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Determination of the dosimetric characteristics of InterSource^{125} Iodine brachytherapy source

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Abstract

The TG-43 recommended dosimetric characteristics of a new ^{125}I brachytherapy source have been experimentally and theoretically determined. The measurements were performed in Solid Water™ using LiF TLDs. The calculations were performed using Monte Carlo simulations in Solid Water™ and water. The measured data were compared with calculated values as well as the reported data in literature for other source designs. The dose rate constant this source in water was $1.01 \pm 3\%$ cGy h^{-1} U^{-1} and the anisotropy constant was 0.956. © 2002 Published by Elsevier Science Ltd.

Keywords: Dosimetry; Brachytherapy; ^{125}I; Thermoluminescent dosimeter; TLD; TG-43

1. Introduction

^{125}I and ^{103}Pd brachytherapy sources are being used for interstitial implants in various anatomical sites, particularly for prostate cancers. Due to their low-energy photon emissions, the radiation will predominantly interact via photoelectric absorption, which helps to deliver the required radiation in a localized area and, hence, reduce unnecessary radiation to the surrounding normal tissue. Due to the ease of the procedure for the patient and the reduction of the side effects over radical prostatectomy (Nori, 1992; Russell and Blasko, 1993; Porrazzo et al., 1992; Blasko et al., 1995), the treatment of prostate cancer using radioactive seed implants has greatly increased within the last few years. The increase in frequency of this procedure had led to a shortage of available sources on the market. To meet the market demand, a new ^{125}I brachytherapy source, commercially known as InterSource^{125} source, has resulted.

The main objective of this project was to determine the dosimetric characteristics of the InterSource^{125} Iodine brachytherapy source. These dosimetric characteristics were determined using experimental and the Monte Carlo simulation approaches in accordance with the AAPM recommendations in the Task Group 43 protocol (Nath et al., 1995) and the AAPM recommendation on source calibration (Williamson et al., 1998, 1999).

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2. Materials and method

2.1. InterSource[125]

Fig. 1 shows a schematic diagram of InterSource[125] Iodine[1] manufactured by International Brachytherapy, Inc. (IBt, 6000 Live Oak Parkway, Suite 107, Norcross, Georgia 30093). The source has a physical length of 4.5 mm and an outer dimension of 0.81 mm. The active length was determined from the distance between the outer edges of the two outer active bands. This source was manufactured by placing a 0.045 mm thick platinum/iridium alloy (90% platinum and 10% iridium) X-ray marker and three cylindrical bands of an insoluble organic matrix containing iodine between two hollow titanium cylindrical tubes. The edges of the cylindrical tubes were laser welded. The inner and outer walls of the source are 0.04 mm thick. The relative composition of the organic matrix was 85.7% carbon and 14.3% hydrogen with a density of $1.0\,g\,cm^{-3}$.

2.2. Dosimeters

Dose distributions around the InterSource[125] source were measured in a Solid Water™ phantom (Radiation Measurements Inc., RMI, Middleton, WI) using TLD-100 LiF thermoluminescent dosimeters (Harshaw/Bicron 6801 Cochran Rd, Solon, OH 44139). For these measurements, slabs of Solid Water™ phantom material were machined to accommodate the source and two sizes of LiF TLD chips of dimensions ($3.1 \times 3.1 \times 0.9\,mm^3$) and ($1.0 \times 1.0 \times 1.0\,mm^3$).

Fig. 2 shows the schematic diagram of the experimental setup for measurements of the dose rate constant and radial dose function. The significance of the pattern and design on this phantom is described in a previous study (Meigooni et al., 2000). Fig. 3 shows the phantom design that was used for the measurement of the source anisotropy function. The method used for TLD dosimetry measurement is briefly described in the following section.

