MONTE CARLO MODELING OF THE XOFT AXXENT™ X-RAY SOURCE

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ABSTRACT

Purpose: Extensive Monte Carlo modeling was performed using MCNP5 to characterize the Xoft Axxent™ miniature X-ray source for electronic brachytherapy. This study assessed the dose distribution, dosimetry parameters using the AAPM TG-43U1 protocol, and the sensitivity of results to source geometric parameters and choices of computational parameters.

Method and Materials: Monte Carlo simulations of radiation generation and transport utilized the MCNP5 code and EPDL97-based mcplib04 cross-section library. Dosimetry parameters using a modified TG-43U1 2-D dosimetry formalism were determined at 40, 45, and 50 kV operating voltages. While the source was modeled as a point due to small anode size, < 1 mm, the 1-D brachytherapy dosimetry formalism is not appropriate due to significant polar anisotropy. Source output was measured in a water phantom using a PTW 34013 Ion Chamber.

Results: Calculated point-source model radial dose functions at $g_P(5)$ were 0.19, 0.24, and 0.29 for the 40, 45, and 50 kV voltage settings, respectively. Measured point-source model radial dose functions were ± 10% of the calculated results for 1.5 cm $\le r \le$ 7.0 cm. Calculated F(r,θ) values for all operating voltages were typically 1.1 along the distal end (θ = 0°) and ranged from F(0.5, 160°) = 0.2 to F(10, 160°) = 0.5 near the catheter proximal end. Default energy substep values, *estep*, for photon generation in the anode film and substrate were found to be adequate. Doubling the default values effected the number of X-rays and brehmsstrahlung photons generated by <1%. Utilizing geometry splitting/rouletting and brehmsstrahlung biasing for variance reduction improved the computational efficiency by >30x.

Conclusion: A miniature X-ray source for electronic brachytherapy has been characterized using MCNP5. The Monte Carlo results agreed with measured results for radial dose function and anisotropy function to within ± 10%.

INTRODUCTION

Extensive Monte Carlo modeling was performed using the Monte Carlo N-Particle radiation transport code MCNP5 to characterize the Xoft Axxent™ X-ray Source (Source) for electronic brachytherapy. "Good Practice" recommendations of the AAPM TG-43U1 report were utilized.[1] Unlike radionuclides where there are recommended photon energy spectra for ^{125}I and ^{103}Pd, the Source photon energy spectrum was initially unknown. This study assessed the dose distribution, dosimetry parameters using the AAPM TG-43U1 protocol, and the sensitivity of results to source geometric parameters and choices of computational parameters.

METHODS

All Source components including the water cooling sheath were modeled using proprietary internal dimensions and compositions. X-ray spectra and spatial distributions were calculated using 40, 45, and 50 keV mono-energetic electron beams striking the anode surface to generate X-rays that were then transmitted through the Source substrate. Because the anode film was quite thin, ESTEP values, the default energy substep values for photon generation in the anode film and substrate, were doubled and found to affect the number of X-rays and brehmsstrahlung photons generated by <1%. The coordinate system origin was centered in the X-ray anode cone. Calculations were performed in a 30 cm diameter spherical liquid water phantom with an atomic ratio of 2:1 for H:O and ρ = 1.000 g/cm³. Data were calculated at $r \le 10$ cm, with at least 5 cm of water for backscatter which was sufficient for the photon energies examined.[10] By utilizing geometry splitting/rouletting and brehmsstrahlung biasing for variance reduction, computational efficiency was improved by >30x.

Photon energy spectra were calculated in-air using MCNP5 with the EPDL97-based cross-section libraries, particle fluence F4 tally estimator with photon energy binned at 1 keV intervals, and the mass-attenuation coefficients of Seltzer.[2-9] Calculations typically required 10^8 histories to achieve sufficient statistics to discern the effects studied. This number of histories produced statistical uncertainties of 0.05% and 0.2% at 1 cm and 5 cm on the transverse plane, and 0.3% and 0.8% at 1 cm and 5 cm near the Source axis, respectively. Spectra were measured at NIST using a Canberra high-purity germanium (HPGe) detector with a 0.25 mm diameter tungsten aperture at a distance of 178 cm with 60 eV energy bins. Figure 1 shows the excellent agreement between calculated and measured spectra. Amplitudes of the characteristic X-ray lines for tungsten below 13 keV and the yttrium lines at 15 and 17 keV are not comparable because the calculated spectra used 1 keV energy bins.

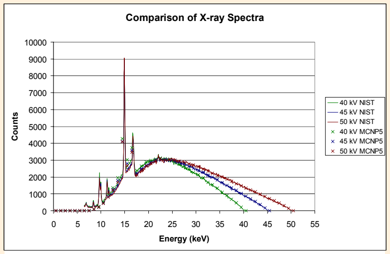

Figure 1. Calculated and measured X-ray spectra for 40, 45 and 50 kV operation. Spectra were normalized over the range from 23 to 26 keV to minimize impact of characteristic X-ray peaks on the shape comparison.

