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Analysis of Activated Materials of Disposed Medical Linear Accelerators according to Clearance Level for Self-Disposal

Young Jae Jang [1,2,†], Na Hye Kwon [3,4,†], Seong Hee Park [2], Yona Choi [2], Kum Bae Kim [1], Dong Wook Kim [3,4], Suk Ho Bhang [5,*] and Sang Hyoun Choi [1,*]

1 Research Team of Radiological Physics & Engineering, Korea Institute of Radiological & Medical Sciences, Seoul 01812, Republic of Korea
2 Department of Accelerator Science, Korea University, Sejong 30015, Republic of Korea
3 Department of Radiation Oncology, Yonsei Cancer Center, Heavy Ion Therapy Research Institute, Yonsei University College of Medicine, Seoul 03722, Republic of Korea
4 Medical Physics and Biomedical Engineering Lab (MPBEL), Yonsei University College of Medicine, Seoul 03722, Republic of Korea
5 School of Chemical Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea
* Correspondence: sukhobhang@skku.edu (S.H.B.); shchoi@kirams.re.kr (S.H.C.); Tel.: +82-31-290-7242 (S.H.B.); +82-2-970-1590 (S.H.C.)
† These authors contributed equally to this work.

Abstract: In Korea, when replacing or discarding parts of a medical linear accelerator (linac), self-disposal is required in the consideration of the activity, but there is no standard regulation to manage radioactive waste. The aim of this study is to check the activity of each part to determine the disposal time according to the clearance level for self-disposal. The results of measuring the components of the linac head parts of the disposed Varian, Elekta, and Siemens equipment were reflected in the Monte Carlo simulation to confirm the radionuclide change according to the presence or absence of impurities. To confirm the degree of activation of the linac, the main radionuclides according to the time after the linac shutdown, considering the workloads of 40/80 Gy/day of 10/15 MV linac irradiated with beams for 10 years in the results of the simulation of the linac parts, and the radionuclide concentration was confirmed. As a result of applying the clearance level for self-disposal in the notice of the Korean Nuclear Safety (KINS) to each linac head part, most parts of the 10 MV linac could be dismantled after 1 month, and 15 MV target and primary collimators were stored after a long period of time before being dismantled. Although additional radionuclides were identified according to the presence or absence of impurities, the disposal timing for each part did not change significantly. In this study, the clearance level for self-disposal for each radionuclide was applied to activated parts by three manufacturers to confirm the self-disposal timing and predict the timing at which workers are not exposed to radiation during dismantling/disposal.

Keywords: radioactive waste; medical linear accelerator; clearance level; radionuclide; Monte Carlo simulation

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1. Introduction

To meet the growing demand for radiotherapy, an increasing number of medical linear accelerators (hereinafter referred to as "linac") are being installed in Korean hospitals every year (n = 185 in 2022) [1]. Alongside new installations, an increasingly higher number of existing linacs has been replaced or disposed of in recent years. The service life of linacs ranges from 10 to 15 years, and they are replaced or disposed of for reasons such as the aging of parts, failure of major parts, and introduction of new treatment equipment [2]. According to the data from the Korean Institute of Nuclear Safety (KINS) in 2018 [3], two or more linacs are replaced or disposed of every year in Republic of Korea. It is recommended that the details of each case of replacement or disposal be reported to the KINS and major parts be subjected to self-disposal or storage for later disposal after evaluating their activity.

The Korean Nuclear Safety and Security Commission (NSSC) Notice No. 2020-6 stipulates the permissible standards for the self-disposal of radioactive waste according to the clearance level of each radionuclide [4]. In the case of medical linacs, however, no accurate information on radionuclides is available and standardized regulations allowing the flexible management of different workloads have yet to be established. Therefore, there is a major need for a management plan for dismantling radioactive parts of medical linear accelerators.

Various radionuclides generated through the activation process in a linac can cause problems to patients and related healthcare workers in general, and workers can be exposed to them during disposal/dismantling in particular. It is, hence, of paramount importance to quantify the radionuclides generated and compute the dose rates [5].

NCRP 79 specifies 10 MeV as the energy threshold for evaluation because only a negligible number of neutrons are generated at energies below 10 MeV, which defines the target, primary collimator, flattening filter, and head parts as the highest risks of activation [6]. In addition, IAEA-TECDOC-1183 suggested the possibility of the surrounding materials being activated by an accelerator using an energy of 10 MeV or greater, and clarified the necessity to assess the radiation hazard when dismantling the head of a medical linac used in radiation oncology [7].

A variety of studies have been conducted to identify and analyze radionuclides to ensure the safety of workers, concluding that radionuclides are mainly generated from the target, primary collimator, flattening filter, jaws, multileaf collimator (MLC), and bending magnet by high-energy photon beams [8,9]. These materials mainly consist of tungsten, gold, copper, and stainless steel. The target to produce photons is made of a high-density metal, such as tungsten or gold, and a primary collimator is made of tungsten, which is used to reduce the amount of scattered radiation. The flattening filter consisting of tungsten or brass is designed to generate a beam with a more uniform intensity across the field, and a jaw (MLC) made of tungsten is used to adjust the size and shape of the treatment beam. The properties of these components are carefully designed to ensure that the radiation beam is accurately directed towards the target area, while minimizing the dose to surrounding healthy tissue.

For the accurate assessment of radionuclides generated by the high-energy photon beams of each part when dismantling a linac, radionuclides emitted from each part should be identified using a gamma spectrometer or a Monte Carlo simulation method based on the data provided by the manufacturer and the component analysis of additional parts using laser-induced breakdown spectroscopy (LIBS) [10].

Adam Konefal et al. and Waller et al. identified and quantified activation products and their estimated activities generated by 18 MV Elekta and 15 MV Varian Truebeam using gamma-ray spectroscopy with HPGe [11,12]. Vichi et al. performed a Monte-Carlo-simulation-based activation study of a 15 MeV linear accelerator, investigating the production of radioactive isotopes and dose rates in various materials [9]. However, these studies did not evaluate the effect of radioactivity caused by impurities in the linear accelerator, nor did they study the change in nuclide and radioactivity over time after shutting down the linear accelerator.