The TLD measurements were performed by surrounding the source and the TLD chips with at least 10 cm of Solid Water™ phantom material to provide full scattering conditions. Each data point represents the average of at least four TLD measurements. TLDs were read using a Harshaw Model 3500 TLD reader and were annealed using a standard technique (Meigooni et al., 1995). The following equation was used to calculate the dose rate from the TLD responses from each point irradiated in the phantom:

$$\frac{\dot{D}(r,\theta)}{S_K} = \frac{R}{T\, S_K\, \varepsilon\, E(r)\, \mathrm{d}(T)\, F_{lin}}, \qquad (1)$$

where $\dot{D}(r,\theta)$ is the dose rate at a point (r,θ), R is the TLD response that has been corrected for background and the physical differences between the TLD chips using the predetermined chip factors (Meigooni et al., 1995), and T is the experimental time. S_K is the measured source air-kerma strength at the time of measurement. ε is the calibration factor for the TLD response (nC/cGy) measured with a 6 MV X-ray beam from a linear accelerator (Clinac 2100C/D, Varian Oncology Systems, 3045 Hanover Street, Palo Alto, CA). $E(r)$ is a correction factor for the energy dependence of the

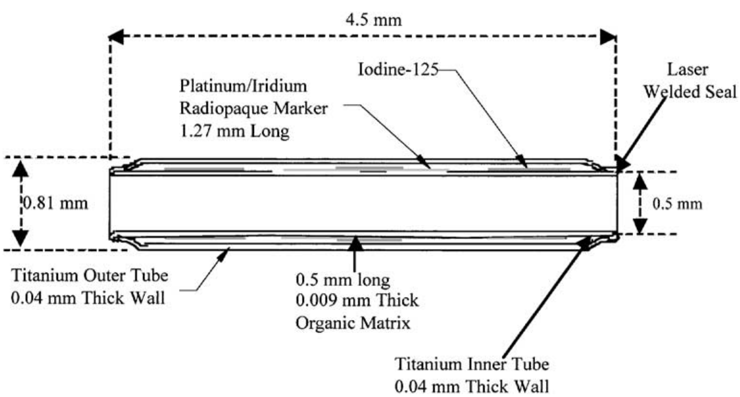

Fig. 1. Schematic diagram of the InterSource[125] Iodine brachytherapy source. Three active organic matrix bands containing ^{125}I and an X-ray marker are placed in between two titanium tubes with laser welded ends.

[1] InterSource[125] is registered trademark of Iodine source introduced by International Brachytherapy, Inc. (IBt).

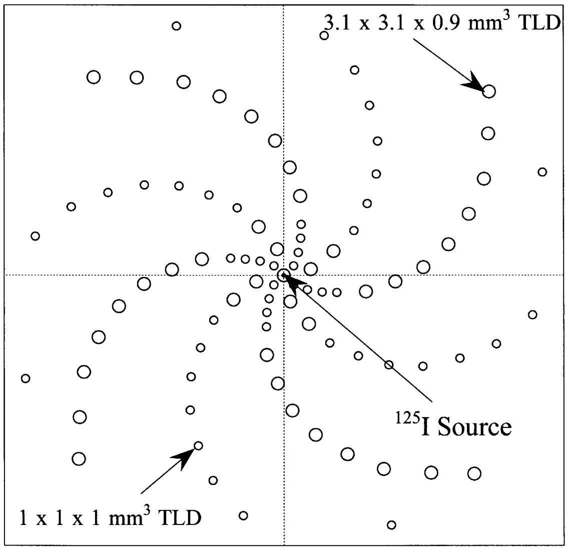

Fig. 2. Schematic diagram of the experimental setup for measurement of the radial dose function and dose rate constant with LiF TLDs. In this arrangement, the position of the source was adjusted such that the source center was at the level of the TLD chips. The smaller holes were made for $1 \times 1 \times 1\,mm^3$ chips and larger holes were made for $3.1 \times 3.1 \times 0.9\,mm^3$ chips.

