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Experimental characterization of the dosimetric properties of a newly designed I-Seed model AgX100 ¹²⁵I interstitial brachytherapy source

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Keywords

¹²⁵I source; interstitial brachytherapy; TLD dosimetry; photon spectrometry

INTRODUCTION

In 2010, Theragenics Corporation® (Buford, GA) introduced a model AgX100 radioactive source for ¹²⁵I-based interstitial brachytherapy. According to manufacturer's design specification, the model AgX100 source uses a cylindrical silver rod as the substrate for radioactive ¹²⁵I which also serves as a radiographic marker for better source localization in patient dosimetry. The silver rod, measuring 3.5 mm in length and 0.59 mm in diameter, is coated with a thin layer (1.0– 5.0 μm thick) of radioactive silver iodide and is sealed inside a titanium encapsulation tube. The titanium tube has an overall length of 4.5 mm and an outer diameter of 0.8 mm with a nominal wall thickness of 0.05 mm (Figure 1). The basic design of the model AgX100 source is similar to the well-established model 6711 OncoSeed™ manufactured by GE Healthcare.[1] Like the model 6711 source, silver fluorescent x-rays at photon energies of 22.2 keV and 25.5 keV will be emitted from the AgX100 source as a result of the interaction of ¹²⁵I photons with the silver substrate. In addition, the principal photon emissions from ¹²⁵I includes the 27.4 keV and 31.0 keV x-rays and a 35.5 keV gamma-ray, among other emissions. Because the silver fluorescent yield and the absorption and scattering of low-energy photons (those resulted from silver fluorescence and emitted by ¹²⁵I) are highly dependent on the geometry and material composition of the source construction, a careful characterization of the dosimetric properties must be performed for this new source model before it can be used clinically as recommended by the American Association of Physicists in Medicine (AAPM).[2] Here, we describe a comprehensive experimental characterization of dose deposition properties for the model AgX100 source. The dosimetry parameters needed for dose calculation using the AAPM Task Group No. 43 (TG-43) dosimetry formalism[1, 2] were determined and compared with the TG-43U1 consensus values already established by AAPM for the model 6711 source as well as the results of a Monte Carlo simulation performed by an independent research group.

MATERIALS AND METHODS

A. Photon spectrometry

A high-purity germanium detector designed for photon spectrometry of low-energy brachytherapy sources was used to measure the photon energy spectrum emitted by the AgX100 source. The measured photon energy spectrum is indicative of the effects of source construction (i.e., encapsulation geometry and materials) on bare ^{125}I photons. These effects include photon absorption and scattering as well as the production of fluorescent x-rays in encapsulation materials. It represents a key radiological property of the AgX100 source and was used in the systematic comparison of its dosimetry characteristics with those of the 6711 source.

The photon energy spectrum measured along the radial direction in the transverse bisector of the source was also used to determine the dose-rate constant of the AgX100 source using the photon spectrometry technique (PST) described by Chen and Nath.[3] PST calculates the dose-rate constant, Λ_{PST} , from first-principles based on the measured photon energy spectrum and the well-characterized dose deposition properties of mono-energetic photons in water. Briefly, Λ_{PST} is derived using the following equation

$$\Lambda_{\text{PST}} = \frac{\sum_i n(E_i) E_i (\mu_{\text{en}}(E_i) / \rho)_{\text{air}} \Lambda(E_i)}{\sum_i n(E_i) E_i (\mu_{\text{en}}(E_i) / \rho)_{\text{air}}}, \quad (1)$$

where $n(E)$ denotes the number of emitted photons with energy E , $[\mu_{\text{en}}(E) / \rho]_{\text{air}}$ is the mass energy absorption coefficient of air, and $\Lambda(E)$ is the dose-rate constant of a mono-energetic photon source with energy E given by

$$\Lambda(E) = [\mu_{\text{en}}(E) / \rho]_{\text{a}}^{\text{w}} \frac{1}{S_K} \int_{-L/2}^{L/2} dx \rho(x) e^{-\mu(E) \sqrt{x^2+y^2}} (x^2+y^2)^{-1} B_{\text{en}}(\mu(E) \sqrt{x^2+y^2}) \Big|_{y=1\text{cm}}. \quad (2)$$

