Experimental Determination of Radial Dose Function and Anisotropy Function of GammaMed Plus ^{192}Ir High-Dose-Rate Brachytherapy Source in a Bounded Water Phantom and its Comparison with egs_brachy Monte Carlo Simulation

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Abstract

Objective: The aim of the present study is to experimentally measure the radial dose function g(r) and anisotropy function F(r,θ) of GammaMed Plus ^{192}Ir high-dose-rate source in a bounded water phantom using thermoluminescent dosimeter (TLD) and film dosimetry and compare the obtained results with egs_brachy Monte Carlo (MC)-calculated values for the same geometry. **Materials and Methods:** The recently developed egs_brachy is a fast Electron Gamma Shower National Research Council of Canada MC application which is intended for brachytherapy applications. The dosimetric dataset recommended by Task Group 43 update (TG43U1) is calculated using egs_brachy for an unbounded phantom. Subsequently, radial dose function g(r) and anisotropy function F(r,θ) are measured experimentally in a bounded water phantom using TLD-100 and Gafchromic EBT2 film. **Results:** The TG43U1 dosimetric parameters were determined using the egs_brachy MC calculation and compared with published data which are found to be in good agreement within 2%. The experimentally measured g(r) and F(r,θ) and its egs_brachy MC code-calculated values for a bounded phantom geometry are found to be good in agreement within the acceptable experimental uncertainties of 3%. **Conclusion:** Our experimental phantom size represents the average patient width of 30 cm; hence, results are closer to scattering conditions in clinical situations. The experimentally measured g(r) and F(r,θ) and egs_brachy MC calculations for bounded geometry are well in agreement within experimental uncertainties. Further, the confidence level of our comparative study is enhanced by validating the egs_brachy MC code for the unbounded phantom with respect to consensus data.

Keywords: ^{192}Ir source, anisotropy function, Monte Carlo, radial dose function

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Introduction

Although a miniaturized high-specific activity ^{60}Co source is available on remote after loading equipment, a ^{192}Ir source is being still widely used for high-dose-rate (HDR) brachytherapy treatment, mainly addressing gynecological lesions. Any radioactive source used in HDR brachytherapy for clinical practice needs a substantial amount of dosimetric data, as recommended by the American Association of Physicists in Medicine, TG43U1.[1] Experimental measurement of such data may result in large uncertainties because of the rapid fall of the dose at distances near the source, and this limitation can be overcome by accurate Monte Carlo (MC) simulations.[2] There have been many studies comparing these dosimetric data using either experimental or MC studies.[3-7] However, most of these studies have compared their results with MC calculations, which do not resemble the exact geometry conditions used in an experimental setup. It may not be possible to compare the MC calculations of unbounded geometry with bounded

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experimental results or MC-calculated values because of the differences in scattering conditions. This would result in dose differences of >10% occurring near the periphery of the bounded phantom, as mentioned by Granero *et al*.[8] and Venselaar *et al*.[9]

The aim of the present study is to compare the experimentally measured radial dose function g(r) and anisotropy function F(r,θ) in a bounded water phantom using thermoluminescent dosimeter (TLD-100 rods) and EBT2 Gafchromic film with egs_brachy MC code calculation by simulating the similar experimental conditions. Before this comparison, the efficacy of egs_brachy MC code was validated by calculating the dose rate constant (Λ^{unb}), along–away dose rate data, radial dose function ($g(r)^{unb}$), and anisotropy function ($F(r,\theta)^{unb}$) around the GammaMed (GM) Plus ^{192}Ir source in an unbounded (unb) liquid water phantom in comparison with published consensus data.[10] This was found to be the routine validation procedure for any new MC code calculation. The dataset calculated in the present work can be considered an input for radiotherapy treatment planning systems (TPSs) or for their quality control.

Materials and Methods

Monte Carlo simulation details

egs_brachy Monte Carlo code

Because there were not many fast MC codes available specifically for brachytherapy simulations, the Electron Gamma Shower National Research Council of Canada (EGSnrc) user code called BrachyDose[11] was developed to address this need. It uses a multigeometry package by Yegin.[12] In addition, a C++-based EGSnrc library called egs++ was introduced,[13] which led to the development of egs_brachy for modeling the particle sources and geometry specifically for brachytherapy applications. The main features of egs_brachy are that it includes a comprehensive library of brachytherapy source geometries, enhanced simulation efficiency, calculation of collision kerma using the track length estimator, phase-space sources, efficient radiation transport and geometry modeling, particle recycling, and variance reduction techniques for electronic brachytherapy. A publication by Chamberland *et al*.[14] provides a general overview of the code, complete discussion of all egs_brachy features, details on egs_brachy benchmarking, and characterization of the simulation efficiency of egs_brachy MC code.

