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Electron Energy Distribution for a Research Electron LINAC

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The energy distribution was calculated for an electron beam from an electron linear accelerator developed for medical applications using computational methods. The depth dose data for monoenergetic electrons from 0.1 MeV to 8.0 MeV were calculated by the DOSXYZ/nrc code. The calculated data were used to generate the energy distribution from the measured depth dose data by numerical iterations. The measured data in a previous work and an in-house computer program were used for the generation of energy distribution. As results, the mean energy and most probable energy of the energy distribution were 5.7 MeV and 6.2 MeV, respectively. These two values agreed with those determined by the IAEA dosimetry protocol using the measured depth dose.

Keywords: Energy distribution, Electron LINAC, Mean Energy

Introduction

A study on the development of a medical linear accelerator (LINAC) has been actively conducted by a research center in Korea. The researchers reported on the development of a 4-MeV compact LINAC and electron beam output dose in 2015, as well as electrical and dosimetry characteristics of the electron LINAC with increased energy to 6 MeV in 2016.[1,2] Currently, studies on performance improvements in high-energy accelerator tubes, pulse modulators, and control systems have been underway to develop an optimal therapeutic radiation source.[3,4]

Although it is important to determine the electron energy or energy distribution generated in the LINAC in terms of the development and operation of a medical electron LINAC, it is highly difficult to construct an energy analysis system such as a magnetic mass spectrometer on a small scale for a laboratory environment. Thus, it is more practical to apply a method that predicts only the mean energy and most probable energy from the measured depth dose ratio, as reported previously.[5]

Although these two energy parameters are important in measuring the absorbed dose in terms of clinical viewpoints, their energy distributions may not be important. Nonetheless, an energy distribution needs to be obtained in order to determine the characteristics and performance of accelerators from the viewpoint of the development of an accelerator. This can also be important data for research on devices such as a bending magnet.

The present study aims to calculate an energy distribution of electron beams in the developed 6-MeV electron LINAC using a numerical analysis method. The present method obtains a combination of depth dose ratio that is well matched with the measured depth dose data through iterative numerical operations via computer programs using monoenergetic depth dose data. This approach was proposed by Kaver et al. in 1982,[6] and Lee and Jeong applied this method to acquire the energy distribution of four types of electron beam energy in a medical LINAC

from Siemens.[7]

In a previous study,[7] calculations based on EGS4 code[8] were conducted to generate monoenergetic depth dose data. However, the present study employed advanced EGSnrc code[9] and increased energy resolution by increasing the number of computations.

The present paper presents the computation code and details about the electron LINAC and dose measurement, in addition to the determination process of energy distribution in the Materials and Methods section. Furthermore, the Result and Discussion section discusses the depth dose ratio and energy distribution for monoenergetic electrons, thereby presenting the mean energy and most probable energy obtained via measurements of the depth dose ratio and a numerical analysis. In the Conclusions section, the calculated results are discussed.

Materials and Methods

1. Energy distribution

The energy of an electron beam is close to that of a monoenergetic beam at the outlet of the accelerator tube, but it has a wider energy distribution at the phantom surface owing to energy loss and multiple scattering as it passes through a scattering foil.[5]

Assuming that the number of electrons of energy, which is incident at the phantom surface between energy E and E+dE, is dN(E), a differential type $\frac{dN(E)}{dE}$ can be expressed as the energy distribution. Assuming that the energy distribution of electrons at the phantom surface can be known when electron beams are irradiated on the phantom, an absorbed dose at depth d can be expressed as follows:

$$D(d) = \int_0^{E_{max}} \frac{dN(E)}{dE} D_1(E,d)\, dE \qquad (1)$$

where $D_1(E,d)$ refers to an absorbed dose at depth d when a single electron with energy E is incident at the phantom surface. Given that D(d) and $D_1(E,d)$ are available, an energy distribution that is well matched with measured results can be determined through an iterative numerical operation.

2. Numerical analysis

The numerical data about energy distribution and depth are discontinuous data, and the integral calculus of (1) can be expressed to compute them as follows:

$$D_{cal,j} = \sum_{i=1}^{n} N_i D_{1ij} \qquad (2)$$

where N_i refers to the number of electrons of energy bin i at the phantom surface. $D_{1,ij}$ refers to an absorbed dose at the depth that corresponds to bin j when the monoenergetic electron that corresponds to energy bin i is incident at the phantom. Thus, $D_{cal,j}$ is equivalent to an absorbed dose at depth bin j when a certain energy distribution is given. Given that the measurement value at depth j is $D_{mea,j}$, the following calculation can be performed with regard to a pair of energy distributions N_1, N_2 ... N_n.

$$\lambda = \sum_{j=1}^{m} \sum_{i=1}^{n} [N_i D_{1,ij} - D_{mea,j}]^2 \qquad (3)$$

In the calculation in Eq. (3), an arbitrary N_i is inputted initially, and iterative calculations can be performed while changing N_i to $N_i \pm \delta$ in the direction of decreasing λ. Here, δ is a very tiny value compared to N_i. This calculation can be programmable. More details can be found in the paper of Lee and Jeong.[7] The present paper implemented the calculation process using the Fortran language.

