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Original Article

Evaluation by thickness of a linear accelerator target at 6-20 MeV electron beam in MCNP6

Dong-Hee Han [a], Kyung-Hwan Jung [a], Jang-Oh Kim [b], Da-Eun Kwon [a], Ki-Yoon Lee [b], Chang-Ho Lee [c, *]

[a] *Department of Medical Health Science, Kangwon National University, Samcheok, 25949, South Korea*
[b] *Department of Radiological Science, Kangwon National University, Samcheok, 25949, South Korea*
[c] *Department of Emergency and Disaster Management, Inje University, Gimhae, 50834, South Korea*

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ABSTRACT

This study quantitatively evaluated the source term of a linear accelerator according to target thickness for a 6-20 MeV electron beam using MCNP6. The elements of the target were tungsten and copper, and a composite target and single target were simulated by setting different thickness parameters depending on energy. The accumulation of energy generated through interaction with the collided target was evaluated at 0.1-mm intervals, and F6 tally was used. The results indicated that less than 3% reference error was maintained according to the MCNP recommendations. At 6, 8, 10, 15, 18, and 20 MeV, the energy accumulation peaks identified for each target were 0.3 mm in tungsten, 1.3 mm in copper, 1.5 mm in copper, 0.5 mm in tungsten, 0.5 mm in tungsten, and 0.5 mm in tungsten. For 8 and 10 MeV in a single target consisting only of copper, the movement of electrons was confirmed at the end of the target, and the proportion of escaped electrons was 0.00011% and 0.00181%, respectively.

1. Introduction

The utilization of linear accelerators is increasing not only in the medical field such as radiation cancer treatment, but also in industrial fields such as container security inspection (CSI). A market trend report from the Korea Innovation Foundation, called INNOPOLIS, predicted that the market size of linear accelerators will reach $5,049.9 million by 2023 [1].

A linear accelerator is a device that uses X-rays generated by accelerating electrons with high voltage and colliding them with a target; in some cases, electron beams themselves are used. The target plays an important role in generating X-rays through interaction with electrons, and X-ray generation is influenced by parameters such as atomic number, mass number, and thickness of the target's constituent elements [2,3]. Also, depending on the threshold energy of the target elements, photo-neutrons, a by-product of photo-nuclear reactions, may be generated simultaneously from the target and the collimator [4,5].

Studies on radiation, photo-neutrons, and photon emission characteristics according to targets are underway. In addition, several studies related to photo-neutron detection and energy spectrum acquisition have been conducted [6–8]. The National Council on Radiation Protection and Measurements (NCRP) Report No. 79 also mentioned the amount and risk of photo-neutrons generated by photon interaction in the head of linear accelerators in various energy regions [9].

The target has difference composition and thickness of elements depending on the energy of each electron occurred. Therefore, research on emission characteristics from source term is necessary to know photon conversion efficiency and particle behavior, but it is insufficient. In particular, unlike accelerators used for CSI in the industrial field, medical linear accelerators generate various energy ranges. This means that it affects patient exposure, and it is necessary to evaluate the radiological impact of each energy by target.

The purpose of this study was to quantitatively evaluate the source term according to the target materials and thicknesses in the linear accelerator head for the electronic energy region of 6–20 MeV using MCNP6, one of the Monte Carlo codes.

2. Methods and materials

Monte Carlo N-Particle6 (MCNP6) developed by Los Alamos National Laboratory (LANL), USA was used. MCNP6 was first

* Corresponding author.
E-mail address: rad112018@inje.ac.kr (C.-H. Lee).

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developed for general purposes in 1977 and can simulate various interactions with high energy photons and the physical movement of radiation particles [10].

The linear accelerator head unit consists of a target, a primary collimator, and a jaws accessory. The materials used for the target are tungsten and copper. Tungsten has a high atomic number, so it generates high energy X-rays, has excellent efficiency and a high melting point, and can generate X-rays via interaction with incident electrons in the accelerating tube. Copper has excellent thermal conductivity, so it disperses the heat generated during the interaction process and stops the movement of electrons [11,12]. We simulated composite targets and single targets in the MCNP6 by setting different component and thickness parameters according to energy, as shown in Table 1 [13]. The target structure is shown in Fig. 1.