Modeling of the GammaMed Plus ^{192}Ir high-dose-rate source

The GM Plus ^{192}Ir source (Mallinckrodt Medical B. V., Petten, The Netherlands) is one of the HDR brachytherapy sources commonly used for the management of most malignancies. The GM Plus ^{192}Ir source consists of a 3.50-mm-long ^{192}Ir core with a diameter of 0.70 mm, enclosed in a 0.90-mm-diameter and 4.52-mm-length AISI 316 L stainless steel capsule (density of 7.8 g/cm^3). The Ir-192 source emits a wide spectrum of relatively low energies, mostly in the range of 201–884 keV with an average value of 360 keV. A total of 6.0 cm of stainless steel cable is included in this simulation. The geometric design and material of the GM Plus source details are taken from a published study.[15] The schematic egs_brachy modeled source is shown in Figure 1.

egs_brachy calculation for unbounded phantom

The dosimetric dataset was calculated for GM Plus ^{192}Ir as recommended by TG43U1 for an unbounded phantom similar to the approach used by Taylor and Rogers.[16,17] A cylindrical phantom of 80 cm in length and 40 cm in radius filled with liquid water having a density of 0.998 g cm^{-3} was modeled for MC simulations. The scoring region, voxel sizes, and other parameters for calculations are as described by Chamberland *et al*.[14] All TG43U1 parameters for unbounded phantom calculations are denoted as superscript to the respective parameters, such as Λ^{unb}, $g(r)^{unb}$, and $F(r,\theta)^{unb}$. For MC calculations, only the photon part of the ^{192}Ir source spectrum is included, as the dose contribution from the electron is negligible, because it is stopped by the stainless steel encapsulation around the source. The cutoff energy for the photon calculation is up to 1 keV. The photoelectric absorption, Rayleigh scattering, fluorescent emission of characteristic X-rays, and bound Compton scattering are modeled in calculations of egs_brachy MC code. The XCOM database[18] and Livermore Evaluated Atomic Data Library[19] for the photon cross sections and atomic transitions, respectively, are included and used the EGSnrc user code "g" for the mass-energy absorption coefficients. The simulations are done up to 4 × 10^9 histories to get 1 σ statistical uncertainties (Type A) of 2% or less.

Experimental dosimeters and phantom design

Thermoluminescent dosimeters

A fresh batch of TLD-100 square rods (LiF:Mg, Ti) with dimensions of 1 mm × 1 mm × 6 mm was used. The annealing procedure before each experiment called the "prereadout" method was performed as described by Booth *et al*.[20] The Harshaw Bicron TLD reader (Model 3500) and the Thermolyne Furnace (Model 47900) were used for analyzing the TLD response and for annealing purposes, respectively. The thermoluminescent output was measured in nanocoulombs by integrating the area under the glow curve for a temperature of 270°C. The whole batch of TLD was irradiated using ^{60}Co γ-rays from a Theratron 780E telecobalt unit to deliver a dose of 2 Gy, and the relative responses, the elemental correction

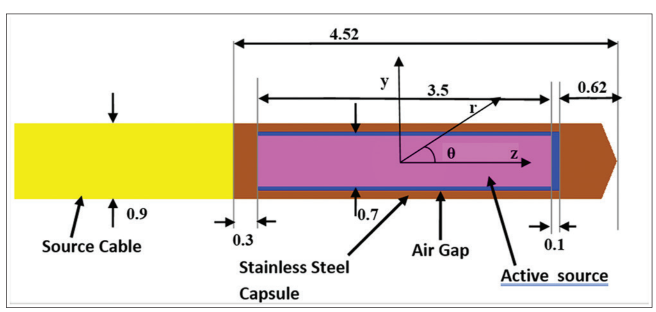

Figure 1: Schematic of GammaMed Plus ^{192}Ir high-dose-rate source modeled in egs_brachy Monte Carlo simulation (All dimensions in mm, but not to scale)

factors, were determined. This procedure was repeated five times, and the TLD rods that showed variation above 2% were discarded. The output of the each TLD was corrected with respective calibration factors to obtain a precision on the order of ± 1% (1 σ, Type A), and the TLD rods showed a linear response up to 10 Gy.