The measured depth dose is standardized with regard to the maximum dose depth. Thus, iterative calculations are performed with regard to all depth bins j, followed by standardizing $D_{cal,j}$, and relative errors of the calculation results can be obtained as follows:

$$e = 100 \times \frac{1}{\langle D_{cal} \rangle} \sqrt{\frac{1}{m-1} \sum_{j=1}^{m} (D_{mea,j} - D_{cal,j})^2} \ [\%] \qquad (4)$$

The calculation is terminated when a relative error becomes lower than 0.2% during the iterative calculations. The present study result will present a depth dose obtained by calculation and measurement on the energy spectrum.

3. Mono-energetic depth dose

$D_{1,ij}$ given at Eq. (3) refers to a value with regard to the

monoenergetic electron, which cannot be determined by measurement. Thus, the present study employed a computational simulation method. The computer code used in this calculation is DOSXYZ/nrc,[10] developed by the National Research Council Canada (NRCC). This code is run by the Monte Carlo calculation engine called EGSnrc,[9] which has a feature that can read three-dimensional image data of patients to calculate a dose.

The medium used in the calculation of the monoenergetic depth dose was a 30 cm×30 cm×10 cm water phantom, whose side of the voxel that recorded an absorbed dose had a length of 1 mm. The input beam was a parallel electron beam with an area of 20 cm×20 cm at the phantom surface, and its cutoff energy was set to 10 keV. The material data used in the Monte Carlo calculation were 521ICRU.dat, which was generated through the PEGS4 code that was an auxiliary code of EGSnrc.[10] The data are contained in a database consisting of the cross-sectional area and restricted stopping power required to calculate interactions between water and electrons or photons. In the calculation of the absorbed dose, the data of restricted stopping power that is calculated with an upper limit of the energy secondary electron (10 keV) are contained.

The history of the calculation was set to 40,000,000, and the preliminary calculation results showed that the statistical error was less than 0.3% up to a depth of R_{50}. The calculation was performed with an energy of incident electrons from 0.1 MeV to 8.0 MeV with a 0.1-MeV interval through the above calculation environment, thereby obtaining 80 types of monoenergetic depth dose data, which were then applied to the calculation in Eq. (3).

4. Measured depth dose

The electron accelerator used in the present study was manufactured in 2015 for the purpose of research and development. It creates electron beams of about 6 MeV by supplying 2.5-MW high-frequency power generated from the C-band magnetron to the accelerator tube.[2] The electron beams emitted from the outlet of the accelerator tube are spread widely via the scattering foil, and form an irradiation surface of 20 cm×20 cm by the applicator. The measured depth dose applied to the numerical operation in the present study was presented in a paper of Lim et al.,[2] which used the same equipment. It was obtained at the closest operating condition of the accelerator used in a nominal-energy 6-MeV medical LINAC. The data are depth doses determined using Gafchromic EBT film measurements, and Fig. 1 shows the device geometry used in the measurement.

Results and Discussion

Fig. 2 shows the energy distribution of electron beams finally calculated through the above process. As shown in the figure, the energy distribution is up to 7 MeV, but the highest frequency is revealed at 6.2 MeV, while a small number of electrons are also found at 2~4 MeV. They are regarded as electron beams scattered by the scattering

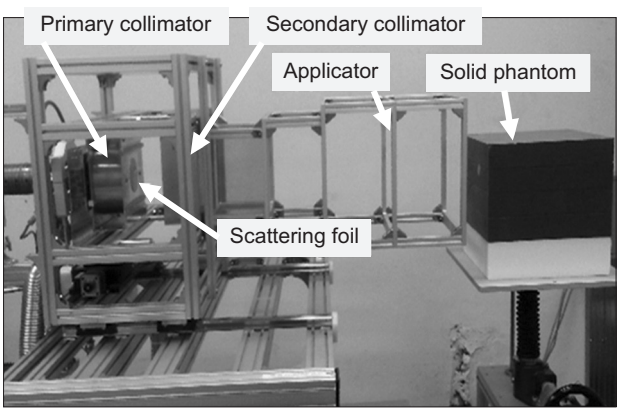

Fig. 1. Geometry of electron beam dosimetry for measurement of depth dose in solid phantom.

