Nuclear Engineering and Technology 54 (2022) 507–513

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original article

Current status of disposal and measurement analysis of radioactive components in linear accelerators in Korea

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ARTICLE INFO

Article history:
Received 17 March 2021
Received in revised form
2 November 2021
Accepted 2 November 2021
Available online 5 November 2021

Keywords:
Photoneutron
Photonuclear reaction
Linear accelerator
Dosimetric analysis
Radioactive component management
Radionuclide

ABSTRACT

When X-ray energy above 8 MV is used, photoneutrons are generated by the photonuclear reaction, which activates the components of linear accelerator (linac). Safely managing the radioactive material, when disposing linac or replacing components, is difficult, as the standards for the radioactive material management are not clear in Korea. We surveyed the management status of radioactive components occurred from medical linacs in Korea. And we also measured the activation of each part of the discarded Elekta linac using a survey meter and portable High Purity Germanium (HPGe) detector. We found that most medical institutions did not perform radiation measurements when disposing of radioactive components. The radioactive material was either stored within the institution or collected by the manufacturer. The surface dose rate measurements showed that the parts with high surface dose rates were target, primary collimator, and multileaf collimator (MLC). ^{60}Co nuclide was detected in most parts, whereas for the target, ^{60}Co and ^{184}Re nuclides were detected. Results suggest that most institutions in Korea did not have the regulations for disposing radioactive waste from linac or the management procedures and standards were unclear. Further studies are underway to evaluate short-lived radionuclides and to lay the foundation for radioactive waste management from medical linacs.

1. Introduction

Conventional techniques that are used to treat cancer include surgical treatment, radiation therapy, and chemotherapy [1]. Among these techniques, radiation therapy is not only used for full recovery purposes but also for the palliative purpose of reducing pain, and thus, it plays a crucial role in the cancer treatment [2]. In addition, approximately 30% and 50% of the cancer patients in Korea and the United States undergo radiation therapy, respectively [3–7].

Radiation therapy devices and therapy techniques have continued to develop since the 2000s, and linear accelerators (linacs) have been used as the most ubiquitous treatment equipment in Korea. Currently, 182 linacs are used in a total of 100 radiation oncology institutes in Korea, accounting for 64% of the total radiation therapy device usage [8]. In addition, the intensity modulated radiation therapy (IMRT) technique is being widely utilized because it protects normal tissue and combats tumor tissues more effectively than the three-dimensional conformal radiation therapy (3D-CRT) [9]. The difference between the 3D CRT and IMRT is the possibility of intensity modulation. IMRT technique can modulate the intensity of specific direction of the radiation. And using the multileaf collimator (MLC), IMRT treats a tumor with a small beamlet according to the shape of the tumor while delivering minimal dose to surrounding normal organs [10,11].

Long-term operation of linacs using high-energy X-rays results in radioactivation in linac components owing to their consistent receipt of radiation. Radioactivation is a phenomenon wherein nuclear reactions occur due to high-energy neutrons, quantum, and gamma rays, thereby generating radioactive nuclides [12]. Photoneutron energy spectrum and angular distribution, photoneutron emission intensity generated from a high-energy linac can affect activation reaction, shielding calculation, and exposure of workers

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https://doi.org/10.1016/j.net.2021.11.002

[13–16]. The use of X-ray energy above 8 MV in the linac catalyzes the production of photoneutrons due to the photonuclear reactions, which ultimately results in components such as targets, collimators, and filters, confirming the presence of radioactivity due to their interaction with such neutrons [17–19]. Tungsten and lead, Aluminum, Copper, Antimony and Manganese etc. are main materials of linac undergoing photonuclear reactions to produce photoneutrons.

From the viewpoint of this phenomenon, dosimetric analysis of the radioactive components should be carried for disposing the linacs or replacing the components. However, there are no established standards for the disposal of linac in Korea, and thus, all the medical institutions have different procedures for the disposal of linacs. In addition, the management procedures for radioactive components and materials generated after dismantling have not been formulated; therefore, the management is currently arduous due to the absence of disposal standards and is kept in hospital facilities or collected by companies.

