation, it is recommended to conservatively set it to 1 because radiation can be emitted in all directions. The recommended values for use factors for radiation generating devices used in the radiation oncology or radiology departments were compared for different regions, as shown in Table 2 [6,7]. Compared to the previous NCRP 49 report, the ANSI/HPS N.43.3 report showed a conservative shift regarding the wall and ceiling orientation.

4) Occupancy factor (T)

The occupancy factor is defined as the percentage of time one stays in the area of interest during irradiation. The recommended values from each report were compared, as shown in Table 3 [6,7]. Compared to the original NCRP 49 report, occupancy factors for partially and irregularly occupied spaces are proposed as the range in the ANSI/HPS N.43.3 report.

5) HVL/TVL

The HVL and the TVL refer to the thickness of the shield-

Table 3. Comparison of occupancy factors by area in the facilities using radiation

Classification/report	NCRP 49 [6]	ANSI/HPS N.43.3 [7]
Permanent occupancy		
Workspaces such as control room, children's access area, (always use) toilet	1	1
Partial occupancy		
Frequently used spaces such as restrooms, parking lots, and elevators	1/4	1/2~1/5
Irregular occupancy		
Rarely used spaces such as stairs and outdoors	1/16	1/8~1/40

ANSI, American National Standards Institute; HPS, Health Physics Society; NCRP, National Council on Radiation Protection & Measurements.

Table 4. The HVL/TVL data in NCRP 49 report

Peak voltage (kV)	Attenuation material					
	Lead (mm)		Concreate (cm)		Iron (cm)	
	HVL	TVL	HVL	TVL	HVL	TVL
50	0.06	0.17	0.43	1.5		
70	0.17	0.52	0.84	2.8		
100	0.27	0.88	1.6	5.3		
125	0.28	0.93	2.0	6.6		
150	0.30	0.99	2.24	7.4		
200	0.52	1.7	2.5	8.4		
250	0.88	2.9	2.8	9.4		
300	1.47	4.8	3.1	10.4		
400	2.5	8.3	3.3	10.9		
500	3.6	11.9	3.6	11.7		
1,000	7.9	26.0	4.4	14.7		
2,000	12.5	42.0	6.4	21.0		
3,000	14.5	48.5	7.4	24.5		
4,000	16.0	53.0	8.8	29.2	2.7	9.1
6,000	16.9	56.0	10.4	34.5	3.0	9.9
8,000	16.9	56.0	11.4	37.8	3.1	10.3
10,000	16.6	55.0	11.9	39.6	3.2	10.5
Cesium-137	6.5	21.6	4.8	15.7	1.6	5.3
Cobalt-60	12.0	40.0	6.2	20.6	2.1	6.9
Radium	16.6	55	6.9	23.4	2.2	7.4

HVL, half-value layer; NCRP, National Council on Radiation Protection & Measurements; TVL, tenth-value layer.
Reused from NCRP (Structural shielding design and evaluation for medical use of X-rays and gamma rays of energies up to 10 MeV; 1976. p. 49) [6] with original copyright holder's permission.

ing body when introduced into the path of a given beam of radiation, reducing the exposure rate by one-half and one-tenth, respectively. The values are suggested according to the tube voltage energy and the shielding material, as shown in Table 4 and 5. The HVL/TVL values by energy and material in Table 4 and 5 are the factors applied for the evaluation of the leakage radiation. The values for leakage radiation was recommended separately because the energy distribution of this radiation is relatively high compared to the primary and scattered radiation and it needs to be applied differently. In addition, the HVL/TVL values presented in the NCRP 49 and the ANSI/HPS N.43.3 reports are identical. Moreover, the ANSI/HPS N.43.3 report suggested the HVL/TVL values for iron in the 50–3,000 kV band.