The presence of impurities in components can be a significant source of uncertainty in radiation measurements. Impurities in materials can produce additional gamma rays or other types of radiation that may not be accurately accounted for in the measurement process. There is a limit to studying the evaluation of radioactivity over time after the shutdown of the linear accelerator using HPGe. Even after the linear accelerator is turned off, the materials used in the construction of the accelerator and its components may continue to emit radiation owing to the residual activity of radioactive isotopes. This residual activity can persist for varying lengths of time depending on the specific isotopes involved, making it difficult to assess the radiation exposure levels in the surrounding environment accurately.

In this study, the degrees of activation of the components and impurities of each major part were assessed using LIBS for mapping out their composition in Varian, Elekta, and Siemens linacs, and by performing a Monte Carlo simulation. Based on the assessment results, it is intended to predict the timing of storage and disposal of each part taking into account its clearance level by determining the radionuclides emitted during the accelerator dismantling/disposal and the activation level over time.

2. Materials and Methods

2.1. Component Analysis of the Parts of Decommissioned Linacs by Manufacturer

Components, including the head of three decommissioned medical linacs, were analyzed. Particularly, the linacs investigated were Clinac iX (Varian), Agilty^{TM} (Elekta), and Oncor Expression (Siemens). The study focused on the parts of the linac head that are prone to activation in terms of the beam pathway, which included the target, primary collimator, ion chamber, jaw (MLC), and bending magnet. To confirm the components of each dismantled linac head part, laser-induced breakdown spectroscopy (LIBS) was used. Surface investigation was conducted at least three times for each part using a portable LIBS element analyzer (Z-300 GeoChem Pro, SciAps Inc., Woburn, MA, USA). The results of the measurements were then compared with the specifications provided by each manufacturer, and the levels of impurities were analyzed. Figure 1a–c shows the process of dismantling the linac head parts manufactured by Varian, Elekta, and Siemens, respectively. Figure 1d shows the portable LIBS device measuring the emission from each major component of the dismantled head parts.

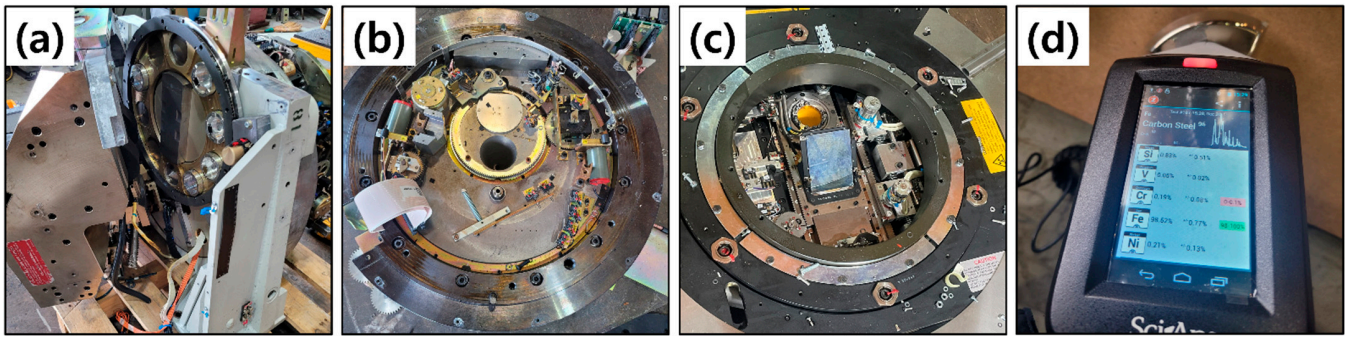

Figure 1. Dismantled linac head parts of (**a**) Clinac iX (Varian); (**b**) Synergy platform (Elekta); (**c**) Oncor Expression (Siemens); and (**d**) LIBS measurement results of the components of their major parts.

2.2. Monte Carlo Simulation of Medical Linacs

Monte Carlo simulation was used to evaluate radionuclides generated by parts of the linear accelerator according to energy and workload. It is a computational method that uses random sampling to obtain numerical solutions to mathematical problems, and it is often used to model the behavior of particles (such as photons, electrons, or neutrons) as they interact with matter. It can simulate the behavior of particles in complex systems to study the effects of different materials, geometries, and other factors.

To perform a Monte Carlo simulation, we obtained the internal structures and specifications of different components of the medical linacs from their respective manufacturers, and devised three-dimensional models using AutoCAD software (Autodesk Inc., San Francisco, CA, USA). Specifically, parts such as target, primary collimator, ion chamber, jaw, and MLC of Varian, Elekta, and Siemens equipment were modeled based on the data provided by the manufacturers, and bending magnets and lead shields were modeled additionally based on the analysis data of the structures of decommissioned linacs. The SuperMC program (Super Monte Carlo simulation program, FDS team, Hefei, China) [13] was used to convert the modeled data into PHITS (Version 3.25) code written in Fortran [14]. The particle and heavy ion transport code system (PHITS) is a widely used general-purpose Monte Carlo simulation code that can handle the transport of all particles over a wide

range of energies using various nuclear reaction models and nuclear data libraries. It is used in numerous fields related to particle and heavy ion transport phenomena, including accelerator technology, radiotherapy, and space radiation. Using this code, radionuclides that can be generated for each part of the linear accelerator were simulated according to the energy of 10/15 MV and the workload of 40 and 80 Gy/day.

2.3. Time-Dependent Activity Level

The PHITS code, which was used to analyze radionuclides and their activity levels, was based on the nuclear data in the ENDF-6 format (ENDF-102), and the coding was performed to include all reactions in the 0.001 to 50 MeV energy band for gamma spectroscopic analysis by using source and tally. The source component in the PHITS code was specified as a transverse Gaussian distribution electron beam with energy levels of 10/15 MeV, which collided with a target to generate a photon beam. The nuclear physics module of PHITS included models for simulating nuclear reactions, such as scattering, fission, and fusion, as well as models to produce secondary particles, such as neutrons and gamma rays, in these reactions.

To calculate the neutron flux from the PHITS code, T-DCHAIN and T-Volume Tally were utilized. These include information such as cell number, beam amplitude, number of irradiations, cooling time steps, and the volume of each part to derive the neutron flux. To precisely determine the radionuclide concentration, time-dependent energy and current values were entered in the DCHAIN code, considering the linac's workload. The decay chain analysis code DCHAIN [15] was used to analyze all radionuclides of each component based on the neutron's flux results, whereby nuclear data were extracted from hybrid data libraries, such as JENDL/AD-2017, FENDL/A-3.0, JENDL-4.0, ENDF/B-VIII.0, and JEFF-3.3, to encompass all nuclides [16,17].

