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Technical Note

Preliminary study for the development of radiation safety evaluation methodology for industrial kV-rated radiation generator facilities

Hye Sung Park [c], Na Hye Kwon [a, b], Sang Rok Kim [d], Hwidong Yoo [c], Jin Sung Kim [a, b], Sang Hyoun Choi [e], Dong Wook Kim [a, b, *]

[a] Department of Radiation Oncology, Yonsei Cancer Center, Heavy Ion Therapy Research Institute, Yonsei University College of Medicine, Seoul, Republic of Korea
[b] Medical Physics and Biomedical Engineering Lab (MPBEL), Yonsei University College of Medicine, Seoul, Republic of Korea
[c] Department of Physics, Yonsei University, Republic of Korea
[d] Radiation Safety & Section, KIRAMS, Republic of Korea
[e] Research Team of Radiological Physics and Engineering, KIRAMS, Republic of Korea

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ABSTRACT

Background: This study aims to develop an evaluator that can quickly and accurately evaluate the shielding of low-energy industrial radiation generators.
Methods: We used PyQt to develop a graphical user interface (GUI)-based program and employed the calculation methodology reported in the National Council on Radiation Protection and Measurements (NCRP)-49 for shielding calculations. We gathered the necessary factors for shielding evaluation using two libraries designed for Python, pandas and NumPy, and processed them into a database. We verified the effectiveness of the proposed program by comparing the results with those from safety reports of six domestic facilities.
Results: After verifying the effectiveness of the program using the NCRP-49 example, we obtained an average error rate of 1.73%. When comparing the facility safety report and results obtained using the program, we found that the error rate was between 1.09% and 6.51%. However, facilities that did not use a defined shielding methodology were underestimated by 31.82% compared with the program (the final barrier thickness satisfied the shielding standard).
Conclusion: The developed program provides a fast and accurate shielding evaluation that can assist personnel that work in radiation generator facilities and government officials in reviewing safety.

1. Introduction

Recently, National Council on Radiation Protection and Measurements (NCRP)-151 was introduced as a guideline for the shielding design of radiation therapy facilities in the department of radiation oncology, but NCRP-49, which was introduced in 1976, is still used as a guide for shielding facilities for low-energy X-rays of kilo-voltage energy [1,2]. In 2008, American National Standards Institute (ANSI/HPS)-43.3 was published to improve upon NCRP-49 for the same radiation-generator energy range [3]. However, for the shield-design calculation method, there was no change except for the improvement in the 50–3000 kV area of the half value layer/tenth value layer (HVL/TVL) iron (Fe) material of the leakage beam.

However, there have been representative changes in industrial radiation generators over the past 45 years, including changes in the tube-voltage application method and an increase in the diversity of filters [4]. Unlike the previous pulse-tube voltage application method, the tube-voltage application method applies a constant potential and high-frequency tube voltage to minimize the change in the applied voltage over time. Furthermore, various composite filters, such as titanium (Ti), polyetherimide (Ultem), polyether ether ketone (PEEK), glass, and oil are currently used, as opposed to beryllium (Be) (window), aluminum (Al), and copper (Cu), which were mainly used as filters in the past [5,6]. These findings suggest that the existing NCRP-49 reference shielding-evaluation method, which evaluates shielding based on data from 45 years ago, can affect radiation safety [2].

* Corresponding author. Department of Radiation Oncology, Yonsei Cancer Center, Heavy Ion Therapy Research Institute, Yonsei University College of Medicine, Seoul, South Korea.
E-mail address: kdw1026@yuhs.ac (D.W. Kim).

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According to statistical data from Korea Radiation Safety Information System, 7,728 facilities use these industrial radiation generators. Among them, 6,343 domestic industrial radiation-generator general-use reporting and permitting facilities were identified. In addition, if the maximum tube voltage is 170 kV or the surface radiation dose rate is higher than 10 μSv/h, permission must be obtained from the Korea Nuclear Safety and Security Commission, and 313 facilities were identified as permitting facilities [7].

