CHARACTERIZATION OF A NEW MINIATURE X-RAY SOURCE FOR ELECTRONIC BRACHYTHERAPY

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ABSTRACT

A new miniature x-ray source attached to a flexible high voltage cable and enclosed in a cooling sheath has been developed for electronically-controlled brachytherapy. Measurements were made to characterize the source dose distribution, and subsequently determine dosimetry parameters using the AAPM TG-43 protocol. Air ionization chambers, TLDs, an intrinsic germanium energy-dispersive x-ray spectrometer and radiochromic film were used to ascertain depth-dose curves in air and water, air kerma strength, angular dose distributions, x-ray energy spectra, and half-value layers. These measurements were compared with source output calculations employing the MCNP-5 radiation transport code.

With the x-ray source operating at 40 kVp and 0.30 mA, the air kerma strength exceeded 800 Gy cm^2 h^{-1} or approximately twice that of a 10 Ci ^{192}Ir source. The depth-dose curve measured in a water phantom (using a 0.005 cc air ionization chamber, PTW Model 34013) gave a radial dose function that agreed with the Monte Carlo model to within 8% over a distance range from 0.5 to 3.0 cm from the source axis. TLD determination of the angular dose distribution agreed with the Monte Carlo model to within 15% over a 270 degree angular range. Integration of the x-ray spectrum as a function of aluminum absorber thickness gave a half-value layer of 0.4 mm for the source operating at 40 kVp. Agreement between predicted and measured miniature x-ray source output established the viability of this source for electronic brachytherapy applications..

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INTRODUCTION

- In 1995 the AAPM task Group No. 43 published a set of guidelines for calibration of interstitial brachytherapy sources that are in common use today.[1] These guidelines were recently updated to revise several definitions and provide consensus data sets for low-energy brachytherapy seeds that meet AAPM dosimetric requirements.[2]
- These guidelines for radionuclide sources apply equally well to the Xoft microTube electronic brachytherapy source with two minor modifications:
  - Air kerma strength must be normalized to beam current because the source dose rate can be easily varied by changing the beam current.
  - Anisotropy can be described using the point-source approximation for the geometry function because the apparent source size is about 1 mm.
- Because the radiation intensity is lower in the proximal direction from the source, the anisotropy function must be specified for the angular range from 0 to 180º.
- One salient difference between the description of the Xoft Flexible X-ray Probe and a radionuclide-based seed is that the air kerma strength and radial dose function may be selected at the time of treatment by the clinician. Hence the source dosimetric parameters need to be determined for a selection of operating voltages.
- Source characterization in this paper will concentrate on 50 kV operation

METHODS

- **Objective**: To characterize within the TG-43 framework a new electronic brachytherapy source, which is based on a miniature x-ray tube.
- **Instrument:** Xoft microTube Flexible X-ray Probe operated at 40, 45 and 50 kVp in a beam current range from 0.10 to 0.30 mA
- **Design:** X-ray probe output was bench tested in air, water and solid water and characterized by Monte Carlo modeling
- **Data Collection:** parameters measured included:
  - Air kerma strength using the Attix Free Air Chamber and the seven-position measurement apparatus (Precision Radiation Measurements Model LE-0.8 Low Energy Ionization Chamber) at the UW MRRC
  - Depth-dose curves in water using a PTW Model 34013 Soft X-ray Chamber (0.005 cm^3) and an Exradin Model A16 Micropoint Ion Chamber (0.007 cm^3) with a Standard Imaging Max 4000 Electrometer
  - Angular anisotropy with LiF 100 TLDs and an Exradin A16 Micropoint Ion Chamber
  - Angular anisotropy with GAFChromic® XR Type T radiochromic film (presented in poster number PO-T-304)
  - Half-value layer using the Attix Free Air Chamber at 100 cm from the source with reference high-purity aluminum sheets interposed in the beam path
  - X-ray spectrum (high purity Ge gamma ray spectrometer)
- **Modeling:** Monte Carlo modeling of the X-ray Probe was done using MCNP version 5 with updated cross-section libraries.

