Original Article

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Measurement of Electron Beam Output for the Prototype Compact Linac

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The C-band compact linear accelerator (linac) is being developed at Dongnam Institute of radiological & Medical Sciences (DIRAMS) for medical and industrial applications. This paper was focused on the output measurement of the electron beam generated from the prototype electron linac. The dose rate was measured in unit of cGy/min per unit pulse frequency according to the IAEA TRS-398 protocol. Exradin-A10 Markus type plane parallel chamber used for the measurement was calibrated in terms of dose to water at the reference depth in water. The beam quality index (R_{50}) was determined by the radiochromic film with a solid water phantom approximately due to low energy electrons. As a result, the determined electron beam output was 17.0 cGy/(min · Hz). The results were used to monitor the accelerator performance during the development procedure.

Key Words: Electron beam output, TRS-398 protocol, Prototype linac

Introduction

The electron linear accelerator (linac) is widely used in the medical, industrial, and research fields.[1,2] In radiotherapy, 4 to 18 MeV electron beams are accelerated from the radio frequency (RF) linac and X-rays generated from the accelerated electrons hitting the target were used to treat the cancer. The electron beam is applied in many industrial fields such as making new product from chemical process, removing pollutants, and sterilization.[3] The nuclear data researches using neutrons generated by high energy X-rays can also be performed in a high energy electron beam facility.[4,5] The linac is being developed at Dongnam Institute of radiological & Medical Sciences (DIRAMS) for medical and industrial applications through the IRPE (Dongnam Institute for Regional Program Evaluation) R&D program. The compact linac consists of C-band accelerator guide, RF generator, wave guide elements, and pulse power modulator. The advantage of C-band linac is that the accelerating length is reduced with maintaining the power RF supply high enough to generate the high intensity X-rays. The initial version of compact linac at DIRAMS is designed to accelerate electrons up to 4 MeV. The linac would be upgraded in many aspects including beam energy, beam focusing, automatic control of the RF and dose, and beam monitoring and diagnosis.

The output measurement of the electron beam generated from the prototype C-band electron linac is the main topic in this paper. The output, which is an important parameters for evaluating the performance of a medical accelerator, is defined as the dose rate at the reference conditions in water. Because the output is directly proportional to the average beam current, the output can be deduced by measuring the beam current during the development procedure.

The TRS-398 protocol published by IAEA was used in this study.[6] The code of practice for reference dosimetry in clinical electron beams with energies from 3 MeV to 50 MeV was provided in the protocol. The calibration factor in terms of

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dose to water for the Co-60 beam quality and beam quality factor was determined by applying the TRS-398 protocol. This study would be used for evaluating the linac performance during the development procedure.

Materials and Methods

1. Prototype linac system

The prototype electron linac system consists of accelerator guide, magnetron, wave guide, pulse modulator, and vacuum and cooling system. The C-band on-axis coupled standing wave technology designed by PAL (Pohang Accelerator Laboratory) was adapted to the accelerating structure.[7] The pulse modulator supplied the pulsed power generated by PFN (pulse forming network) circuit to the magnetron via high voltage pulse transformer. The CCPS (Capacitor Charging Power Supply) device was used for charging capacitors to the PFN circuit with a maximum voltage of 15 kV. The high voltage pulse transformer provided approximately 40 kV and 100 A pulsed high power to the magnetron. The electrons were accelerated and emitted from the accelerating window radially by interaction with the window materials and the measured pulsed beam current was about 50 mA. The designed average and pulsed beam power were 200 W and 200 kW at a pulse length of 4 μsec and pulse frequency of 250 Hz (the number of pulses per second) in the maximum operation condition. The prototype system was equipped with the irradiation head and the electron applicator for shaping the electron field. The initial operations were performed with very low frequency pulse to avoid the high electrical power and to operate under the stable condition.