Although Kwak et al. and Fisher et al. investigated the radioactivation phenomena occurring in medical linacs using detectors, the radioactivation measurements on every discarded equipment and their components have not been evaluated [20–23]. Weber et al. conducted radiation measurement studies on unused filters, used filters, and MLC leaves that were separated from actual equipment from Elekta; however, radioactivation assessments regarding these three components were conducted after artificially exposing the radiation, and radioactivation assessment studies on all parts of the equipment were not conducted [24]. Various other researchers have also conducted radioactivation studies on linacs; however, most of them, including Vichi et al., have utilized Monte Carlo methods to conduct limited studies on radioactivation evaluation or measurement studies of particular components [15,25–27].

Linac radioactivation has attracted significant attention in Korea. The disposal process of linac's radioactive components are conducted differently as follow own system of hospitals or radioactive waste managing companies due to the absence of radiation safety regulations related with those matters. So, there are necessity of uniform procedures and standards for the dispose the radioactive components and it is important to get aware of the situation and investigate the current management conditions. In this study, we conducted surveys to investigate the disposal status of radioactive components of linacs, such as disposal experience and management status of radioactive materials produced in medical linacs.

We aim to establish a regulatory for the disposal of radioactive components of linacs in Korea by conducting activation measurements and analysis on medical linac equipment from Elekta.

2. Material and methods

2.1. Investigating the status of radioactive waste management of medical linacs in Korea

We inspected linacs used in a total of 100 radiation oncology institutes that are initiating radiation therapy in Korea, and the annual trends were investigated. In addition, web-based surveys were conducted using SurveyMonkey® (Palo Alto, CA, USA) to determine the status of processing and disposal of radioactive components of linacs for different institutes. A survey was conducted on medical physicists working in radiation oncology departments in Korea, and the medical physicists from 53 out of the 100 institutes responded.

The survey aims to identify the management status of radioactive waste in medical linacs. The survey contained 15 questions, which were largely divided into the following sections: (1) disposal of the entire linac system, (2) disposal of linac components, and (3) common questions. Multiple responses were allowed for some questions. The survey consisted of 15 questions in total, whose details are listed in Table 1.

2.2. Measurement and evaluation of radioactivation of disposed components of medical linacs

In this study, radioactivation measurements were carried out for the linac equipment from Elekta discarded on the April 28th, 2020. The disposed Elekta linac used the energy of 6 and 10 MV and the workload was about 300 Gy/wk. The linac installed in September 2005 and discarded on the April 28th, 2020. The linac equipment was shut down a week before being discarded. And we measured 1st dose rate at the time of the dismantling the linac, we conducted 2nd dose rate measurement and the spectroscopy after 45 days from the disposal.

A survey meter (ESM FH 40 GL, Thermo Inc., Germany) was used to measure the surface dose rate, and a portable High Purity Germanium (HPGe) detector (Falcon 5000, Canberra Inc., Meriden, USA) was used to analyze the nuclides. The HPGe detector was used for measurement after energy calibration using ^{60}Co and ^{137}Cs sources. We analyzed the radioactive nuclei generated by each component based on the energy spectrum obtained using the HPGe detector. The gamma spectroscopy was carried out with HPGe detector positioned 1 cm from each component and the measurement was conducted for 5 min. Since the components of the linac were separated and measured, gamma spectroscopy was performed without a collimator. The dose rate measurements were carried out twice with survey meter, i.e., once during the time of disposal and then 45 days after disposal; the two dose rates were compared. The dose rate measurement was conducted for 1 min and measured at surface of each component. And we calculated the dose rate at a distance of 1 m, which is useful for estimating dose to personnel. Fig. 1-Left is the measurement setup for HPGe detector, and Fig. 1-Right is one of the spectrum acquired by HPGe detector. The following were subjected to measurements: magnetron, waveguide, target, primary collimator, carousel, flattening filter (high and low energy), scattering foil, and MLC, among others.

