

RADIOLOGICAL DEPENDENCE OF ELECTRONIC BRACHYTHERAPY SIMULATION ON INPUT PARAMETERS

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ABSTRACT

Purpose: In comparison to ¹²⁵I or ¹⁹²Ir, characterization of dose rate distributions from electronic brachytherapy (EBT) sources is subject to the additional challenge of determining the broad bremsstrahlung photon energy spectrum based on source geometry and materials. Towards simulating photon energy spectra and resultant dose rate distributions, Monte Carlo investigators first generate electrons which bombard the x-ray tube anode and subsequently create photons via bremsstrahlung. These modeling techniques for this endeavor are largely unexplored. Therefore, sensitivities of spectra and dose rate distributions were assessed through varying Monte Carlo modeling parameters for the Xoft Axxent™ HDR X-ray Source, model S700.

Materials & Methods: MCNP5 was used to simulate photon spectra and dose rate distributions, with comparisons to experimental measurements (PTW model 34013 ionization chamber in liquid water) for $1 < r \leq 7$ cm and $0^\circ \leq \theta \leq 150^\circ$ with simulations covering $0.3 \leq t \leq 15$ cm and all available angles. The following source modeling parameters were evaluated for their impact on in-water spectra and dose: electron beam spot size, electron beam radius (R), electron beam spot annularity FN(R) like a doughnut, and anode film thickness (t). Since electron:photon transport is grossly inefficient in comparison to conventional Monte Carlo modeling of radionuclides, MCNP variance reduction techniques such as adjusting high-energy biasing of bremsstrahlung spectrum (BBREM), bremsstrahlung reduction techniques such as adjusting high-energy biasing of bremsstrahlung spectrum (BBREM), bremsstrahlung photon multiplicity (BNUM), electron cutoff energies (PHYS:E), and cell importances (IMP) were also assessed.

Results: Due to the complex nature of anode shape, $F(r,\theta)$ was highly-dependent on R, varying a factor of 2 when changing R from 0 to 0.084 cm. This effect was more pronounced when varying annularity due to less radial volume averaging. Through comparison with experimental measurements, the optimal electron beam shape had the largest spot size which could fit within the anode and no annularity; it was a uniform pencil beam without a central hole. Altering MCNP variance reduction techniques did not significantly impact the magnitude of results, but greatly hastened simulation efficiency.

Conflict of Interest: This research was supported in part by Xoft, Inc.

BACKGROUND

- Xoft has developed an electronic (non-isotopic) high dose rate brachytherapy device. The Xoft Axxent™ HDR X-ray Source, model S700, delivers tight, conformal doses of x-radiation to the inner surface of a body cavity such as an excised tumor bed.
- The initial application of the Xoft Axxent™ Electronic Brachytherapy System is to the conservative treatment of breast cancer utilizing balloon-based partial breast irradiation.
- The Axxent™ System is designed to shorten treatment time compared to external beam radiation. The Axxent™ System does not require a heavily shielded environment, making treatment potentially available for women without access to a facility with an HDR afterloader. This technology eliminates handling and disposal of isotope sources.

DEVICE DESCRIPTION

- The Xoft Axxent™ Electronic Brachytherapy System, consists of the X-ray Source, the Balloon Applicator and the Controller.
- The disposable X-ray Source comprises an X-ray tube in a multi-lumen catheter that allows cooling fluid to circulate over the tube. The X-ray tube is ~2.25 mm in diameter by 15 mm long and is attached to a high voltage cable and encapsulated within an electrical ground.
- The disposable Balloon Applicator Kit contains one of five balloon sizes/shapes: three spherical and two ellipsoidal.
- The Axxent™ System Controller provides power to the X-ray Source as well as allows the X-ray Source, positioned within the Applicator, to be translated. The translation or pullback movement of the X-ray Source within the balloon is designed to provide a predictable dose of radiation in the tissue surrounding the balloon. It also provides a user interface with a control panel. It houses all safety and interlock circuitry and manages coolant pump activity.