Electron energy was applied at 6, 8, 10, 15, 18, and 20 MeV to evaluate the energy accumulation characteristics according to the thickness of the source term. To comply with the MCNP recommendation, we maintained the relative reference error for calculated simulation results below 3%, and the results represent mean probabilistic values for primary electrons [14]. F6 tally cards (unit: MeV/g) were used to evaluate the accumulation of energy caused by the electron-target interaction at 0.1-mm intervals for each target element. The density of the target tungsten and copper was 19.30 and 8.96 g/cm3, respectively, and the composition of each element is shown in Table 2.

Also, the angular distribution of secondary photons generated from the interaction with the target for 6-20 MeV photon energy was analyzed. At this time, based on the irradiation track of electrons in the sphere centered on the target, 180° was divided at intervals of 0°–10° as shown in Fig. 2, and photon flux was evaluated through F4 tally cards. Among the various regions, the X-ray irradiation field angle from the head of linear accelerator to the patient surface was analyzed up to 30° [15].

3. Results

We evaluated the characteristics of the source term for various electron beam energies by thickness. As shown in Fig. 3, at electron beam energies of 6, 15, and 18 MeV, it was confirmed that among the electrons that collided with the target, most of the primary particles were stopped within the target. However, with 8 and 10 MeV energy and a single target, the movement of electrons was confirmed through F6 tally at the end of the target. At this time, the ratio of the exiting electrons was 0.00011% and 0.00181%, respectively, compared to the total ratio.

The energy accumulation peak points from 6, 8, 10, 15, 18, and

Table 1
Target thicknesses with photon energy.

Photon energy [MV]	Thickness of target materials [mm]	
	Tungsten	Copper
6	0.8890	1.5748
8	-	5.0800
10	-	5.0800
15	0.6350	7.9248
18	0.6350	10.1600
20	0.6350	10.1600

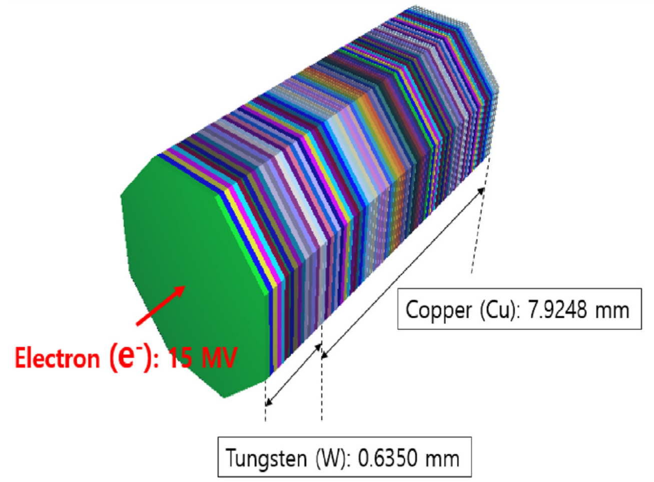

Fig. 1. An example of target structure for photon generation at 15 MV photon energy.

Table 2
Material composition of target elements.

Element	Isotope	Content ratio [%]
Tungsten (W)	180-W	0.120
	182-W	26.498
	183-W	14.314
	184-W	30.642
	186-W	28.426
Copper (Cu)	63-Cu	69.170
	65-Cu	30.830