To assess the degree of activation of a medical linac, workloads of 80 Gy/day and 40 Gy/day were reflected in the DCHAIN code for equipment irradiated with beams for 10 years, and the time-dependent change in the activation level of radionuclides of each part was monitored by measuring it immediately after the linac shutdown and 6 h, 1 month, 3 months, 1 year, 5 years, and 10 years later. Major radionuclides were selected as those from the components whose activity level accounted for 0.01% or more of the total activity level among those with an activity level of 10^{-6} Bq/g or higher immediately after linac shutdown and a half-life of 5 s or more.

3. Results

3.1. Component Analysis of the Parts of Decommissioned Linacs by Manufacturer

In Table 1, the elements of each of the main parts (target, primary collimator, flattening filter, ion chamber, mirror, jaw, and MLC) that affect major impurities and additional radionuclides, whose element composition ratios account for more than 0.5% of the total element composition, are listed along with the data provided by each manufacturer.

Among the parts with no data provided by the manufacturers and whose components were measured by LIBS, the bending magnet was found to be mainly composed of Fe, with the bending magnet provided by Varian containing large amounts of Cr and Ni, unlike those provided by Elekta and Siemens. In the LIBS measurement results, Varian's flattening filter 15 MV, Elekta's primary collimator, and Siemens' MLC were composed of 100% tungsten, with no impurities detected. As for the target, primary collimator, and jaw, the largest share of impurities was detected in those manufactured by Varian. Only the primary collimator manufactured by Siemens includes an absorber; therefore, it is annotated as Varian and Elekta in Table 1.

Table 1. Elements of the major parts of the medical linacs by manufacturer.

Major Parts	Varian	Elekta	Siemens
Target	Cu W Zn *	W Re Cu	Au Fe Cr Ni Cu *
Bending magnet	Fe * Cr * Ni *	Fe * Si * Ni * Pb * Cu *	Fe * Mo *
Primary collimator	W Fe * Cr * Ni * Mn *	W Ni Fe	W
Absorber	**	**	Al Ag * Cu * Mg *
Flattening filter 15 MV	W	Fe Cr Mn Ni Mo *	Fe Cr Mn Ni Mo *
Flattening filter 10 MV	Cu O Zn *		
Ion chamber	H C O N	Al Si Fe Mn Mg	Al O Mg * Ag * Cu *
Mirror	H C O	H C O	O Si Ca Na
Jaw	W Ni * Cu * Nb * Mo *	W Ni Fe	W
MLC	W Ni Fe Cu	W Ni Fe Cr * Mo *	W

* Components additionally identified in LIBS measurements; ** head part components with no specifications provided by the manufacturers.

3.2. Medical Linac Modeling and Workload-Based Activation Evaluation

The schematic representations in Figure 2 are the results of modeling the main components and shield structures of the head parts of the three manufacturers. Siemens' target, unlike those of Varian and Elekta, is made of different materials, such as graphite, gold, and SST304, and is modeled in such a way that the absorber is placed inside the primary collimator; a beam of 10 MV or greater is applied. While the MLC of Varian is placed after the jaw, that of Elekta is placed before the jaw. For this reason, unlike other manufacturers, Elekta's MLC has a higher activity than the jaw. In addition to the main head part components, radiation shielding mainly composed of lead was additionally modeled to evaluate radionuclides and activity levels.

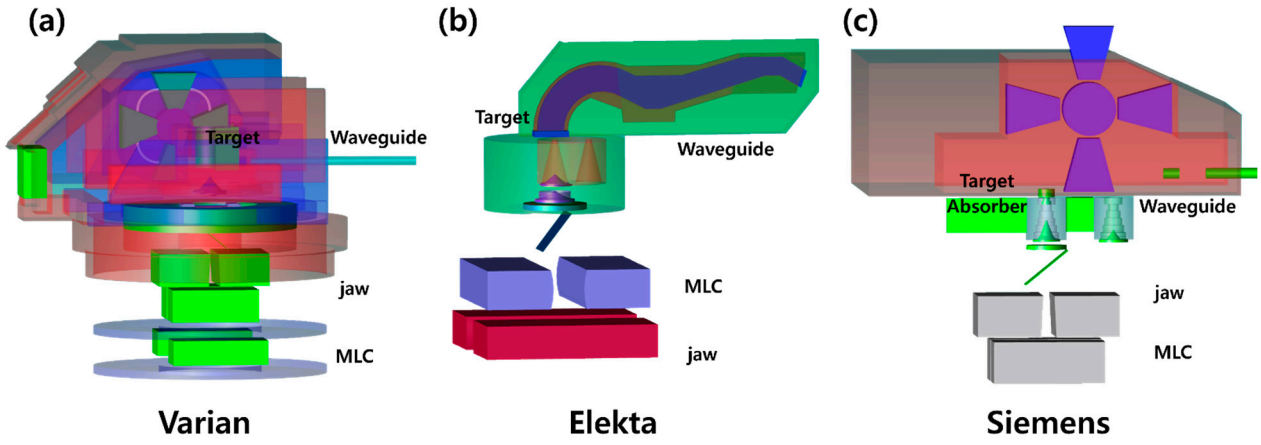

Figure 2. Medical linac modeling results of the three manufacturers: (**a**) Varian; (**b**) Elekta; and (**c**) Siemens.

No workload-dependent differences in the radionuclides were observed among the parts, and an analysis of the activity level revealed that the radiation of beams at a workload of 80 Gy/day was about twice as high as that of 40 Gy/day. In this study, radionuclides and their activity level analysis were analyzed based and compared on the workload of 80 Gy/day, taking a conservative approach. The main radionuclides from each manufacturer's parts are listed in Table 2. Radionuclides in Table 2 are the results of photonuclear reactions, such as (γ, n), (n, γ), (γ, 2n), and (γ, np). Nuclear reactions were confirmed through Monte Carlo simulations, including ^{182}W(γ, n)^{181}W, ^{197}Au(γ, n)^{196}Au, ^{66}Zn(γ, n)^{65}Zn, ^{186}W(n, γ)^{187}W, ^{27}Al(n, γ)^{28}Al, ^{54}Fe(n, p)^{54}Mn, and ^{58}Ni(n, p)^{58}Co. As additional radionuclides were contained in the parts with large proportions of impurities, ^{94m}Nb, ^{58}Co, and ^{99}Mo were detected in the jaw of Varian, ^{99}Mo in the MLC of Elekta, and ^{108}Ag, ^{65}Zn, and ^{58}Co in the absorber of Siemens.