BACKGROUND

- In comparison to ¹²⁵I or ¹⁹²Ir, characterization of dose rate distributions from electronic brachytherapy (EBT) sources are subject to the additional challenge of determining the broad bremsstrahlung photon energy spectrum based on source geometry and materials rather than starting with a known isotopic line spectrum. When simulating photon energy spectra and resultant dose rate distribution, Monte Carlo investigators first generate electrons which bombard the x-ray tube anode and subsequently create photons via bremsstrahlung. These modeling techniques for this endeavor are largely unexplored.

PURPOSE

- To assess the sensitivities of spectra and dose rate distributions through varying Monte Carlo modeling parameters for the Xoft Axxent™ model S700 X-ray Source.

METHODS

- The Xoft model S700 source geometry shown in Fig. 1, was held fixed throughout this Monte Carlo study.
- As defined above, R and t were varied over the entire physically possible range. Specifically, R varied from 0 to 0.8 mm, where the outer bound corresponds to the maximum inner radius within the anode/tube.
- Anode film thickness for bremsstrahlung photon generation varied from 0 to 6 μm, where the upper limit was based on the 50 keV electron range within a thick-target.
- The impact of these variables on the 2-D anisotropy function, $F(r,\theta)$, and radial dose function, $g(r)$, was determined.
- In terms of MCNP jargon, BBREM, BNUM, PHYS:E, and IMP were varied to determine their impact on values and calculation efficiencies for dose rate distributions, $F(r,\theta)$, and $g(r)$.

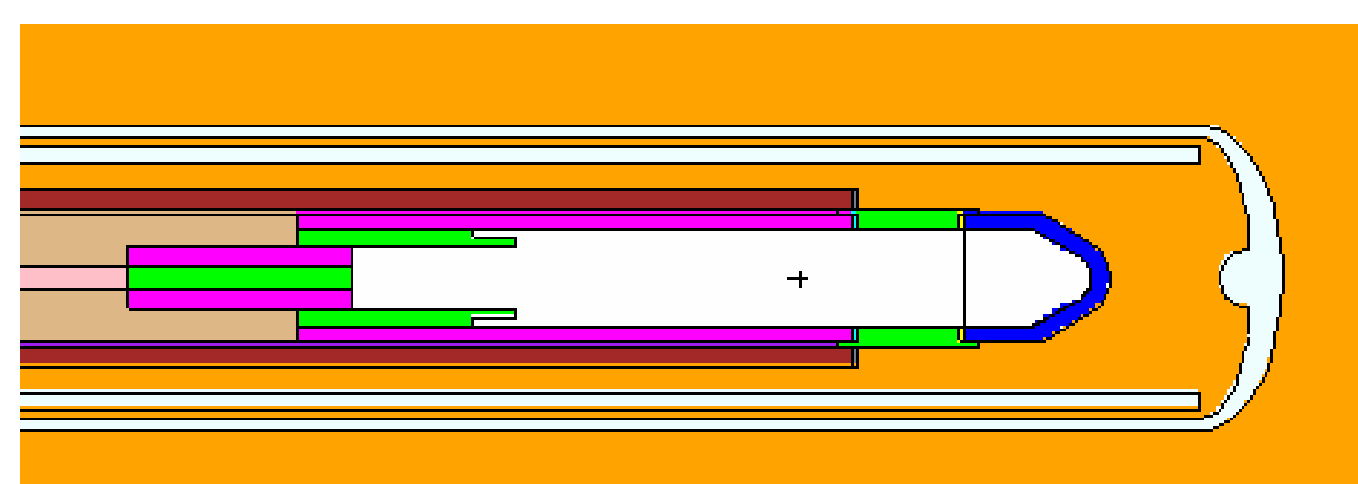


Fig. 1 Source geometry used for radiation transport simulations. Monoenergetic, 50 keV electrons originate from the hot cathode, and travel from left to right in the above diagram. Size and shape of the impinging electron beam were studied, along with anode thickness.