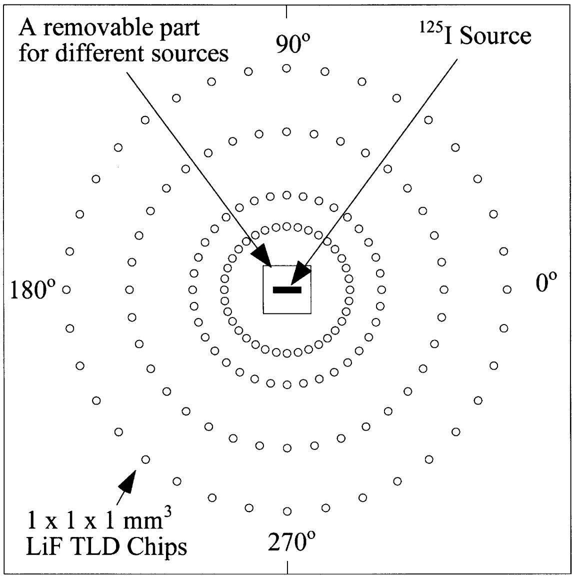

Fig. 3. Schematic diagram of the Solid Water™ phantom design for TLD measurements of the anisotropy functions, $F(r, \theta)$. Similar to Fig. 2, the holes were made for $1 \times 1 \times 1\,mm^3$ chips.

TLD between the calibration beam and the ^{125}I photons. It has been shown that for ^{125}I, there is no significant variation of photon spectrum as a function of depth (Meigooni et al., 1988) and hence a single value of 1.4 was used (Muench et al., 1991). $d(T)$ is a correction factor used to account for the decay of the source during irradiation. F_{lin} represented a correction for non-linearity in TLD response and was assumed to be unity due to the range of doses (10 to 100 cGy) measured herein. In these measurements, T was selected such that the absorbed doses ranged from 10 to 100 cGy for which TLD responses are linear.

2.3. Monte Carlo simulation

In the past several years, the Monte Carlo simulation has become a reliable tool for the characterization of new brachytherapy sources. The PTRAN computer code, Version 6.3, was used in this study. This code was developed by Williamson and explained in detail in several studies (Williamson 1987, 1988, 1991; Williamson et al., 1993). By introducing the accurate internal source geometry and composition of the source, the PTRAN code can provide reliable results which are comparable with the measured data. This code simulates photoelectric absorption, followed by K- and L-shell characteristic X-ray emissions, as well as incoherent and coherent scattering. The photon cross-section library (DLC, Data Library Code) used in this code was DLC-99 (Roussin et al., 1983).

The code also uses the corresponding mass-energy absorption coefficients by Hubbell and Seltzer (Hubbell, 1995) for converting energy fluence into absorbed dose. The primary photon spectrum used is provided by NCRP report 58 (NCRP, 1985). The PTRAN code includes a geometric modeling system that allows the source and calculation geometry to be accurately modeled. This code calculates the collision kerma rate at a point located in the phantom material in units of $\mathrm{cGy\,h^{-1}}$ per unit activity contained in the source. For low-energy photon emitters, secondary charged particle equilibrium can be assumed, which implies that the collision kerma closely approximates absorbed dose (Williamson 1987).

In this project, dose distribution of the InterSource^{125} source was calculated using the PTRAN code in Solid Water™ and liquid water as described in the following sections. Simulations were performed for a total of 2,275,000 histories divided into 65 batches. This number of histories combined with using a distance and attenuation averaged bounded next flight point kerma estimator (Williamson 1988) resulted in standard errors about the mean (67% confidence intervals) ranging from 1.5% (near the source: $r<3$ cm) to 5–6% (far from the source: $r>5$ cm).

Simulations were performed to calculate absorbed dose to water in Solid Water™ in order to obtain data comparable with the TLD measurements. Once the Monte Carlo simulations in Solid Water™ were shown to be in agreement with the TLD data (within experimental uncertainty), the calculations were performed in liquid water to provide data for clinical applications per TG-43 recommendations.

The dose rate constant, Λ, was calculated by dividing the Monte Carlo simulated dose rate of the source in water at 1 cm from the source center along the transverse bisector of the source to the simulated air kerma strength of the source. S_K was determined by calculating air kerma rate at 5 cm (to closely simulate the NIST measured value) distance and correcting for the inverse square of the distance to obtain the value at 1 cm. In this simulation, titanium characteristic X-ray production was suppressed. The air kerma rate strength per unit contained activity in the units of $\mathrm{cGy\,cm^2\,h^{-1}\,mCi^{-1}}$ provided comparison between the measured and calculated dose distributions.