Table 2. List of major radionuclides in the parts of each manufacturer emitted at the workload of 80 Gy/day and activity in each part after shutdown.

Major Parts	Varian			Elekta			Siemens		
	Nuclide ($T_{1/2}$)	Activity [Bq/g]		Nuclide ($T_{1/2}$)	Activity [Bq/g]		Nuclide ($T_{1/2}$)	Activity [Bq/g]	
		15 MV	10 MV		15 MV	10 MV		15 MV	10 MV
Target	^{64}Cu (12.70 h) ^{181}W (121.18 d) ^{185}W (75.12 d) ^{63}Ni (101.15 y)	7.58×10^4	9.71×10^2	^{181}W (121.18 d) ^{64}Cu (12.70 h) ^{65}Zn (243.98 d) ^{58}Co (70.86 d)	1.47×10^7	1.84×10^5	^{196}Au (6.17 d) ^{55}Fe (2.75 y) ^{58}Co (70.86 d) ^{64}Cu * (12.70 h)	1.88×10^7	2.03×10^5
Bending magnet	^{55}Fe * (2.75 y) ^{57}Co * (271.76 d) ^{58}Co * (70.86 d) ^{57}Ni * (1.48 d)	14.47	5.26×10^{-2}	^{55}Fe * (2.75 y) ^{54}Mn * (312.04 d) ^{59}Fe * (44.49 d)	9.65	9.65×10^{-2}	^{55}Fe * (2.75 y) ^{54}Mn * (312.04 d) ^{59}Fe * (44.49 d)	0.52	1.97×10^{-3}
Primary collimator	^{185}W (75.12 d) ^{181}W (121.18 d) ^{179}Ta (1.82 y) ^{55}Fe * (2.75 y)	1.09×10^4	3.52×10^2	^{185}W (75.12 d) ^{181}W (121.18 d)	1.88×10^3	14.46	^{185}W (75.12 d) ^{181}W (121.18 d) ^{179}Ta (1.82 y)	1.58×10^4	6.79×10^2
Absorber		**			**		^{28}Al (134.50 s) ^{108}Ag * (142.90 s) ^{65}Zn * (243.98 d) ^{58}Co * (70.86 d)	7.35×10^2	0.48
Flattening filter	^{181}W (121.18 d) ^{185}W (75.12 d)	19.12		^{58}Co (70.86 d) ^{54}Mn (312.04 d) ^{55}Fe (2.75 y) ^{99}Mo * (2.75 d)	2.63×10^3	2.65×10^{-2}	^{55}Fe (2.75 y) ^{51}Cr (27.70 d) ^{54}Mn (312.04 d) ^{99}Mo * (2.75 d)	6.58×10^3	2.90×10^2
	^{66}Cu (307.20 s) ^{64}Cu (12.70 h)		0.28						
Ion chamber	^{3}H (12.33 y) ^{14}C (5704.59 y)	2.60	2.49×10^{-2}	^{28}Al (134.50 s) ^{56}Mn (2.58 h) ^{65}Zn (243.98 d) ^{63}Ni (101.15 y)	0.62	1.37×10^{-2}	^{28}Al (134.50 s) ^{108}Ag * (142.90 s) ^{66}Cu * (307.20 s) ^{65}Zn * (243.98 d)	17.74	0.17
Mirror	^{3}H (12.33 y) ^{14}C (5704.59 y)	3.00×10^{-7}	4.32×10^{-7}	^{3}H (12.33 y) ^{14}C (5704.59 y)	3.12×10^{-4}	4.12×10^{-5}	^{24}Na (15.00 h) ^{37}Ar (35.03 d) ^{31}Si (2.62 h) ^{45}Ca (162.62 d)	0.12	9.13×10^{-4}
Jaw	^{185}W (75.12 d) ^{94m}Nb * (375.80 s) ^{58}Co * (70.86 d) ^{99}Mo * (2.75 d)	3.51	3.82×10^{-2}	^{181}W (121.18 d) ^{58}Co (70.86 d)	58.29	0.4	^{185}W (75.12 d) ^{181}W (121.18 d) ^{179}Ta (1.82 y) ^{183}W (1.10×10^{17} y)	4.48×10^2	19.43
MLC	^{185}W (75.12 d) ^{181}W (121.18 d) ^{64}Cu (12.70 h) ^{55}Fe (2.75 y)	0.62	3.82×10^{-3}	^{185}W (75.12 d) ^{181}W (121.18 d) ^{93m}Nb (16.14 y) ^{99}Mo * (2.75 d)	87.44	1.14	^{185}W (75.12 d) ^{181}W (121.18 d) ^{179}Ta (1.82 y) ^{183}W (1.10×10^{17} y)	1.59×10^2	6.59

* Components additionally identified in LIBS measurements; ** head part components with no specifications provided by the manufacturers.

3.3. Time-Dependent Activity Level of Each Linac Part

The major radionuclides detected in the target after stopping the beam were ^{185}W, ^{181}W, and ^{64}Cu in Varian, with the highest activity level changing from ^{64}Cu (2.69×10^4 Bq/g) immediately after the linac shutdown to ^{185}W and ^{181}W one day later. This change of the major radionuclide from ^{64}Cu to tungsten isotopes can be explained by the former's half-life of 12.7 h (Figure 3a,b). In the target of Elekta, the major radionuclides changed from ^{181}W, ^{64}Cu, and ^{65}Zn immediately after the linac shutdown to ^{181}W and ^{64}Cu after one day. In particular, since ^{181}W, which is a long half-life radionuclide, maintained a high concentration of 1.83×10^6 Bq/g even after one year, not much lower than the initial concentration of 1.47×10^7 Bq/g (Figure 3c,d).