Gafchromic EBT2 film

The Gafchromic EBT2 films (ISP Technologies) are highly sensitive, having high spatial resolution, and they were used in the dose range of 0.01–40 Gy. For the purpose of calibration, the film was cut into 4 cm × 4 cm samples and marked at the left corner to reproduce the orientation. These sample films were irradiated for the dose range of 0.1–40 Gy in ^{60}Co γ-rays from a Theratron 780E telecobalt unit. The scanning of the irradiated film after 24 h of exposure was carried out on an EPSON Dual Lens Perfection V700 desktop scanner. The film-scanning protocol was adopted from the published literature.[21] PTW- Verisoft version 6.0.1 (PTW-Freiburg, Germany) software was used for analyzing scanned films in tag image file format. The pixel values of the irradiated and unirradiated films were used to obtain the optical density and converted into dose as described in the literature.[22]

Experimental water phantom and slab inserts

A precisely machined 30 cm × 30 cm × 30 cm water phantom with polymethyl methacrylate (PMMA) walls with thicknesses of 1 cm was indigenously fabricated for the experimental measurement. For measuring radial dose function g(r), a PMMA slab insert with dimensions of 30 cm × 30 cm × 1 cm was carefully machined for housing TLD rods and an MRI compatible tube, inside which the source was driven as shown in Figure 2a. With this TLD arrangement in the slab, eight measurements were simultaneously performed at each distance. This pattern for the TLD locations was selected to minimize the interference of anyone TLD with the absorbed dose measured by the other TLD rods. The slab containing the TLDs was inserted horizontally in a water phantom and located at the center of the phantom, surrounded by a water medium. For the film measurements, Gafchromic EBT2 film was attached to the PMMA slab to hold the film rigidly in the water medium and was inserted into the water phantom. The irradiation conditions were kept the same as those for the TLDs. Another PMMA slab insert of 30 cm × 30 cm × 1 cm was fabricated for measuring anisotropy functions, as shown in Figure 2b. This PMMA slab containing the TLDs was placed vertically to be at the center of the water phantom. The measurement conditions for EBT2 film were kept similar to those of the TLDs. The design of the PMMA slab inserts was taken from Meigooni *et al*.[23] The positional accuracy of the source in the phantom with respect to the TLD and film was verified before each measurement, using square samples of the EBT2 films.

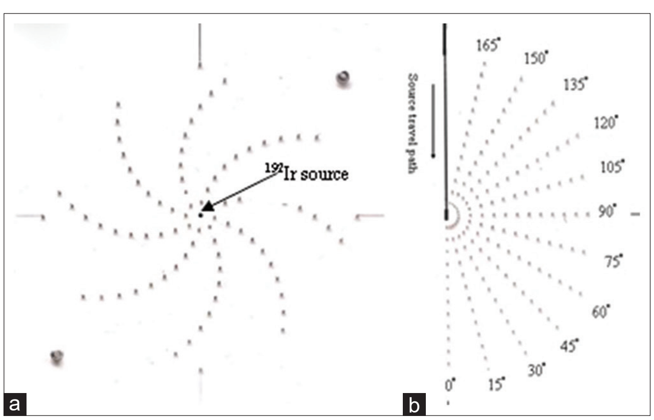

Figure 2: Designing of the precisely machined (a) radial polymethyl methacrylate slab insert and (b) anisotropy polymethyl methacrylate slab insert

Measurement techniques

The measurements were carried out using Varian GM Plus HDR unit (Varian Medical Systems, USA), and the dwell position and dwell times were planned with BrachyVision TPS. The dwell times for irradiating TLD-100 rods to a dose of 3 Gy at all measurement distances from 1 cm to 10 cm varied from 23.8 s to 856.8 s, respectively, for a nominal activity of 370 GBq (10 Ci) source strength. For the EBT-2 film measurements, dwell time was 82.9 s for a dose of 8 Gy at 1 cm.

Thermoluminescent dosimeter-100

For experimental measurements with TLDs, the g(r) and F(r,θ) are denoted as $g(r)^{TLD}$ and $F(r,\theta)^{TLD}$. The $g(r)^{TLD}$ and $F(r,\theta)^{TLD}$ were measured at the distances and polar angles, as shown in Figure 2. An average reading with reproducibility of better than 1% from three consecutive measurements with TLD at each point was considered. As mentioned by Thomason and Higgins,[24] volume correction factors for the finite size of the TLDs are calculated as 1.028 for 1-cm distance and 1.0 for distances beyond 1 cm and applied at respective radial distances. All the TLD-100 rods were exposed to doses <3 Gy.