RESULTS

- Variance reduction techniques were employed to address photon formation efficiency. High-energy biasing of bremsstrahlung spectrum (BBREM) and bremsstrahlung photon multiplicity (BNUM) were assessed from 0.1 to 10,000. Artificially increasing the BBREM up to ~100 increased the bremsstrahlung photon energy with linear increases in simulation efficiency for $r < 1$ cm. For BBREM > 100, simulations started to perturb the bremsstrahlung photon spectra, significantly reducing characteristic K-edge photon production by tube components. Increasing BNUM linearly increased transport efficiency up to ~BNUM=10. Efficiency slowly decreased above this value due to reduced source electron generation.
- To hasten calculations outside the tube, a cutoff of PHYS:E=20 keV was used outside the tube while 1 keV was used inside the tube. Efficiency only improved by ~3% since the electron range at either cutoff energy was small in comparison to the voxel size. Changing cell importances for photon-splitting and increased photon population at large distances also netted a small improvement due to 4π sr sampling geometry and decreased clinical relevance at larger distances.
- Impact of varying anode film thickness and the simulated positioning of electrons impinging the anode are illustrated in Figs. 3-6. Results generally show sharp behavior. Modeling parameter values were chosen to produce dosimetry results which mimicked measured results.

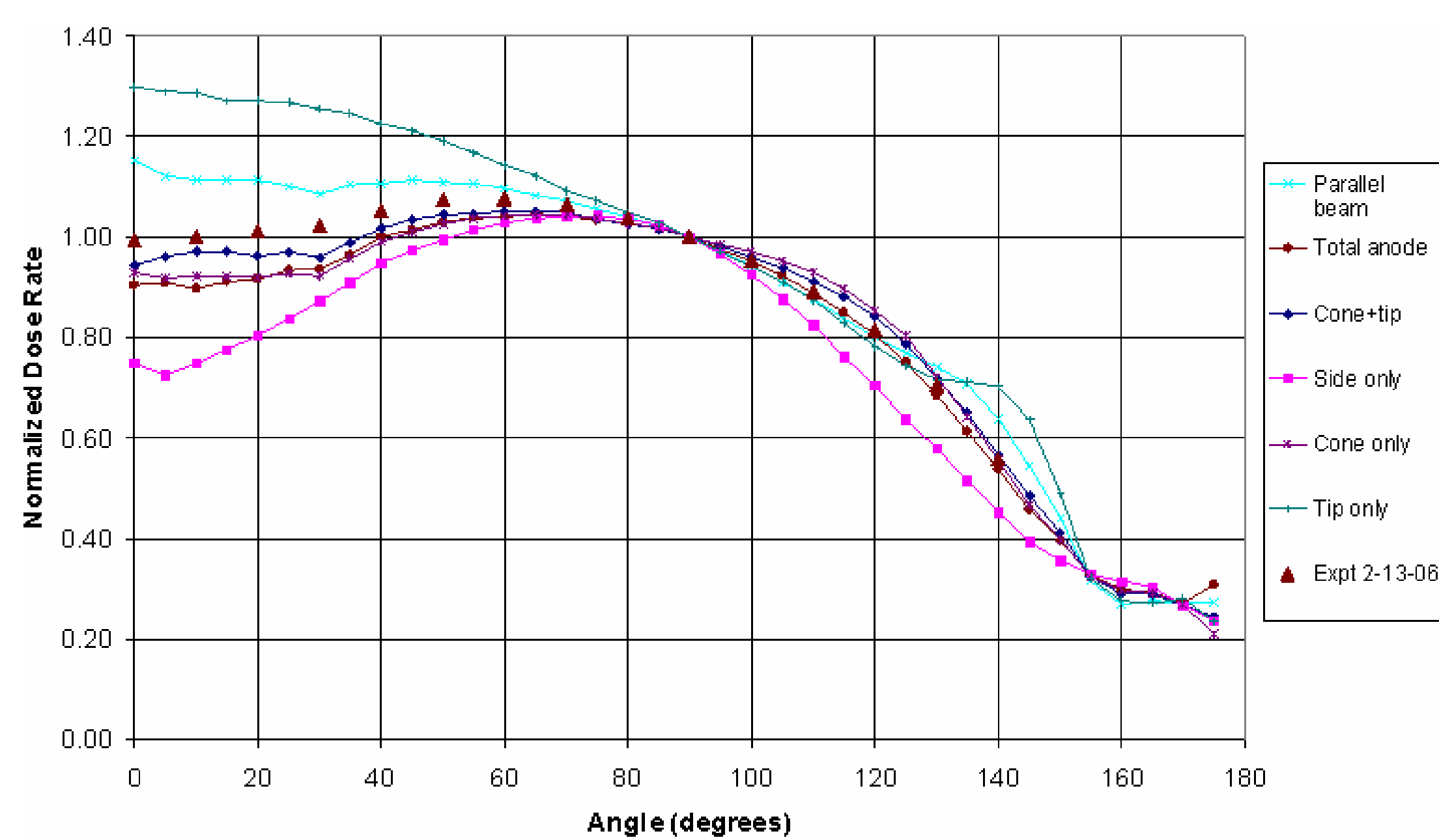


Fig. 3 Dependence of $F(2,0)$ on the origin of bremsstrahlung production in the anode. 2-D anisotropy function results where photons originated from the "Cone + tip" provided results most similar to measurements. Based on separate electric field modeling of the system, minimal photons are expected to be produced by the interior sides of the tube. Note: The zero degree direction is towards the anode (the distal end).

METHODS

- While this EBT source may be operated at 40, 45, or 50 kVp, results presented herein were examined solely for 50 kVp since similar trends were expected for all three operating voltages.
- To determine the most appropriate value for each modeling parameter, simulation results were directly compared to measured results to provide a firm foundation for the comparison.
- Measured results were obtained with a PTW model T34013 ionization chamber calibrated over a range of photon energies (15-60 keV) to encompass all photons which would reach the detector in a realistic environment. The detector was positioned in the vicinity of the x-ray source using a calibrated, computer-controlled stage immersed in a large water phantom to approximate infinite scatter conditions. Dose rate distribution measurements were converted in a relative sense to $F(r,\theta)$, and $g(r)$ for comparison with calculated results. The ion chamber and measurement jig are shown in Fig. 2a and Fig. 2b, respectively.



Fig. 2a PTW model T34013 ionization chamber with dimensions on schematic drawing.