In this study, we attempted to verify the safety of facilities that use industrial radiation generators and promote the convenience of radiation-shielding assessors. Accordingly, we analyzed the shielding evaluation methodology and investigated the X-ray tubes of the facilities using a recent industrial radiation generator to determine whether the NCRP-49 shielding evaluation guidelines are valid [2,8–10]. Additionally, we compared the safety report of six domestic facilities with NCRP-49 and analyzed the current status of shielding evaluation [2].

Human errors may occur if shielding evaluation is performed manually. Therefore, based on the above, research was conducted to develop a program that provides a more convenient and accurate shielding evaluation [11–14].

2. Material and methods

2.1. Development of the shielding evaluation program

The program was developed based on Python and the NCRP-49 shielding calculation methodology [2]. The user can select the type of barrier and radiation (primary, leakage, or scattering beam and secondary barrier) to be evaluated, and the factors used for the shielding calculation (workload, design exposure rate, use factor, etc.) are input to calculate the transmission factor and barrier thickness. A flowchart of the program is shown in Fig. 1. Using Python Qt5 5.15.7, the program was developed using a graphical user interface.

The shielding evaluation calculations were performed using values from a database. The attenuation curve data were converted into a table, and with the HVL/TVL tables, they were converted into two-dimensional arrays (transmission factor and barrier thickness) corresponding to energy and material. A shielding evaluation database was constructed by aligning the converted two-dimensional arrays (transmission factor and barrier thickness), tube voltage energy, and shielding material information.

The barrier thickness output was implemented by outputting the barrier thickness in the same array through searching the database for the nearest transmission factor that is higher than the calculated transmission factor. The search process is implemented as a binary search algorithm, which is advantageous for a sorted data search, and the NumPy 1.23.0 version library was used in this process.

2.2. NCRP-49 shielding methodology

To develop the program, the shielding evaluation methodology from the NCRP-49 report as well as the X-ray tube voltage and filter were investigated. In the case of the leakage beam, it was investigated based on the diagnostic radiation generator [2].

The thickness of the primary barrier was calculated by determining transmission factor K_p (Eq. (1)) for the primary beam, followed by substituting the obtained value into the logarithmic graph, which shows the ratio of attenuation according to the barrier. The conditions for the filter were considered for each energy on the graph (NCRP-49, Figs. 1–7) [2].

$$K_P = \frac{P(d_{pri})^2}{WUT} \left[\frac{Rm^2}{mA\cdot min}\right] \bullet\bullet\bullet \quad (1)$$

Here, P denotes the design exposure rate and the [R] unit, d_{pri} denotes the source-to-primary barrier distance and the [m], W denotes the workload rate and the [mA·min] unit, U denotes the use factor, and T denotes the occupancy factor.

The thickness of the secondary barrier was determined by calculating the barrier thicknesses of the leakage and scattered beams. The transmission factors of the leakage beam B_L and scattered beam K_S were calculated using Eqs. (2) and (3), respectively.

$$B_L = \frac{P(d_{sec})^2 600I}{WT} \left[\frac{Rm^2}{min}\right] \bullet\bullet\bullet \quad (2)$$

Here, d_{sec} denotes the distance from the source to the exposure point and the [m] unit, I denotes the tube current and the [mA] unit.

$$K_S = \frac{P}{aWT}(d_{sca})^2(d_{sec})^2\frac{400}{F} \left[\frac{Rm^2}{mA\cdot min}\right] \bullet\bullet\bullet \quad (3)$$

Here, d_{sca} denotes the distance from the exposure point to the secondary barrier and the [m] unit, a denotes the scatter ratio.

For the scattered beam, the same graph as that used for the primary beam was used to calculate the barrier thickness (NCRP-49 Figs. 1–7) from) [2]. However, in the case of the leakage beam, the energy distribution is high because the beam is attenuated by the housing; therefore, the barrier thickness was calculated using the HVL/TVL table (NCRP-49 Table 27) [2].

Finally, the thickness of the secondary barrier was calculated by determining the difference in the barrier thickness between the leakage and scatter beams, specifying the barrier thickness as the larger value, and if the difference value was smaller than the HVL/TVL, the barrier was evaluated by adding the HVL/TVL.