2.4. Dosimetry technique

Characteristics of the InterSource^{125} source were determined experimentally following AAPM recommendations published in the TG-43 report (Nath et al., 1995) and the AAPM recommendation on source calibration (Williamson et al., 1998, 1999). Following this protocol, the dose distribution around a sealed brachytherapy source can be determined using the following formalism:

$$\dot{D}(r,\theta) = \frac{\Lambda\, S_K\, G(r,\theta)}{G(1\ \mathrm{cm}, \pi/2)}\, g(r)\, F(r,\theta), \tag{2}$$

where Λ is the dose rate constant, $G(r,\theta)$ is the geometry function, $g(r)$ is the radial dose function, $F(r,\theta)$ is the anisotropy function.

The above quantities are defined and discussed in detail in TG-43 (Nath et al., 1995). In the following sections, our methods of determination of these parameters have been briefly described.

2.5. Dose rate constant, Λ

The dose rate constant of the InterSource^{125} source was measured using LiF TLDs in a Solid Water™ phantom. This parameter has also been calculated using Monte Carlo simulations in Solid Water™ and liquid water. The dose rate constant was obtained from Eq. (3) as

$$\Lambda = \frac{\dot{D}(1\ \mathrm{cm}, \pi/2)}{S_K}. \tag{3}$$

An agreement between the measured and calculated dose rate constant in Solid Water™ was an indication that the correct source geometry was used in the simulation.

2.6. Radial dose function, $g(r)$

The radial dose function, $g(r)$, describes the attenuation in tissue of the photons emitted from the brachytherapy source. The radial dose function is defined as:

$$g(r) = \frac{\dot{D}(r, \pi/2)\, G(1\text{ cm}, \pi/2)}{\dot{D}(1\text{ cm}, \pi/2)\, G(r, \pi/2)}, \tag{4}$$

where $D(r, \pi/2)$ and $D(1, \pi/2)$ are the dose rates measured at distances of r and 1 cm, respectively, along the transverse axis of the source. $G(r, \theta)$ is known as the geometry function which takes into account the effect of the interior geometry of source on the dose distribution at a given point. The geometry function is defined by the AAPM TG-43 (Nath et al., 1995) as

$$G(r,\theta) = \begin{cases} \dfrac{1}{r^2}, & \text{Point source approximation,} \\ \dfrac{\tan^{-1}((x+L/2)/y) - \tan^{-1}((x-L/2)/y)}{Ly}, & \text{Linear source approximation.} \end{cases} \tag{5}$$

An active length (L) of 3.7 mm was used for the source in this study.

Table 1
A comparison of Λ of the InterSource[125] with the dose rate constants of commercially available sources

Source model	Method	Medium	Dose rate constant ($cGy\,h^{-1}\,U^{-1}$)
InterSource[125]	Measurement	Solid Water™	1.014±8%[a]
	Monte Carlo simulation	Solid Water™	0.981±3%[a]
	Monte Carlo simulation	Water	1.013±3%[a]
Best I-125 (Meigooni, 2000)	Measurement	Solid Water™	0.961±6.8%[a]
	Monte Carlo simulation	Water	1.01±6.8%[a]
Model 6711 (Williamson, 1991)	Monte Carlo simulation	Solid Water™	0.934
	Monte Carlo simulation	Water	0.973
Model 6702 (Williamson, 1991)	Monte Carlo simulation	Solid Water™	0.998
	Monte Carlo simulation	Water	1.030
IoGold MED3631-A/M (Wallace and Fan, 1999)	Measurement	Water	1.06