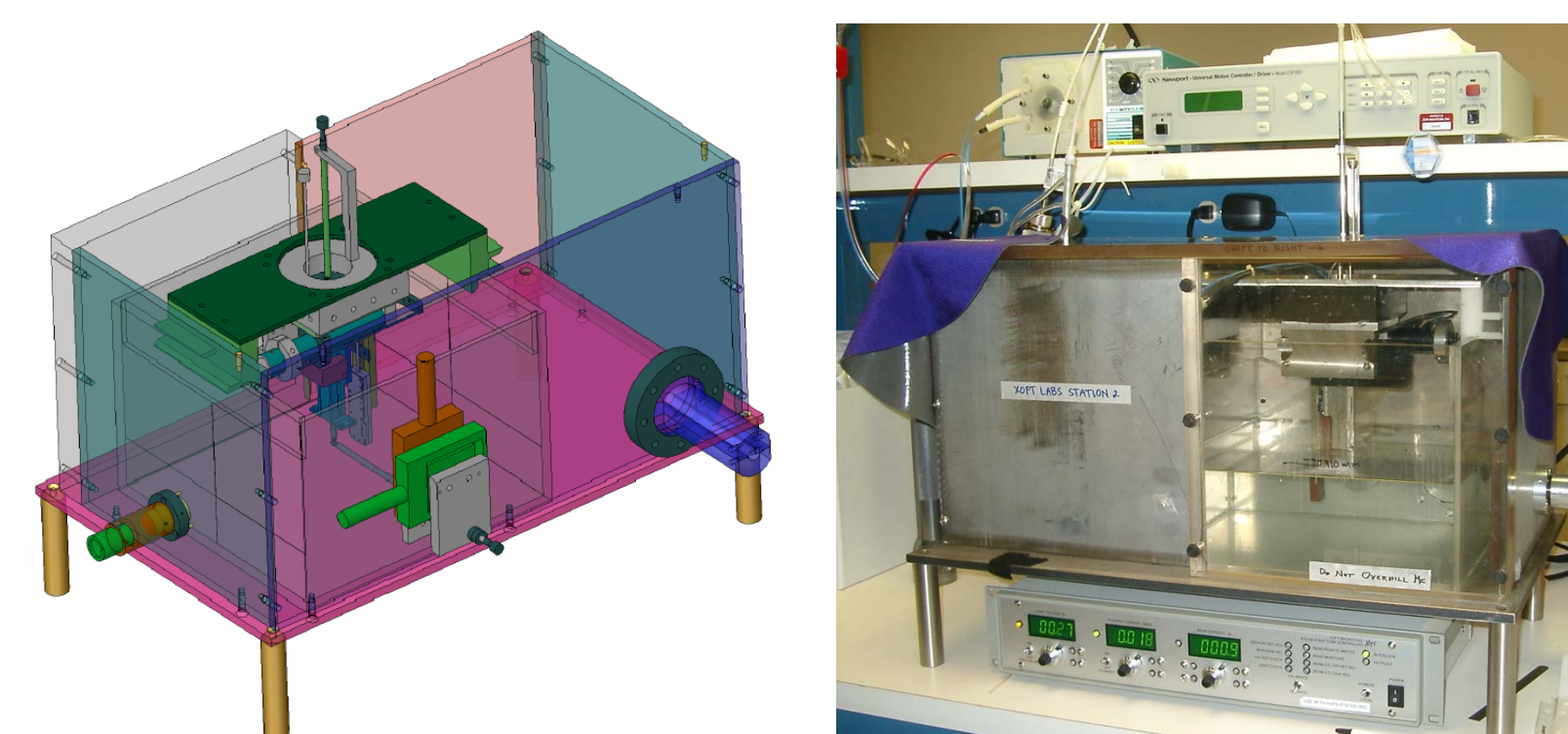


Fig. 2b Measurement apparatus used to precisely position the PTW ionization chamber relative to the x-ray source.

RESULTS

- Electron impingement on the anode was independently checked using electric field modeling to predict electron trajectories within the tube.