EBT2 Gafchromic film

The measured g(r) and F(r, θ) of EBT2 films are denoted as $g(r)^{film}$ and $F(r,\theta)^{film}$. The measurement distances and polar angles for $g(r)^{film}$ and $F(r,\theta)^{film}$ were similar to the TLD measurement for unirradiated and irradiated films. The experimental setup to measure radial dose function g(r) and anisotropy function F(r,θ) using the fabricated water phantom with respective PMMA slabs is shown in Figure 3. The irradiated films were scanned using "face up" protocol at 150 DPI and 48-bit color depth.

egs_brachy calculation of g(r) and F(r,θ) for bounded phantom

For the bounded (bou) phantom, egs_brachy calculation g(r) and F(r,θ) are denoted as $g(r)^{bou}$ and $F(r,\theta)^{bou}$. A liquid water phantom of dimension 30 cm × 30 cm × 30 cm was simulated to reproduce the experimental phantom geometry in the MC calculations. The calculation parameters were the same as mentioned in the earlier section on egs_brachy calculation for the unbounded phantom. It is relevant to compare the

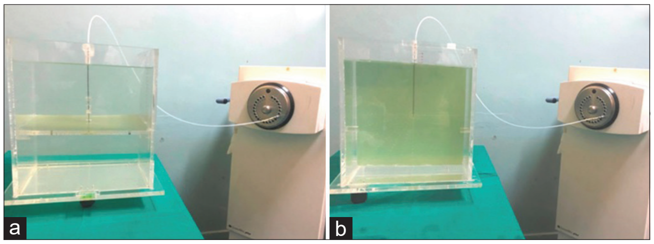

Figure 3: Experimental measurement setup of (a) radial dose function and (b) anisotropy function with their respective polymethyl methacrylate slab inserts

experimentally measured values in a bounded geometry against egs_brachy MC-calculated values of a similar bounded geometry.

Results

The obtained dose rate constant Λ^{unb} for the GM plus ^{192}Ir source using egs_brachy MC calculations was 1.110 ± 0.005 cGyh^{-1} U^{-1} and deviates with consensus data by 0.6%. The g(r)^{unb} results calculated from a radial distance of 0.2–20 cm with corresponding calculated uncertainties are shown in Table 1. Figure 4 shows a comparison with consensus data[10] and the results reported by Taylor *et al*.[17] The maximum variation was observed as 0.8% at 0.2 cm distance with consensus data and 0.6% at 8 cm distance with Taylor *et al*.,[17] and the approximate uncertainty in our calculation was 0.3%. Table 2 summarizes the calculated F(r,θ)^{unb}, and it is found to be in agreement with consensus data within 2%. The overall uncertainties (Type A) were 1.5%, 0.5%, and 1.5% for $\theta < 5$, $7 \geq \theta \leq 170$, and $175 \geq \theta \leq 179$, respectively, for the radial distance of 0.25–20 cm. The along–away dose rate values are shown in Table 3 which shows a variation of <2% in comparison with consensus data. The dose rate along z = 0 cm and away y = 0.2 cm is 22.8 cGy h^{-1}U^{-1}, and the corresponding value calculated by Ballester *et al*.[15] is 23.2 cGy h^{-1}U^{-1}. In addition to the consensus data, the TG43U1 dataset is found to be in good agreement, with a variation of <2%, with Taylor *et al*.[17] for the same source.

Table 4 shows the experimentally measured g(r)^{TLD} and g(r)^{film} for radial distances from 1 to 10 cm in comparison with egs_brachy MC-calculated g(r)^{bou} values from 0.2 to 10 cm. A maximum variation of 2.8% was found between g(r)^{TLD} and g(r)^{bou}, and the range of variation was from 0.7% to 2.8%. In a similar comparison between g(r)^{film} and g(r)^{bou}, the maximum variation was found to be 2.1%, and the range was from 0.08% to 2.1%. The approximate uncertainties (Type A) in the measurements were 1% for film, 1.5% for TLD-100, and 0.5% for egs_brachy calculation.

Figure 5 shows the comparison between experimentally measured F(r,θ)^{TLD} and F(r,θ)^{film} with egs_brachy MC-calculated values F(r, θ)^{bou} for the radial distances of 1, 5, and 10 cm. The maximum variation of 2.5% was found between F(r,θ)^{TLD} in comparison with egs_brachy, and most of the variations were well below 2%. Similarly, comparing F(r,θ)^{film} with F(r,θ)^{bou},

Table 1: Egs_brachy Monte Carlo-calculated radial dose function g(r)^{unb} for GammaMed Plus ^{192}Ir source in an unbounded phantom with calculated uncertainties