2.3. Facility safety report shielding methodology

To investigate the shielding status of facilities, safety reports for the years 2015–2022 from six domestic facilities using industrial radiation generators were utilized. Among them, two facilities evaluated whether the permitted dose was exceeded behind the barrier when using a specific X-ray based on the thickness of the shield wall that had already been erected. All facilities adhered to the standards for the shielding calculation methodology followed by NCRP-49, and it was confirmed that the method of applying voltage to the X-ray tube or the type of filter used was not considered.

3. Results

3.1. Development of the program

The program home screen is shown in Fig. 2. When moving to the calculation window, users can select the material and energy and input the necessary factors for the shielding calculation. If all values are correctly input, the shielding evaluation can be performed using the calculation button, and the previous shielding evaluation results can be verified using the logarithmic graph. The program is designed to show a warning message pop-up window if the input value is incorrect, and the program manual can be accessed at the top of the program to assist with calculations.

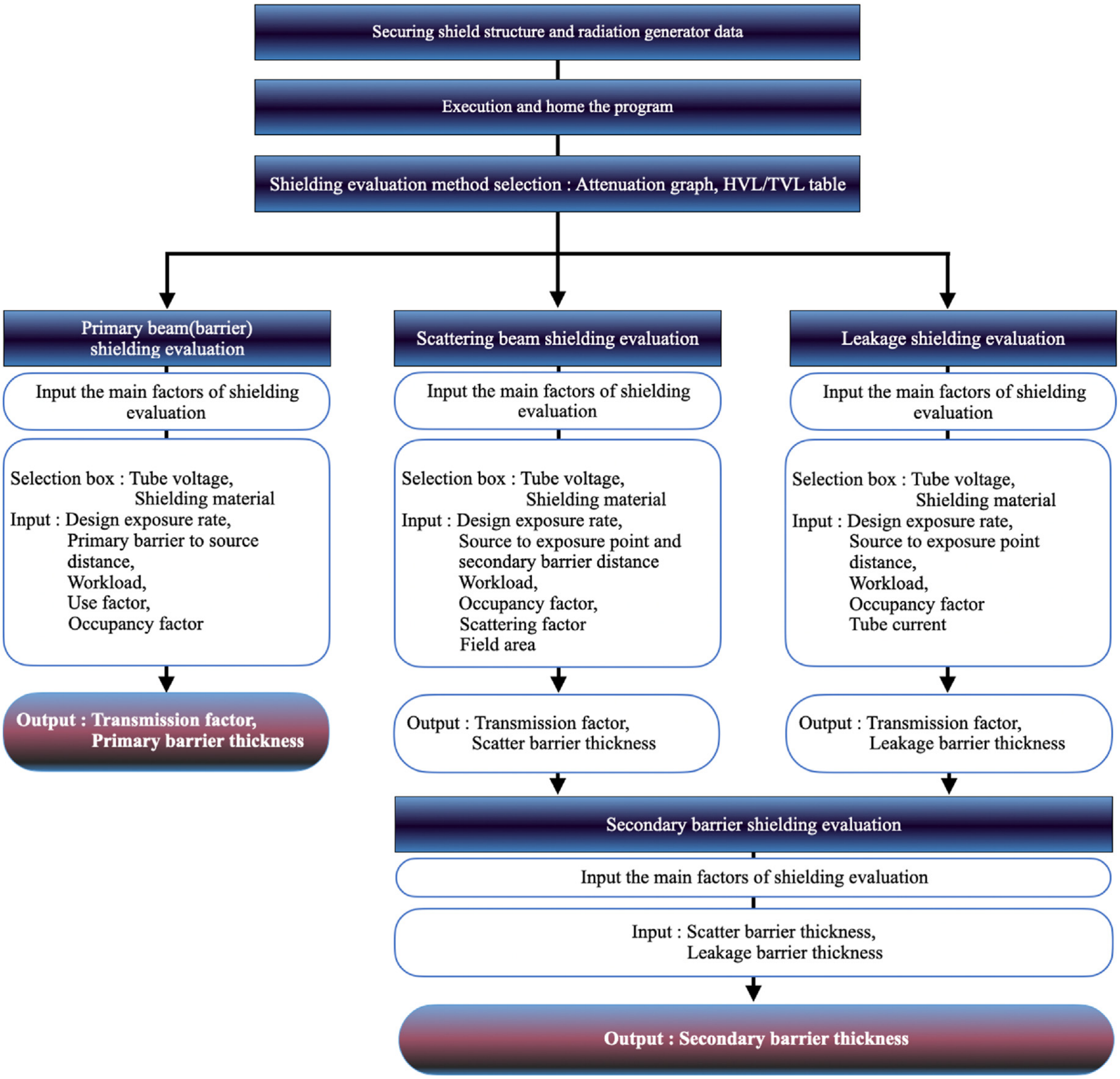

Fig. 1. Program flowchart.

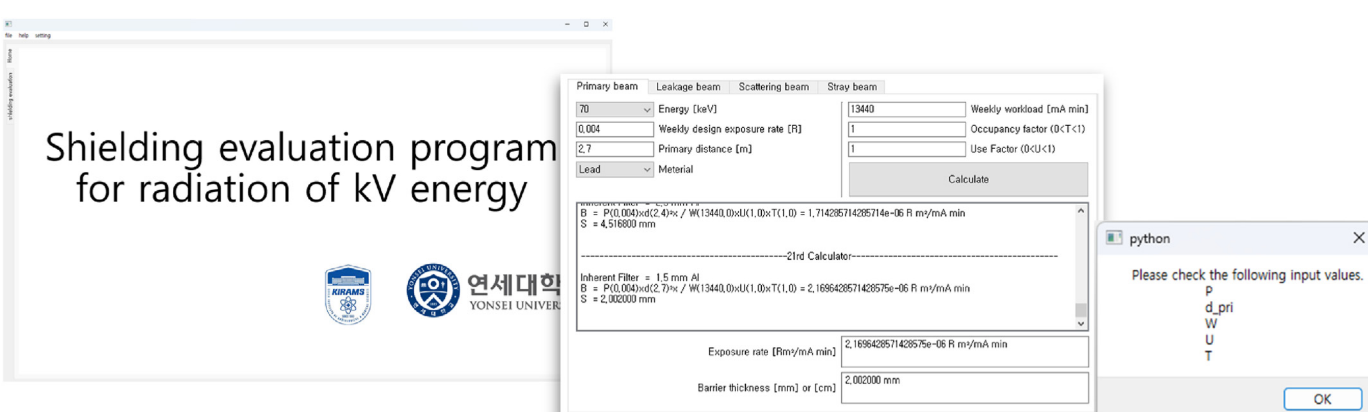

Fig. 2. Execuation screen of program.

Table 1
Comparative calculation results for programs and the NCRP-49 example.

Evaluation Methods		Primary beam		Leakage beam		Scattering beam	
		Program calculation (NCRP-49 Figs. 1–7 [2])	NCRP-49 example (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Table 27 [2])	NCRP-49 Example (NCRP-49 Table 27 [2])	Program calculation (NCRP-49 Figs. 1–7 [2])	NCRP-49 example (NCRP-49 Figs. 1–7 [2])
Barrier thickness	Pb	7.71 mm	7.90 mm	4.57 mm	4.57 mm	3.71 mm	3.80 mm
	Relative error	2.4%		0.00%		2.37%	
	Concrete	37.95 mm	37.00 mm	14.82 mm	14.40 mm	23.53 mm	23.50 mm
	Relative error	2.57%		2.92%		0.12%	

3.2. Program methodology verification

We verified the accuracy of the developed program using the example of an NCRP-49 shielding evaluation [2]. As shown in Table 1, the relative error rate was the highest in the concrete calculation of leakage at 2.92% and lowest in the Pb calculation of leakage at 0.00%. The average relative error rate was 1.73%, indicating that the program is similar to NCRP-49.

