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Research paper

A Study on Photoneutrons Generated in a Linear Accelerator Head using GEANT4

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Abstract

Medical linear accelerators use high energy for treatment of deeply located tumors. However, linear accelerators using energy above 6 MeV are likely to cause photoneutron contamination. In this paper, we analyzed photoneutrons generated in a linear accelerator head using GEANT4 (GEometry ANd Tracking) simulation. From the simulation results, it was confirmed that the generation of photoneutrons increases in the linear accelerator head as higher the energy of the electron beam.

Keywords: *Radiotherapy, Radiation protection, Linear accelerator, Photoneutron, GEANT4*

1. Introduction

A typical device used in radiotherapy is a medical linear accelerator [1]. Medical linear accelerators kill cancer cells by concentrating the radiation beam on the cancer cells [2]. Recently, medical linear accelerators use high energy photon beams to kill cancer cells located in the deep parts of the human body.

The photoneutrons are produced by excitation of high atomic materials whenever the energy of the photons exceeds the threshold energy of the photonuclear reaction for the material contained in the components of the linear accelerator head [3, 4]. The generated photoneutrons cause the activation of the linear accelerator head and the treatment room [5, 6]. In addition, it causes radiation exposure to the treated patient and the radiation worker [7]. Therefore, a study on radiation protection considering photoneutrons is required [8].

The priority of radiation protection is to analyze the dose distribution in the treatment room. For these, the dose distribution of the photons generated by the interaction between the accelerated electrons and the target in the linear accelerator head should be measured. In addition, the dose distribution of neutrons generated by the interaction between the photons and the materials in the treatment room should be measured. Monte Carlo simulation has been used in studies to analyze dose distributions because neutrons with continuous energy distributions are difficult to make clinical measurements [9]. The conventional studies using Monte Carlo simulation for radiation protection have analyzed the dose distribution of the photons and the neutrons in linear accelerators and treatment rooms [10, 11]. The conventional studies considering photoneutrons have analyzed the dose distribution of photoneutrons on the walls of the treatment room [12]. However, the dose distribution of photoneutrons in the linear accelerators head was not studied sufficiently.

Monte Carlo simulation calculates particle transport and dose distribution according to material properties. Monte Carlo simulations used in the studies for radiotherapy are EGSnrc, MCNP, and GEANT4 [13, 14]. GEANT4 among Monte Carlo simulations has been increasingly used in medical physics because it has been proven to be reliable in conventional studies [15, 16]. In this paper, we analyze the dose distribution of photoneutrons generated in linear accelerator head using GEANT4.

2. Linear Accelerator Head Modeling and Simulation

We modeled the linear accelerator head except for the acceleration tube by simplifying the equipment used in clinical practice. The modeled linear accelerator head consists of the target, the primary collimator, the flattening filter, and the secondary collimator as shown in Figure 1. The materials of the modeled linear accelerator head were set as shown in Table 1 with reference to the conventional study [11, 12].

In order to analyze photoneutrons generated from the modeled linear accelerator head, GEANT4 9.10 p02 [17] was used to simulate. The particle transport method and the cross section data are sourced from GEANT4 physics reference manual [17], and materials are defined by NIST [18]. Simulations for measuring the photons and neutrons generated in the linear accelerator head are performed as follows. First, the electron beam is irradiated perpendicular to the target surface from a position 1 mm above the target of the linear accelerator head. When the electron beam is incident perpendicular to the target, the photons generated by the interaction between the electrons and the target material scatter. When the photons are incident on the components of the linear accelerator head, neutrons generated by the interaction between the photons and the material of that component scatter. The photons and neutrons generated in this process were measured, and the simulations were repeated 10^8 times to minimize statistical uncertainty.