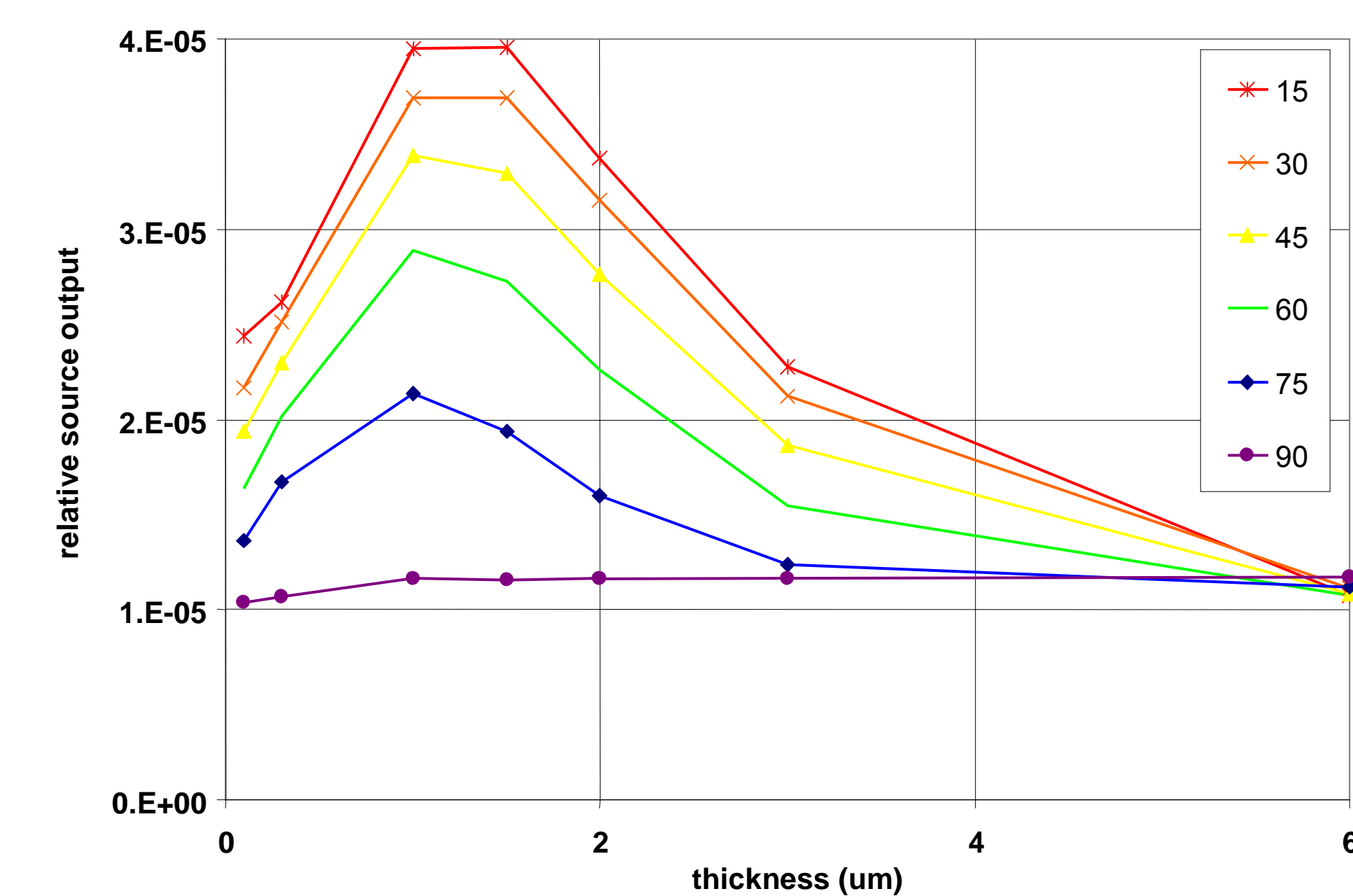


Fig. 4 Angular dependence (legend illustrating $15^\circ \leq \theta \leq 90^\circ$ curves) of output on anode thickness. The maximum occurs between 1-2 μm, and is in agreement with measured results. Changing anode film thickness by 1 μm changed $g(5)$ by < 10%.