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DEVICE DESCRIPTION

- The Xoft microTube Flexible X-ray Probe consists of a disposable, micro-miniature X-ray source integrated into a cooled, flexible, disposable probe (Figure 1).
- X-rays of 40-50 keV maximum energy are produced at the tip of the directable probe, which otherwise closely resembles current remote afterloading units.
- The X-ray source can be intensity modulated to mimic penetration and/or dose rate characteristics of many different isotopes, including HDR ^{192}Ir, ^{125}I and ^{103}Pd.
- Control variables are source operating voltage (penetration depth), beam current (dose rate), dwell time and dwell position.
- The Xoft microTube Flexible X-ray Probe can be inserted directly into tissue or into one or more lumens of an intracavitary or interstitial brachytherapy applicator, which is inserted during surgery (e.g. lumpectomy) or as an outpatient procedure up to five weeks later.
- This X-ray source is potentially appropriate for any accessible body cavity or excised tumor bed such as with breast cancer or gynecologic cancers.

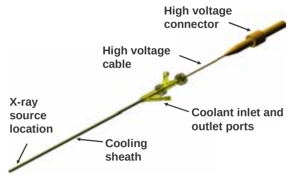

Figure 1. Xoft microTube Flexible X-Ray Probe

RESULTS

- The x-ray source geometry was simulated using MCNP version 5 as shown in Figure 2. Elements included in the model were the tungsten thin film x-ray anode and substrate, x-ray source wall materials, and x-ray source cooling water jacket shown in simplified form.
- Depth-dose curves have been calculated for the x-ray probe immersed in air, water, Solid Water™ and breast tissue (as defined in ICRU Report No. 44, 1989). In all cases, the model started with an electron beam striking the anode surface to generate x-rays that were then emitted by transmission through the substrate.
- Calculated depth-dose curves in water compare favorably with results published for ^{192}Ir, ^{125}I and ^{103}Pd as shown in Figure 3.[4-6] Because the source operating voltage can change, the Xoft X-ray Probe can mimic each of these isotopes for depths ≥1 cm. It has the additional advantage that the dose rates can be significantly higher than ^{125}I or ^{103}Pd seeds.

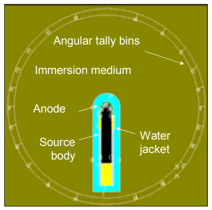

Figure 2. **MCNP model geometry for angular distribution calculations.**

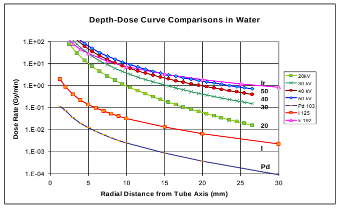

Figure 3. **Comparison of calculated depth-dose curves for standard brachytherapy seeds with the Xoft X-ray Probe at operating voltages of 20-50 kVp.**

- Source output was measured in air for an operating voltage of 40 with 0.10 mA of beam current over a distance range from 10 to 40 cm in seven steps. Air kerma strength was then calculated using the formalism described by Stump, *et al* [3] to be 27,000 cGy·cm ^{2} ·h $^{-1}$. An air absorption correction of 3%, calculated using MCNP v5, increased the value to 27,800 cGy·cm ^{2} ·h $^{-1}$.
- Air kerma strengths measured using the Attix Free Air Chamber were 22,300 and 33,700 cGy·cm ^{2} ·h $^{-1}$ for sources #906 and #926 at 40 kVp and 47,100 and 48,700 cGy·cm ^{2} ·h $^{-1}$ for sources #962 and #963 at 50 kVp.
- **Air kerma strength** normalized for beam current is **280 ± 58 cGy·cm ^{2} ·h $^{-1}$ ·μA $^{-1}$** at **40 kVp** and **479 ± 7 cGy·cm ^{2} ·h $^{-1}$ ·μA $^{-1}$ at 50 kVp.**
- Air kerma strength is proportional to dose in water for this type of source as shown in Figure 4. By adjusting either beam current or dwell time it is possible to compensate for ±20% differences in source output, if necessary.
- Half-value layer and second half-value layer were measured to be 0.42 ± 0.4 mm Al and 0.79 ± 0.5 mm Al, respectively, at 40 kVp. Theses values are in excellent agreement with 0.45 mm and 0.79 mm reported by Birch, *et al* for a tungsten x-ray tube with 17 degree target and 1.0 mm Be plus 0.5 mm Al filtering (Catalogue of Spectral Data for Diagnostic X-rays, Birch, Marshall and Ardran, Hospital Physicists Association Report 30).
- Depth-dose curves for three sources measured in distilled water by precision translation of an Exradin A16 Micropoint ion chamber for 50 kV operation have a 7.3% standard deviation for radii greater than 1.2 cm (Figure 5).
- The source-to-source variation shown in Figure 5 is well within the compensation range achievable using the well chamber.