6) Attenuation curve

The attenuation curve is a graph representing the transmission coefficient, which decreases with the tube voltage

Table 5. The HVL/TVL data in ANSI N.43.3 report

Peak voltage (kV)	Attenuation material					
	Lead (mm)		Concrete (cm)		Iron (cm)	
	HVL	TVL	HVL	TVL	HVL	TVL
50	0.06	0.17	0.43	1.5	0.017	0.07
70	0.17	0.52	0.84	2.8	0.03	0.1
100	0.27	0.88	1.6	5.3	0.08	0.3
125	0.28	0.93	2.0	6.6	0.1	0.4
150	0.30	0.99	2.24	7.4	0.13	0.5
200	0.52	1.7	2.5	8.4	0.3	0.9
250	0.88	2.9	2.8	9.4	0.35	1.1
300	1.47	4.8	3.1	10.4	0.40	1.3
400	2.5	8.3	3.3	10.9	0.6	1.8
500	3.6	11.9	3.6	11.7	0.8	3.0
1,000	7.9	26.0	4.4	14.7	1.5	5.5
2,000	12.5	42.0	6.4	21.0	2.0	7.0
3,000	14.5	48.5	7.4	24.5	2.2	8.0
4,000	16.0	53.0	8.8	29.2	2.72.7	9.1
6,000	16.9	56.0	10.4	34.5	3.03.0	9.9
8,000	16.9	56.0	11.4	37.8	3.1	10.3
10,000	16.6	55.0	11.9	39.6	3.2	10.5
Cesium-137	6.5	21.6	4.8	15.7	1.6	5.3
Cobalt-60	12.0	40.0	6.2	20.6	2.1	6.9
Iridium-192	6.0	20.0	4.3	14.7	1.3	4.3
Radium-226	16.6	55	6.9	23.4	2.2	7.4

ANSI, American National Standards Institute; HVL, half-value layer; TVL, tenth-value layer.
Reused from ANSI (ANSI/HPS N43.3. Installations using non-medical X-ray and sealed gamma-ray sources, energies up to 10 MeV; 2008.) [7] with original copyright holder's permission.

and thickness of the shielding material, as a log function. The conditions for the filter are considered for each energy band, and both the NCRP 49 and the ANSI/HPS N.43.3 reports provide the same attenuation curve. In the attenuation curves, the y-axis represents the transmission coefficient calculated by considering the permissible dose per week, distance from the source, tube current of the equipment, and operation time, and the x-axis represents the barrier thickness determined by the transmission coefficient and tube voltage.

2. Analysis of shielding evaluation and calculation methodology based on the overseas shielding design evaluation report

The shielding evaluation methodology covered in the NCRP 49 and ANSI/HPS N.43.3 reports applied the same shielding evaluation methodology, as shown in Fig. 1 below. The transmission coefficient is calculated according to Fig. 1 and equations (1)–(3) for the primary, scattered, and leakage radiations, and the thickness of the barrier is determined by using the value of transmission coefficient. In the case of the primary and scattered radiations, the barrier thickness is determined directly from the attenuation curves. However, for leakage radiation, both reports calculated the transmission coefficient, took its log value to calculate the numerical value, and calculated the barrier thickness by multiplying it with the HVL (or TVL) value according to the shielding material and tube voltage.

1) Primary radiation shielding evaluation methodology

When calculating the shielding barrier for the primary radiation, the following equation (1) is used, where W is the workload [mA・min/week], U is the use factor, T is the occupancy factor, P is the target dose [R/week], and d means the distance from the target [m]. The workload is a value