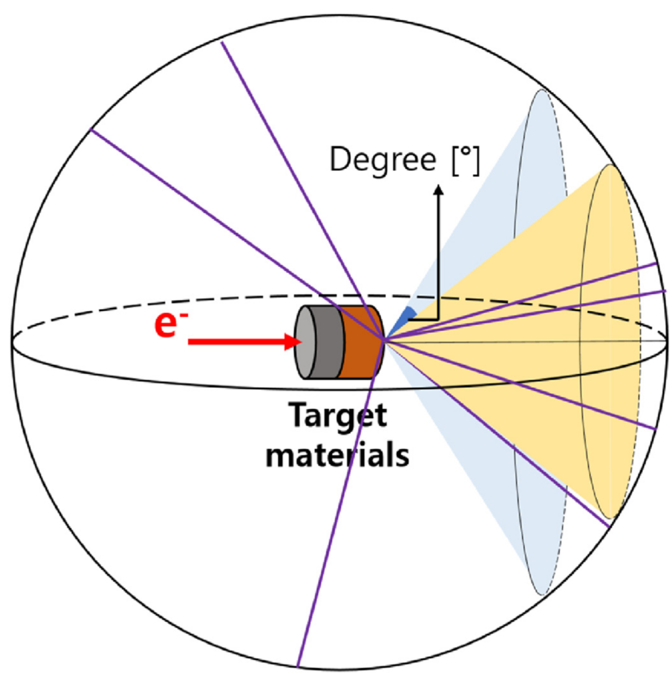

Fig. 2. A schematic diagram for angular distribution of secondary photons.

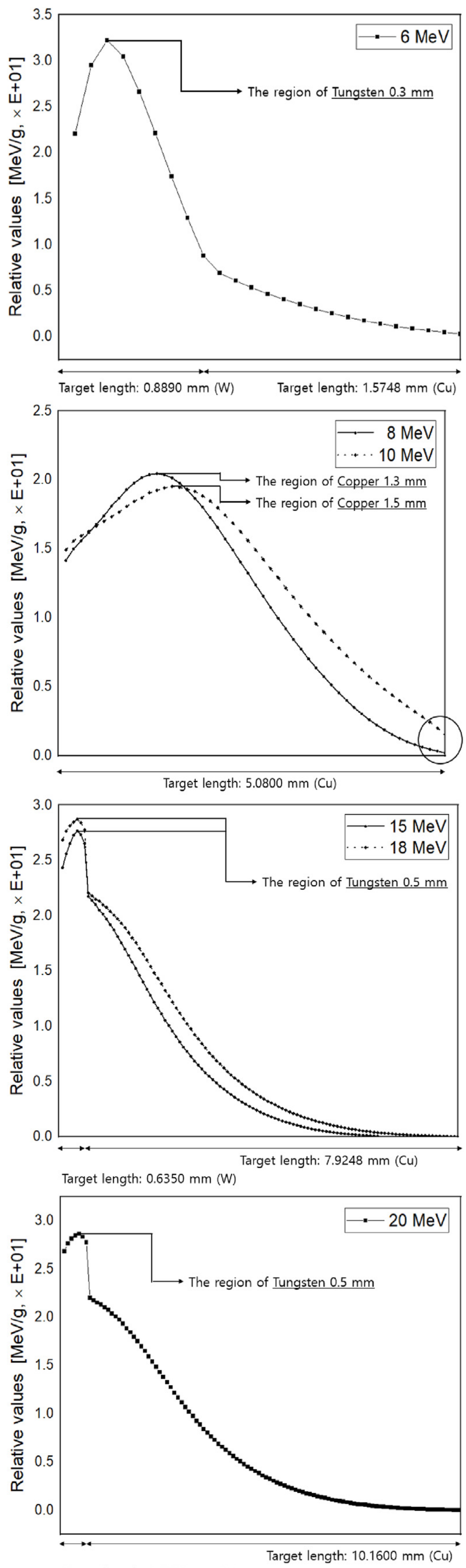

Fig. 3. Evaluation of energy deposition by target thickness according to electron beam energy.