In Eq.(2), S_K is the air-kerma strength of the source, $\rho(x)$ is the linear density of source strength along the longitudinal axis of the source (with $\int_{-L/2}^{L/2} \rho(x) dx = S_K$), $[\mu_{\text{en}}(E) / \rho]_{\text{a}}^{\text{w}}$ is the ratio of mass energy absorption coefficients of water to air, $\mu(E)$ is the mass attenuation coefficient of water, and $B_{\text{en}}(\mu(E)r)$ is the energy buildup factor that accounts for the relative dose contribution from the scattered photons in water.[3] The x -axis in Eq.(2) coincides with the longitudinal axis of the source, the origin of the x and y axes coincides with the center of the source, and L denotes the active length of the source. In numerical calculations, the mass attenuation and mass energy absorption coefficients were taken from the database maintained by NIST[4] and the energy buildup factor was taken from the data published by Angelopoulos *et al.*,[5] which included both Rayleigh scattering and Compton scattering with bound atomic electrons as well as the transport of secondary electrons. The dose-rate constant determined by PST for the AgX100 was compared to that determined earlier in our lab for the 6711 source.

B. TLD dosimetry

Radiation dosimetry using thermoluminescent dosimeters (TLD) is currently regarded by AAPM as the experimental technique of choice for dosimetric characterization of low-energy interstitial brachytherapy sources.[2] In this work, absolute dose distributions around the AgX100 I-Seed ^{125}I source were measured using micro LiF TLD (1mm $\times$ 1mm $\times$ 1mm) in water-equivalent solid phantoms using the techniques which has been used in our laboratory for several other interstitial brachytherapy sources.[6] The SolidWaterTM phantom

(Radiation Measurement Inc.) was machined to accommodate the source and the micro TLDs.

Three experimental setups, identical to those used in Ref. #7, were used for the measurement of dose-rate constant, radial dose function and anisotropy function. For dose-rate constant measurement, two micro TLD chips were placed on the opposite side of the source along the source central transverse axis. The radial distance between each TLD chip and the source center was 1 cm. Nine measurements (each with a pair of TLDs) were performed on three different AgX100 sources. The air kerma strength of the AgX100 sources used in this study were provided by the manufacturer, based on direct comparison to the source strength of NIST calibrated AgX100 sources.

The radial dose function was measured from a radial distance of 0.5 cm up to 7.0 cm in 0.5 cm increments. The experimental setup consisted of a total of 28 micro TLD chips placed on both sides of the source along source's central transverse axis. A total of six experiments were performed on three different sources. Because of the steep dose falloff away from the source, the TLDs placed farther away from the source needed significantly longer irradiation time than the TLDs placed close to the source. The loss of thermo-luminescence (TL) signal during the long irradiations was investigated and corrected as follows. First, 100 micro-TLDs were irradiated simultaneously to the same dose. Second, ten groups of TLDs (each consists of 10 TLDs to minimize statistical uncertainties) was read at different post-irradiation times that cover the time span of radial dose function experiment. This data was fitted to a mathematical function which quantifies the amount of TL loss as a function of elapsed time between dose deposition and TLD readout. Third, this function was then used as a convolution kernel to correct the on-going TL fading during the continuous irradiations used in the radial dose function experiments. The magnitude of TL-loss correction ranged from approximately 1% for TLDs irradiated at the radial distance of 2 cm to approximately 3.2% for TLDs irradiated at the radial distance of 7 cm.

