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Analysis of radiation safety management status of medical linear accelerator facilities in Korea

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ABSTRACT

The rapid rise in the application of novel treatment techniques, such as intensity-modulated radiotherapy (IMRT), motivated us to survey the status of Korea's radiation safety management and the shielding designs of facilities employing medical linear accelerators (LINACs). To this end, a questionnaire was used to collect information on LINAC facilities and treatments, workload, shielding design, shielding management, and path of obtaining shielding information. Out of 100 domestic institutions, 52 responded to the survey. Approximately 70% of the institutions utilized IMRT for more than 60% of their cases, and an IMRT factor of 5 was adopted by 75% of these institutions. Over 80% of the institutions accounted for the applied time-averaged dose rate per week and instantaneous dose equivalent rates in their shielding designs. Approximately 45% of the institutions obtained important shielding information via a radiation shielding design company and the NCRP-151 report. Overall, most facilities were shown to follow the standards recommended by the relevant international agencies. However, the requirement to establish standardized shielding design information and clarify ambiguous paths for information acquisition was also highlighted. Therefore, the study's results can be used as a foundation for establishing a safety control system and for creating adequate shielding designs.

1. Introduction

Intensity-modulated radiation therapy (IMRT) is a well-known radiation therapy technology whereby radiation intensity is modulated to increase treatment efficacy. IMRT commonly uses high-energy of 4–15 MV to deliver strong doses to the target. Several studies, such as those of Bucci et al. Freedman et al., and Sung et al. have analyzed the treatment effectiveness of this technique [1–3].

Radiation delivery to tumor tissues through IMRT is more conformal than that in three-dimensional conformal radiation therapy (3D-CRT). Thus, the former is more effective than the latter in protecting normal tissues [4]. Recent advances in radiation therapy technology have led to the development of high-precision radiation therapies, such as IMRT, stereotactic body radiation therapy (SBRT), and tomotherapy [5]. Since the inception of insurance payments in Korea in 2015, the applications of these techniques have increased 18-fold from 1921 in 2011 to 34,759 at present [6].

In IMRT, unlike in 3D-CRT, the beam is shaped via constant application of a multi-leaf collimator (MLC) that locally shields the beam. This requires a relatively long time and several monitor units (MUs) of beam irradiation to deliver the same dose to the patient [7,8]. Therefore, relatively conservative shielding conditions are desirable in IMRT because larger beam-on time is required in this case than that for 3D-CRT. Thus, the dose from the leakage radiation, instead of the prescribed dose, should be carefully considered because it is a measure of the actual quantity of MUs consumed [9,10]. The increasing usage of IMRT has made it critical for medical institutes to consider this trend for shielding designs for linear accelerator (LINAC) facilities.

Regulatory bodies in Korea's clinical field have recently been issuing warnings against exceeding the values of workload and also

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recommending workload re-evaluations [11]. A few concerns were raised against the evaluation of the safety of shielding wherein the instantaneous dose rate (IDR) was considered, without considering the use factor or occupancy factor and workload. Differences may arise between the regulatory and licensing authorities' interpretations of regulatory provisions if detailed, standardized safety regulation procedures are not established or clear standards for LINAC facilities are absent. In this regard, previous studies on radiation therapy and the corresponding innovations in shielding design are limited in Korea.

In light of the above limitation, this study presents a detailed review of the management and statuses of shielding facilities in radiation oncology departments in Korea. With the aim of developing a suitable safety management system for medical LINAC facilities in Korea, we conducted a survey directed toward domestic radiation oncology departments. We also analyzed the applications of LINAC and shielding management standards as part of the safety management and shielding design study through IMRT.

2. Materials and methods

2.1. Status of radiation safety management of medical LINAC facilities in Korea

The present study was conducted by using the web-based survey tool SurveyMonkey® (SurveyMonkey, Palo Alto, CA, USA). The survey was conducted on medical physicists working in radiation oncology departments in Korea.