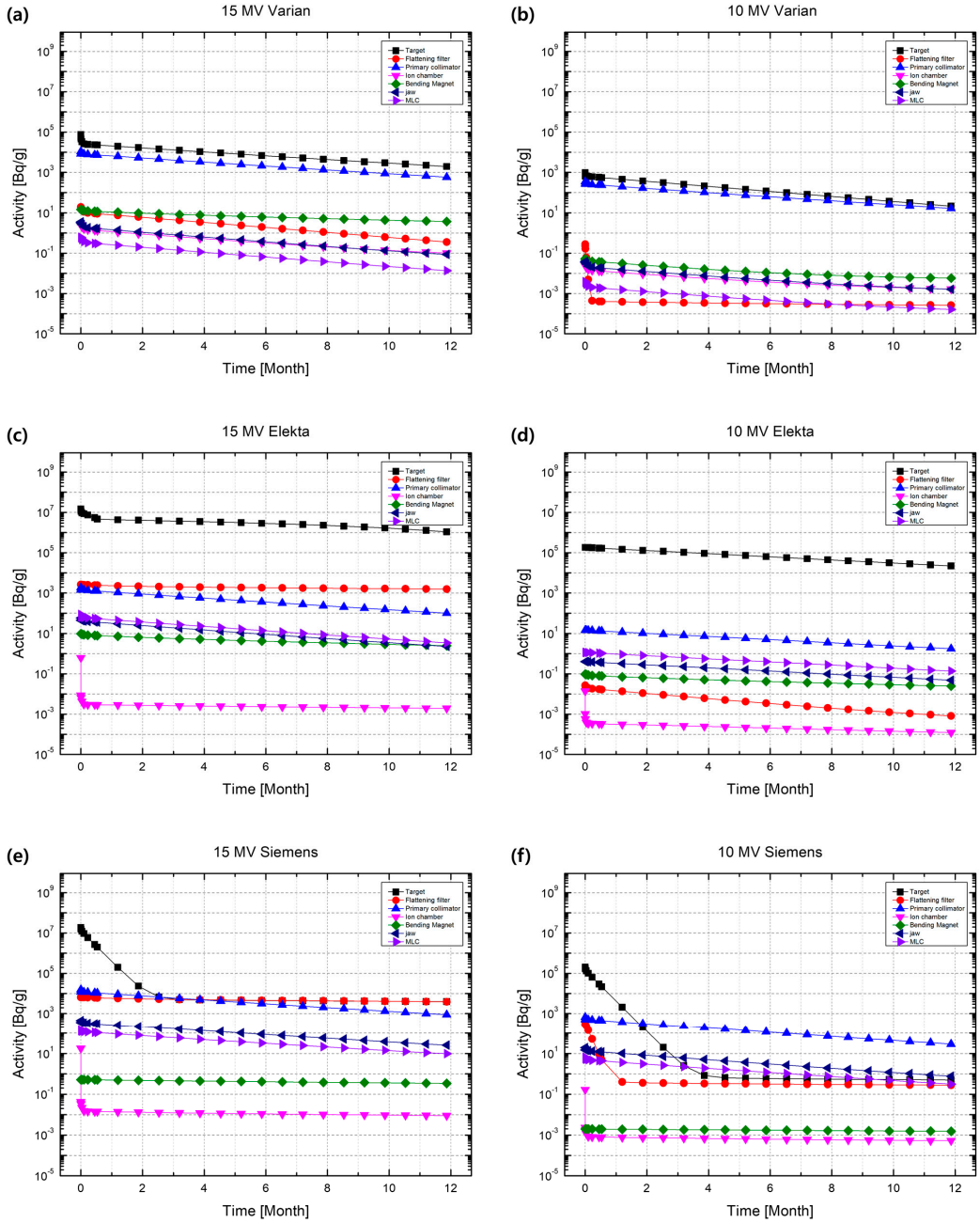

Figure 3. Time-dependent changes in the activity levels of the linac major parts obtained by applying a workload of 80 Gy/day at the energy levels of 15 and 10 MV: (**a**) 15 MV Varian; (**b**) 10 MV Varian; (**c**) 15 MV Elekta; (**d**) 10 MV Elekta; (**e**) 15 MV Siemens; and (**f**) 10 MV Siemens.

Unlike Varian and Elekta, Siemens' target is composed of materials such as graphite, gold and SST304, giving rise to various radionuclide changes for each material. The main radionuclides detected immediately after stopping the beam were ^{3}H and ^{14}C in graphite, ^{196}Au and ^{198}Au in gold, and ^{55}Fe, ^{51}Cr, ^{99}Mo in SST304. In particular, ^{196}Au had a very high initial concentration of 1.23×10^{7} Bq/g, which fell to 1×10^{3} Bq/g two months later because it has a short half-life of 6.183 days (Figure 3e,f). From two months after the linac shutdown onward, ^{55}Fe, ^{51}Cr, and ^{58}Co, which are long half-life radionuclide in SST304, were identified as the major radionuclides. The highest time-dependent activity levels were found in the target up to two months after the linac shutdown in all three manufacturers (Figure 3).

On the other hand, although various radionuclides in impurities were additionally detected (Table 2), the content of the impurities in each part was negligibly low when their activity levels were checked against the composition of the components of the parts provided by the manufacturers. However, the bending magnet, for which no data were provided by the manufacturers, was found to have initial activity levels ranging from 0.1 to 10 Bq/g due to the long half-life radionuclides ^{57}Co and ^{58}Co.

4. Discussion

Leprince assessed ^{187}W, ^{183m}W, ^{185}W, ^{181}W, and ^{178}Ta as major radionuclides in tungsten targets, with an activity level of 4.03×10^{17} Bq, using the MCNPX code, in equipment with a service life of five years [18]. Patil et al. identified radionuclides, such as ^{198}Au, ^{196}Au, ^{181}W, ^{178}W, ^{60}Co, ^{58}Co, ^{57}Co, ^{54}Mn, and ^{51}Cr, in gold and SST304 targets [19–22]. Roig et al. identified ^{196}Au, ^{57}Co, ^{60}Co, ^{54}Mn, and ^{58}Ni in Siemens KDS 18 MV, and specified a separate storage period of at least 30 days for ^{196}Au radionuclide in the target pursuant in accordance with Spanish regulations (IS/05, 2003) until the activity level fell below 10^{6} Bq [23]. While these results are consistent with those of this study, this study differentiates itself from others in that it also investigated the radionuclides additionally obtained by considering impurities.