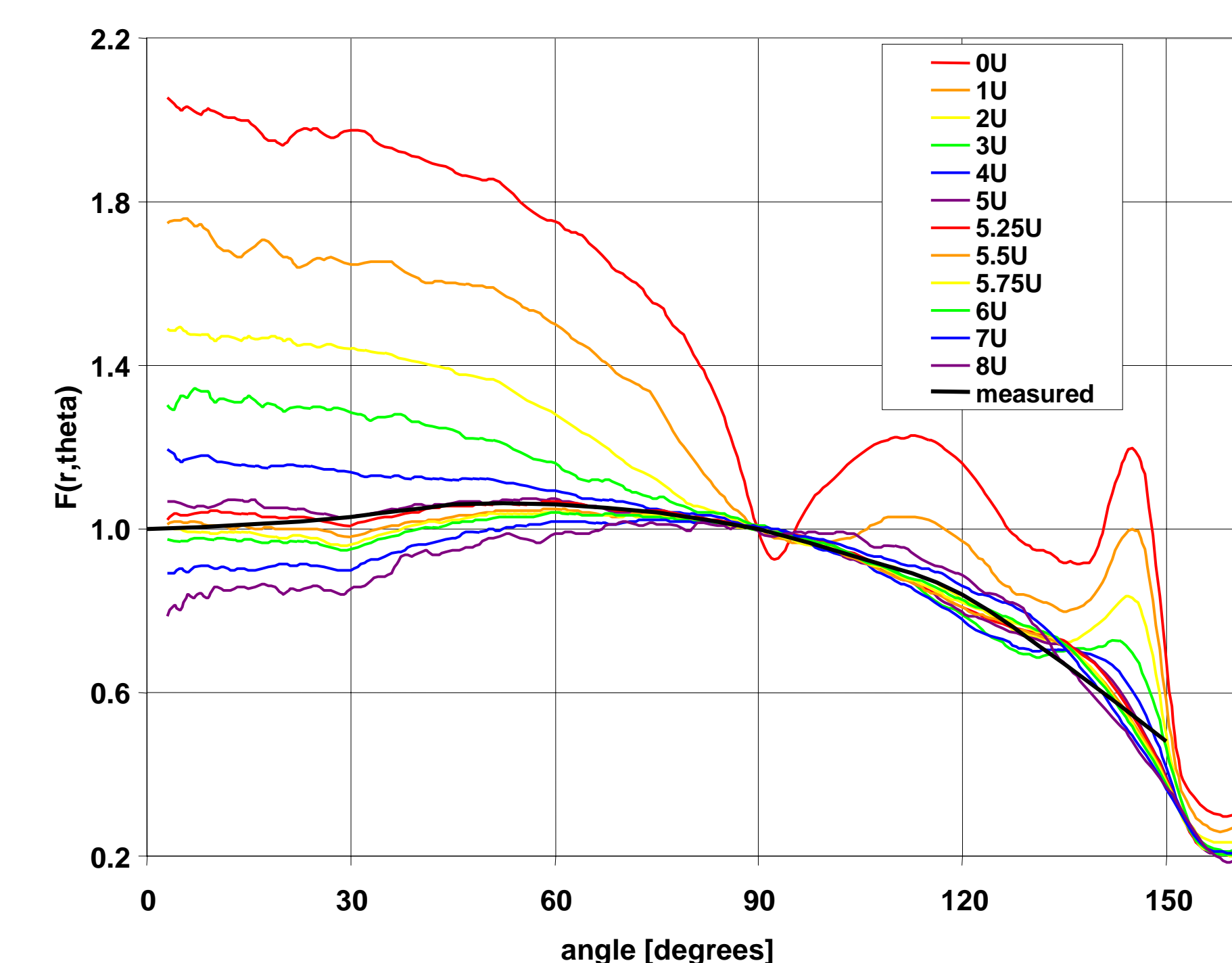


Fig. 5 Dependence of $F(r,\theta)$ on electron beam radius, where radii "0" through "8" correspond to radii $0 \leq R \leq 0.8$ mm for pencil beams with uniform intensity across the beam. Note: $r = 1$ cm