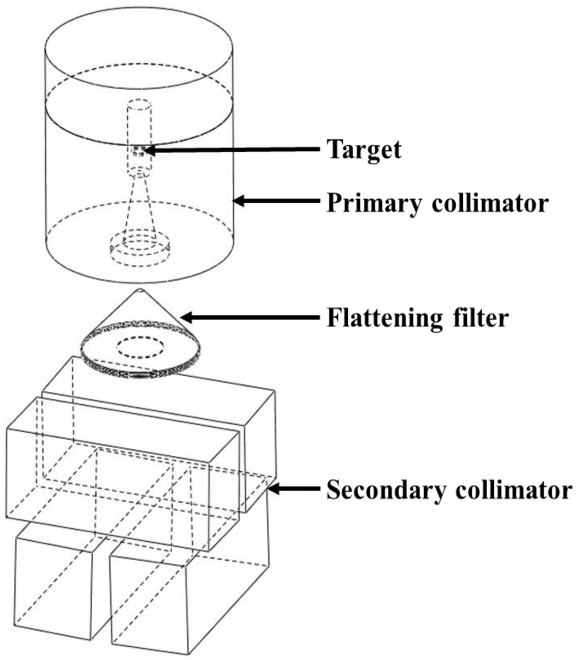

Fig. 1: The structure of the modeled linear accelerator head

Table 1: The materials of the modeled linear accelerator head

Component	Material
Target	Tungsten, Copper
Primary collimator	Tungsten
Flattening filter	Copper
Secondary collimator	Tungsten

3. Experiment and Discussion

In order to analyze photoneutrons generated by photonuclear reaction, it is necessary to analyze photons that can cause photonuclear reaction. Photons are generated by the interaction between electrons and targets. Therefore, photons generated by irradiating the target with 6, 8, 10, 15, 20, 25, and 30 MeV electron beams were measured as shown in Table 2. The abundance in Table 2 means the ratio of photons over 7.41 MV (threshold energy for photonuclear reaction of tungsten) to all photons. From the measurement results, it was confirmed that photons over 7.41 MV are increased as higher the energy of the electron beam.

In order to analyze the photoneutrons characteristics in the linear accelerator head, neutrons generated by irradiating the target with 10, 15, 20, 25, and 30 MeV electron beams were measured. Neutrons have different cross section depending on energy, and especially have a large cross section in thermal neutron. In addition, since neutrons have a high relative biological effectiveness, even small doses can be harmful to the patient. Therefore, the ratios of thermal neutrons (0~1 eV), epithermal neutrons (1~10 keV), and fast neutrons (10 keV~10 MeV) were analyzed in consideration of the properties of neutrons.

The neutron fluence spectrum measured at the target was below 9 MeV as shown in Figure 2. The average ratios of thermal neutrons, epithermal neutrons, and fast neutrons were 1 %, 2 %, and 97 %, respectively, as shown in Table 3.

The neutron fluence spectrum measured at the primary collimator was below 4 MeV as shown in Figure 3. The average ratios of thermal neutrons, epithermal neutrons, and fast neutrons were 10 %, 5 %, and 85 %, respectively, as shown in Table 4.

The neutron fluence spectrum measured at the flattening filter was below 6 MeV as shown in Figure 4. The average ratios of thermal neutrons, epithermal neutrons, and fast neutrons were 4 %, 3 %, and 93 %, respectively, as shown in Table 5.

The neutron fluence spectrum measured at the secondary collimator was below 4 MeV as shown in Figure 5. The average ratios of thermal neutrons, epithermal neutrons, and fast neutrons were 5 %, 4 %, and 91 %, respectively, as shown in Table 6.

Table 7 shows the ratio of the neutrons (see Table 3-6) measured in components of the linear accelerator head to the all photons (see Table 2). The ratio of photon-to-neutron is higher in order of the target (1.09E-03), the primary collimator (1.64E-04), the flattening filter (9.21E-05), and the secondary collimator (9.22E-06). From these results, it can be seen that the generation of neutrons is affected by the distance from the source. However, the ratio of thermal neutron is higher in order of the primary collimator (10 % in Table 4), the secondary collimator (5 % in Table 6), the flattening filter (4 % in Table 5), and the target (1 % in Table 3) regardless of distance. Thermal neutrons are an important factor to consider in terms of radiation protection because they have a greater impact on activation to higher nuclear reactions than other neutrons. These results are considered to be due to the material of linear accelerator head components.