To present, the allowable disposal time for each part of a dismantled linac, the clearance level of the radionuclides identified in each part should be applied. Regarding the self-disposal standards for radioactive waste, the United States use the technical standards published by the Department of Energy (DOE) for the disposal of radioactive waste from accelerators and accelerator facilities. Accordingly, Varian provides DOE-standards-based recommendations [24,25]. Japan has also established academic society standards for the management of radioactive materials of radiotherapy devices, specifying radioactive waste disposal procedures, parts subject to regulations, and measurement methods [26]. In the Korean notice, pursuant to the regulations on radioactive waste classification and self-disposal standards [4], clearance levels are indicated in Appendix 1 (related to Article 2 (2) and Article 3 (1)), and in the case of mixed radionuclides, the clearance level of each radionuclide should be calculated using Equation (1):

$$\sum_{i} \frac{C_i}{C_{L,i}} < 1 \quad (1)$$

C_i: activity level (Bq/g) of radionuclide i
$C_{L,i}$: clearance level (Bq/g) of radionuclide i

For the application of the clearance levels in compliance with the methods specified in the notice, the time-dependent concentrations of all radionuclides ($C_{L,i}$) pertaining to each part obtained using the DCHAIN code were added, and the clearance level of a given radionuclide (C_i) was checked, and a part calculated (using Equation (1)) to have a value exceeding its clearance level was analyzed to be stored until it reaches a value below the clearance level. Among the clearance level of the radionuclide specified by the NSSC notice, those on the radionuclides analyzed in this study are listed in Table 3. As recommended

in the notice, the concentration of 0.1 Bq/g was applied to radionuclides for which no clearance level is provided.

Table 3. Clearance level of each radionuclide detected in the medical linacs manufactured by Varian, Elekta, and Siemens.

Radionuclides	Clearance Level (Bq/g)
^{24}Na, ^{28}Al, ^{31}Si, ^{37}Ar, ^{45}Ca, ^{54}Mn, ^{57}Ni, ^{65}Zn, ^{66}Cu, ^{108}Ag, ^{179}Ta, ^{183}W, ^{196}Au	0.1
^{14}C, ^{57}Co, ^{58}Co, ^{59}Fe	1
^{56}Mn, ^{93m}Nb, ^{99}Mo, ^{181}W	10
^{3}H, ^{51}Cr, ^{63}Ni, ^{64}Cu	100
^{55}Fe, ^{185}W	1000

Radionuclide ^{64}Cu had the highest initial concentration (2.62×10^4 Bq/g) in Varian's target 15 MV, followed by ^{185}W (1.23×10^4 Bq/g). As mentioned in another study, ^{64}Cu and ^{62}Cu have very short half-lives, and the concentration of ^{185}W had to be considered for their self-disposal [27]. In Elekta's tungsten target 15 MV, ^{181}W had the highest initial concentration (1.47×10^7 Bq/g), followed by ^{62}Cu (2.99×10^3 Bq/g). Likewise, the concentration of ^{181}W was considered for their self-disposal. In Siemens' target, ^{196}Au pertaining to gold material had the highest initial concentration (1.23×10^7 Bq/g), followed by ^{55}Fe (3.17×10^3 Bq/g) among the non-gold materials. As shown in Figure 3e,f, after about 2 months, with major radionuclide changing from Au isotopes with short half-lives to Fe isotopes with long half-lives, the activity level is maintained, and the activity level of ^{55}Fe should be considered for self-disposal.

In Figure 4, Equation (1) and Table 3 were applied to indicate the clearance levels based on the activity levels assessed for the head parts of the equipment of the three manufacturers that operated at 10 and 15 MV energy for 10 years, applying the workload of 80 Gy/day.

Six hours after the linac shutdown, the activity levels of the ion chamber and mirror were found to be lower than the clearance level among all parts of the linacs using 10 and 15 MV energy (Figure 4). Most of the parts of the linacs of the three manufacturers using 10 MV energy were found to have an activity level below the clearance level after one month, but Siemens' 10 MV target reached the clearance level after two months, and Elekta's 10 MV target was found to have an activity level exceeding the clearance level even after one year. In particular, the 15 MV targets of the linacs of the three manufacturers maintained the activity level of 10^3 Bq/g or higher even after one year, exceeding the clearance level. The 15 MV flattening filter of Elekta and Siemens also had to be stored for one year or longer.

As regards the 15 MV primary collimator, which is composed mainly of tungsten, those of Elekta and Varian could be disposed after two and 11 years, respectively, but that of Siemens had an activity level in excess of the clearance level even after 20 years (Figure 4e). This is due to the fact that, unlike Elekta and Varian, Siemens' primary collimator has an absorber attached to it, and its clearance level exceeds 1 due to the radionuclide ^{108m}Ag identified as an impurity. ^{108m}Ag radionuclide has a significantly long half-life of 418 years and a high radionuclide concentration of 6.93 Bq/g immediately after the linac shutdown. Since the notice does not provide its clearance level, 0.1 Bq/g, which is recommended for radionuclides with an unspecified clearance level, was applied, and its activity level still exceeded the reference value of 1 even 20 years after linac shutdown. Since only the radionuclide ^{28}Al was detected in Siemens' absorber without impurities, its tungsten primary collimator could be disposed after 15 years.