Radial distance (cm)	g(r)^{unb}	Absolute uncertainty
0.20	0.990	0.0005
0.25	0.992	0.0005
0.30	0.993	0.0006
0.40	0.994	0.0006
0.50	0.995	0.0006
0.60	0.997	0.0006
0.70	0.998	0.0006
0.75	0.998	0.0006
0.80	0.998	0.0007
0.90	0.999	0.0007
1.00	1.000	0.0007
1.25	1.001	0.0005
1.50	1.003	0.0006
1.75	1.005	0.0006
2.00	1.006	0.0006
2.50	1.007	0.0006
3.00	1.009	0.0006
3.50	1.009	0.0006
4.00	1.008	0.0006
4.50	1.007	0.0007
5.00	1.005	0.0007
6.00	0.998	0.0006
7.00	0.988	0.0006
8.00	0.975	0.0006
9.00	0.959	0.0006
10.00	0.942	0.0006
11.00	0.922	0.0005
12.00	0.900	0.0005
13.00	0.876	0.0005
14.00	0.852	0.0005
15.00	0.826	0.0005
16.00	0.799	0.0005
17.00	0.772	0.0005
18.00	0.744	0.0005
19.00	0.715	0.0005
20.00	0.687	0.0005

most of the values are within 1.5% variation, and the maximum variation was 1.7%. The approximate uncertainties (Type A) in the measurements were 1% for film, 1.5% for TLD-100, and 1.5% for egs_brachy calculation.

Discussion

In HDR brachytherapy dosimetry, it is a routine methodology to verify the MC calculations with experimental methods by any possible dosimeters, such as TLD and film, in regions where the experimental uncertainties are minimum. On successful validation, the MC-calculated dosimetric parameters can be used as input to the clinical dosimetry through TPSs. Williamson[25] compared the MC calculations for a ^{192}Ir source assuming an unbounded liquid water medium with the

Table 2: Anisotropy function $F(r,\theta)^{unb}$ for the GammaMed Plus ^{192}Ir source calculated using the line source approximation with L=3.5 mm

θ (deg)	Radial distance *r* (cm)										
	0.25	0.50	0.75	1.00	2.00	3.00	4.00	5.00	10.00	15.00	20.00
0	-	-	-	-	-	-	-	-	0.781	0.829	0.854
1	-	-	-	-	-	0.667	0.688	0.708	0.782	0.832	0.851
2	-	-	-	-	0.652	0.679	0.700	0.719	0.792	0.836	0.855
3	-	-	-	0.646	0.663	0.686	0.708	0.725	0.794	0.839	0.859
5	-	-	0.669	0.670	0.687	0.708	0.728	0.745	0.808	0.845	0.867
7	-	0.707	0.695	0.695	0.713	0.732	0.749	0.764	0.822	0.855	0.875
10	-	0.744	0.736	0.737	0.752	0.768	0.782	0.795	0.842	0.871	0.887
12	0.755	0.770	0.764	0.764	0.778	0.792	0.804	0.815	0.856	0.880	0.896
15	0.860	0.808	0.801	0.801	0.811	0.821	0.831	0.841	0.874	0.896	0.906
20	0.901	0.857	0.850	0.849	0.856	0.864	0.871	0.877	0.901	0.915	0.923
25	0.928	0.892	0.885	0.886	0.889	0.894	0.899	0.903	0.921	0.932	0.937
30	0.947	0.918	0.913	0.913	0.915	0.918	0.921	0.924	0.937	0.945	0.949
35	0.960	0.938	0.934	0.933	0.935	0.938	0.940	0.942	0.951	0.957	0.959
40	0.970	0.954	0.951	0.949	0.951	0.953	0.955	0.955	0.962	0.967	0.967
45	0.977	0.965	0.962	0.962	0.963	0.964	0.965	0.966	0.971	0.974	0.974
50	0.983	0.975	0.973	0.972	0.972	0.973	0.974	0.974	0.977	0.981	0.981
55	0.987	0.982	0.981	0.980	0.981	0.981	0.981	0.981	0.984	0.986	0.986
60	0.990	0.988	0.987	0.986	0.987	0.987	0.988	0.987	0.989	0.991	0.990
65	0.994	0.992	0.991	0.991	0.992	0.992	0.992	0.992	0.992	0.994	0.994
70	0.996	0.996	0.995	0.995	0.995	0.995	0.995	0.995	0.996	0.996	0.997
75	0.998	0.998	0.997	0.998	0.998	0.998	0.998	0.997	0.998	0.999	0.999
80	0.999	0.999	0.999	0.999	1.000	0.999	0.999	0.999	0.999	1.000	0.999
85	0.999	1.000	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.001	1.001
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
95	0.999	1.000	0.999	0.999	0.999	0.998	0.999	0.999	0.998	1.000	1.001
100	0.999	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.999	0.999
105	0.997	0.997	0.995	0.995	0.996	0.996	0.996	0.995	0.996	0.997	0.997
110	0.996	0.993	0.993	0.992	0.992	0.992	0.992	0.992	0.994	0.993	0.994
115	0.993	0.989	0.988	0.988	0.988	0.988	0.988	0.989	0.990	0.991	0.990
120	0.989	0.984	0.983	0.983	0.983	0.984	0.984	0.984	0.986	0.987	0.987
125	0.985	0.977	0.976	0.975	0.977	0.977	0.977	0.978	0.981	0.983	0.983
130	0.980	0.969	0.967	0.967	0.968	0.969	0.970	0.971	0.974	0.977	0.977
135	0.973	0.960	0.957	0.956	0.958	0.959	0.960	0.961	0.966	0.971	0.971
140	0.963	0.947	0.944	0.942	0.945	0.947	0.949	0.951	0.957	0.961	0.963
145	0.952	0.931	0.927	0.926	0.929	0.931	0.934	0.936	0.946	0.952	0.955
150	0.936	0.909	0.905	0.905	0.908	0.912	0.915	0.919	0.932	0.940	0.944
155	0.915	0.881	0.876	0.876	0.881	0.886	0.891	0.896	0.914	0.924	0.929
165	0.835	0.789	0.784	0.784	0.795	0.807	0.818	0.827	0.862	0.884	0.896
170	-	0.712	0.706	0.706	0.723	0.741	0.757	0.771	0.824	0.854	0.872
175	-	-	0.586	0.588	0.617	0.646	0.667	0.690	0.768	0.814	0.842
177	-	-	-	0.507	0.536	0.572	0.602	0.633	0.732	0.787	0.827
178	-	-	-	-	-	0.507	0.546	0.581	0.697	0.766	0.810
179	-	-	-	-	-	-	0.502	0.522	0.640	0.732	0.779