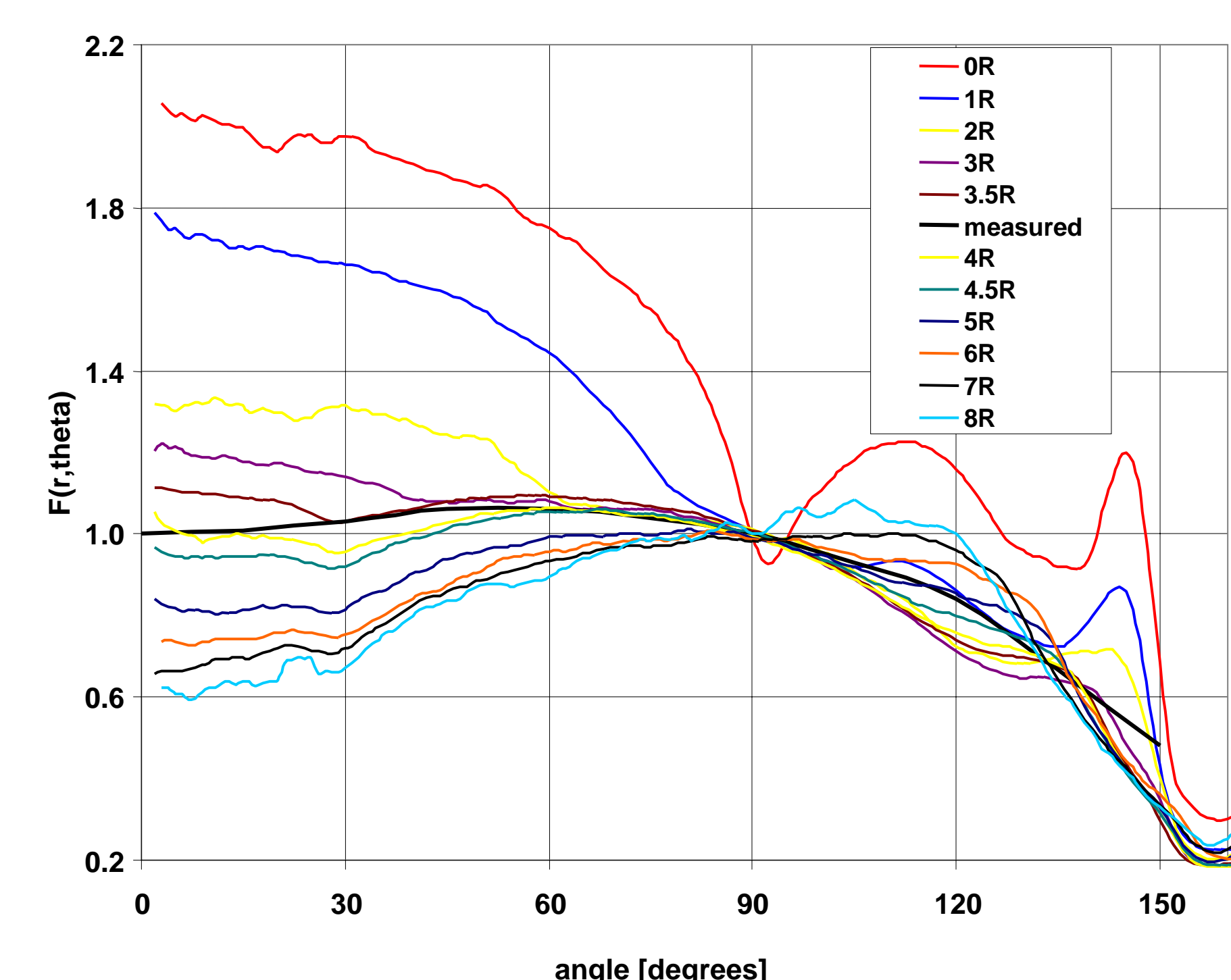


Fig. 6 Dependence of $F(r,\theta)$ on electron beam annularity, where radii "0" through "8" correspond to radii $0 \leq R \leq 0.8$ mm, yet the annulus minor axis is 0.001 mm thick. There is less radial averaging in this approach compared to the uniform beam approach in Fig. 5. As expected, note that both techniques give the same results for $R=0$. Note: $r = 1$ cm

SUMMARY

- As determined using electric field simulation and comparisons of relative dose rate distributions, location of electron impingement on the anode was restricted primarily to the anode cone and tip.
- Upon $F(r,\theta)$ comparison of simulations with measured results, size and shape of the electron beam spot appears to be a uniform beam of maximum physical extent within the tube.
- Variation of anode film thickness substantially varied $F(r,\theta)$ and absolute tube output, with negligible effects on the dose rate constant or $g(r)$.
- An assortment of variance reduction techniques significantly improved the calculation efficiency, yet made no observable changes in simulated dose distributions outside the tube.
- For more information, please see Poster #110 at AAPM 2006: Benchmarking MCNP Low-Energy Bremsstrahlung Modeling for Electronic Brachytherapy Simulations, by M.J. Rivard, S. Axelrod, and T.W. Rusch.