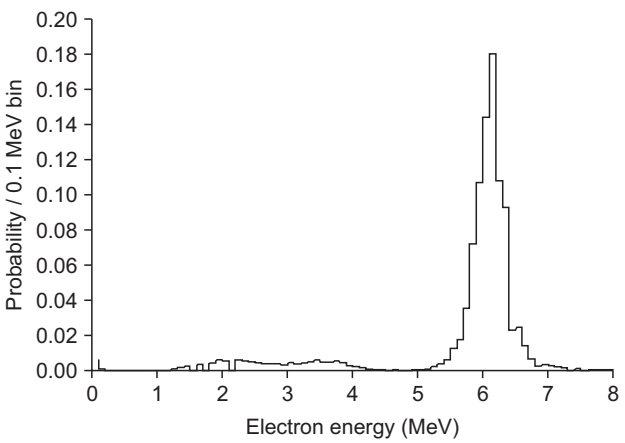

Fig. 2. Calculated energy distribution (normalized) for research LINAC in this study.

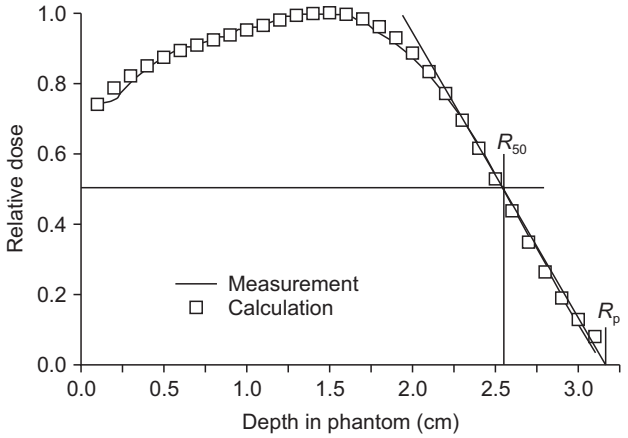

Fig. 3. Measured and calculated depth dose data. In calculations, energy distribution of Fig. 2 and film dosimetry data in previous work[2] were used.

foil and applicator. The electron distribution in the data showed that 12.7% of them were distributed below 5 MeV, 86% were distributed between 5 MeV and 7 MeV, and around 1% were distributed above 7 MeV.

Fig. 3 shows the depth dose ratios determined by measurements and calculations. Here, the measurement results were derived from a previous study, and the calculation results were obtained by applying the energy distribution in Fig. 2 to Eq. (2). The difference between the measurement and calculation results was about 0.2% on the basis of an evaluation using Eq. (4). In the figure, R_p and R_{50} refer to factors to obtain the most probable energy and mean energy according to the IAEA protocol,[5] and are R_p= 3.2 g/cm^2 and R_{50}= 2.6 g/cm^2, respectively.

The mean energy can be calculated given that the energy distribution in Fig. 2 is supplied.

$$\overline{E} = \sum_i p_i E_i \quad (5)$$

where p_i refers to the frequency of standardized electrons with regard to energy bin i, and E_i refers to energy of energy bin i. Table 1 summarizes the most probable energy and mean energy determined through the above method.

The two results as shown in the above table are well matched within around 0.2 MeV, or 3% in terms of relative value. The measurement values were slightly higher than the corresponding calculated values, which was a result of the inclusion of uncertainties during the application

Table 1. Comparison of measured and calculated energy parameters in previous work and this study.

	Measured	Calculated
Most probable energy	6.4±0.2 MeV	6.2±0.1 MeV
Mean energy	5.9±0.2 MeV	5.7±0.1 MeV

process of the protocol and the uncertainty of the film measurement using solid phantom. Considering this, the two results are deemed to be consistent.

The most probable energy is evaluated via practical range R_p, and the mean energy is evaluated via quality factor R_{50} according to the IAEA protocol.[5] Since about 0.1 cm of error can be revealed in the depth estimation, 0.2 MeV of uncertainty can be presented. The calculation results have also uncertainties according to the size of the energy bin. The deviation shown in Table 1 indicates this uncertainty.

Since the energy distribution of electron beams over 1 MeV is considerably difficult to be measured with general detectors, a mass analysis method using a magnetic field is regarded as the only method to measure the distribution. Nonetheless, it is important to determine an approximate trend using only depth dose ratios measured via the above method in the present study. Although a method that can obtain the energy distribution of electron beams using a Monte Carlo calculation has been proposed by Rogers et al.[11] with regard to a medical LINAC, it has a problem in that is difficult to determine information about the initial beam emitted from the outlet of the accelerator tube. Thus, it is necessary to develop a method that is improved by applying known methods in a future study.

Conclusion

The present study calculated an energy distribution of electron beams generated by an electron LINAC for research on radiation therapy, and compared values determined through known methods. The present study verified that these two values matched well. The method and results in the present study are expected to be utilized in characteristic data of an electron LINAC that is under development, as well as improvements in the performance of the electron LINAC. The method is also applicable to

other electron beams, and calculations can be done up to a wide range when monoenergetic data are available, even with regard to high energy up to 8 MeV or higher. Thus, the present method can be widely utilized in related research on the electron LINAC.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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