experimentally measured data in a 20 cm × 20 cm × 20 cm^3 phantom reported in the literature and found that up to 5 cm from the source showed good agreement but varied from 5% to 10% at larger distances. Richter *et al*.[26] compared the dosimetric parameters of ^{60}Co and ^{192}Ir sources in HDR brachytherapy using MC calculation in spherical phantoms of two different radii of 15 and 50 cm to find the influence of phantom size on the dose at larger distances from the source. Their results show that radial dose function is influenced by the phantom size. The consensus data[10] for the GM plus ^{192}Ir HDR source refer to Ballester *et al*.,[15] in which GEANT3 MC code was used for simulating an unbounded cylindrical water phantom of 40-cm diameter and 40-cm length. The TG43U1 dataset consists of dose rate constant, radial dose function, anisotropy function, and two-dimensional along-and-away dose rate table.

Table 3: Dose rate - away-along data in an unbounded liquid water phantom per unit air-kerma strength (cGy h^{-1} U^{-1}) around GammaMed Plus ^{192}Ir source

Along/cm	Away/cm											
	0.00	0.20	0.40	0.60	0.80	1.00	2.00	3.00	4.00	5.00	7.50	10.00
−10.0	0.008318	0.008265	0.008375	0.008406	0.008461	0.008487	0.008617	0.008524	0.008158	0.007651	0.006108	0.00463
−5.0	0.03169	0.03251	0.03322	0.0339	0.03458	0.03507	0.03449	0.0307	0.02595	0.02144	0.01304	0.008169
−4.0	0.04868	0.04987	0.0514	0.05301	0.05421	0.05486	0.05131	0.04276	0.03392	0.02659	0.01487	0.008911
−3.0	0.08294	0.08705	0.09145	0.09495	0.09671	0.09665	0.08142	0.06062	0.04415	0.0325	0.01664	0.009567
−2.0	0.1805	0.1958	0.2099	0.2156	0.2126	0.2038	0.1363	0.08545	0.05593	0.0385	0.01816	0.0101
−1.5	0.3201	0.3541	0.38	0.3773	0.3549	0.324	0.1769	0.09957	0.06152	0.04112	0.01875	0.0103
−1.0	0.7419	0.8373	0.8537	0.7677	0.6529	0.543	0.2235	0.1126	0.0663	0.04323	0.0192	0.01044
−0.8	1.196	1.355	1.287	1.07	0.8498	0.6697	0.2414	0.1169	0.06781	0.04383	0.01932	0.01048
−0.6	2.186	2.503	2.069	1.517	1.099	0.8131	0.2575	0.1206	0.06903	0.0444	0.01944	0.01051
−0.4	6.085	5.64	3.464	2.122	1.382	0.9568	0.2702	0.1233	0.0699	0.04472	0.0195	0.01054
−0.2	-	14.81	5.448	2.739	1.623	1.068	0.2784	0.125	0.07041	0.04494	0.01956	0.01055
0.0	-	22.8	6.567	3.019	1.721	1.11	0.2811	0.1255	0.07059	0.04504	0.01956	0.01056
0.2	-	14.73	5.438	2.734	1.621	1.065	0.278	0.1249	0.07036	0.04493	0.01955	0.01055
0.4	-	5.575	3.444	2.11	1.378	0.9538	0.2697	0.1232	0.06976	0.04468	0.01949	0.01052
0.6	-	2.464	2.053	1.507	1.094	0.8097	0.2568	0.1204	0.06891	0.04433	0.01942	0.01051
0.8	-	1.322	1.275	1.062	0.8439	0.6664	0.2407	0.1167	0.06772	0.04379	0.01932	0.01047
1.0	-	0.8076	0.8424	0.7612	0.6489	0.5403	0.2226	0.1123	0.06614	0.04315	0.01918	0.01044
2.0	-	0.1789	0.2036	0.2119	0.2102	0.202	0.1356	0.08523	0.0557	0.03841	0.01812	0.01008
3.0	-	0.07726	0.08678	0.09231	0.09496	0.09533	0.08095	0.06033	0.04398	0.03238	0.01659	0.009557
4.0	-	0.0442	0.04804	0.05092	0.05281	0.05385	0.05095	0.04245	0.03372	0.02647	0.01482	0.008888
5.0	-	0.02907	0.03073	0.03227	0.03341	0.03424	0.03414	0.03047	0.02583	0.02134	0.013	0.008145
10.0	0.007743	0.007752	0.007799	0.007906	0.008024	0.008122	0.008474	0.008417	0.008087	0.007598	0.006074	0.004607

