Dosimetric Characteristics for A New Electronic Brachytherapy Source Based on Carbon Nanotube Field Emitter

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1. Introduction

A new electronic x-ray source based on carbon nanotube (CNT) field emitter has been developed for electronically-controlled brachytherapy [1]. The x-ray source is capable of voltages up to 70 kV. The source current and photon beam intensity may be modulated to approximately perform the dose rate of clinically suitable radionuclides such as high-dose rate (HDR) and low-dose rate (LDR) brachytherapy sources. At an operating voltage of 50 kV, the source can produce air kerma rate ranging from 108.1 Gy cm^2 min^{-1} with a tube current of 252 μA.

This study assessed the photon energy spectrum and dose distribution in air of the electronic x-ray brachytherapy source using Monte Carlo code (MCNP6 Beta3).

2. Methods and Materials

2.1 Electronic x-ray brachytherapy source

The schematic diagram of the x-ray tube is shown in **Figure 1**. The x-ray tube has a diode structure, which consists of a CNT cathode tip and a focusing electrode on one side and a conical-shaped transmission-type x-ray target on the other side. An alumina ceramic tube (inner diameter 7 mm, outer diameter 10 mm) is used for the high-voltage insulation between the cathode and the x-ray target [1].

The x-ray target was fabricated by coating tungsten on a conically machined beryllium (Be) X-ray window using a magnetron sputter. The thickness of the coated tungsten film is 1.5 μm, which is optimized to produce a maximum x-ray output for a given electron beam input.

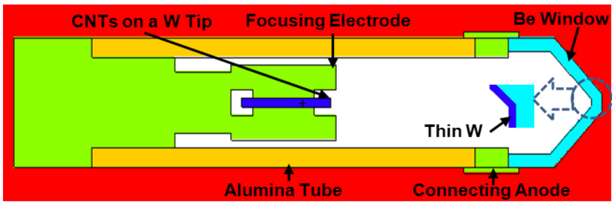

Figure 1. Schematic diagram of the electronic x-ray brachytherapy source for modeling the Monte Carlo simulations.

2.2 Radiation transport calculations

Photon energy spectrum and dose distributions in air was calculated using the Monte Carlo (MC) N-Particle radiation transport code (MCNP6 Beta3) [2] using particle fluence F4 tally estimator. The source geometry was simulated as shown in **Figure 1**. MC simulations were calculated using mono-energetic electrons striking the anode surface to generate x-rays [3]. The electrons had kinetic energy of 50 keV. Mode P E was used with default modeling of bremsstrahlung. MCPLIB12 and el03 cross-sectional libraries were used for the electron and photon-coupled transport. The cutoff energy for electrons outside of and inside of the source is considered 10 keV and 1 keV, respectively. Moreover, the low energy cutoff was 1 keV for photon transport. The coordinate system origin was centered in the x-ray anode of the electronic brachytherapy source. The dose distributions in air were obtained for angles from 0° to 140° in 5 ° increments at distances of 1 cm from the source center.

2.3 Measurement of energy spectrum and dose distribution in air

Measured photon energy spectrum was determined in air. Measurements were performed using a CdTe detector XR-100T, AMPTEK Inc., USA) at Korea Advanced Institute of Science and Technology (KAIST).

The spatial dose distributions of electronic x-ray source were performed using a ionization chamber (PinPoint®, PTW-Freiburg GMBH, Germany). The dose rates in air were measured at 1cm for θ = 0° to 122.5° in approximately 3.5° increments.

All experimental results of the electronic x-ray tube were obtained at a voltage of 50 kV.

3. Results

Figure 2 shows the measured and calculated photon energy spectra determined in air. MC calculations were performed with photon energy binned at 0.2 keV intervals. Calculated photon energies for the source operating in air at 50 kV were 8.4, 9.8, and 11.4 keV, with average measured photon energies of 8.39, 9.67, and 11.28 keV, respectively. These peaks result from tungsten L-edge characteristic x-rays. For major peaks of tungsten characteristic x-rays, the differences between measurements and calculations were generally within 4%.

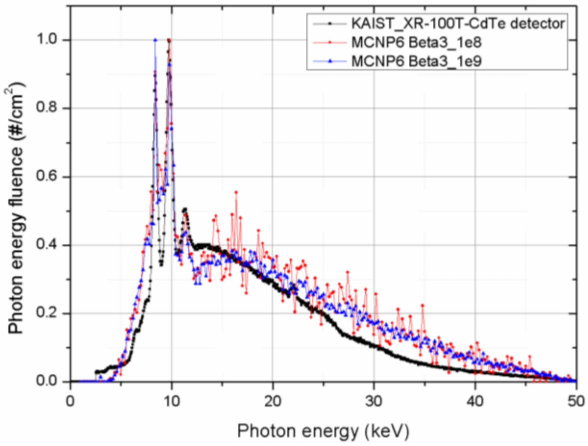

Figure 2. Measured and calculated relative photon energy spectra at 50 kV for the electronic x-ray brachytherapy source. The MC calculations were performed up to 10^8 (red solid line) and 10^9 (blue solid line) electron histories.

Figure 3 shows the measured and calculated dose rates in air at the operating voltage of 50 kV. The dose rates in air at 1 cm are higher towards the proximal direction (θ = 0°) increased filtration within the source. The MC results were generally good agreements within 8 % in the range of θ = 0° and 90°, comparing the measured results. However, the MC results show considerable differences in the distal direction along the source longitudinal axis due to imprecise electron beam shape of x-ray tube.

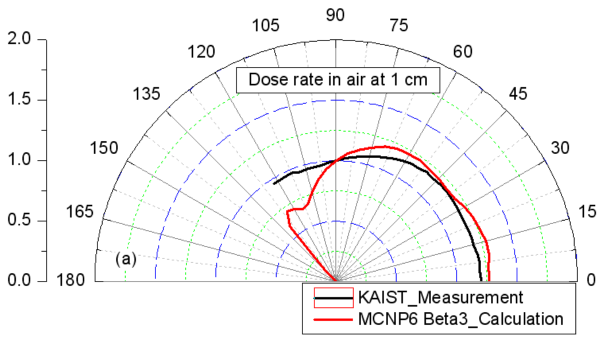

Figure 3. Measured and calculated relative dose rate in air at 50 kV for the electronic x-ray brachytherapy source. Relative dose rates in air are normalized at 1cm and 90°.

4. Conclusions

In this study, the photon energy spectrum and dose distribution in air were simulated for the electronic x-ray brachytherapy source by using the MCNP6 code. Three major peaks of tungsten characteristic x-rays for the x-ray source shows the good agreement between measured and calculated spectra. The MC results agreed with measured results for the dose rates in air towards the proximal direction of the source. Further study is needed to determine the precise electron beam shape of x-ray tube.

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