As of December 2020, the population of Korea amounts to 51, 830, 000. Korea consists of one special city (Seoul), six metropolitan cities, eight provinces, one autonomous special province, and one autonomous special city. The average population of a province and metropolitan city are 3,540,000 and 2,130,000, respectively, while Seoul has 9,670,000 residents [12].

The purpose of the survey conducted in this study was to review the shielding management status of medical LINAC facilities to promote an ideal safety environment for radiation workers and patients.

The survey consisted of the following sections.

(1) Status of the facilities and treatments based on medical LINAC;
(2) Workload;
(3) Shielding design standards of medical LINAC facilities;
(4) Status of shielding management in the medical LINAC facilities;
(5) Path of obtaining information on the standards of radiation protection.

Details pertaining to the 17 questions presented in the survey are listed in Table 1.

The first set of questions based on the status of the facilities and treatment techniques using medical LINACs sought information on the facilities and was used to determine the IMRT rate trend. The second set of questions on the workload facilitated a comparison of the workload estimated for the shielding design of a facility with the actual workload. The questions on shielding design standards were meant to investigate the factors influencing the shielding design process, such as the IMRT factor and permissible radiation dose per week. The fourth group of questions on the status of shielding management were used to assess the methods employed for evaluating the radiation safety of LINAC facilities and the standards of shielding evaluation. The final set of questions on the paths for obtaining information facilitated analysis of the referenced sources of standards or information on shielding designs and evaluation methods.

2.2. Workload and IMRT factor

In most reports, including the National Council for Radiation Protection (NCRP) report 151 [9], workload is defined as the maximum expected radiation dose from the LINAC during operation. Workload (W) per week [Gy/week] in this study is the sum of the product of the average absorbed radiation dose per treatment [D_f], average number of patients [N] treated per day, and the number of facility operating days in a week and the periodical quality assurance (QA) and patient-specific QA, as shown in Equations (1)–(1).

$$W[Gy/week] = \left(D_f[Gy/treatment] \times N[treatments/day] \times 5[work\ days/week]\right) + W_{QA}. \quad 1\text{-}1$$

The neutron equivalent dose was accounted for in the primary barrier shield for photon beams above 10 MV with the increasing generation of photoneutrons. Equations (1) and (2) is used to estimate the neutron dose equivalent per week beyond the laminated barrier for when the collimator was opened to its maximum size. H_n is the neutron dose equivalent per week, D_o is the x-ray absorbed

Table 1
Survey contents: LINAC, linear accelerator; IMRT, intensity-modulated radiation therapy; IDR, instantaneous dose rate.

Survey classification	Survey contents
(1) Review of medical LINAC facilities and treatment	① Holding status for each medical LINAC manufacturer
	② The rate of IMRT treatments in the last six months
	③ Door structure in the medical LINAC facilities
(2) Maximum workload per week, 2019–2020	④ Workload: in safety report and calculated workload in six months
(3) Shielding design standards for medical LINAC	⑤ Types of radiation that accounted for the IMRT factor during workload estimation
	⑥ IMRT factor value used in the radiation safety report
	⑦ IMRT factor: consideration of the neutron capture gamma ray and neutron ray
	⑧ Permissible radiation dose per week (mSv/week) in the radiation control area
	⑨ Permissible radiation dose per week (mSv/week) in the public area
(4) The status of shielding management in medical LINAC facilities	⑩ Measurement period of radiation control area and public area
	⑪ Calibration period of the survey meter
	⑫ Measurement location of the spatial dose rate
	⑬ Distribution of measurement values of the IDR
	⑭ Applicability of the IDR
(5) Path of obtaining information on the standards of radiation protection	⑮ Path of obtaining recent information on the radiation safety control
	⑯ Path of obtaining information on the IMRT factor used in the radiation safety report
	⑰ Path of obtaining information about the permissible radiation dose per week

dose per week at the isocenter, R is the neutron production coefficient for the maximum field area F_{max} at the isocenter, t_m is the metal slab thickness, t_1 is the thickness of the first concrete, t_2 is thickness of the second concrete slab, TVL_x is the tenth-value layer in the concrete for the primary x-ray beam, TVL_n is the tenth-value layer in the concrete for neutrons, and *0.3* is the distance between the outer surface of the barrier and the point of occupancy.