The anisotropy function was measured at radial distances of 1, 2, 3, 4, 5 and 6 cm ranging from 0 degree to 350 degree in 10-degree increments. Two phantoms, one accommodates TLDs at the radial distances of 1.0 cm, 3.0 cm, and 5.0 cm and the other accommodates TLDs at the radial distances of 2.0 cm, 4.0 cm and 6.0 cm, were used.

For all experimental setups, at least 10 cm thick of phantom materials was placed around the source and TLDs. The shielding effects of TLDs are not significant as reported in a previous study.[7] Before the measurement, a group of TLDs from the same batch were annealed at 400°C for one hour and then kept at room temperature for 45 minutes followed by 80°C heating for 24 hours. These TLDs were then irradiated uniformly in a large cavity Cs-137 irradiator for biomedical research (Shepherd, Mark III) so that the relative sensitivities (chip factors) of the individual TLDs could be established. The annealing process was then repeated for the TLDs, and was repeated after each use of TLDs in experiments to bring the TLDs back to the ground states. The chip factors were measured three times for each TLD used in the experiment. For the determination of dose-rate constant, the TLDs were first calibrated in a 6 MV x-ray beam from a Varian Trilogy linear accelerator. The x-ray beam was calibrated with a PTW 0.6 cc Farmer-type cylindrical chamber according to AAPM Task Group 51 (TG-51) protocol.[8] A energy-response correction factor was used to convert the TLD sensitivity from 6 MV photons to ^{125}I photons.[7] The measurements were performed by leaving a ^{125}I source in the source location for a certain amount of time so that the TLDs at 1 cm away from the source center along the source central transverse axis received an estimated dose of 100 cGy. For the measurement of radial dose function, the TLDs at $r = 0.5$ cm were taken out when an estimated dose in the range of 100 cGy had been delivered to the TLDs and replaced with a dummy TLD to fill the void. For all experiments,

a 24 hours waiting period was applied between the end of irradiation and reading of TLDs to minimize the fading effects of the irradiated TLDs.

The cumulative dose measured by a TLD at a point of interest (r, θ) in SolidWater™ from time T_i to T_f , $D(r, \theta)$, was used to determine the dose rate in water at the point of interest and time T_i using the following equation,

$$\dot{D}_i(r, \theta) = \frac{P(r) \times D(r, \theta)}{E(r) \times S_{K0} \times e^{-\lambda(T_i - T_o)} \times \frac{1}{\lambda} \times (1 - e^{-\lambda(T_f - T_i)})} \quad (3)$$

In Eq.(3), S_{K0} denotes the air kerma strength of the source at a reference time T_o ; λ is the decay constant of ^{125}I which equals to $\ln 2/59.43$ (day^{-1}); $P(r)$ is the phantom-to-water correction factor which converts TLD measured dose in phantom to dose in water; and $E(r)$ is the energy-response correction factor. Because the average photon energies at radial distances of 1 cm to 7 cm along the transverse axis are within 1 keV from each other, a single value of 1.41 for $E(r)$ was obtained from Ref. #8 and used in this work. The $P(r)$ for the SolidWater™ and the AgX100 source used in the work was determined by Mourtada et al. using the MCNP5 Monte Carlo code[9]. The $P(r)$ calculated for the AgX100 source was similar to that calculated by Williamson for the 6711 source.[10] At $r = 1$ cm, they are virtually identical (1.044 and 1.043 for AgX100 and 6711, respectively).

With the dose rate in water at (r, θ) obtained from Eq.(3), the dose rate constant Λ , the radial dose function $g(r)$, and the 1D and 2D anisotropy functions were determined following the AAPM TG-43 formalism[2]. An active length of 3.5 mm was used in the calculation of radial dose function under line source approximation.

RESULTS AND DISCUSSION

A. Photon energy spectrum

Table 1 summarizes the relative photon energy spectrum measured for the AgX100 and the 6711 sources. The relative spectra were obtained by normalizing each spectrum to their respective K_a spectral intensity. A combined relative standard uncertainty ($k=1$) of 3.7% was estimated for the measured energy spectra according to the method described in detail in Ref #3. It included both the uncertainties of the spectrometry system and the standard deviation among the three sources used in the spectrometry measurements. As shown in Table 1, the spectrum emitted by the AgX100 source was nearly identical to that emitted by the 6711 source.