2. Beam quality index

In the IAEA protocol, the beam quality index for high energy electron beams was specified as the half-value depth in water, R_{50}.[6] Because the electron beam was irradiated to the horizontal direction and the expected beam energy was lower than 4 MeV, the measurement of full depth dose curve was challenging due to the thickness of the water phantom window. In addition, due to 1 mm thickness waterproof cap in a plane parallel chamber, depth dose curve containing the dose maximum could not be determined. Therefore, radiochromic film with the solid water phantom can be an alternative method to measure the electron beam quality of the system. The Gafchromic EBT3^{TM} (ISP, US) films and FilmQApro^{TM} (ISP, US) software were used for measurement and analysis. The mean energy and the most probable energy, the useful quantities to evaluate the electron beam energy at the phantom surface, can be determined from the R_{50} and R_p, where R_p is the practical range of the electron beam in water.[6]

3. Absorbed dose determination

The dose to water at the reference depth, z_{ref} with a beam quality Q, is given by,[6]

$$D_{W,Q}(z_{ref}) = M_Q \cdot N_{D,W,Q_0} \cdot k_{Q,Q_0} \tag{1}$$

where M_Q is the corrected reading of the electrometer and N_{D,W,Q_0} is the calibration factor in terms of absorbed dose to water for the reference beam quality, Q_0. The k_{Q,Q_0} is the correction factor to consider the difference between the reference beam quality Q_0 and actual beam quality Q. The z_{ref} is a reference depth for the given beam quality, and is given from ref. 6, $z_{ref} = 0.6R_{50} - 0.1\ \text{g/cm}^2$.

The Markus type Exradin-A10 ionization chamber was positioned in the PTW 41023 water phantom. At the chamber position, the phantom window thickness (0.35 g/cm^2) and the waterproof cap thickness (0.1 g/cm^2) were considered. The calibrated thermometer and barometer were used to correct the air density in the chamber cavity to the reference air density. The configuration of the accelerator, the irradiation head, and the measurement devices is shown in Fig. 1.

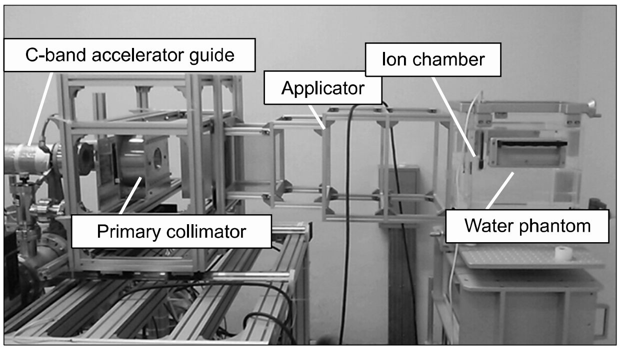

Fig. 1. The configuration of instruments for the measurement of output with accelerating structure and irradiation head.

The N_{D,W,Q_0}, calibration factor in terms of dose to water for a reference beam quality, was determined with a extended uncertainty of 1.0% from the standard laboratory. The beam quality factor k_{Q,Q_0} (≈ 0.960) was determined with the published values for the Markus chamber.[8]

The prototype linac was operated by the high power RF (radio frequency) generated from the magnetron. The pulsed power of several mega-watts was supplied from the pulse modulator system through the pulse transformer. The beam currents or the beam intensities could be varied by several factors including RF power, pulsed power, and vacuum and cooling conditions due to lack of automatic control functions such as AFC (automatic frequency control) in this prototype system. The measurements has been performed at the low pulse frequency of 5 Hz to provide the stable conditions during the measurement, although frequency can be increased up to 250 Hz. The maximum dose can be estimated by the linear relationship between the dose and the pulse frequency. The polarity, ion recombinations, and environmental conditions were applied to correct the output according to the TRS-398 protocol.