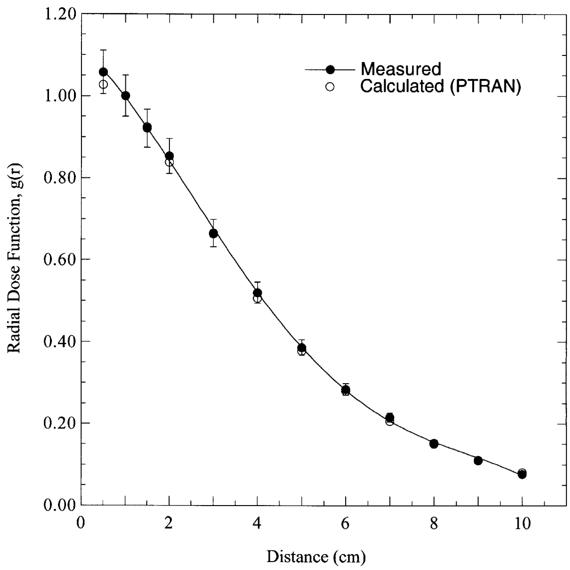

Fig. 4. Comparison of the measured and calculated radial dose function in Solid Water™ of the InterSource[125] brachytherapy source.

The radial dose function, $g(r)$, of InterSource[125] was measured using Solid Water™ phantom material (Fig. 2). The measurements were performed from 0.5 cm to 2 cm at 0.5 cm increments and from 2 cm to 10 cm at 1 cm increments. The large TLD chips were used for $r > 2$ cm with the small for $r \leqslant 2$ cm. The TLD responses were converted into absorbed dose using Eq. (1) and $g(r)$ derived using TG-43 formalism (Nath et al., 1995). The data at each distance were obtained from the average of at least eight TLD chips with a standard deviation of about $\pm 5\%$.

In addition to the measured data, $g(r)$ was calculated in both Solid Water™ and liquid water using the PTRAN Monte Carlo code. An agreement between the measured and calculated $g(r)$ data in Solid Water™ was another indication that the proper source geometry was used for simulation.

2.7. Anisotropy function, $F(r, \theta)$

The anisotropy function of InterSource[125] source was measured at distances of 2, 3, 5, and 7 cm from the source center using a Solid Water™ phantom that was accurately machined to accommodate the TLD chips at 10° angle increments relative to the source axis (Fig. 3).

At least eight TLDs were exposed for each data point. TLD responses were converted to absorbed dose using Eq. (1) and the anisotropy functions were extracted using the TG-43 formalism. (Nath et al., 1995) From the measured dose distribution around the source at a given radius, the anisotropy function, $F(r, \theta)$, was calculated following the TG-43 recommendation as

$$F(r,\theta) = \frac{\dot{D}(r,\theta)\, G(r,\pi/2)}{\dot{D}(r,\pi/2)\, G(r,\theta)}, \tag{6}$$

where θ is the solid angle around the source. The anisotropy factors, $\phi_{an}(r)$, of the InterSource[125] as a function of radial distance from the source was calculated using the following equation:

$$\phi_{an}(r) = \frac{\int_0^{\pi/2} \dot{D}(r,\theta) \sin(\theta)\, \mathrm{d}\theta}{\dot{D}(r,\pi/2)}. \tag{7}$$

The anisotropy constant, $\bar{\phi}_{an}$, of the new source was determined as the mean of the individual anisotropy factors.

3. Results

The dose rate constant, Λ, of the InterSource[125] source was measured in Solid Water™ and calculated in both Solid Water™ and liquid water. The TLD measured dose rate constant of $1.01 \pm 8\%$ cGy h^{-1} U^{-1} in was in good agreement

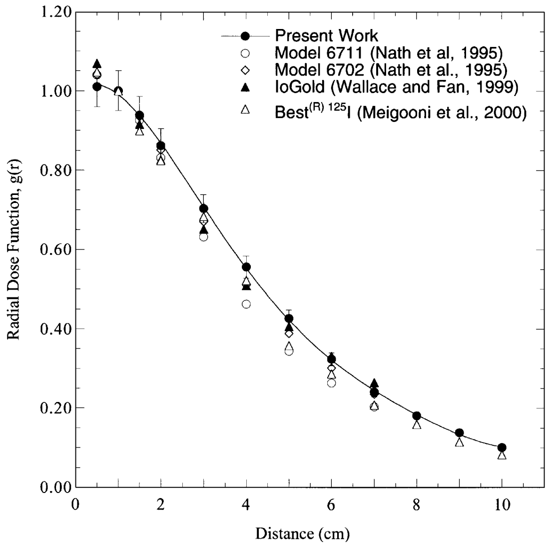

Fig. 5. Comparison of the radial dose function of the InterSource[125] source in water with Nycomed/Amersham model 6711, model 6702, NAS/Mentor IoGold, and Best® ^{125}I. The solid line is connecting the data points from the current study.