20 MeV electron beam energies identified within each target were 0.3 mm in tungsten, 1.3 mm in copper, 1.5 mm in copper, 0.5 mm in tungsten, 0.5 mm in tungsten, and 0.5 mm in tungsten. As the energy increased, a peak point formed near the rear of the target. In addition, energy peak points at 15, 18, and 20 MeV utilized as composite targets were identified in the tungsten part of target. After that, energy was absorbed by copper in the rear and rapidly disappeared. The average result error for all energy regions was less than 3%. At 6 MeV, very few electrons reached the 2.1-2.3 mm point after passing the 0.3 mm point of tungsten in the target, which is the accumulation peak point, and the error tended to increase.

As a result of the angular flux distribution of the secondary photons, as illustrated in Fig. 4, the ratio of photons contained within the X-ray irradiation angle of 10°, 20°, and 30° was relatively high. In addition, single and composite targets were confirmed through energy deposition and angular distribution graphs. Photon conversion occurs better in 6, 15, 19, and 20 MeV targeted with composite materials (Tungsten + Copper), compared to 8, 10 MeV targeted with single materials (Copper), and distribution within 30° also shows a gentle slope in the low energy section.

4. Discussion

Through this study, we evaluated the source term for the target in the head of a medical linear accelerator. Six 6-20 MeV energies were selected, and both composite and single material targets were compared and analyzed through simulation with a MCNP6, the Monte Carlo code tool. Simulation results showed that in a composite target of tungsten and copper, the energy accumulation peak point occurred in tungsten through F6 tally cards, then absorbed into copper elements and disappeared rapidly. This means that the difference between the density of each target and the ratio of the interaction by atomic number affected. In contrast to linear accelerators used in industry field with limited energy (mainly 9 MeV), linear accelerators in the medical field have a wide range of energy used. This is directly related to photoneutron generation considering the threshold energy of the target materials, and subsequent activation studies should be conducted. In addition, in the industry, electron beams are rarely used directly, but the clinic is mainly used to treat superficial cancer such as skin cancer, breast cancer, etc.

In the 8 and 10 MeV experiments with single target, trace amounts of electron movement were identified at the target end. Considering the values of 0.00011% and 0.00181%, respectively, compared to the total ratio of incident electrons, it is thought to be intended to reduce the occurrence of photon-neutrons. This is because the threshold energy of the photo-nuclear reactions of tungsten is 7.41 MeV, and in the case of copper, it is 9.91 MeV or more. However, particles from the target in the linear accelerator head must pass through the primary collimator and jaws in the process of being released. In addition, in some cases, a multileaf collimator is used, so it is unlikely that escaped electrons will be released and contribute to the exposure dose.

And, the reason why the secondary photon flux is low at 0° in Fig. 4 is that the horizontal bottom surface of other angular regions has a ring shape, and the area is relatively large. But, it is judged that 0° takes into account a narrow cone base area with a cosine angle of 5°.

There are two limitations to this study. First, only energy accumulation at the target for electrons was considered. Therefore, the efficiency of conversion to photons was not considered. Second, the results were not measured and analyzed experimentally, but were simulated in Monte Carlo code. Accordingly, the linear accelerator head parts were designed to be geometrically simple.

Future simulation studies should explore photon distribution based on electron beam energy and target angle and thickness, and further radio-activation analysis characteristic research is needed.