Results

The measured depth dose curve with film dosimetry for prototype electron linac was shown in Fig. 2. The R_{50} and R_p were determined by depth dose curve as shown in Fig. 2 (right). According to the IAEA TRS-277 protocol, the mean energy and the most probable energy at the phantom surface for the electron beam is calculated by,[9]

$$\bar{E} = 2.33\,R_{50} \approx 2.3\ \mathrm{MeV}, \tag{2}$$

$$E_p = 0.22 + 1.98R_p + 0.0025\,R_p^2 = 2.99 \approx 3.0\ \mathrm{MeV}. \tag{3}$$

The E_0 and R_p were used to determine the energy dependent parameters such as stoping power ratio at a given depth in the water phantom. The values could be used for measuring the dose at the arbitrary depth in water. However, at the particular depth z_{ref}, the overall correction factor for correcting beam quality k_{Q,Q_0} was given in the TRS-398 protocol.[6]

The measured results were summarized in Table 1. The raw charge measured from the chamber, M_{raw} was the average val-

Table 1. Applied values for the determination of dose for the electron beam from prototype linac in water.

Items	Values
Pulse frequency (f)	5 Hz (Maximum 250 Hz)
Measuring time	1 min
z_{ref}	0.5 g/cm^2
M_{raw}	1.438 nC±1.2%
k_{TP}	1.012
k_{pol}	0.999±1.4%
k_s	1.023±1.1%
N_{D,W,Q_0}	59.6 cGy/nC
k_{Q,Q_0}	0.960
$D(z_{ref})$	17.0 cGy/(min・Hz)
$D(z_{ref})$ for maximum pulse frequency	42.5 Gy/min

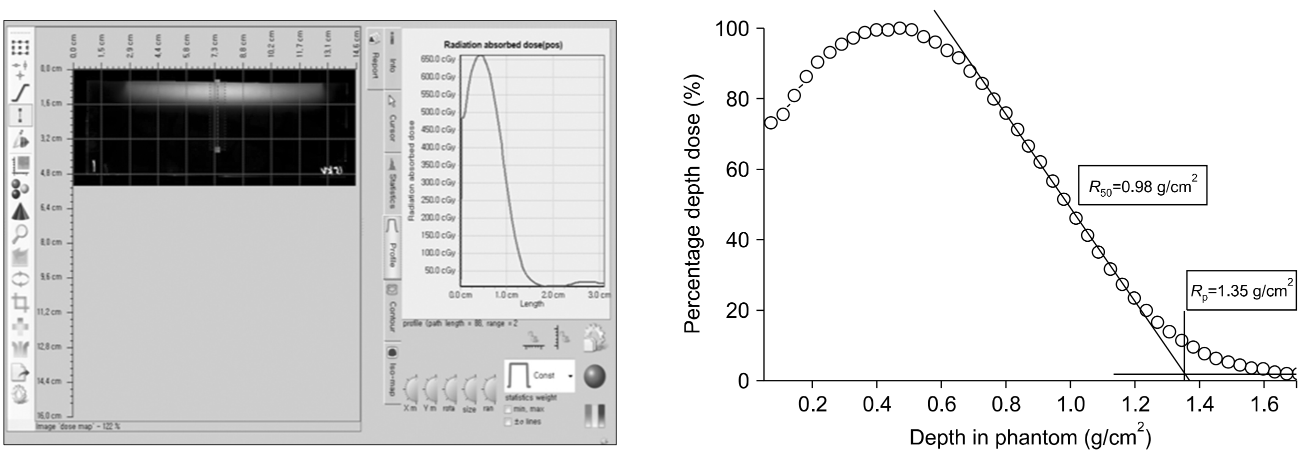

Fig. 2. Film dosimetry (left) and analysis of percentage depth dose curve (right) for electron beam from the prototype linac.

ues from five measurements, and the coefficient of variation was 1.2%. The recombination correction factor was derived from the two voltage technique using +200 and +400 V in polarizing voltage of the chamber. The polarity and recombination correction factors were determined by the average values from three measurements and the coefficient of variations were demonstrated in Table 1. The dose to water measured at reference depth z_{ref} was 85.1 cGy/min for 5 Hz pulse frequency and the dose rate for unit frequency was 17.0 cGy/(min·Hz) as shown in Table 1. The maximum electron output of 42.5 Gy/min with the pulse frequency of 250 Hz was predicted with the current linac system with optimized operation conditions and improved stability. The uncertainty estimation for the measured dose would be described in the next chapter in this paper.