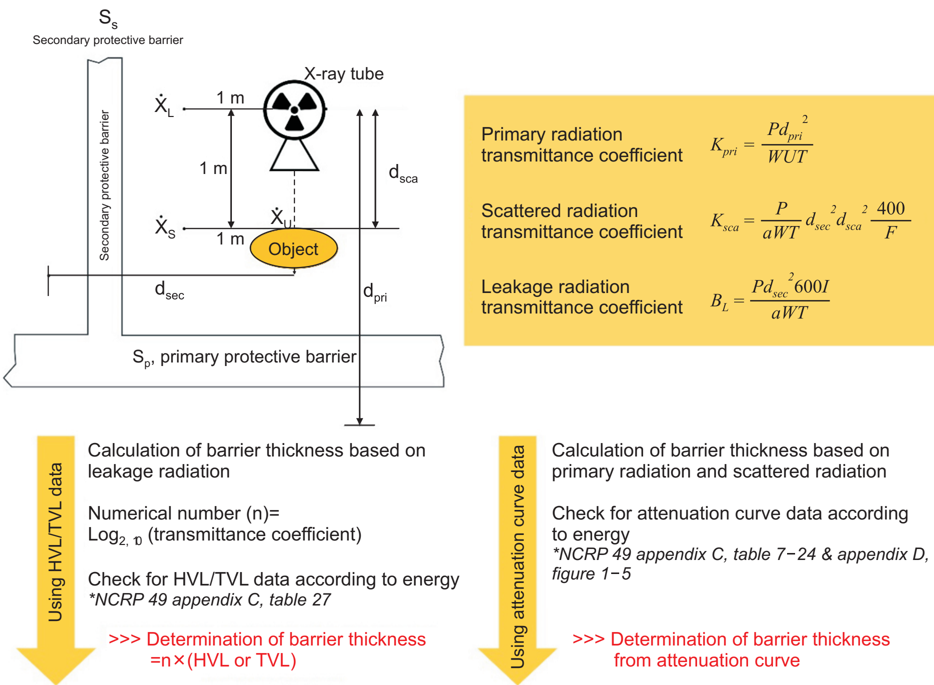

Fig. 1. Transmission coefficient calculation method according to shielding barrier and barrier thickness calculation. Reused from NCRP (Structural shielding design and evaluation for medical use of X-rays and gamma rays of energies up to 10 MeV; 1976. p. 49) [6] with original copyright holder's permission.

determined from the facility using the radiation generators and is applied by multiplying the tube current of the equipment by the operation time of the equipment. After deriving the transmission coefficient according to equation (1), the thickness of the shielding material is determined by selecting the attenuation curve for each energy value and shielding material.

$$K_{pri} = \frac{Pd^2}{WUT}\ [R/mA \cdot min] \tag{1}$$

However, the factors presented in the report for primary radiation shielding evaluation are the values from measurements obtained with specific equipment and conditions. The attenuation curves presented in the two reports are based on papers published during 1950s–1970s, and the thickness correlation of the shielding material with respect to the transmission coefficient was derived through measurements. The equipment used for the measurement uses a pulse beam. As shown in Table 6 below, when the shielding material is lead, the thickness of the filter is different with respect to energy. For industrial radiation generators installed and used in Korea, most of them use a constant current high-voltage application method, and the method of using filters varies depending on the equipment and company. Therefore, it must be considered that when using the attenuation curve presented in two reports, the results of the shielding evaluation may be different.

2) Scattered radiation shielding evaluation methodology

For the shielding evaluation for the scattered radiation, the transmission coefficient is determined by equation (2) below, and the thickness of the shielding material is determined by using the attenuation curve as in the primary radiation shielding evaluation method. Unlike the primary radiation, the transmission coefficient is calculated by further considering the effect of scattering, such as the scattering probability (a) and the irradiation plane (F) at each angle.

$$K_{sca} = \frac{400P(d_{sec})^2(d_{sca})^2}{aWTF}\ [R/ma \cdot min] \tag{2}$$

3) Leakage radiation shielding evaluation methodology

Shielding evaluation according to leakage radiation is based on the leakage dose rate at 1 m from the industrial radiation generators. The transmission coefficient for the leakage radiation (B_L) is calculated according to equation (3), where d_{sec} is the distance from the source to the second-

Table 6. Filters by energy corresponding to the attenuation curve graph (shielding material: lead) provided by the reports

Energy (kV)		NCRP 49 [6] ANSI 43.3 [7]	Kelly et al. [9] Miller et al. [10]	Domestically sold/installed Radiation generator filter distribution
Pulse Beam	50	0.5 mm Al	3 mm Be+0.5 mm Al	0.25 mm Be Or Glass
	70	1.5 mm Al	3 mm Be+1.5 mm Al	0.8 or 1.0 mm Be (75 kV)
	100/125/150	2.5 mm Al	3 mm Be+2.5 mm Al	150 um Be or 0.8 Be 1.0 mm Be+2.0 mm Al
	200/250/300	3.0 mm Al	5 mm Be mm+3 mm Al	Glass or Be
Constant current	300/400	3.0 mm Cu	1.5 mm Cu+1.5 mm Brass+3.0 mm water	3.0 mm Be 3.0 mm Be+3.0 mm Al+0.5 mm Cu 3.0 mm+2.0 mm Be

ANSI, American National Standards Institute; NCRP, National Council on Radiation Protection & Measurements.