3. Result

3.1. Management status of radioactive waste from medical linacs in Korea

The number of linacs installed in radiation oncology and medical institutions in Korea as of 2020 is shown in Fig. 2. A total of 182 linacs was installed between 1992 and 2020, and among of 182, 66 linacs were installed between 1992 and 2010. Fig. 2 shows the number of installed linacs and we classified according to highest energy of linac (Highest energy 6 MV/10 MV/15 MV). Only 4.4% (8 out of 182 institutes) radiation oncology institutes are using the energy of 6 MV medical linacs that are not subject to activation. More than 90% of the 53 institutes are equipped with linacs capable of producing X-rays with more than 8 MV of energy, which can induce radioactivation.

(1) Disposal of entire linac system

Among the 53 institutes that responded to the survey, 19 (33%) stated that they had experience in disposing of the entire linac system; the responses to the related questions are shown in Fig. 3. Among these 19 institutes, 13 stated that they used the equipment for more than 10 years to less than 15 years, and this was the most popular response. The most common reason for equipment

Table 1
Survey contents.

Survey classification	Survey contents
(1) Disposal of the Entire Linac System	1 Experience in clearance of medical linacs greater than 8 MV
	2 Usage period of discarded equipment
	3 Reason for disposal
	4 Method of disposal
	5 Whether radioactivity was measured at disposal
	6 Whether a disposal report was written
(2) Disposal of Linac Components	7 Experience in clearance of components of medical linacs greater than 8 MV
	8 Disposed components of linac
	9 Method of disposal
	10 Whether radioactivity was measured at disposal
	11 Whether a disposal report was written
(3) Mutual Questions	12 Method of measuring radioactivation
	13 Presence of storage facilities for disposed radioactive components
	14 Regulations for Radiation Safety Management in Institutes: Whether contents on radioactivated waste are specified
	15 Regulations for Radiation Safety Management in Institutes: Whether standards regarding management procedures of radioactivated waste are present

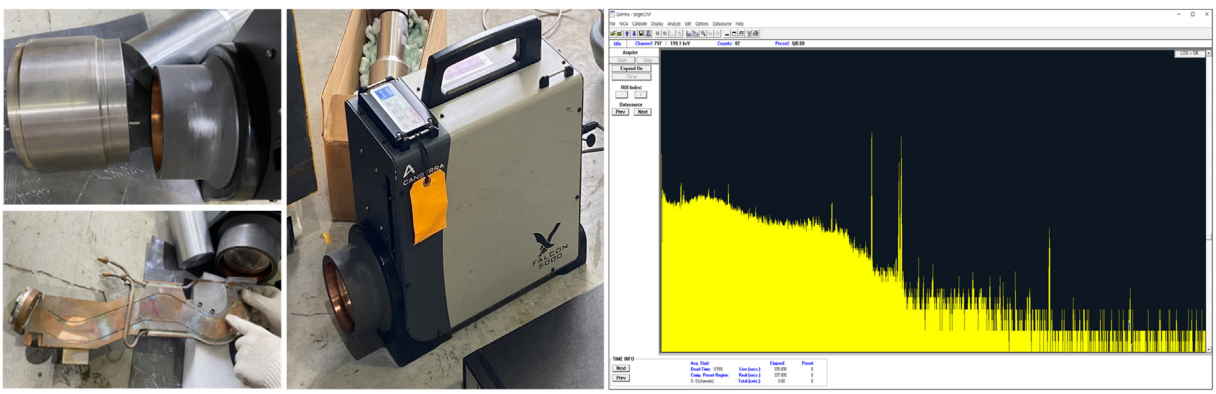

Fig. 1. Measurement setup of HPGe detector (Left) and example of gamma spectrum obtained (Right).