B. Dose-rate constant

The dose-rate constant determined by photon spectrometry technique for the three AgX100 sources had a mean value of $0.957 \text{ cGyh}^{-1}\text{U}^{-1}$ and relative inter-source variation (1σ) of less than 0.01%. Including the uncertainties of the spectrometry technique, the combined standard uncertainty ($k=1$) was estimated to be $\pm 0.037 \text{ cGyh}^{-1}\text{U}^{-1}$ following the method of Ref. #3. The dose-rate constant measured by TLD had a mean value of $0.995 \text{ cGyh}^{-1}\text{U}^{-1}$ and a standard deviation ($k=1$) of $0.014 \text{ cGyh}^{-1}\text{U}^{-1}$ among the nine TLD experiments. The combined standard uncertainty ($k=1$) associated with the TLD dosimetry (including other sources of uncertainty in the TLD dosimetry process to be discussed in section D) was estimated to be $0.066 \text{ cGyh}^{-1}\text{U}^{-1}$.

The dose-rate constant determined by PST for the AgX100 source ($0.957 \pm 0.037 \text{ cGyh}^{-1}\text{U}^{-1}$) is nearly identical (within 0.2%) to that of the 6711 source ($0.960 \pm 0.037 \text{ cGyh}^{-1}\text{U}^{-1}$). This is consistent with the nearly identical photon energy spectra emitted by both source models as

shown in Table 1. The dose-rate constant determined by TLD for the AgX100 source ($0.995 \pm 0.066 \text{ cGyh}^{-1}\text{U}^{-1}$) was approximately 3.9% greater than that determined by PST, but was within 1.5% of the average TLD-determined values for the model 6711 source ($0.980 \text{ cGyh}^{-1}\text{U}^{-1}$)[2], which is well within the experimental uncertainties of the TLD technique.

Mourtada et al. has performed an independent dosimetric characterization for the AgX100 source using MCNP5 Monte Carlo codes[9]. They have obtained a dose-rate constant value of $0.943 \pm 0.015 \text{ cGyh}^{-1}\text{U}^{-1}$ for the AgX100 source. Following the practice of AAPM TG-43, when the Monte Carlo calculated value was averaged with the mean value of our TLD and PST measured values, we obtained a dose-rate constant value of $0.960 \text{ cGyh}^{-1}\text{U}^{-1}$ based on the three techniques. This value is within 0.5% of the consensus value, $0.965 \text{ cGyh}^{-1}\text{U}^{-1}$, established by AAPM TG-43 for the model 6711 source.

C. Radial dose function and anisotropy function determined by TLD

Table 2 lists the radial dose function determined by TLD dosimetry for the AgX100 source. The radial dose functions determined by Monte Carlo simulation[9] for this source model and by AAPM TG-43 consensus for model 6711 source were also included in Table 2 for comparison. For the model 6711 source, the log-linear interpolation as recommended by TG-43U1S1[11] was used to determine the radial dose function values at those radial distances where original data was not available. The TLD-measured radial dose function agreed within 5% with those determined by Monte Carlo and by TG-43 consensus for the 6711 source for radial distances up to 6.5cm.