Table 2: The photons measured at the target (unit: photon/cm^2/e)

Beam energy	Over 7.41 MV	All	Abundance
6 MeV	0	0.08	0 %
8 MeV	9.35E-05	0.13	0.07 %
10 MeV	1.78E-03	0.18	0.97 %
15 MeV	1.19E-02	0.28	4.24 %
20 MeV	2.48E-02	0.34	7.19 %
25 MeV	3.70E-02	0.38	9.63 %
30 MeV	4.79E-02	0.41	11.65 %

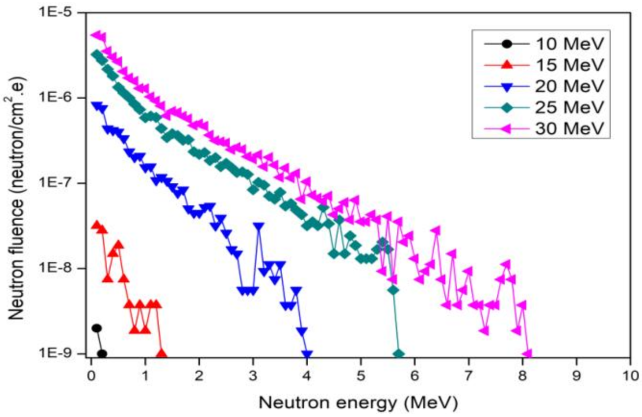

Fig. 2: The neutron fluence spectrum measured at the target

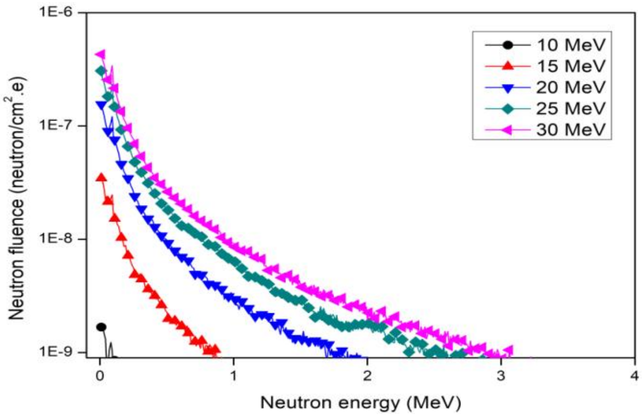

Fig. 3: The neutron fluence spectrum measured at the primary collimator

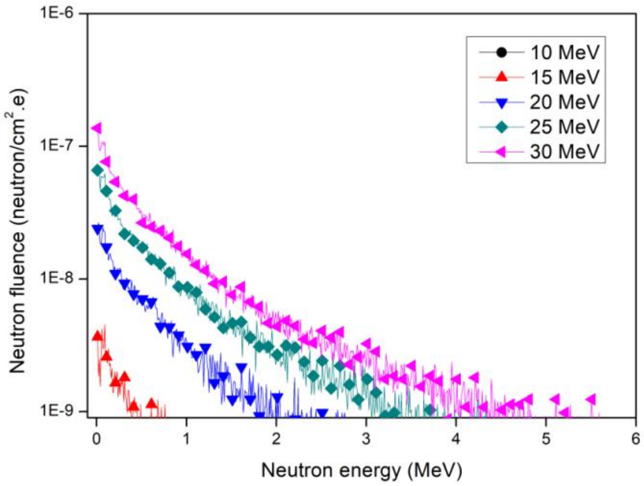

Fig. 4: The neutron fluence spectrum measured at the flattening filter

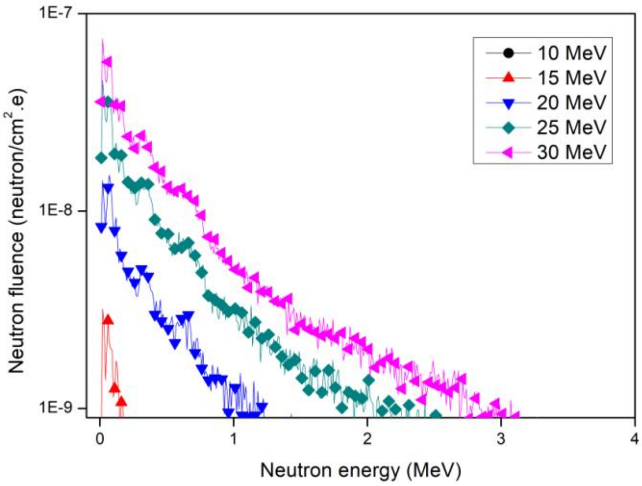

Fig. 5: The neutron fluence spectrum measured at the secondary collimator

Table 3: The neutrons measured at the target (unit: neutron/cm^2/e)