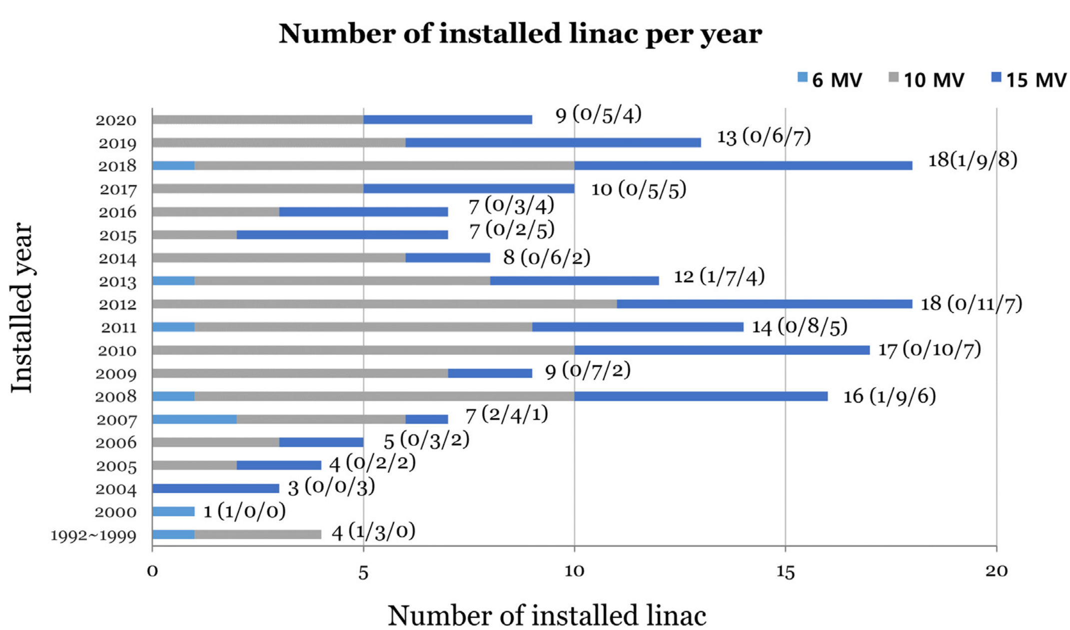

Fig. 2. Number of linacs installed in Korea in 1992–2020: Total number (Highest energy 6 MV/10 MV/15 MV).

disposal was equipment aging and replacement with the latest equipment. Furthermore, 11 institutes with an experience in disposing the equipment responded that they were storing the equipment within the hospital for clearance, whereas others

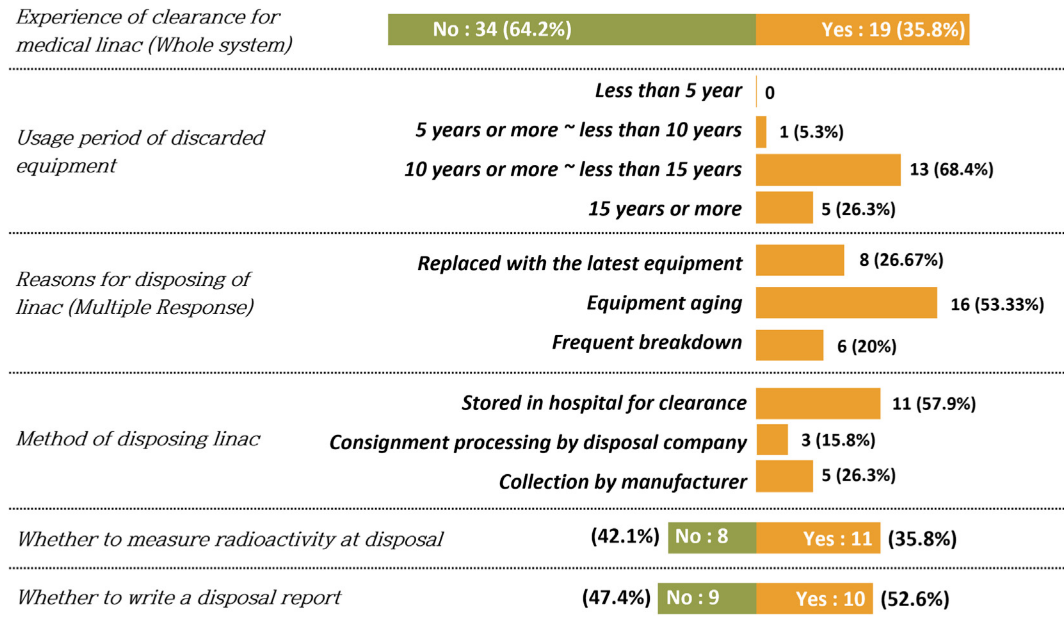

Fig. 3. Survey results for the disposal of medical linacs (entire system).

responded that they underwent consignment processing through disposal specialists or manufacturers. Approximately 50% of the institutes that have responded have disposed the equipment without conducting radioactivation measurements; they also did not produce relevant disposal reports.