3.3. Facility safety report shielding methodology evaluation

The safety reports of six domestic facilities using industrial radiation generators were evaluated by comparing the shielding evaluation of the program with the safety reports of the facilities that followed the shielding evaluation methodology of the NCRP-49 report. As shown in Table 2, the average relative error rate was maximum −31.82% to +50.88%. Because facility A conducted leakage beam evaluation NCRP-49 Figs. 1–7 [2], the shielding evaluation compared to the program was underestimated by 31.82%. The E facility evaluated the X-ray tube of constant potential differently from the A facility. Since the leakage beam calculation was used the same as for A facility (NCRP-49 Figs. 1–7 [2]), it was overestimated by 50.88%. The final barrier thickness satisfied the shielding standards and did not violate the relevant regulations.

Some facilities used a shielding evaluation method based on the design exposure rate, and all barriers that were erected identically satisfied the shielding criteria. Accordingly in the case of facilities D and F, the calculation method was left blank. Because the shielding evaluation was conducted by calculating the expected dose rate based on the thickness of the shield wall erected on the right side of the blank and checking whether it exceeded the legal dose rate.

In addition, as shown in this study, it has been confirmed that facilities use constant-potential X-ray tubes instead of the pulsed-waveform X-ray tubes, as mentioned in the NCRP-49 report [2,4]. Moreover, various composite filters, such as Ti, Ultem, PEEK, glass, and oil, are currently used in industrial radiation generators as opposed to Be (window), Al, and Cu, which were used as filters as per the NCRP-49 report [2,5,6].

Additionally, because the upper limit of the leakage dose rate has not been announced for industrial radiation generators, the reference distance and measured leakage dose are different, as shown in Figs. 3 and 4, respectively. This implies that the shielding evaluation may have been underestimated.

4. Discussion

The results showed that facility safety shielding reports were underestimated by up to 31.82% and overestimated by up to 50.88%. However, it was found that the final barrier thickness satisfied the shielding standard because the shielding barrier of the facility was constructed conservatively. Because these errors were caused by facilities not complying with the shielding evaluation method, care must be taken during the evaluation. However, even after calculating the correct *trans*-mission factor, it was confirmed that there was a difference of up to 6% for each organ because the barrier thickness was obtained from the NCRP-49 Attenuation figure.

The program selects the energy and tube voltage and inputs the factors that print the transmission factor calculation and shielding thickness conversion; thus, the error is low. The program displays the errors; therefore, human errors rarely occur, even when arguments are incorrectly input. The program provides a safe and easy shielding evaluation method, which has an error rate of less than 3% with respect to NCRP-49; thus, it is a useful tool for shielding managers.

In the NCRP-49 report, data of less than 300 kV is provided for pulsed waveforms, but only data of 300 kV or more is presented for constant potential. As most industrial radiation generators use a high frequency and constant potential, if the rated voltage of the radiation generators is less than 300 kV, following the NCRP-49 methodology for shielding evaluation may underestimate the shielding evaluation.

Unlike the filters evaluated in NCRP-49, modern radiation generators are composed of various composite filters such as Ti, Ultem, PEEK, glass, and oil. Because the degree of radiation attenuation varies depending on the filter, the shielding evaluation may be overestimated or underestimated. Therefore, certain criteria should be added for modern filters.

Despite these limitations, the developed program is practical for radiation managers in the current situation of evaluating the shielding of industrial radiation generators based on NCRP-49 owing to its convenience and accuracy.

Accordingly, we are currently conducting a dose-rate experiment with a modern radiation generator and filter, and through this, we hope to advance the shielding regulation technology. In the future, we plan to update the program to reflect this and add an automatic safety report-creation function to build an automatic shielding safety evaluation/management system.

5. Conclusion

We developed a simple and accurate program to provide shielding evaluation results for low energy x-ray generator facilities. We are developing shield regulation technology and adding automatic safety report creation of program. After that, it is hoped that the results obtained through measurements from various options will be introduced into developed shielding design program so that users can manage them more safely.

Table 2
Comparative calculation results for programs and domestic facilities obtained through shielding evaluation method.