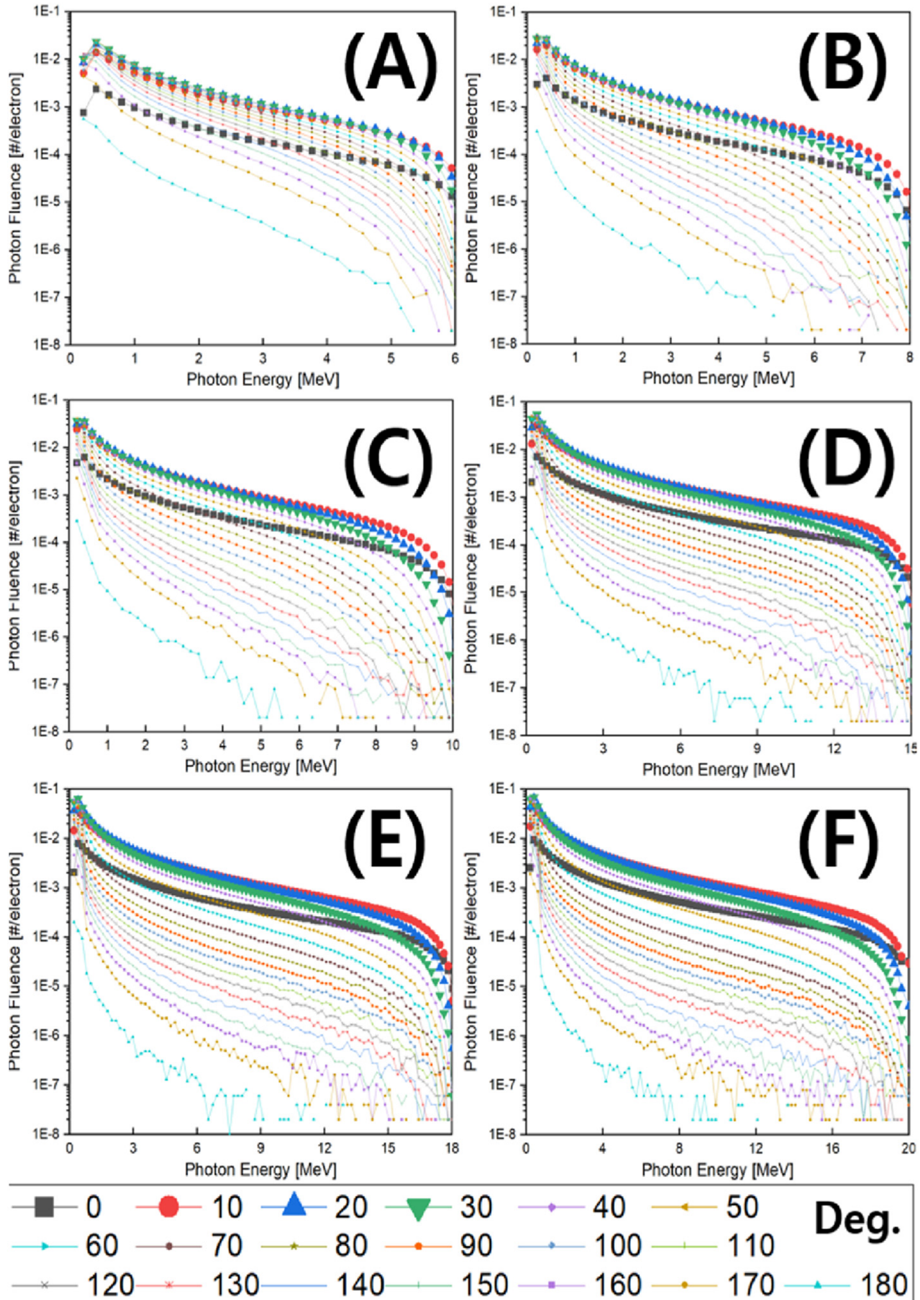

Fig. 4. Secondary photon flux distribution by angular region (A) 6 MeV (B) 8 MeV (C) 10 MeV (D) 15 MeV (E) 18 MeV (F) 20 MeV.

5. Conclusion

Using MCNP6, a Monte Carlo code tool, this study quantitatively evaluated the linear accelerator source term according to composite and single target thickness in the linear accelerator head at electron beam energies in the 6-20 MeV region. The simulation was conducted in compliance with the MCNP recommendations, maintaining a relative reference error below 3%, and the F6 tally cards tool was used. In composite targets including tungsten, electron beam energy accumulation peaked at relatively short distances due to the high density of tungsten. However, energy accumulation peaks for 8 and 10 MeV using a single target consisting only of copper elements were identified at depths of 1.3 and 1.5 mm, respectively, with 0.00011% and 0.00181% proportions of electrons escaping. This research provides a foundation for further research on the source term. A photon distribution study using the same targets utilized in this study should be conducted, and radioactivation analysis of each component of the linear accelerator would also be useful.

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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