$$H_n\left[\frac{\mu\text{Sv}}{\text{week}}\right]=\frac{D_0\times R\times F_{max}}{\left(\frac{t_m}{2}+t_2+0.3\right)}\times\left[10^{-\left(\frac{t_1}{TVL_x}\right)}\right]\left[10^{-\left(\frac{t_2}{TVL_n}\right)}\right]. \quad 1\text{-}2$$

IMRT involves the use of a multi-leaf collimator (MLC) or a mechanical shutter to control the beam intensity and ensure that the radiation dose is highly concentrated on the tumor. IMRT, or volumetric modulated arc therapy (VMAT), requires a significantly greater beam-on time and radiation MUs than those required in 3D-CRT. The prescribed radiation dose in IMRT is identical to that in 3D-CRT. However, the leakage radiation emitted from the accelerator head increases with increasing MUs; thus, the IMRT factor (IF) is used to calculate the rise in the leakage radiation due to the application of IMRT in the radiotherapy facility.

NCRP-151 [9] states that the IMRT factor is calculated according to Equation (2). The IMRT factor is the ratio of the MU per unit delivered through the IMRT technique to that delivered through the 3D-CRT technique. The recommended range thereof is 2–10.

$$\text{IMRT factor(IF)}=\frac{\text{MU}_{(\text{IMRT})}}{\text{MU}_{3\text{D}-\text{CRT}}};\ \text{MU}_{\text{IMRT}}=\sum_{i=1}^{n}\frac{\text{MU}_i}{\text{Prescribeddose}_i} \quad 2$$

p is the treatment ratio of the IMRT/VMAT not associated with 3D-CRT out of the total number of treatments in Equations (3)–(1). The workload in Equations (3)–(2), which accounts for the IMRT factor, involves the dose from leakage radiation W_L, which is equal to the product of W and f.

$$f=(1-p)+p\times IF \quad 3\text{-}1$$

$$W_L=f\times W. \quad 3\text{-}2$$

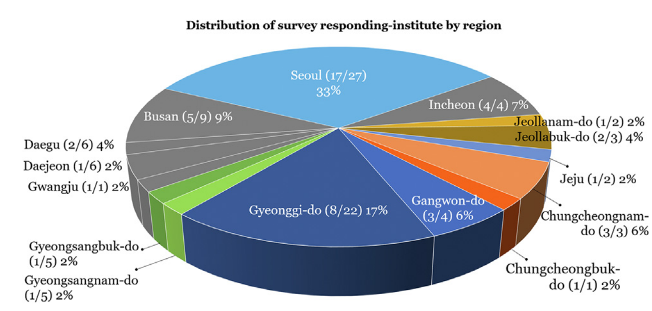

Fig. 1. Distribution of the survey-responding organizations by region.

3. Result

Of the 100 radiation oncology departments in the Republic of Korea, 52 institutes responded to our survey used. Fig. 1 displays the geographic distribution of the organizations that responded. The response ratio for each geographical region is denoted by (b/a), where (a) is the number of medical organizations located in the corresponding region, and (b) is the number of organizations in the region that responded. The numbers of responders are also denoted as the percentage of the total responders in the figure. Most regions, excluding Busan, Gyeongsangbuk-do, and Gyeongsangnam-do, showed a response ratio of 50–100%. Fig. 2 displays the statistics of the facilities and the treatment procedures using a medical LINAC.