Table 3 lists the 2D and 1D anisotropy functions measured for the AgX100 source. Since the source is cylindrically symmetric, the results were tabulated only for polar angles from 0 to 90 degrees. The TLD-measured anisotropy function was found to agree well with the Monte Carlo calculated values and with the TG-43 consensus data for the 6711 source at almost all polar angles and radial distances from 1 to 6 cm. Figure 6 illustrates the graphical comparison at radial distances of 2, 4 and 6 cm. Quantitatively, for $\theta = 10^\circ$, the agreement between TLD-measured and Monte Carlo-calculated anisotropy functions was $<4.8\%$ at all measurement point listed in Table 3 except at the point of $r = 5 \text{ cm}$ and $\theta = 10^\circ$, which had a relative difference of 8.1%. Over 90% and 80% of the measurement points had agreement better than 4% and 3%, respectively. For $\theta = 0^\circ$, the agreement was not as good with relative differences varying from 6.7% to 20.5% over the six radial distances. The relatively larger disagreement between the measured and calculated anisotropy functions at $\theta = 0^\circ$ is due in part to the finite size of micro-TLD cubes in addition to the intrinsic uncertainties of TLD dosimetry.

D. Uncertainty analysis

Detailed discussion of the uncertainties associated with each component of the PST technique has been presented earlier by Chen and Nath,[3] which will not be reproduced here. The uncertainties associated with the specific photon spectrometry measurements for the AgX100 included the Type A statistical uncertainties of repetitive measurements among the three seeds used in this work as presented already in section A. The uncertainties associated with our TLD measurements were estimated following the guidelines of AAPM TG-138 and TG-43U1 reports as detailed below. [2, 12]

For the TLD-measured dose-rate constant, a total relative standard uncertainty ($k=1$) was estimated to be 6.6% and the total expanded uncertainty ($k=2$) was 13.2%. As listed in Table 4, the estimation took into account the relative uncertainties ($k=1$) associated with the source strength (1.9%), source and TLD positioning in the Solid Water[®] phantom (2.2%), TLD dose calibration (2.9%), TLD energy response correction (5%), Solid Water[®] to water

conversion (0.2%), and statistical variations of TLD readout in repetitive measurements (1.4%). The estimation of these uncertainties is detailed below. The air-kerma strength of the AgX100 seeds used in this study was measured by the manufacturer using equipment calibrated directly from the NIST calibrated AgX100 sources. The combined relative standard uncertainty ($k=1$) of S_K depended on the relative standard uncertainties associated with 1) the NIST calibrated AgX100 sources, 2) manufacturer's calibration equipment, and 3) the reproducibility of S_K measurement by the manufacturer. The relative standard uncertainty of NIST calibrated AgX100 sources was 1.3%, taken directly from the NIST calibration report. The relative standard uncertainty associated with the manufacturer's calibration equipment and the reproducibility of S_K measurement by the manufacturer was taken from the TG-138 report as 0.9% and 1.1%, respectively. The combined standard uncertainty of S_K was then estimated from the quadrature sum of 1) to 3) to be 1.9%. The source-to-TLD positioning uncertainty in Solid Water[®] depended on the geometric tolerance of the machined cavities for the source (0.1 mm) and TLD cubes (0.2mm) in the Solid Water[®] phantom. A combined relative standard uncertainty of 2.2% in source-to-TLD distance was estimated from the quadrature sum of relative uncertainties in source and TLD positioning. The uncertainty in TLD dose calibration depended on the TG-51 calibration for the 6 MV photon beam (1.5%) and the intrinsic TLD sensitivity (chip factor) determination (2.5%). The combined relative standard uncertainty in 6 MV photon TG-51 calibration was estimated from the relative standard uncertainties associated with the chamber calibration coefficient provided by the standards lab (0.6%) and our dose calibration measurement (1.4%, which included calibration setup (0.4%), beam quality correction (1.0%), electrometer readout (0.6%), chamber correction factor (0.4%), and long-term chamber stability (0.3%)). The relative uncertainty in TLD chip factor determination (2.5%) was determined from three independent chip factor measurements for each batch of 100 TLDs under the identical irradiation condition. So the combined relative standard uncertainty in TLD dose calibration was estimated to be 2.9%. The relative standard uncertainty associated with the TLD energy response correction for the LiF TLD cube was taken from the AAPM TG-43U1 recommended uncertainty budget to be 5.0%. The relative standard uncertainty associated with the Monte Carlo calculated Solid Water[®]-to-water conversion factor (0.2%) was estimated from the relative uncertainties of the dose rates calculated at the radial distance of 1 cm for the AgX100 source in Solid Water[®] and in water. The relative standard uncertainty (type A) of repetitive TLD measurements (1.4%) was estimated from the nine experiments performed for the dose-rate constant measurements.