Table 7. Comparison of data presented in the NCRP 49 report and the ANSI/HPS N.43.3 report

Classification/report		NCRP 49 report [6]	ANSI/HPS N.43.3 report [7]
Half-value layer/tenth-value layer: shielding material and energy range	Lead, concrete	50, 70, 100, 125, 150, 200, 250, 300, 400, 500, 1,000, 2,000, 3,000, 4,000, 6,000, 8,000, 10,000 [kV]	Added energy range for iron (50~10000 kV) Same as NCRP 49 report
	Iron	4,000, 6,000, 8,000, 10,000 [kV]	
Barrier thickness according to shielding conditions	Energy [kV or MV]	50, 100, 150, 200, 250, 300 [kV] 1, 2, 3, 4, 6, 8, 10 [MV]	Not available
	W·U·T	50 kV–3 MV band: 2.35–5000 [mA·min] 4 MV–10 MV band: 2,500–160,000 [R]	
	To the management area: distance conditions [m]	50 kV–3 MV band: 1.5–12.2 m 4 MV–10 MV band: 1.5–17.0 m	
	Shielding material	Lead, concrete	
Attenuation curve: energy range, shielding material and filter range	Energy	50, 70, 100, 125, 150, 200, 250, 300, 400, 500, 1,000, 2,000, 3,000, 4,000, 6,000, 8,000, 10,000 [kV]	Same as NCRP 49 report
	Shielding material	Lead, concrete	
	Filter	Aluminum 0.5 mm–3.0 mm Copper 3.0 mm	

ANSI, American National Standards Institute; HPS, Health Physics Society; NCRP, National Council on Radiation Protection & Measurements.

ary wall, P is the maximum permissible dose, $\dot{X}_L$ is the dose rate at 1 m, t is the annual operation time of the X-ray beam (min), and T is the occupancy factor. The log value of the transmission coefficient calculated based on equation (3) is multiplied by the HVL/TVL value with respect to the tube voltage to calculate the thickness of the shielding material for the leakage radiation.

$$B_L = \frac{P(d_{sec})^2}{[\dot{X}_L](t)(T)} \quad (3)$$

In the case of therapeutic radiation generators that use energy of 500 kV or less, the leakage dose rate standard is applied as 1 R/h at 1 m [6]. In the case of diagnostic radiation generators, the standard is applied as 0.1 R/h at 1 m [6], a 1/10 times more conservative value. For the industrial radiation generators, the evaluation criteria for medical radiation generators are followed. Since the upper limit standard for leakage dose rate is not separately announced, the shielding evaluation should be carried out considering that the shielding results may be underestimated.

Reflection on Shielding Evaluation of Domestic Industrial Radiation generators

In this study, the NCRP 49 report was compared with the ANSI/HPS N.43.3 report regarding the evaluation of shielding effect at the facilities using industrial radiation generators using kV-level energy. We compared the radiation facilities' shielding evaluation factors recommended in two

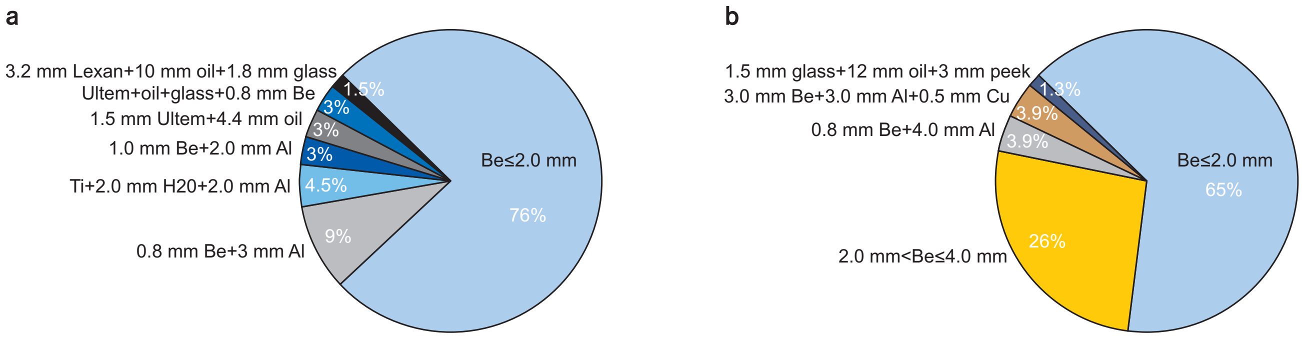

Fig. 2. The status of industrial radiation generator filters sold in Korea. (a) Generators using energy less than or equal to 160 kV. (b) Generators using energy greater than 160 kV and less than or equal to 320 kV.

reports and analyzed their methodology of shielding evaluation.