3.1. Status of LINAC facilities and treatment procedures

A total of 101 medical LINACs were used across the 52 institutions at the time of this study, which is equivalent to an average of 1.68 per institution. Of the 52 responding institutions, 36 reported that their utilization ratio of IMRT treatment was greater than 60%. Most institutions had employed IMRT treatment more than 3D-CRT over the last six months. A total of 19 institutions used IMRT for 60–80% of the relevant cases, while 17 institutions employed it for 80–100% of their cases.

In terms of the structure of the medical LINAC facilities, 43 institutions conveyed that they used a maze door, and 58 used a direct door for space utilization and convenience.

3.2. Maximum workload per week (2019–2020)

Data on the maximum allowable workload per week, according to the safety report provided by each institute (report submitted to the government to obtain permission for production, sale, and use of radioactive isotopes/radiation generators) were compared with the actual workloads calculated by using the patient's treatment and QA history. The workload data on primary radiation and secondary leakage radiation were collected individually. A comparison

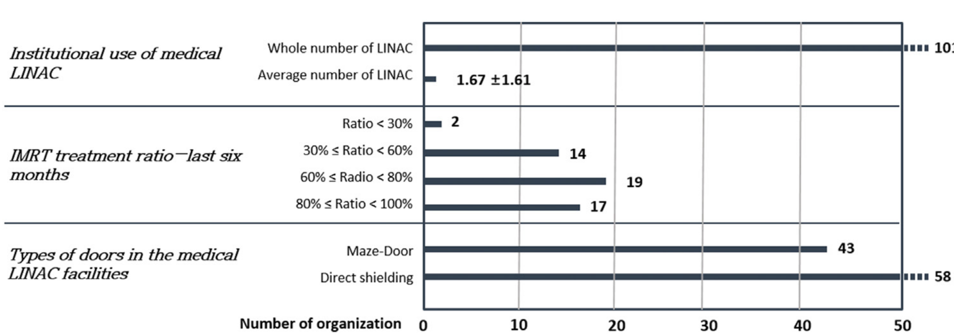

Fig. 2. Statuses of the facilities and treatments procedures using a medical LINAC.

between the institutions' workload distributions, as mentioned in the safety report, and the calculated workload distributions over six months, is shown in Fig. 3. The number of institutions and workload (Gy/week) are plotted along the X and Y axes, respectively.

The workload written in safety reports indicated that 25 institutions (48.1%) reported a value of 1000–1499 Gy/week for primary radiation, which was the most prevalent response. A total of 27 institutions (51.9%) reported secondary radiation values greater than 3000 Gy/week, which was the most prevalent response. According to these responses, the maximum workload per week, which depends on the actual treatment status, was differently distributed from the values recorded in the safety report.

Out of the 52 institutions, 29 (55.8%) reported a primary radiation value less than 500 Gy, which was the most prevalent response. A total of 18 institutions (34.6%) reported a secondary leakage radiation value lesser than 500 Gy, which was the most prevalent response. Similar rates were reported for all domains. Additionally, 10 institutions (19.2%) reported a secondary leakage radiation value greater than 3000 Gy, which was the second-highest distribution.

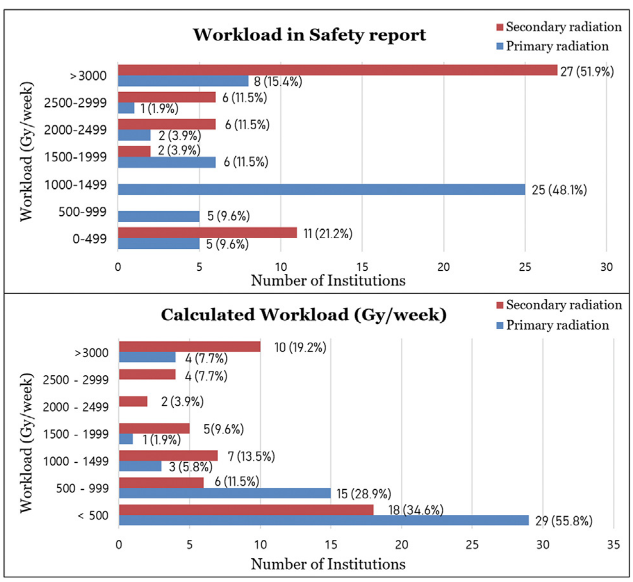

Fig. 3. Workload: in safety report (Lt) and calculated workload in six months (Rt).