	Primary beam		Leakage beam		Scattering beam		Actual barrier installation thickness	
Facility A barrier calculation								
225 kV	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Table 27 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Primary barrier thickness	Secondary barrier thickness
Barrier thickness	10.04 mm [Pb]	9.81 mm [Pb]	11.44 mm [Pb]	7.88 mm [Pb]	9.25 mm [Pb]	9.00 mm [Pb]	12.00 mm [Pb]	10.00 mm [Pb]
Relative error rate	2.29%		31.82%		2.70%			
Facility B barrier calculation								
130 kV	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Table 27 [2])	Safety report (NCRP-49 Table 27 [2])	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Primary barrier thickness	Secondary barrier thickness
Barrier thickness	4.81 mm [Pb]	4.50 mm [Pb]	4.91 mm [Pb]	4.61 mm [Pb]	3.53 mm [Pb]	3.30 mm [Pb]	5.00 mm [Pb]	5.00 mm [Pb]
Relative error rate	6.44%		6.11%		6.51%			
Facility C barrier calculation								
100 kV	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Table 27 [2])	Safety report (NCRP-49 Table 27 [2])	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Primary barrier thickness	Secondary barrier thickness
Barrier thickness	2.68 mm [Pb]	2.65 mm [Pb]	2.58 mm [Pb]	2.64 mm [Pb]	0.83 mm [Pb]	0.85 mm [Pb]	2.65 mm [Pb]	2.89 mm [Pb]
Relative error rate	1.09%		2.32%		1.64%			
Facility D barrier calculation								
160 kV	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (Dose rate evaluation)	Program calculation (NCRP-49 Table 27 [2])	Safety report (Dose rate evaluation)	Program calculation (NCRP-49 Figs. 1–7 [2])	–	Primary barrier thickness	Secondary barrier thickness
Barrier thickness	4.72 mm [Pb]	–	4.73 mm [Pb]	–	–	–	5.00 mm [Pb]	5.00 mm [Pb]
Relative error rate	–		–		–			
Facility E barrier calculation								
320 kV	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Table 27 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (NCRP-49 Figs. 1–7 [2])	Primary barrier thickness	Secondary barrier thickness
Barrier thickness	27.99 mm [Pb]	32.52 mm [Pb]	11.93 mm [Pb]	18.00 mm [Pb]	21.40 mm [Pb]	24.50 mm [Pb]	35.00 mm [Pb]	30.00 mm [Pb]
Relative error rate	16.07%		50.88%		14.49%			
Facility F barrier calculation								
320 kV	Program calculation (NCRP-49 Figs. 1–7 [2])	Safety report (Dose rate evaluation)	Program calculation (NCRP-49 Table 27 [2])	Safety report (Dose rate evaluation)	Program calculation (NCRP-49 Figs. 1–7 [2])	–	Primary barrier thickness	Secondary barrier thickness
Barrier thickness	12.96 mm [Pb]	–	21.43 mm [Pb]	–	–	–	30.00 mm [Pb]	30.00 mm [Pb]
Relative error rate	–		–		–			

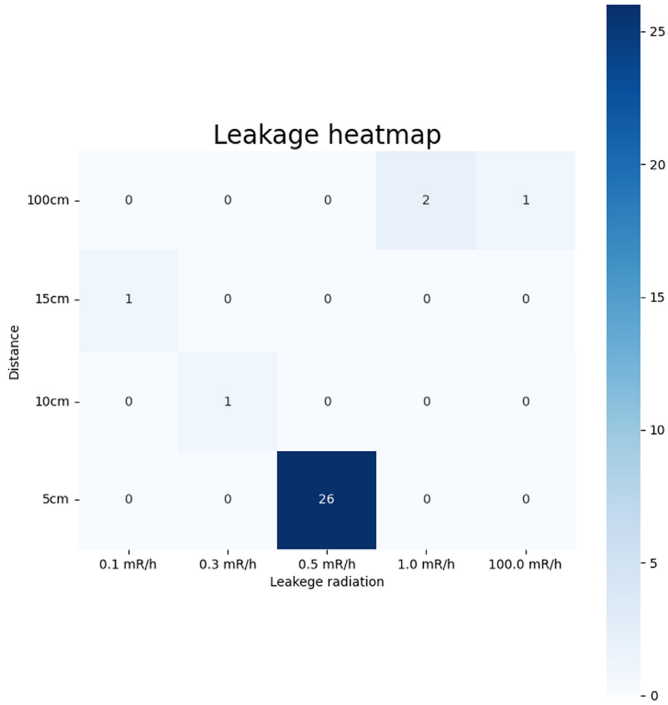

Fig. 3. Comparison of leakage dose rates by 31 domestic industrial radiation generators heatmap
heatmap is means leakage beam evaluation by distance being adopted by the facilities.