Neutron	Beam energy					Average	Ratio
	10 MeV	15 MeV	20 MeV	25 MeV	30 MeV		
Thermal	0	6.53E-08	2.03E-07	3.88E-07	5.63E-07	2.44E-07	1 %
Epithermal	1.87E-09	9.51E-08	5.19E-07	8.66E-07	9.74E-07	4.91E-07	2 %
Fast	1.34E-07	5.23E-06	2.21E-05	4.01E-05	5.33E-05	2.42E-05	97 %
Total	1.36E-07	5.39E-06	2.29E-05	4.13E-05	5.49E-05	2.49E-05	100 %

Table 4: The neutrons measured at the primary collimator (unit: neutron/cm^2/e)

Neutron	Beam energy					Average	Ratio
	10 MeV	15 MeV	20 MeV	25 MeV	30 MeV		
Thermal	1.39E-09	6.63E-08	3.02E-07	6.11E-07	8.98E-07	3.76E-07	10 %
Epithermal	1.85E-09	3.02E-08	1.50E-07	2.91E-07	4.11E-07	1.77E-07	5 %
Fast	2.13E-08	5.89E-07	2.65E-06	5.23E-06	7.59E-06	3.21E-06	85 %
Total	2.46E-08	6.86E-07	3.1E-06	6.13E-06	8.9E-06	3.77E-06	100 %

Table 5: The neutrons measured at the flattening filter (unit: neutron/cm^2/e)

Neutron	Beam energy					Average	Ratio
	10 MeV	15 MeV	20 MeV	25 MeV	30 MeV		
Thermal	0	2.47E-09	4.60E-08	1.31E-07	2.43E-07	8.45E-08	4 %
Epithermal	0	5.46E-09	3.36E-08	9.40E-08	1.54E-07	5.74E-08	3 %
Fast	1.39E-09	1.37E-07	1.17E-06	3.14E-06	5.67E-06	2.02E-06	93 %
Total	1.39E-09	1.45E-07	1.25E-06	3.37E-06	6.06E-06	2.17E-06	100 %

Table 6: The neutrons measured at the secondary collimator (unit: neutron/cm^2/e)

Neutron	Beam energy					Average	Ratio
	10 MeV	15 MeV	20 MeV	25 MeV	30 MeV		
Thermal	3.79E-12	3.56E-10	5.55E-09	1.63E-08	2.98E-08	1.04E-08	5 %
Epithermal	2.08E-10	4.62E-10	6.50E-09	1.44E-08	2.64E-08	9.59E-09	4 %
Fast	9.09E-11	1.39E-08	1.12E-07	3.10E-07	5.47E-07	1.97E-07	91 %
Total	3.03E-10	1.47E-08	1.24E-07	3.41E-07	6.03E-07	2.17E-07	100 %

Table 7: The ratio of photon-to-neutron (unit: %)

Component	Beam energy					Average
	10 MeV	15 MeV	20 MeV	25 MeV	30 MeV	
Target	1.24E-05	3.18E-04	1.10E-03	1.79E-03	2.22E-03	1.09E-03
Primary Collimator	2.24E-06	4.04E-05	1.50E-04	2.66E-04	3.60E-04	1.64E-04
Flattening filter	1.27E-07	8.53E-06	6.05E-05	1.46E-04	2.46E-04	9.21E-05
Secondary Collimator	2.76E-08	8.69E-07	6.00E-06	1.48E-05	2.44E-05	9.22E-06
Average	3.70E-06	9.19E-05	3.29E-04	5.54E-04	7.13E-04	-

4. Conclusion

In this paper, we analyzed the photoneutrons generated in the linear accelerator head using GEANT4 simulation. The simulation results show that the number of neutrons measured in the components of the linear accelerator head is average 0.003 % less than the number of photons. However, the neutron measured in GEANT4 simulation is the amount measured based on one electron. Photoneutrons generated in the linear accelerator head cannot be ignored considering the number of incident electrons used in actual radiotherapy. Furthermore, the possibility of activation due to the photoneutrons is predicted to be high enough considering the operation period of linear accelerators. Therefore, the linear accelerator will have to be improved considering the photoneutrons. In order to improve the linear accelerator, precise analysis of the photoneutrons must be preceded. We measured thermal neutrons, epithermal neutrons, and fast neutrons classified by the neutron energy in each component of the linear accelerator head because neutrons have different effects depending on energy. In the future, we expect that these measurement results will be used as basic data for improving linear accelerators.

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