3.3. Shielding design standards in medical LINAC facilities

Radiation types that account for the IMRT factor were applied while calculating the workload required by the shielding design through the multiple responses provided in the survey [9]. The responses that accounted for the IMRT factor applied primary, scatter, and leakage radiations of 32%, 29%, and 39%, respectively. A total of 38 institutions reported an IMRT factor of 5, while 3 institutions reported a value of 7. The remaining 11 institutions did not respond on this front (Fig. 4).

A total of 21 institutions reported that they had considered the neutron capture gamma ray and neutron ray while calculating the IMRT factor, whereas 20 institutions only accounted for the neutron capture gamma-ray. The remaining 11 institutions did not respond on this front.

The permissible radiation dose per week is the target value for the shielding design for the radiation-controlled and public areas that the institutions select as a reference for shielding calculations. The permissible dose per week values adopted by each institution for the radiation-controlled and public areas are shown in Fig. 5.

The permissible dose per week in the radiation control area was 0.4 mSv/week for 27 institutions and 0.1 mSv/week for 20 institutions. Here, 3 institutions did not respond, while the remaining 2 institutions reported values of 1 mSv/week and 0.9 mSv/week.

The permissible dose per week in the public area for 41 institutions was 0.02 mSv/week (78.8%). A value of 0.04 mSv/week was reported by 3 institutions, while 5 responded with a value of 0.1 mSv/week. Two institutions did not respond, while 1 institution did not have a public area (Fig. 6).

3.4. Status of shielding management at medical LINAC facility

A duration of 1 month was considered by 41 institutions as the measurement period of the spatial dose rate in the radiation-controlled and public areas, which was the most prevalent response. An analysis of the calibration of the survey meter, which was used to measure the spatial dose rate, demonstrated that 38 institutions reported a duration of 6 months for x-rays and gamma rays, while 13 institutions reported a duration of 12 months. The responses on neutron rays indicated that 35 institutions, 14

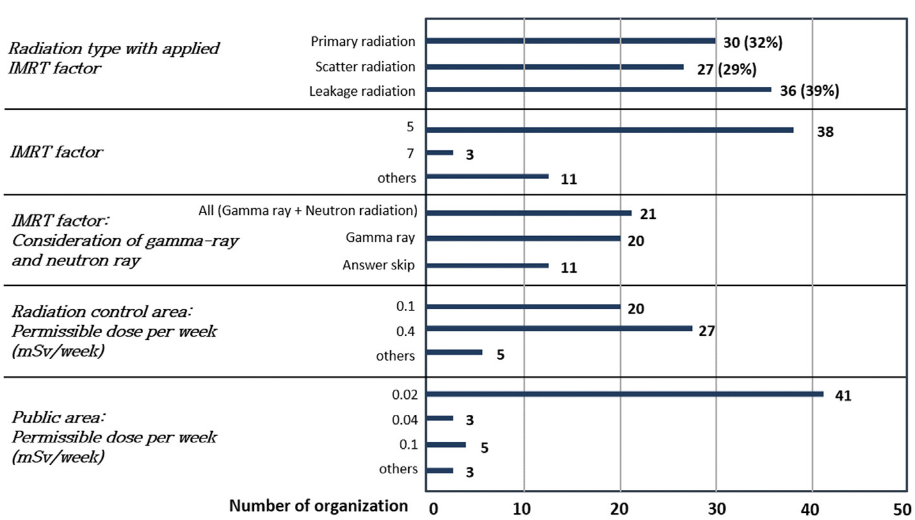

Fig. 4. Shielding reference of the medical LINAC facility.

institutions, and 1 institution adopted durations of 12 months, 6 months, and more than 24 months, respectively. Most institutions (36) responded that the spatial dose rate was measured at a designated location. A total of 11 institutions responded that they explored the site for the ideal location of the highest dose rate, while the remaining 3 institutions responded that they had performed measurements at an arbitrary location.