The uncertainty of measured radial dose function depended on the relative uncertainty of dose rate measurements at both the reference position and the point of interest on the transverse plane. Since the 6 MV beam calibration and TLD energy response correction remained the same in the relative dose measurements, the uncertainty arose primarily from the uncertainties in source-to-TLD distance, repetitive TLD measurements, Solid Water[®]-to-water conversion, and distance dependent TL-loss correction. Based on the source and TLD positioning uncertainty of 0.1 and 0.2 mm, respectively, the relative standard uncertainty of source-to-TLD distance was estimated to be 2.2%, 0.4%, and 0.3% at radial distances of 1 cm, 5 cm and 7 cm. The uncertainty associated with repetitive TLD reading was estimated from the three radial dose function experiments, which increased from 1.4% at 1 cm to 2.3% and 7.3% at 5 cm and 7 cm, respectively. The relative standard uncertainty for the Monte Carlo calculated $P(r)$ was estimated from the relative uncertainties associated with the dose rates calculated in water and in Solid Water[®] media as a function of radial distances. The relative standard uncertainty of $P(r)$ estimated using the quadrature sum approach was approximately 0.2%, 0.6% and 1.0% at radial distances of 1, 5 and 7 cm, respectively. The uncertainty of TL-loss correction for continuous irradiation with different durations was estimated from the TL-loss kernel. The uncertainty for this kernel function arose primarily from the uncertainties in TLD readout at each post-irradiation time and in the curve-fitting

process. The standard deviation for the 10 TLDs at each post-irradiation time was 1.0%, 1.6% and 2.1% at $r = 1$ cm, 5 cm and 7 cm, respectively. The standard error in fitting the average TL-loss data to an analytic curve was approximately 0.8% at all radial distances. The combined relative standard uncertainty for the TL-loss kernel was estimated to be 1.3%, 1.8% and 2.2% at $r = 1$ cm, 5 cm and 7 cm, respectively. The combined relative standard uncertainty ($k=1$) for our TLD-measured radial dose function was therefore 2.9%, 3.0% and 7.7% at radial distances of 1 cm, 5 cm and 7 cm, respectively.

The uncertainty of TLD-measured anisotropy function depended on the relative uncertainties of TLD-measured dose rates at angle θ and $\theta = \pi/2$. Because the 6 MV beam calibration, TLD energy response correction and radial distance were kept the same in these relative dose measurements, the uncertainty arose primarily from the uncertainties in source-to-TLD distance, angle θ , and repetitive TLD measurements. As discussed early for radial dose function, the relative standard uncertainty in source-to-TLD varied from 2.2% at $r = 1$ cm to 0.4% at $r = 5$ cm. The uncertainty in θ was less than 0.2 degree with a maximum Type B relative standard uncertainty of 2%. The uncertainty in repetitive TLD measurements was assessed from the multiple experiments of anisotropy function determination. The relative standard uncertainty ranged from approximately 6% to 0.1% when θ increased from 0 degree to 90 degree (in a general trend). So the relative standard uncertainty for our measured anisotropy function ranged from 2% to 6.3% at $r = 5$ cm. The uncertainty is expected to vary with radial distance and polar angle θ .

CONCLUSION

A comprehensive experimental characterization of the dosimetric properties has been performed using high-resolution photon spectrometry and LiF TLD dosimetry for the model AgX100 I-Seed source. The dosimetric parameters needed for clinical dosimetry using the AAPM TG-43 dose calculation formalism were determined. It was found that 1) the photon energy spectrum emitted by the AgX100 source was nearly identical to that emitted by the model 6711 source; 2) the dose rate constant determined by the photon spectrometry technique and by the TLD technique was similar to that of the model 6711 source; 3) the radial dose function and the anisotropy function of the AgX100 source was also similar to those of model 6711 ^{125}I source.