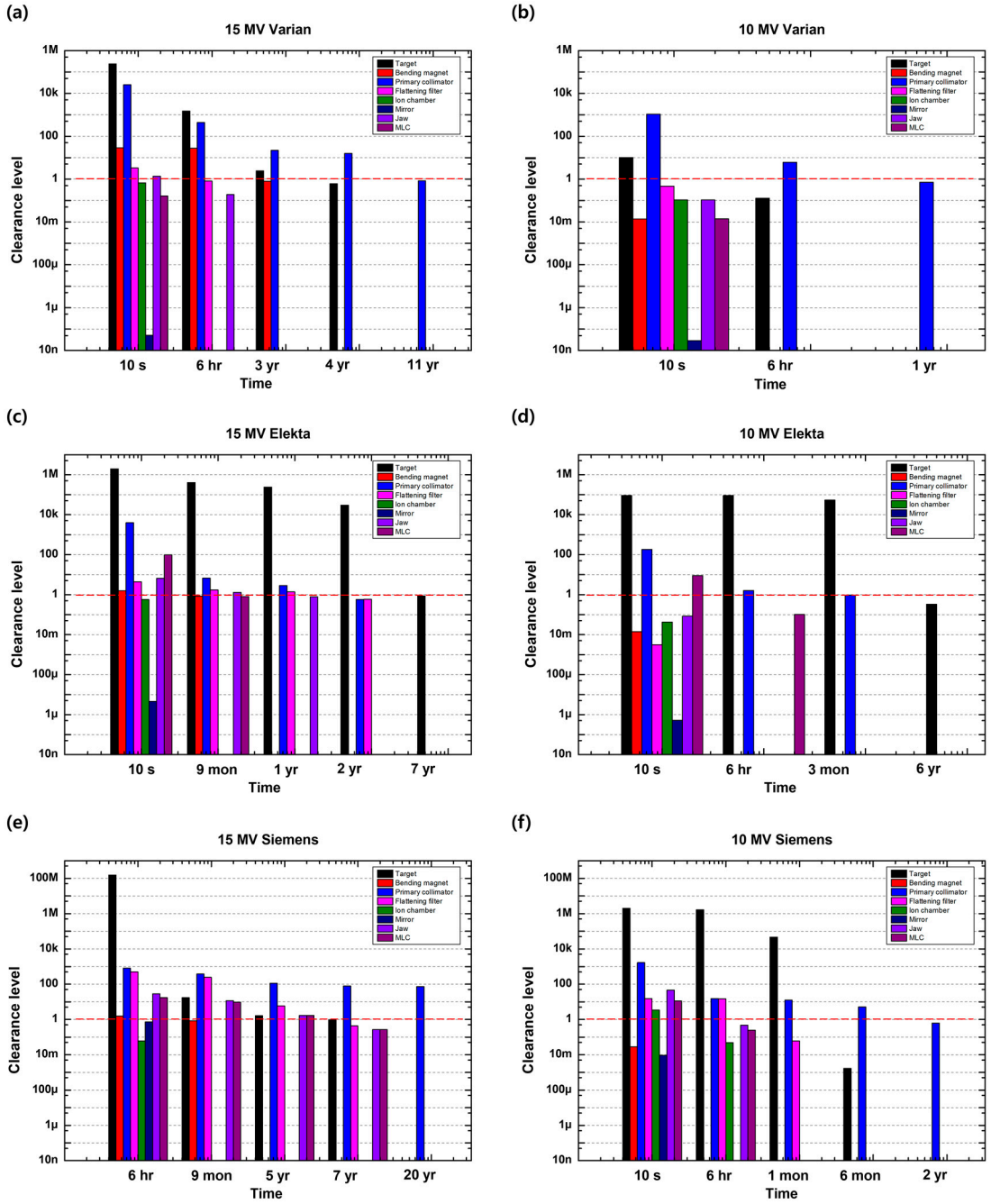

Figure 4. Clearance level by part and by equipment (15 MV/10 MV linacs of three manufacturers), applying a workload of 80 Gy/day (dotted red line: reference clearance level of 1; self-disposal is allowed at the activity level below this line): (**a**) 15 MV Varian; (**b**) 10 MV Varian; (**c**) 15 MV Elekta, (**d**) 10 MV Elekta; (**e**) 15 MV Siemens; (**f**) 10 MV Siemens.

The parts that were analyzed to be stored for six months or longer until self-disposal, were those with radionuclides with mid-to-long half-lives ($\geq 1 \times 10^6$ s) and high initial activity levels, such that their activity levels are still in excess of 10^3 Bq/g even after six months. Typical radionuclides with these attributes are ^{51}Cr, ^{54}Mn, ^{55}Fe, ^{57}Co, ^{58}Co, ^{179}Ta, ^{181}W, and ^{185}W generated from the SST304 and tungsten materials (Table 3).

When a workload of 40 Gy/day is applied, earlier disposal is possible because the activity levels of the parts are lower than when a workload of 80 Gy/day is applied. For the parts that require a long storage time ($\geq$2 years), i.e., target and primary collimator, no great changes occurred in the time for disposal when the workload was halved. However,

among those whose clearance level was reached after nine months, Elekta's MLC and bending magnet and Siemens' bending magnet could be disposed after one month when the workload was halved. As mentioned previously, a workload of 80 Gy/day was applied, adopting a conservative approach, and more accurate disposal time can be predicted by reflecting the energy and workload applied in actually decommissioned medical linacs.

5. Conclusions

This study was conducted to provide basic data for preparing regulations on the disposal of linear accelerators (linacs) by performing a component analysis of the linac parts of three manufacturers (Varian, Elekta, and Siemens), and assessing and analyzing the time-dependent activity levels of radionuclides using the Monte Carlo PHITS code and DCHAIN.

Although various radionuclides were additionally detected due to impurities, it was determined that their activity levels were negligible for the total activity level of each part and that the clearance level could be sufficiently examined using the Monte Carlo simulation results based on the data provided by the manufacturers. According to the clearance levels of the radionuclides specified in the pertinent Korean notice, the 15 MV targets of the three manufacturers should be stored at least for 3.5 to 7 years until they reach the clearance levels, whereas the 10 MV targets of Varian, Elekta, and Siemens can be disposed 6 h, 5.5 years, and 6 months after the linac shutdown, respectively. In order to avoid workers' exposure to radiation during dismantling/disposal, it is recommended to work after storing the parts until the clearance level (<1) is reached, as shown in Figure 4.

As demonstrated in this study, if values exceeding the clearance level can be computed through Monte Carlo simulation applying the workload until the dismantling/disposal of a linac, the storage period of each part after which workers can safely work on dismantling/disposal can be predicted. It is planned to perform a qualitative and quantitative analysis of radionuclides using HPGe-based gamma spectroscopy in addition to the Monte Carlo simulation with a view to providing a groundwork for clear safety management regulations for the disposal of decommissioned linacs.

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References

1. Kwon, N.H.; Jang, Y.J.; Kim, D.W.; Shin, D.O.; Kim, K.B.; Kim, J.S.; Choi, S.H. Trend Analysis on Korean and International Management for Activated Material Waste from Medical Linear Accelerator. *Prog. Med. Phys.* **2020**, *31*, 194–204. [CrossRef]
2. Kwon, N.H.; Shin, D.O.; Kim, J.S.; Yoo, J.; Park, M.S.; Kim, K.B.; Kim, D.W.; Choi, S.H. Current status of disposal and measurement analysis of radioactive components in linear accelerators in Korea. *Nucl. Eng. Technol.* **2022**, *54*, 507–513. [CrossRef]
3. Korea Institute of Nuclear Safety. *Improving Radiation Safety Management in the Medical Sector [Workshop]*; Korea Institute of Nuclear Safety: Daejeon, Republic of Korea, 2018.
4. Radioactive Waste Safety Division, Nuclear Safety and Security Commission. *Nuclear Safety and Security Commission No-Tification No. 2020-6, Regulations on Radioactive Waste Classification and Clearance Standards*; (Implementation and Revision in 2020.05.26); Radioactive Waste Safety Division, Nuclear Safety and Security Commission: Seoul, Republic of Korea, 2020.