Table 2
Measured and calculated $g(r)$ of the InterSource[125] brachytherapy source in Solid Water™ and water

r(cm)	$g(r)$		
	Measured (Solid Water™)	Calculated (Solid Water™)	Calculated (Water)
0.1		0.708	0.685
0.2		0.908	0.884
0.3		0.984	0.963
0.4		1.011	0.992
0.5	1.086	1.027	1.010
0.6		1.029	1.018
0.7		1.032	1.025
0.8		1.027	1.017
0.9		1.011	1.010
1.0	1.000	1.000	1.000
1.5	0.921	0.924	0.939
2.0	0.853	0.838	0.862
2.5		0.753	0.783
3.0	0.665	0.663	0.703
3.5		0.583	0.625
4.0	0.520	0.506	0.556
4.5		0.437	0.490
5.0	0.386	0.378	0.427
5.5		0.326	0.371
6.0	0.284	0.280	0.324
6.5		0.237	0.279
7.0	0.215	0.206	0.241
7.5		0.176	0.209
8.0	0.153	0.151	0.181
8.5		0.130	0.156
9.0	0.110	0.111	0.139
9.5		0.094	0.119
10.0	0.077	0.081	0.101

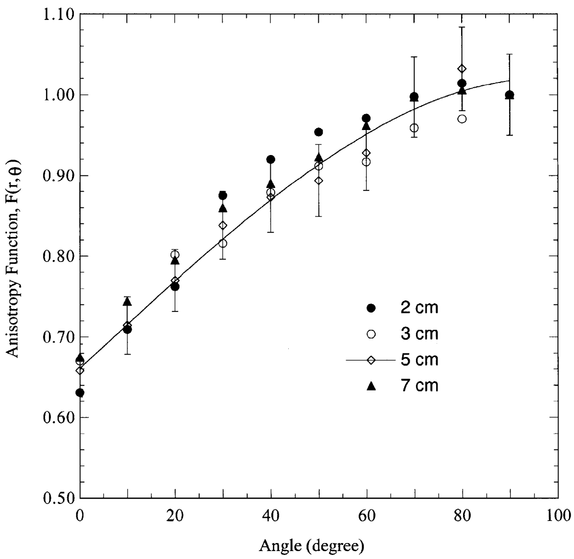

Fig. 6. Comparison of the measured and calculated values of the anisotropy function of the InterSource[125] brachytherapy source at 5 cm distance. The solid line is a 4th order polynomial fit to the calculated values.

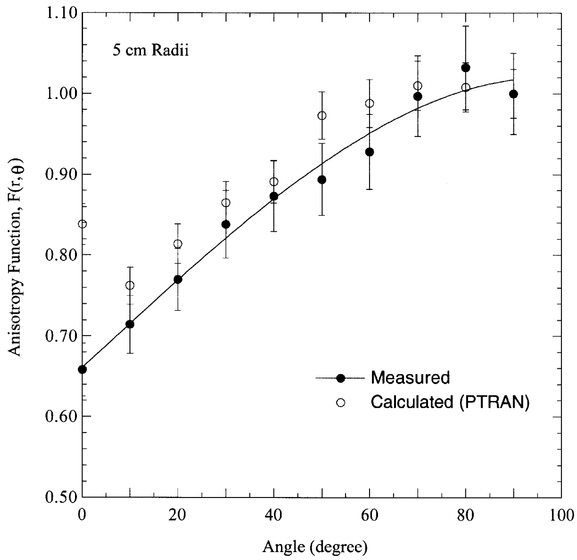

Fig. 7. Measured anisotropy function of the InterSource[125] source at radial distances of 2, 3, 5, and 7 cm. The solid line is a 4th order polynomial fit to the data at 5 cm. The error bars represent 5% uncertainty of the measured value at 5 cm.