The IDR distributions for public areas were also analyzed. Most institutions responded an IDR less than or equal to 10 μSv/hr; 7 institutions reported values greater than 30 μSv/hr; and 9 institutions responded with values greater than 10 μSv/hr but less than or equal to 30 μSv/hr. A total of 7 institutions did not respond.

A total of 42 institutions claimed that they applied the time-averaged dose rate per week (TADR/w) and IDR concepts in their shielding designs. However, 8 institutions did not utilize these concepts, while 2 institutions did not respond.

3.5. Obtaining information on the standards of radiation protection

The path used to obtain recent information on radiation safety and control is shown in Fig. 7. The approaches chosen to obtain the latest information on the facility's barrier shielding design and other safety managements are shown in this figure. Each institution was allowed to submit multiple responses. The results demonstrated that 33 institutions acquired information from regulatory organizations, such as the Nuclear Safety and Security Commission (NSSC) and the Korea Institute of Nuclear Safety (KINS), while 31 institutions acquired information from the National Council on Radiation Protection & Measurements (NCRP) and the International Atomic Energy Agency (IAEA). Other sources included academic societies, such as the Korean Society of Medical Physics (KSMP) (21), radiation safety managers at their institutions (9), and radiation shielding companies (5). A total of 36 institutions consulted radiation shielding design companies to obtain information on the IMRT factor, while 33 institutions obtained information from an international organization on nuclear safety and radiation protection, such as the IAEA. Medical LINAC manufacturers were utilized by 7 institutions, while 4 institutions selected "others," which included several options, such as "the decision was based on the information from the last five years in the hospital," "a decision reflecting the actual treatment design value," "guidelines from the regulatory organization," and "no response".

The approaches used to obtain information on the permissible dose per week in the radiation safety report included the NCRP-49 [13], NCRP-51 [14], NCRP-151 [9], nuclear-related laws, and responsible ministry acts from the Ministry of Education and Science, and others. Multiple responses were permitted. A total of 36 institutions referred to the NCRP-151 report [9], while 23 institutions obtained information through acts from the responsible ministry in the nuclear field. A few institutions consulted the NCRP-

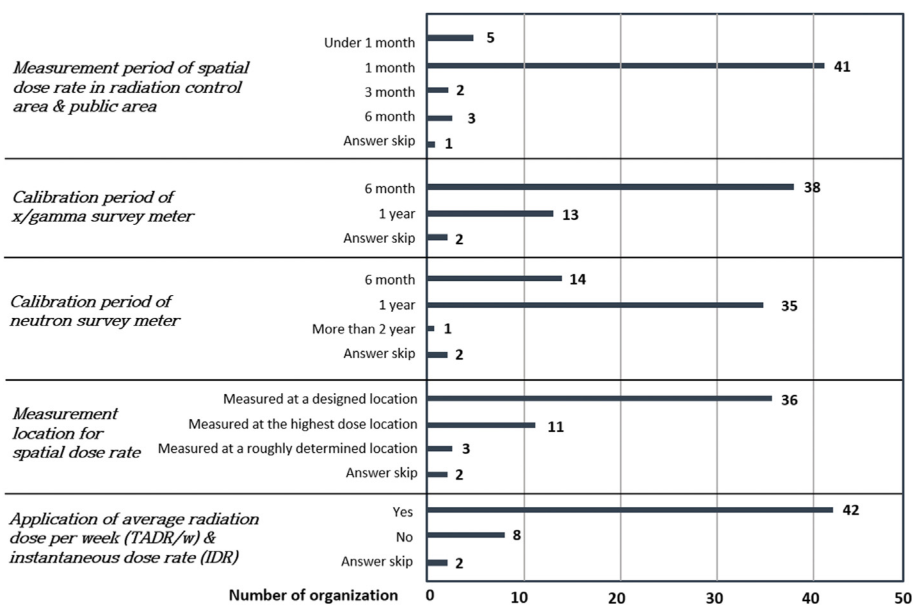

Fig. 5. Shielding management status of medical LINAC facility.