(2) Disposal of linac components

Among the 53 institutes that responded to the survey, 21 (40%) stated that they had an experience in disposing linac components; the responses to the related questions are shown in Fig. 4. Most of the components disposed were components of the linac gantry head, including the target, electron gun, ion chamber, and filter. Furthermore, 11 institutes with an experience in disposing linac components responded that they were storing the equipment within the hospital for clearance, whereas others responded that they underwent consignment processing through disposal specialists or manufacturers. In addition, 8 out of 21 institutes responded that they did not take radioactivation measurements, and 14 were found to have not produced the relevant disposal reports.

(3) Common questions

Among the 53 institutes, 24 responded that they had an experience in the disposal of linacs and their components. Furthermore, 19 stated that they disposed the entire linac, whereas 21 stated that they had partially disposed the linac components. In the case of disposal of equipment or components, 14 institutes responded that they conducted radioactivation evaluations using a survey meter.

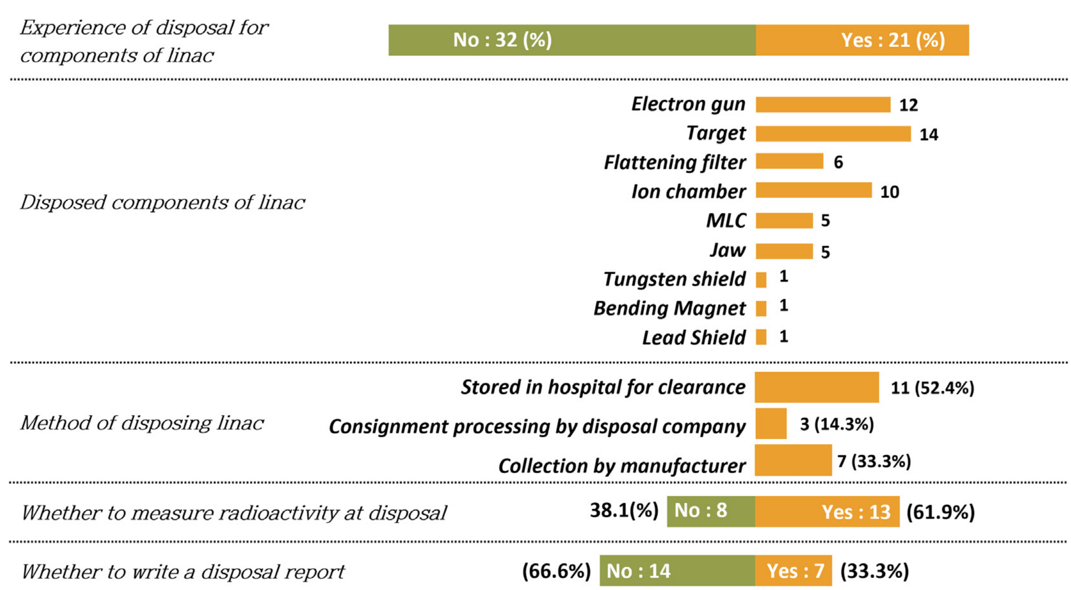

Fig. 4. Survey results for the disposal of the components of medical linacs.

Furthermore, 10 other institutes did not take any measurements, whereas 1 institute used an HPGe detector to carry out such measurements. In the case of waste generated after dismantling the equipment and individually generated radioactive components, 14 institutes responded that they kept them in storage facilities. Furthermore, 10 of the 14 institutes responded that they were operating storage facilities for radioactive waste, including sealed/opened radioisotopes, whereas 4 responded that they were operating sites dedicated to solely storing radioactive components of linacs. Meanwhile, 10 institutes responded that they did not know or did not possess any storage facilities. In addition, 18 institutes responded that the radiation safety management regulations within the institute specify contents regarding the management and disposal of linac radioactive wastes, and among them, 8 institutes responded that there are procedures and standards for such actions.