Table 4: Comparison between bounded phantom measured radial dose function g(r) using TLD-100 ($g(r)^{TLD}$), Gafchromic EBT2 film ($g(r)^{film}$), and egs_brachy MC-calculated ($g(r)^{bou}$) values

Distance, r (cm)	egs_brachy $g(r)^{bou}$	$g(r)^{TLD}$	$g(r)^{Film}$
0.2	0.992	-	-
0.3	0.993	-	-
0.4	0.995	-	-
0.5	0.997	-	-
0.6	0.994	-	-
0.7	0.997	-	-
0.8	1.001	-	-
0.9	0.999	-	-
1	1.000	1.000	1.000
1.5	1.0009	-	-
2	1.003	1.010	1.004
3	0.997	1.006	0.999
4	0.990	1.002	0.970
5	0.975	0.989	0.966
6	0.964	0.978	0.951
7	0.946	0.964	0.932
8	0.924	0.946	0.908
9	0.896	0.920	0.882
10	0.864	0.888	0.846

In the present study, the TG43U1 dosimetric dataset was calculated for a cylindrical liquid water phantom of 80-cm length and 40-cm radius using egs_brachy MC code and compared with consensus data for its validation. In a literature survey, numerous publications were found on TLDs used for brachytherapy dose measurements including the dosimetric dataset based on TG43U1.[27-29] However, there are many conflicting results reported in the literature based on TLD measurements in a phantom. The reasons are (i) energy dependence of TLD when calibrating TLDs in a ^{60}Co photon beam and measuring in a ^{192}Ir photon spectrum and (ii) the depth-dependent response of TLD from the source. Mobit

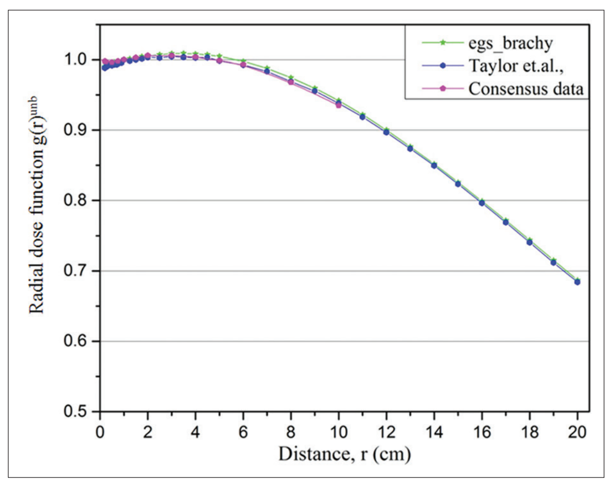

Figure 4: Comparison of egs_brachy Monte Carlo-calculated radial dose function $g(r)^{unb}$ for GammaMed Plus ^{192}Ir source in an unbounded phantom with published data