As shown in Table 7 below, the information presented in the NCRP 49 report and the ANSI/HPS N.43.3 report was compared, and the HVL/TVL information was identical in both reports except that data on lead was added in the ANSI/HPS N.43.3 report. The attenuation curve data were also confirmed to be identical in the NCRP 49 and the ANSI/HPS N.43.3 reports. In addition, the NCRP 49 report recommended an appropriate barrier thickness according to minimum shielding conditions, suggesting the barrier thickness with respect to the conditions, energy, movable factors, occupancy factors, use factors, distance, and shielding materials. As such, the NCRP 49 and the ANSI/HPS N.43.3 reports propose shielding evaluation/calculation methodologies with examples for easy application in practice, but these are based on the data measured under specific conditions. While the differences that arise from quoting historical data verbatim are considered, shielding assessments based on the NCRP 49 report are still in practice.

In addition, after investigating the current status of radiation generators installed and sold in Korea, it was confirmed that filters are used in various ways depending on the energy, as shown in Fig. 2 below. For all organizations using devices that use energy of 160 kV or less, 75.8% were using beryllium (Be) windows of 2 mm or less in size, and 9.1% were using a mixture of Be windows and aluminum (Al). For all organizations using energy greater than 160 kV and less than or equal to 320 kV, 64.9% were using 2 mm or less Be, and 26% were using 2 mm to 4 mm or less.

After comparing the filter information of the radiation generator used in the process of deriving the data in the NCRP 49 and ANSI/HPS N.43.3 reports, it was confirmed that the thickness and type were different from the status of distributed filters in Korea, as shown in Table 6. When the information on the filters with respect to the tube voltage was compiled, the two reports described filters with the same characteristics. The paper cited by the NCRP 49 report [9,10] specified the thickness of the Be window in addition to extra filters. If the attenuation curve data previously presented in the report is to be used in the existing shielding evaluation method as is, there is a risk of underestimation or overestimation in calculating the barrier thickness. This is because only the tube voltage of the equipment was considered in the report, and the characteristics between different equipment may be different.

In the case of the domestic facilities using industrial radiation generators, shielding evaluation and management are still conducted based on the NCRP 49 report, and the shielding calculations are conducted using the HVL/TVL data and the attenuation curve. Not only is the shielding evaluation not sufficiently considering the characteristics of the latest equipment, but also the differences in the methods applied by different organizations have been identified. Therefore, reverification of factors in the NCRP 49 report is required for safe management of shielding and preparation of a standardized system.

Conclusions

In this study, international reports related to the management of shielding at facilities using industrial radiation generating devices are compared, and the factors and methodologies related to shielding evaluation are examined. The factor values and data presented in the reports are somewhat different from the characteristics of the radiation generating devices currently used in Korea, and reverifying the shielding factors and preparing a systematic foundation seem essential for a practical evaluation of radiation shielding. Through the methodology analyzed and summarized in this study, we intend to lay a foundation for recommending safety management of the domestic industrial radiation generating devices in the future.

Acknowledgments

The Nuclear Safety Research Program supported this work through the Korea Foundation of Nuclear Safety (KoFONS) using financial resources granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2003013 and 2205013) and National Research Foundation of Korea (NRF) grant funded by the Korean government (No. 2020M2D9A3094170 and RS-2022-00144201).

Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

The data that support the findings of this study are available on request from the corresponding author.