3.2. Measurement and evaluation of radioactivation of discarded components of medical linacs

In this study, we measured the surface dose rate of each component of the discarded linac and conducted nuclide analysis. Table 2 shows the results for the surface dose rate of each component using a survey meter. We found that the components with the highest surface dose rate at the time of disposal were the target, primary collimator and MLC with 3.318, 27.1 and 2.032 μSv/h, respectively. The dose rate of the target decreased to 0.578 μSv/h which is still higher than background dose rate. For the primary collimator and MLC, the dose rate was found to mostly fall back down to the background level, after 45 days. In the case of the waveguide, the dose rate after 45 days seems to be background level when considering the uncertainty of the survey meter and of the measurement and the different background level according to different measurement days.

Nuclide analysis using HPGe detectors showed that ^{60}Co nuclides were mainly detected in most linac components, and the results are shown in Table 3. Furthermore, ^{60}Co and ^{184}Re were identified for targets. Elekta linac target comprise target insert and target block. The target insert comprises tungsten and rhenium, and the target block comprises copper, lead, bismuth, cadmium, nickel, cobalt, zinc, iron and so on. Therefore, the ^{60}Co can be predicted that produced through the nuclear reaction ^{61}Ni(γ, p)^{60}Co, ^{60}Ni(n, p)^{60}Co, ^{61}Ni(γ, n)^{60}Co, ^{59}Co(n, γ)^{60}Co [28,29]. And the ^{184}Re can be predicted that produced through the reaction ^{185}Re(γ,n)^{184}Re [30,31]. The measurement error for spectroscopy was about 0.26%.

Table 3
Detected main-radionuclides of linac components.

Components of Linac	Detected Radionuclides (Half-life)
Magnetron	^{60}Co (5.27 y)
Waveguide	^{60}Co
Target	^{60}Co,^{184} Re (38 d)
Primary Collimator	^{60}Co
Carousel	^{60}Co
Filter	^{60}Co
Scattering foil	^{60}Co
MLC	^{60}Co
Others	^{60}Co

4. Discussion

In this study, a survey was conducted to understand the management status of radioactive components within radiation oncology departments in medical institutes in Korea, and measurement and evaluation of radioactivation were conducted on discarded medical linacs. The survey results show that 53% (53 out of 100 institutes) radiation oncology institutes responded, which is considered as a high response rate. To retrieve unbiased answers to the procedures and current status of the institutes, the survey was designed to be answered anonymously.

The results demonstrate the necessity of establishing procedures and disposal standards for the management of radioactive components derived from linacs. In addition, the measurement values of the radioactivation of real discarded linacs should serve as the basis of establishment of these standards.

In Korea, each institute had slightly different disposal procedures due to the lack of definitive standards and procedures for disposal. It has been confirmed that radioactive components generated after the dismantling of linacs are stored within the hospitals or are collected by manufacturers because of the absence of dose rate or disposal standards. A total of 66 linacs were installed in Korea from 1992 to 2010, and considering the survey results which indicate that the average usage period of linacs is approximately 10–15 years, we can assume that a large number of linacs are discarded relatively soon. In addition, it was revealed that approximately 50% of institutes did not carry out any measurements during disposal and did not make relevant disposal reports.

In Korea, legal standards related to radiation safety management in the medical sector are set in the Nuclear Safety Act and radiation protection standards. However, as there is no specific information on the disposal and management of linacs, a legal framework regarding this area should be established.

The Canadian Nuclear Safety Commission recommends the use of a survey meter to measure and evaluate radioactivity owing to its time- and cost-effectiveness based on the ALARA (as low as

Table 2
Result of surface dose rate (survey meter).