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LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine (AAPM)
TG-43	Task Group No. 43
PST	Photon spectrometry technique
NIST	National Institute of Science and Technology
TLD	Thermoluminescent dosimeter
TG-51	Task Group 51

Figure 1. Schematic drawing of the I-Seed AgX100 ^{125}I source. Courtesy of Theragenics Corporation®.

Figure 2. Comparison of the anisotropy functions between the AgX100 source (TLD measured and Monte Carlo calculated) and the 6711 source (TG-43 consensus value when available) at radial distances of 2, 4, and 6 cm.

Table 1

Measured relative photon energy spectrum

Photon Type	Level	Energy (keV)	Relative Energy Spectrum	
			I-Seed AgX100	OncoSeed 6711
X-ray	Ag - K _α	22.1	0.272 ± 0.010	0.268 ± 0.010
X-ray	Ag - K _β	24.9	0.068 ± 0.003	0.067 ± 0.003
X-ray	¹²⁵ I - K _α	27.3	1	1
X-ray	¹²⁵ I - K _β	31.0	0.245 ± 0.009	0.249 ± 0.009
Gamma	¹²⁵ I - γ	35.5	0.067 ± 0.002	0.067 ± 0.002

Note: Errors displayed in this table represent one standard deviation

Table 2

Comparison of radial dose function

Radial Distance (cm)	Point source approximation		Line source approximation	
	AgX100	AgX100 (EXPL=3.5 mm)	AgX100 ^a (MC L = 3.5 mm)	6711 ^b (CON L = 3.0 mm)
0.5	1.034	1.064	1.076	1.071
1.0	1.000	1.000	1.000	1.000
1.5	0.918	0.914	0.908	0.908
2.0	0.816	0.810	0.813	0.814
2.5	0.715	0.709	0.720	0.713
3.0	0.632	0.627	0.633	0.632
3.5	0.549	0.544	0.553	0.560
4.0	0.477	0.472	0.482	0.496
4.5	0.412	0.408	0.418	0.425
5.0	0.353	0.350	0.361	0.364
5.5	0.302	0.299	0.315	0.313
6.0	0.262	0.259	0.269	0.270
6.5	0.223	0.221	0.234	0.232
7.0	0.188	0.186	0.199	0.199

^aData from Ref. 11 with interpolation when needed;^bData from Ref. 2 with interpolation when needed.

Table 3Measured 1D and 2D anisotropy functions for the AgX100 ¹²⁵I source

Polar angle θ (degree)	r [cm]					
	1	2	3	4	5	6
0	0.354	0.427	0.554	0.564	0.676	0.634
10	0.498	0.588	0.651	0.646	0.728	0.706
20	0.671	0.752	0.753	0.782	0.816	0.787
30	0.79	0.859	0.841	0.854	0.875	0.862
40	0.892	0.945	0.908	0.957	0.911	0.91
50	0.955	0.972	0.946	0.956	0.954	0.956
60	0.975	1.009	0.971	0.987	0.963	0.977
70	0.992	1.011	1.023	0.994	0.989	1.003
80	0.994	1.052	1.009	1.013	1.006	0.97
90	1	1	1	1	1	1
$\phi_{an}(r)$	0.934	0.966	0.945	0.953	0.948	0.943

Table 4

Uncertainty in TLD measured dose-rate constant

Component	<u>Relative Standard Uncertainty (%)</u>	
	Type A	Type B
Source Strength		1.9
TLD-Source Distance		2.2
Dose Calibration		2.9
Energy Response		5.0
SolidWater® to Water Conversion		0.2
Repetitive Measurements	1.4	
Total Standard Uncertainty	6.6 (k=1)	
Total Expanded Uncertainty	13.2 (k=2)	