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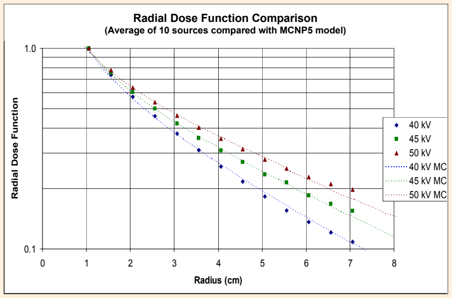
RESULTS

Dose rate to water. Table 1 presents the measured and calculated dose rates to water per μA of beam current at the reference position at all three operating voltages. Increases in dose rates to water as a function of operating voltage are attributed to increased conversion efficiency for brehmsstrahlung radiation emission. The maximum values for dose rates to water at the reference position were typically 40% less than the Monte Carlo results. This implied that the average tube efficiency to produce photons was approximately 60% of that calculated by the MCNP model.

Table 1. Water dose rate at 1 cm and θ_0 [cGy.h^{-1}.μA^{-1}]

Source	40 kV	45 kV	50 kV
Measured maximum	199	260	346
Measured average	129	196	265
Calculated MCNP5	254	325	382
Average/calculated	0.509	0.602	0.694



Radial dose function. Calculated point-source model radial dose functions at $g_P(5)$ were 0.19, 0.24, and 0.29 for the 40, 45, and 50 kV voltage settings, respectively. From 1 cm to 7 cm for the 50 kV Source, calculated and measured $g_P(r)^{50}$ results were in agreement within ± 5% with a range of 9% (Figure 2). Agreement somewhat worsened as operating voltage decreased, reaching a maximum difference of +9% at 7.0 cm for the 40 kV Source. However, the overall range of differences was less than 12% regardless of operating voltage and did not exhibit a monotonic behavior as a function of distance.

Figure 2. Comparison between measured and calculated radial dose functions.

2-D Anisotropy function. Calculated F(r,θ) values for all operating voltages were typically 1.1 along the distal end (θ = 0°) and ranged from F(0.5, 160°) = 0.2 to F(10, 160°) = 0.5 near the Source proximal end. As expected due to increased average photon energy, the anisotropy decreases with increasing operating voltage. Anisotropy is higher towards the proximal direction due to increased filtration within the Source. The Monte Carlo results were consistently 10% and 15% higher than the measured results in the distal direction along the Source long-axis at 5 cm and 3 cm, respectively. The comparison for 50 kVp is shown in Figure 3. However, the proportion of tissue along this axis is relatively small. On average, for all three operating voltages at both radial distances, the measured results were within 6% of the Monte Carlo results.

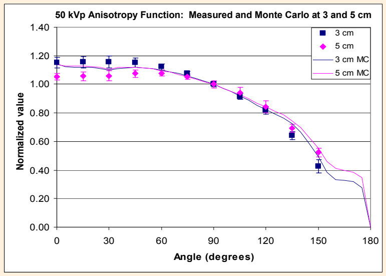


Figure 3. Measured (points) and calculated (lines) anisotropy functions for radial distances of 3cm and 5cm for an operating voltage of 50 kV. Error bars are one sigma standard deviations.

Calculation uncertainties. On average, the Monte Carlo statistical uncertainties (k=1) in calculations of dose to water at 1 and 5 cm on the transverse-plane (θ = 90°) were 0.5% and 2.0%, respectively. The photoionization cross-sections used were those recommended in the 2004 AAPM TG-43U1 report, with k=1 uncertainties of 1.2% as reported by Rivard *et al.*[11] Averaged over the energy spectra for the three operating voltages, the impacts of this uncertainty on dose rates to water at θ_0 and 1 and 5 cm are 0.2% and 0.9%, respectively. These are less than those reported by Rivard *et al.* for the ^{103}Pd source because of the higher-average photon energy of the Source. The estimated dosimetric impact of Source geometry uncertainties due to variation in anode thickness (3%) and internal positioning (± 1.1 mm) within the sheath are 26% and 7.4% at r = 1 cm and r = 5 cm, respectively. Estimates of uncertainties in photon energy spectra, based on a Monte Carlo parametric study varying material thicknesses, indicate that the dosimetric impact of Source spectrum uncertainties at θ_0 could be as high as 2% and 8% at 1 and 5 cm, respectively. In total, the quadrature sum of these uncertainties on dose rates to water at θ_0 and 1 and 5 cm are 26.3% and 11.1%, respectively.

CONCLUSIONS

A miniature X-ray source for electronic brachytherapy has been characterized using MCNP5. The Monte Carlo results agreed with measured results for radial dose function and anisotropy function to within ±10%.

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DEVICE DESCRIPTION

- The Xoft Axxent™ Electronic Brachytherapy System, consists of the X-ray Source, the Balloon Applicator and the Controller. The X-ray Source comprises an X-ray tube in a multi-lumen catheter that allows cooling fluid to circulate over the tube. The balloon applicator, a sterile, disposable, single use device, is designed for the water-cooled X-ray source and functions as its guide. The controller provides power to the Source, allows translation of the Source, and provides a user interface with a control panel.
- Research was supported by Xoft, Inc.
- The Xoft Axxent™ Electronic Brachytherapy System is for investigational use only. FDA clearance pending.

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