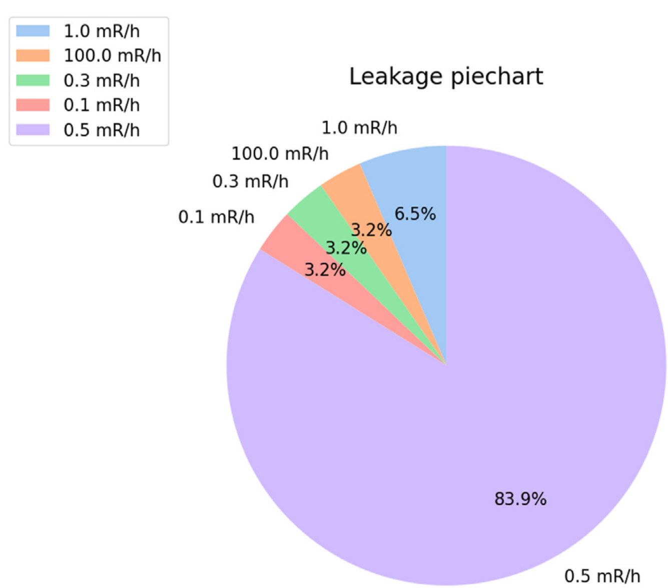

Fig. 4. Comparison of leakage dose rates by 31 domestic industrial radiation generators piechart

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] National Council on Radiation Protection and Measure- ments (NCRP), Structural shielding design and evaluation for megavoltage x-and gamma-ray radiotherapy facilities, NCRP 151 (2006).
[2] National Council on Radiation Protection and Measure- ments (NCRP), Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies up to 10 MeV, vol. 49, NCRP, Bethesda, 1976.
[3] 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.
[4] Na Hye Kwon, Hye Sung Park, Dong Wook Kim, Progress in Medical Physics 33 (4) (2022) 53–62.
[5] E.D. Trout, J.P. Kelly, AC Lucas, Radiology 72 (1) (1959 Jan) 62–67.
[6] W. Miller, R.J. Kennedy, Radiology 65 (6) (1955 Dec) 920–925.
[7] Radiation Safety Management Integrated Information Network, Industry/regional Licensing Information on Radioisotopes. Daejeon Radiation Safety Management Integrated Information Network, 2023. Available from: https://rasis.kins.re.kr/.
[8] Internatioanl Atomic Energy Agency (IAEA). Radiation protection in the design of radiotherapy facilities, IAEA safety report series No. 47, Vienna, 2006.
[9] J.E. Martin, Physics for Radiation Protection, Wiley, WeinHeim, 2013.
[10] Sang-Tae Kim, Simple calculation method as a supplementary radiation safety assessment for facility with radiation generator, International JOURNAL OF CONTENTS 14 (4) (2018) 65–69.
[11] C.R. Rhodes III, Development of an Automated Program for Calculating Radiation Shielding in a Radiotherapy Vault, Master's thesis, University of Toledo, OhioLINK Electronic Theses and Dissertations Center, 2012, http://rave.ohiolink.edu/etdc/view?acc_num=mco1331557547.
[12] Z.E. Hassan, N.M. Farag, W.M. Elshemey, A versatile program for the calculation of linear accelerator room shielding, J. Radiol. Prot. 38 (2018) 666–677.
[13] Dong Hyeok Choi, Dong Wook Kim, Jin Sung Kim, Radiat. Phys. Chem., ISSN: 0969-806X, Vol: 201, Page: 110410.
[14] Francis Newman, Masoud Asadi–Zeydabadi, Med. Phys. 35 (1) (2008, Jan) 171–180.