Table 3
Measured and calculated $F(r,\theta)$ for the InterSource[125] brachytherapy source in Solid Water

Degrees	$F(r,\theta)$						
	Measured (Solid Water™)				Calculated (Solid Water™)		
	2 cm	3 cm	5 cm	7 cm	2 cm	3 cm	5 cm
0	0.631	0.670	0.674	0.675	0.788	0.856	0.838
10	0.709	0.709	0.714	0.744	0.736	0.744	0.762
20	0.762	0.802	0.770	0.795	0.793	0.797	0.814
30	0.875	0.816	0.838	0.860	0.852	0.855	0.865
40	0.920	0.879	0.873	0.890	0.901	0.905	0.891
50	0.954	0.912	0.916	0.923	0.946	0.946	0.973
60	1.030	0.917	0.954	0.962	0.974	0.974	0.988
70	0.998	0.959	0.997	0.997	0.983	0.992	1.010
80	1.014	0.970	0.999	1.006	0.988	0.991	1.008
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$\phi_{an}(r)$	0.945	0.931	0.913	0.955	0.944	0.942	0.956
$\bar{\phi}_{an}$		0.936				0.947	

with the Monte Carlo calculated value of $0.98 \pm 3\%$ cGy h^{-1} U^{-1} in Solid Water™. The Monte Carlo simulated dose rate constant in liquid water was found to be $1.01 \pm 3\%$ cGy h^{-1} U^{-1} (Table 1). Table 1 also presents a comparison between the dose rate constant obtained for this source with other commercially available sources.

The radial dose function, $g(r)$, of the InterSource[125] source was measured in Solid Water™ and also calculated in both Solid Water™ and liquid water. Figs. 4 and 5 shows a comparison between measured and calculated $g(r)$ in Solid Water™ phantom material and indicate agreement within the experimental uncertainties. The measured and calculated $g(r)$ values in Solid Water™ and water are presented in Table 2. The water data was fitted to a 5th order polynomial function as follows:

$$g(r) = a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + a_5 r^5, \tag{8}$$

where $a_0 = 1.0109$, $a_1 = 7.5881 \times 10^{-2}$, $a_2 = -1.0756 \times 10^{-1}$, $a_3 = 2.1398 \times 10^{-2}$, $a_4 = -1.7904 \times 10^{-3}$, $a_5 = 5.6035 \times 10^{-5}$.

Table 4
Calculated $F(r,\theta)$ for the InterSource[125] brachytherapy source in water

θ (deg)	r (cm)						
	1	2	3	4	5	6	7
0	0.893	0.799	0.910	0.802	0.698	0.827	0.843
10	0.759	0.743	0.804	0.759	0.687	0.768	0.783
20	0.823	0.799	0.846	0.804	0.736	0.818	0.824
30	0.877	0.859	0.896	0.859	0.806	0.868	0.883
40	0.917	0.904	0.946	0.906	0.832	0.913	0.918
50	0.951	0.949	0.989	0.948	0.885	0.946	0.982
60	0.967	0.976	1.017	0.974	0.880	0.975	0.995
70	0.963	0.985	1.026	0.991	0.893	0.987	1.016
80	0.959	0.989	1.023	0.990	0.883	1.010	1.013
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$\phi_{an}(r)$	0.959	0.947	0.983	0.943	0.949	0.949	0.965
$\bar{\phi}_{an}$				0.956			

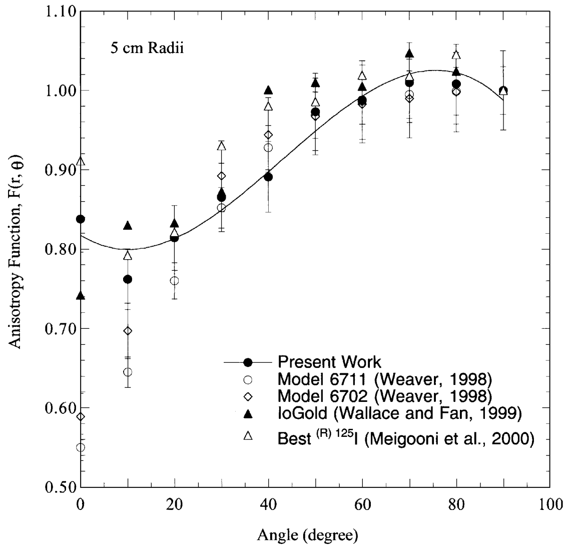

Fig. 8. Comparison of the calculated anisotropy function of the InterSource[125] source at 5 cm radius in water with Model 6711, Model 6702, NAS/Mentor IoGold, and Best® ^{125}I. The solid line represents a 4th polynomial fit for the present work.