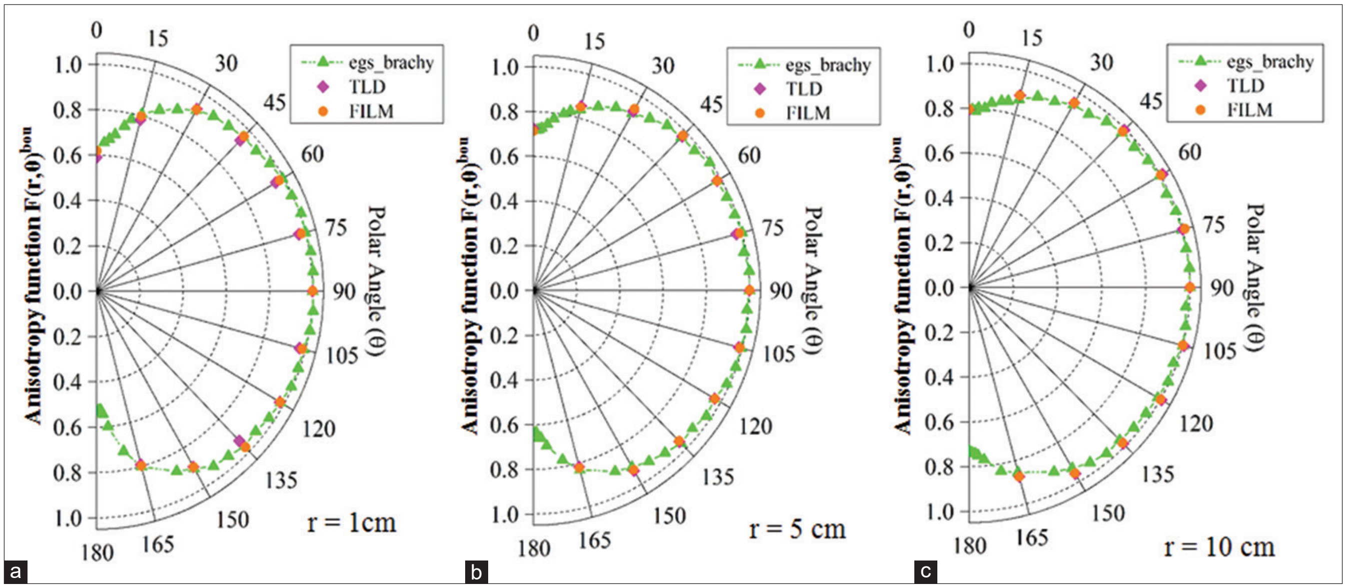

Figure 5: Comparison between bounded phantom measured anisotropy function using TLD-100 ($F(r,\theta)^{TLD}$) and Gafchromic EBT2 film ($F(r,\theta)^{film}$) versus egs_brachy Monte Carlo-calculated values ($F(r,\theta)^{bou}$) for the radial distance of 1, 5, and 10 cm is shown in (a-c) respectively

et al.[30] found that, even for ^{60}Co gamma energies, the TLD-100 rods behave like a large cavity rather than a small cavity, and the MC-calculated average dose ratio of water to LiF for ^{60}Co gamma rays is not more than 0.8%. Karaiskos *et al*.[31] also performed weighted photon spectra calculations for LiF using MC code, and their findings are in agreement with Mobit *et al*.[30] They also found that the variation in TLD response with the shift in the ^{192}Ir spectrum toward lower energies up to a depth of 15 cm is within 3%, which is within the error for the experimental setup. Das *et al*.[27] did not apply either an energy correction factor or a depth correction factor when calibrating TLDs using a 6-MV beam for the measurements in a ^{192}Ir beam and justified their methodology based on Pradhan and Quast[32] They acknowledged that there is an over-response of TLDs at depth in a ^{192}Ir phantom, and this correction was found to be within 3% up to 10 cm from the source, which is negligible when measurement uncertainties are considered. As mentioned by Arjomandy *et al*.,[33] EBT 2 Gafchromic film shows a weak energy dependence for clinical useful energies. Based on these studies, herein, no correction factors for both energy and depth dependence were considered in the experimental work.

Subsequent to the validation by egs_brachy calculation, the radial dose function g(r) and anisotropy function F(r,θ) of the GM Plus ^{192}Ir source using TLD-100 and EBT2 Gafchromic film in an indigenously fabricated water phantom were measured and compared with the egs_brachy calculation. To reduce the uncertainty in MC calculation and to get accurate calculation results, the geometry of the phantom was mimicked to be similar to the experimental setup as a bounded water phantom with PMMA wall material. From the experimental results of g(r) and F(r,θ), the observed variation with egs_brachy code calculation was found to be reasonably well within the acceptable experimental uncertainties of 3%.

Conclusion

The experimentally measured parameters and their comparison with egs_brachy MC calculations for bounded geometry are well within the experimental uncertainties. There are no published values in literature for the source type studied with a bounded water phantom using two different dosimeters in comparison with MC calculation for the same geometry. Further, the confidence level of the comparative study was enhanced by validating egs_brachy MC code for an unbounded phantom with respect to consensus data. The experimental phantom size represents the average patient width of 30 cm; hence, the results are closer to scattering conditions in clinical situations.

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Conflicts of interest

There are no conflicts of interest.

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