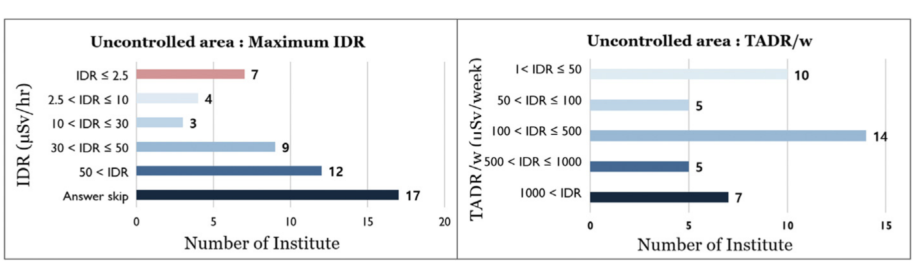

Fig. 6. IDR of the uncontrolled regions.

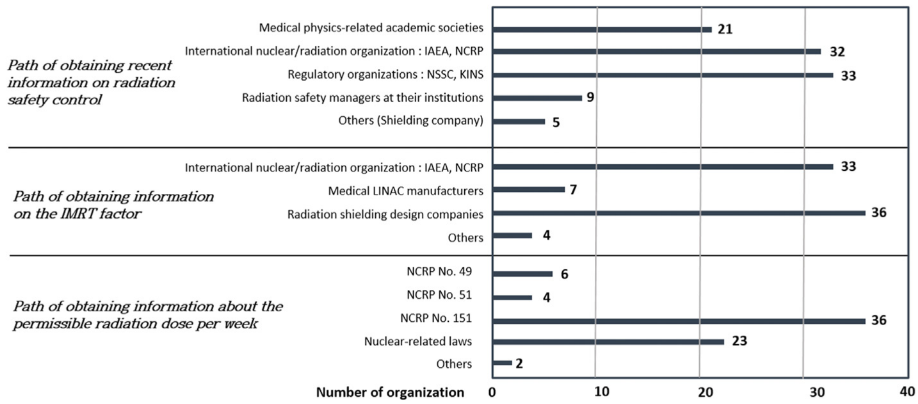

Fig. 7. Path of obtaining information on the standards of radiation protection.

49 report (8.4%) and the NCRP-51 report (5.6%), while the remaining opted for no response.

4. Discussion

A survey was conducted in this study to investigate the statuses of shielding designs and their management in medical LINAC facilities at medical institutions in Korea. The survey was conducted for 100 radiation oncology departments, and 52 of these institutions responded (52% response rate). The survey was based on each department's status, and the responses were recorded anonymously to eliminate bias.

The survey results revealed that most medical institutions across Korea had a relatively high IMRT utilization ratio, thereby highlighting the importance of establishing domestic standards for shielding designs and evaluating facilities using medical LINACs through IMRT. It was observed that 69% of the 52 responders utilized IMRT for more than 60% of their cases, and 33% of those responders used IMRT for more than 80% of their cases. The development of shielding designs that account for the IMRT factor has been implemented in all domestic medical institutions. Most medical institutions used an IMRT factor of 5—a value that has not been estimated according to the methods suggested in NCRP or IAEA reports. As this is an exemplary value used for shielding calculations in the NCRP-151 report, it is important to develop detailed IMRT factor calculation for shielding designs in these facilities by using medical LINAC. In addition, 61.3% of the responders accounted for the IMRT factor for primary and scattered radiation in the shielding designs.