5. MOTIE. *Radioactive Waste Control Act No. 15082*; (Implementation and Revision in 2017.11.28); Ministry of Trade Industry and Energy (MOTIE): Seoul, Republic of Korea, 2017.
6. Olsen, K.J. Neutron Contamination from Medical Electron Accelerators (NCRP Report No. 79). *Med. Phys.* **1986**, *13*, 968–969. [CrossRef]
7. International Atomic Energy Agency. *Management of Radioactive Waste from the Use of Radionuclides in Medicine*; IAEA-TECDOC-1183; IAEA: Vienna, Austria, 2000.
8. Naseri, A.; Mesbahi, A. A review on photoneutrons characteristics in radiation therapy with high-energy photon beams. *Rep. Pract. Oncol. Radiother.* **2010**, *15*, 138–144. [CrossRef] [PubMed]
9. Vichi, S.; Dean, D.; Ricci, S.; Zagni, F.; Berardi, P.; Mostacci, D. Activation study of a 15MeV LINAC via Monte Carlo simulations. *Radiat. Phys. Chem.* **2020**, *172*, 108758. [CrossRef]
10. Jang, Y.-J.; Kwon, N.H.; Park, S.H.; Choi, Y.; Yu, H.; Kim, K.B.; Kim, D.W.; Choi, S.H. Activation evaluation of Siemens linear accelerator using Monte Carlo simulation. *J. Korean Phys. Soc.* **2022**, *81*, 1107–1114. [CrossRef]
11. Konefał, A.; Bieniasiewicz, M.; Wendykier, J.; Adamczyk, S.; Wrońska, A. Additional radiation sources in a treatment and control room of medical linear accelerators. *Radiat. Phys. Chem.* **2021**, *185*, 109513. [CrossRef]
12. Waller, E.; Ram, R.; Steadman, I. Preliminary Determination of Activation Products for a Varian Truebeam Linear Accelerator. *Health Phys.* **2017**, *113*, 227–233. [CrossRef] [PubMed]
13. Wu, Y.; Song, J.; Zheng, H.; Sun, G.; Hao, L.; Long, P.; Hu, L. CAD-based Monte Carlo program for integrated simulation of nuclear system SuperMC. *Ann. Nucl. Energy* **2015**, *82*, 161–168. [CrossRef]
14. Sato, T.; Iwamoto, Y.; Hashimoto, S.; Ogawa, T.; Furuta, T.; Abe, S.-I.; Kai, T.; Tsai, P.-E.; Matsuda, N.; Iwase, H.; et al. Features of Particle and Heavy Ion Transport code System (PHITS) version 3.02. *J. Nucl. Sci. Technol.* **2018**, *55*, 684–690. [CrossRef]
15. Ratliff, H.N.; Matsuda, N.; Abe, S.-I.; Miura, T.; Furuta, T.; Iwamoto, Y.; Sato, T. Modernization of the DCHAIN-PHITS activation code with new features and updated data libraries. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* **2020**, *484*, 29–41. [CrossRef]
16. Zheng, L.; Huang, S.; Wang, K. Criticality benchmarking of ENDF/B-VIII.0 and JEFF-3.3 neutron data libraries with RMC code. *Nucl. Eng. Technol.* **2020**, *52*, 1917–1925. [CrossRef]
17. Shibata, K.; Iwamoto, O.; Nakagawa, T.; Iwamoto, N.; Ichihara, A.; Kunieda, S.; Chiba, S.; Furutaka, K.; Otuka, N.; Ohsawa, T.; et al. JENDL-4.0: A New Library for Nuclear Science and Engineering. *J. Nucl. Sci. Technol.* **2012**, *48*, 1–30. [CrossRef]
18. Leprince, A.; David, J.-C.; Ene, D.; Leray, S. Reliability and use of INCL4.6-Abla07 spallation model in the frame of European Spallation Source target design. *Prog. Nucl. Sci. Technol.* **2014**, *4*, 491–495. [CrossRef]
19. Patil, B.; Chavan, S.; Pethe, S.; Krishnan, R.; Bhoraskar, V.; Dhole, S. Estimation of neutron production from accelerator head assembly of 15MV medical LINAC using FLUKA simulations. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* **2011**, *269*, 3261–3265. [CrossRef]
20. Saeed, M.K.; Poppe, B.; Fischer, H. Direct air activation measurements at a 15-MV medical linear accelerator. *Radiat. Prot. Dosim.* **2015**, *163*, 233–237. [CrossRef] [PubMed]
21. Šagátová, A.; Fülöp, M.; Pavlovič, M.; Sedlačková, K.; Nečas, V. Electron-beam accelerator with conversion to X-rays: Optimal radiation type according to application. *Radiat. Phys. Chem.* **2020**, *172*, 108789. [CrossRef]
22. Długosz-Lisiecka, M.; Biegała, M.; Jakubowska, T. Activation of medical accelerator components and radioactive waste classification based on low beam energy model Clinac 2300. *Radiat. Phys. Chem.* **2023**, *205*, 110730. [CrossRef]
23. Roig, M.; Panettieri, V.; Ginjaume, M.; Sánchez-Reyes, A. Photonuclear isotope characterization of a Siemens KDS 18 MV linac head. *Phys. Med. Biol.* **2004**, *49*, N243–N246. [CrossRef]
24. U.S. Department of Energy. *Clearance and Release of Personal Property from Accelerator Facilities*; DOE-STD-6004-2016; U.S. Department of Energy: Washington, DC, USA, 2016.
25. U.S. Department of Energy. *Radiation Protection of the Public and the Environment*; DOE O 458.1; U.S. Department of Energy: Washington, DC, USA, 2013.
26. Japanese Society of Radiation Oncology. *Society Standard for the Management of Radioactive Substances in Radiotherapy Equipment*; Japanese Society of Radiation Oncology: Tokyo, Japan, 2014.
27. Dellepiane, G.; Casolaro, P.; Mateu, I.; Scampoli, P.; Braccini, S. Alternative routes for 64Cu production using an 18 MeV medical cyclotron in view of theranostic applications. *Appl. Radiat. Isot.* **2023**, *191*, 110518. [CrossRef] [PubMed]