Discussion and Conclusion

The output measurement of the electron beam generated from the prototype C-band electron linac was performed and the maximum output of 42.5 Gy/min was evaluated. A-type and B-type uncertainties were described in this measurements from the protocols.[6,9] The uncertainty from the directly measured values were estimated as the A-type uncertainty by dividing a standard deviation by square root of the number of measurements. The other uncertainty elements were estimated from the literatures such as the calibration certificate of the instrument and the code of practice in the protocols.[6,9] The total uncertainties estimated for these measurements were 2.2% as shown in Table 2.

Table 2. Estimated relative standard uncertainty for the output measurement.

Items	Uncertainty (%)	Note
Long term stability of dosimeter	0.4	TRS-398
Establishment of reference conditions	0.6	TRS-398
M_{raw}	0.5	A-type
k_{TP}	0.1	Certificate
k_{pol}	0.8	A-type
k_s	0.6	A-type
N_{D,W,Q_0}	0.5	Certificate
k_{Q,Q_0}	1.7	TRS-398
$D(z_{ref})$	2.2	

The prototype electron accelerating structure was designed to generate 4 MeV electron beam, but the beam energy at the exit window was difficult to measure directly. The mean energy of 2.3 MeV and the most probable energy of 3.0 MeV at the phantom surface were estimated from the depth dose curve. Therefore the current linac generated the 75% of the expected energy and the system should be tuned further to improve the operating conditions in RF power and frequency matching between resonance frequency in accelerating cavity and RF frequency. It is important that the electron beam energy was simply obtained from the depth dose curves without a complex system such as mass spectrometer or a detector system. The lower limit in the quality index, R_{50}, by applying TRS-398 dosimetry protocol, was approximately 1.0 g/cm^2, which corresponds to the mean energy of 2.33 MeV. No dosimetry protocols could be applied for the beam energy lower than 2.33 MeV, because current dosimetry protocols were developed for the clinical electron beams higher than 3 MeV in most cases. However, electron energies lower than 2 MeV were used in the industrial fields for surface processing. Therefore, the code of practice in electron beam dosimetry should be extended to lower energy electron beams, although it is not suitable for the clinical purpose. The current prototype linac system would be upgraded continuously in terms of beam energy and this study would be used for evaluating the linac performance during the development.

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콤팩트 전자 선형가속기 시작품의 출력측정에 관한 연구

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의료용 및 산업용으로 활용하기 위한 C-밴드형 콤팩트 선형가속기의 개발이 동남권원자력의학원에서 진행되고 있다. 본 논문에서는 선형가속기 시작품에서 발생한 전자빔의 출력 측정 결과를 보고하고자 한다. 출력 측정은 물흡수선량에 대해 교정된 Exradin-A10 마커스형 평행평판형 전리함을 사용하여 물속 기준 깊이에서 IAEA TRS-398 프로토콜에 따라 흡수선량율을 결정하는 과정으로 진행되었다. 전자선 에너지가 낮은 점으로 인하여 선질지표(R_{50})은 필름 측정법을 써서 근사적으로 결정하였다. 결과로서 단위 펄스 진동수당의 선형가속기 전자빔의 출력은 17.0 cGy/(min · Hz)로 나타났다. 본 연구의 결과는 개발 중인 전자가속기의 성능 평가 자료로 활용될 것이다.

중심단어: 전자선 출력, TRS-398 프로토콜, 선형가속기 시작품