Component	2020.04.28		2020.06.18	
	Surface Dose rate (μSv/h)	Dose rate from 1 m (nSv/h)	Surface Dose rate (μSv/h)	Dose rate from 1 m (nSv/h)
Magnetron	0.161	16.1	0.131	13.1
Waveguide	0.191	19.1	0.265	26.5
Target	3.318	331.8	0.578	57.8
Primary collimator	27.1	2710	0.152	15.2
Carousel	0.137	13.7	0.118	11.8
Flattening filter (High Energy)	0.161	16.1	0.128	12.8
Flattening filter (Low Energy)	0.107	10.7	0.133	13.3
Scattering foil	0.149	14.9	0.139	13.9
MLC	2.032	203.2	0.153	15.3
Others	0.371–0.557	37.1–55.7	0.158–0.178	15.8–17.8

reasonably practicable) principle [32]. The reference point of dose rate measurement in Canada is 5 cm from the surface of the radioactive component, and disposal is allowed if the value bellows 0.5 μSv/h. The dose rate measurements conducted in this study show that the dose rate of the component "target" is 0.519 μSv/h, which is higher than the criteria presented in Canada, even after 45 days of disposal. However, these measurements were taken near the component's surface, suggesting that the dose rate value can be expected to be smaller if measured at a 5 cm distance. It can also be seen that after approximately a month, the dose rate of most components decreased back to the background level. According to ELEKTA's technical report, suggested isotopes which can be found in the target, primary collimator and MLC are ^{57}Ni (36 h), ^{60}Co (5.3 y), ^{62}Cu (9.74 min), ^{64}Cu (12.7 h), ^{65}Zn (244 d), ^{124}Sb (60.3 days), ^{184}Re (38 d), ^{187}W (24 h), ^{106}Ag (24 min). We expect that the activity had decreased to background as those short-lived nuclides vanished after 45 days [33].

In 2014, Japan proposed academic standards for dismantling, radioactivity measurement, storage, and management of radioactive materials, among others, for medical linacs through "Academic Standards for Management of Radioactive Materials of Radiation Therapeutic Devices" [34]. This report indicates the type of nuclide that can be detected in each material, including the fundamental material, conversion factors, and weights that make up the components according to the linac manufacturer. The results of this study were compared and analyzed for the major component for each component and the nuclides in the Japanese report. Since magnetron, waveguide, target, primary collimator, carousel, filter, scattering foil and MLC are mostly composed of tungsten alloy and stainless alloy, ^{60}Co was detected as the main nuclide. For target component, the ^{184}Re was detected additionally with the ^{60}Co nuclide as presented in report. As the head shield surrounding the linac and the shields of other components are mainly composed of lead alloy and tungsten alloy, ^{60}Co nuclide was detected as in the Japanese report. ^{124}Sb was detected as presented in Japanese report, but the cps (count per seconds) was not enough compared to ^{60}Co. So, we did not classify the ^{124}Sb as main nuclide in Table 3.

In addition, the research team conducted the nuclide evaluation after 45 days of dismantling the equipment, suggesting that nuclides with short half-lives were not identified; in the case of primary collimators, a distinct nuclide spectrum could not be obtained, possibly due to insufficient measurement time.

5. Conclusion

Herein, we conducted a survey to determine the current status of management in accordance with the discarding and disposal patterns of medical linacs in Korea. Since there are no definitive management standards regarding the radioactive components that are generated in discarded linacs or during component replacement in Korea, some institutions store radioactive materials or discard radioactive materials without measuring radioactivation. Additionally, we measured the surface dose rates for discarded Elekta equipment's separated components and the radioactive nuclides were analyzed. We found that the main components showed high activity immediately after shut down the linac, and the dose rate decreased to the background level after 45 days. With the results of dose rate and spectroscopy, short-lived nuclides were mainly exert a dominant effect of dose rate. As a result of this study, we recommend that radioactive materials be stored and discarded until the radioactivity of the nuclides is sufficiently reduced by analyzing the nuclide through spectroscopy or measuring the dose rate when disposing the linear accelerator or replacing major parts. This study is expected to be utilized as foundation data for the management standards and regulations on the disposal of radioactive components arising from medical linacs.

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.

Acknowledgments

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea(No. 2003013) and the National Research Foundation of Korea (NRF) grant funded by the Korean government (No. 2020M2D9A3094170).

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