Author Contributions

Conceptualization: Na Hye Kwon and Dong Wook Kim. Data curation: Na Hye Kwon and Taehwan Kim. Formal analysis: Na Hye Kwon and Hye Sung Park. Funding acquisition: Sanghyun Choi and Dong Wook Kim. Investigation: Na Hye Kwon and Kum Bae Kim. Methodology: Sang Rok Kim and Kum Bae Kim. Project administration: Sanghyun Choi and Dong Wook Kim. Resources: Taehwan Kim and Sang Rok Kim. Software: Na Hye Kwon and Hye Sung Park. Supervision: Sanghyun Choi and Dong Wook Kim. Validation: Jin Sung Kim and Dong Wook Kim. Visualization: Taehwan Kim and Sang Rok Kim. Writing – original draft: Na Hye Kwon and Hye Sung Park. Writing – review & editing: Sanghyun Choi and Dong Wook Kim.

References

1. Radiation Safety Management Integrated Information Network. Industry/regional licensing information on radioisotopes (RI). Daejeon: Radiation Safety Management Integrated Information Network, 2022 [cited 2022 Nov 29]. Available from: https://rasis.kins.re.kr/
2. Nuclear Safety and Security Commission. Nuclear Safety Commission Notice No. 2019-10. Standards for radiation protection, etc. Seoul: Nuclear Safety and Security Commission, 2019 [cited 2022 Nov 29]. Available from: https://www.law.go.kr/%ED%96%89%EC%A0%95%EA%B7%9C%EC%B9%99/%EB%B0%A9%EC%82%AC%EC%84%A0%EB%B0%A9%ED%98%B8%EB%93%B1%EC%97%90%EA%B4%80%ED%95%9C%EA%B8%B0%EC%A4%80/
3. Nuclear Safety and Security Commission. Presidential Decree No. 31824. Nuclear safety law enforcement decree. Seoul: Nuclear Safety and Security Commission, 2021 [cited 2022 Nov 29]. Available from: https://www.law.go.kr/%EB%B2%95%EB%A0%B9/%EC%9B%90%EC%9E%90%EB%A0%A5%EC%95%88%EC%A0%84%EB%B2%95%EC%8B%9C%ED%96%89%EB%A0%B9
4. Nuclear Safety and Security Commission. Nuclear Safety Commission Notice No. 2021-3. Standards for design approval and inspection of radiation equipment. Seoul: Nuclear Safety and Security Commission, 2021 [cited 2022 Nov 29]. Available from: https://www.law.go.kr/%ED%96%89%EC%A0%95%EA%B7%9C%EC%B9%99/%EB%B0%A9%EC%82%AC%EC%84%A0%EA%B8%B0%EA%B8%B0%EC%9D%98%EC%84%A4%EA%B3%84%EC%8A%B9%EC%9D%B8%EB%B0%8F%EA%B2%80%EC%82%AC%EC%97%90%EA%B4%80%ED%95%9C%EA%B8%B0%EC%A4%80/
5. Nuclear Safety and Security Commission. Nuclear Safety Commission Notice No. 2019-21. Guidelines for preparing radiation safety reports. Seoul: Nuclear Safety and Security Commission, 2019 [cited 2022 Nov 29]. Available from: https://www.law.go.kr/%ED%96%89%EC%A0%95%EA%

B7%9C%EC%B9%99/%EB%B0%A9%EC%82%AC%EC%84%A0%EC%95%88%EC%A0%84%EB%B3%B4%EA%B3%A0%EC%84%9C%EC%9E%91%EC%84%B1%EC%A7%80%EC%B9%A8/
6. National Council on Radiation Protection and Measurements (NCRP). Structural shielding design and evaluation for medical use of X rays and gamma rays of energies up to 10 MeV. Bethesda: NCRP. 1976; 49.
7. American National Standards Institute (ANSI). ANSI/HPS N43.3. Installations using non-medical X-ray and sealed gamma-ray sources, energies up to 10 MeV. ANSI; 2008.
8. National Council on Radiation Protection and Measurements (NCRP). Structural shielding design and evaluation for megavoltage x-and gamma-ray radiotherapy facilities. Bethesda: NCRP. 2006; 151.
9. Kelley JP, Trout ED. Braod-beam attenuation in lead for x rays from 50 to 300 kVp. Radiology. 1972;104:171-175.
10. Miller W, Kennedy RJ. X-ray attenuation in lead, aluminum, and concrete in the range 275 to 525 kilovolts. Radiology. 1955;65:920-925.