Consideration of the IMRT factor is recommended by NCRP-151 [9] and IAEA Safety Report Series 47 [10] for creating the shielding design considering leakage radiation. Medical institutions in Korea had implemented a conservative shielding design. This survey analyzed each institution's treatment status with respect to the shielding of the medical LINAC facilities in Korea. This is an indicator of the importance of establishing a system or providing standards to develop an effective and safe barrier shielding.

The permissible dose per week was recommended as a design standard in article 13 of the radiation protection standards in Korea [15]. It must not exceed 1 mSv/week in regular access areas, such as utilization facilities, and 0.1 mSv/week for public areas. However, most medical institutions adhere to more conservative norms than those specified in these standards. Control areas are limited to 0.4 mSv/week or 0.1 mSv/week, while public areas use 0.02 mSv/week as a design reference. These values are lesser than 10% of the legal standard, thereby confirming that these treatment facilities have implemented safe designs.

A total of 27 institutions (52%) have implemented a workload of 3000 Gy/week in their safety reports while designing their shielding, which is also a conservative value. The maximum distribution in the actual workload was greater than 500 Gy/week for the primary and leakage radiations. Further, the second highest leakage radiation workload was greater than 3000 Gy/week. The distribution of workload values varied according to the varying workload distributions across hospitals owing to their different patient treatment capacities.

IDR standards are being used for the safety evaluation of facilities using medical LINAC in Korea through article 4, paragraph 2 of the “Standards for the radiation protection” (enforced on January 10, 2019). The guidelines state that the permissible dose exposure of the public during limited or instantaneous applications of radioactive isotopes must not exceed 0.1 mSv per week or 0.02 mSv per hour, as long as the annual dose limit is not breached [16].

The reference value used for design shielding in Korea is 0.02 mSv/hr (20 μSv/hr). The IDR measurements in public areas exceeded this value for 9 out of the 52 institutions (17.3%). Although a warning can be issued against the shielding for exceeding the reference value, several reports, including the Institute of Physics and Engineering in Medicine (IPEM) report 75 [17], state that the dose rate measurement for a short period, such as the IDR, is an inadequate standard to evaluate shielding. The time average dose rate per week (TADR/w) and the TADR calculated at any hour, which accounts for the utilization factor, workload, time, and distance of measurement, are recommended in addition to IDR. However, these standards must first be established in Korea.

The path for obtaining the information on the shielding design varied across medical institutions; thus, their designs were based on non-standardized information. Every medical institution must account for the IMRT use ratio and the treatment room structure while evaluating and designing the shielding. It is imperative to establish a standardized system, and its methodology should be shared as fundamental material. Although it could be practically challenging for these medical institutions with existing designs and shielding to re-establish their shielding designs and constructions according to the updated guidelines, this can improve shielding in radiation oncology departments that have just opened or are expanding their facilities with additional devices.

Status determination is necessary before suggesting shielding factors or new standards. Our survey demonstrated that although several institutions employ different shielding standards, they are highly conservative. Further, over-budgeting for shielding can be avoided by employing uniform standards and developing a superior shielding design that is suitable for the institution's treatment status and the shielding evaluations.

5. Conclusion

This study investigated the statuses of the shielding designs and managements of the medical LINAC facilities in Korea. Most institutions utilized IMRT more than they utilized 3D CRT. As the former must account for the rise in the leakage dose for appropriate shielding management, it is important to evaluate the status of shielding design, management, and safety standards across different institutions using IMRT or other treatment techniques.

The survey demonstrated that most facilities followed the standard recommendations prescribed by relevant international organizations, including the NCRP-151 guidelines, in their shielding design. Several institutions followed more conservative per-week permissible radiation dose standards than those specified in the guidelines proposed by the nuclear safety commissioner. However, the necessity of developing and publishing standardized shielding design information and clarifying the ambiguous acquisition paths for obtaining shielding information. These results can be used as a foundation to establish a safety control system for facilities using medical LINACs, thereby ensuring the developing of adequately safe shielding designs. Future studies shall provide guidance on the development of an appropriate shielding according to survey results.

Declaration of competing interest

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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