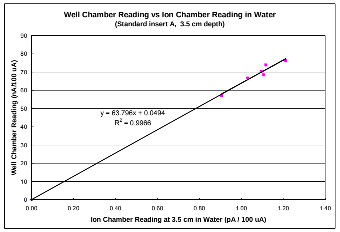

Figure 4. Correlation between source calibration in a well ionization chamber and the ion chamber readings at a prescription point 3.5 cm from the probe in water

RESULTS

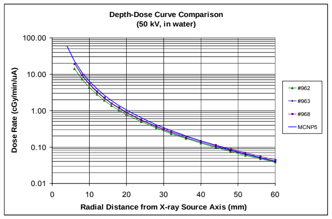

Figure 5. Comparison of measured and calculated depth-dose curves in water for 50 kVp.

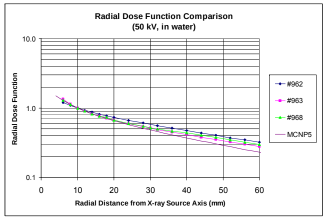

Figure 6. Radial dose functions corresponding to depth-dose curves in Figure 4.

- Radial dose functions at 50 kV for individual sources have a standard deviation of 4.1%. The deviation with respect to the MCNP model may result from dosimeter alignment uncertainties and size effects at small radii and from not totally compensating for the energy-dependence of the A16 ion chamber calibration.
- From the air kerma strengths and depth-dose curves, the **dose rate constant** was measured to be **0.86 ± 0.06 cGy·h $^{-1}$·U $^{-1}$** at **40 kVp** and **0.64 ± 0.08 cGy·h $^{-1}$·U $^{-1}$ at 50 kVp**. The calculated value from MNCP is 0.61 at 40 and 50 kV. For comparison, consensus values are 0.69 for ^{103}Pd and 0.94-1.04 for ^{125}I. [2]
- The measured angular anisotropy from the sources agrees well with calculated values as shown in Figure 7. The measured values are independent of distance from 2.0 to 4.0 cm within experimental error and independent of operating voltage from 40 to 50 kVp (Figure 8). Note that, in Figure 7, 0º (360º) is the proximal direction along the high voltage cable.

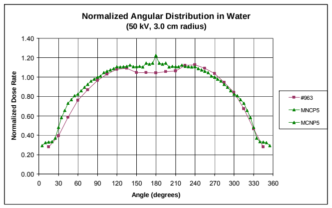

Figure 7. Comparison of measured and calculated angular anisotropy normalized to 1.00 for the average value of readings at 90 and 270º.

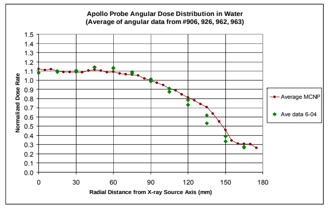

Figure 8. Measured and calculated anisotropy functions averaged over radius and operating voltage (0º corresponds to 180º in Fig. 7).

CONCLUSIONS

- Dosimetric parameters of the Xoft microTube Flexible X-ray Probe, a new electronic brachytherapy source based on a miniature x-ray tube, can be characterized within the updated TG-43 protocol with very minor modifications.
- Initial measurements have been done to compare actual and calculated source performance. Measured depth-dose curves agree with predictions to within 20% for operation at 50 kVp.
- The measured Xoft microTube x-ray source operating at 50 kVp had an air kerma strength of approximately 1440 Gy·cm ^{2} ·h $^{-1}$ when scaled to a beam current of 0.3 mA, which is about three times that of a 10 Ci ^{192}Ir source. The measured dose rate constant at 50 kVp was 0.64 ± 0.08 cGy·h $^{-1}$·U $^{-1}$.
- Measured source anisotropy in water agrees well with MCNP5 calculations for 2.0 to 4.0 cm radii and 40 to 50 kVp.
- Measurements confirm that the Xoft microTube Flexible X-ray Probe is suitable as a high dose rate brachytherapy source with tunable depth-dose characteristics.

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