The anisotropy function, $F(r,\theta)$, data measured and calculated in Solid Water™ at $r = 5\,\text{cm}$ are presented in Fig. 6. Again, data are in agreement within the experimental uncertainty. Fig. 7 shows measured $F(r,\theta)$ data in Solid Water™ at various angles and radii. These data are also indicated in Table 3, while Table 4 presents calculated $F(r,\theta)$ data in water. A comparison of anisotropy for the InterSource[125] with other source models at $r = 5\,\text{cm}$ is made in Fig. 8. $\phi_{an}(r)$ and $\bar{\phi}_{an}$ determined in Solid water and water and presented in Tables 3 and 4, respectively. The measured anisotropy constant of the InterSource[125] source in Solid Water™ was found to be 0.936, which is in good agreement with the calculated value of 0.947 in the same medium.

4. Discussion and conclusions

A new design of the ^{125}I brachytherapy source has been recently introduced by IBt for interstitial seed implants in order to meet the increasing demands of this method of treatment. Dosimetric characteristics (i.e. dose rate constant, radial dose function, and anisotropy function) of the new InterSource^{125} seed have been determined using experimental and theoretical methods. Measurements were performed in Solid Water™ using LiF TLD chips. Monte Carlo simulations were performed in Solid Water™ and liquid water using the PTRAN code. These determinations were performed in accordance with the AAPM TG-43 task group recommendations (Nath et al., 1995) and the AAPM recommendation on source calibration (Williamson et al., 1998, 1999).

The dose rate constant was measured to be $1.014 \pm 8\%$ cGy h^{-1} U^{-1} using LiF TLDs in Solid Water™ phantom. This value was in good agreement with Monte Carlo simulation in Solid Water™ ($0.981 \pm 3\%$ cGy h^{-1} U^{-1}). The agreement between the measured and calculated Λ gave the confidence of simulating the same source geometry that has been used in measurements. Therefore, this source geometry was used to simulate the dose rate constant in water. The value of Λ in water was found to be $1.013 \pm 3\%$ cGy h^{-1} U^{-1} using Monte Carlo Simulation.

The radial dose function of the InterSource^{125} source was measured at 0.5 cm increments from 0.5 to 2.0 cm and 1 cm increments for distances between 2.0 cm to 10.0 cm using two different sizes of LiF TLD chips. The $g(r)$ was also calculated in Solid Water™ and liquid water using a Monte Carlo simulation code. The good agreement within experimental error between the measured and calculated values in Solid Water™ indicates that the correct source geometry was used in the Monte Carlo simulation. Based on this agreement, the calculations were performed in water in the range of 0.1–10 cm.

The anisotropy function of the InterSource^{125} source was measured at 10° increments relative to the source axis (Fig. 3) at distances of 2, 3, 5, and 7 cm using LiF TLDs. Also, the Monte Carlo simulated $F(r,\theta)$ of the InterSource^{125} source in Solid Water™ and liquid water has been determined at distances of 1, 2, 3, 4, 5, 6, and 7 cm. The measured $F(r,\theta)$ for this source in Solid Water™ was in good agreement with the calculated values in the same medium. The variation between the measured anisotropy functions at different radii was within the experimental uncertainty ($\pm 5\%$). Fig. 8 shows the comparison of the $F(r,\theta)$ of the InterSource^{125} source with Model 6711 (Weaver, 1998), Model 6702 (Weaver, 1998), IoGold (Wallace and Fan, 1999), and Best$^{(R)}$ ^{125}I (Meigooni et al., 2000) at a distance of 5 cm.

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