Original paper

EGSnrc Monte Carlo-aided dosimetric studies of the new BEBIG ^{60}Co HDR brachytherapy source

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Abstract

Purpose: The purpose of this study is to obtain the dosimetric parameters of the new BEBIG ^{60}Co brachytherapy source following by TG-43U1 recommendation with appropriate electron cutoff energy (0.521 MeV).

Material and methods: The new BEBIG ^{60}Co brachytherapy source is used to calculate the TG-43U1 parameters. EGSnrc-based Monte Carlo simulation code has been used to calculate the radial dose functions and anisotropy functions. 2D dose rate table is obtained with Cartesian coordinate system for surrounding the source.

Results: The radial dose functions are calculated for the distance of 0.06 cm to 100 cm from the source center with different cutoff energies and compared. The anisotropy functions values are calculated with the range of 1° to 179°, and apart from 0.2 cm to 20 cm of radial distances. The along-away dose rate data are calculated for quality assurance purposes. The calculated values are compared with the consensus data set and previous published results.

Conclusions: The radial dose function values from 0.06 cm to 0.16 cm are low, and these values gradually increased up to 0.3 cm radial distance. The radial dose function values are compared with the values of consensus data set using EGSnrc code system, and it is in good agreement with the published data range. The data for < 0.1 cm is not available in consensus data set, and extrapolated value is included for 0 distances which is the same as the value of 0.1 cm. In this study, the obtained values are strictly fall-off to < 0.1 cm distances. Good agreement with the published data was observed, except the values less than 40° angle at 0.5 cm distance for anisotropy function values.

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Key words: BEBIG, brachytherapy, ^{60}Co, EGSnrc, HDR brachytherapy.

Purpose

Eckert & Ziegler BEBIG, GmbH, Germany, introduced a new afterloading brachytherapy machine (MultiSource®). It has two options to use either ^{60}Co or ^{192}Ir source for high dose rate (HDR) brachytherapy. The dimensions of the sources are about identical. The ^{60}Co source has an advantage due to its longer half lives (5.27 years). Miniaturized ^{60}Co source with sufficient activity (70 GBq) is available on afterloading equipment, dedicated to HDR brachytherapy. The new ^{60}Co source (model Co0.A86) referred as new BEBIG ^{60}Co HDR source is a modified version of the old ^{60}Co source (model GK60M21) from BEBIG. This study is aimed at obtaining the dosimetry parameters with the TG-43U1 formalism of the American Association of Physicists in Medicine (AAPM) [1], and with prerequisites of HEBD report [2]. This study is performed using the EGSnrc [3] Monte Carlo transport code (version V4-R2-3-1) with appropriate electron cutoff energy 0.521 MeV (rest of electron energy + 10 keV as kinetic energy), referred as true dose calculation for all subsequent calculations. Meanwhile, some authors have published the relevant dosimetry data with different methodology. Richter *et al.* [4] have reported a comparison of ^{60}Co and ^{192}Ir sources using EGS-Ray Monte Carlo based calculations, and only photon emission has been considered for the simulations. Recently, Selvam *et al.* [5] have published EGSnrc [3] Monte Carlo based dosimetry data except anisotropy functions, and collision kerma is approximated the dose at the close surface of the source. Moreover, Ballester *et al.* [6] and Granero *et al.* [7] have reported GEANT4 based Monte Carlo dosimetry data in accordance with TG-43U1 [1] formalism for the same source. Recently, AAPM and ESTRO published consensus data set for photon-emitting brachytherapy sources and the dosimetric data for the BEBIG ^{60}Co source with same model are available [2] which was taken from Granero *et al.* [7] and Selvam *et al.* [5]. This report consist of radial dose function data, and anisotropy function data are apart from the 0.1 cm and 0.25 cm of radial distances, respectively from the source. This study, the radial dose function data, and anisotropy function data are calculated apart from the 0.06 cm and 0.2 cm of radial distances, respectively from the source. The radial dose function data are calculated with electron cutoff energy 2 MeV and 0.521 MeV, and the calculated data are compared. 2D dose rate data are calculated for Cartesian and Polar coordinate system using the DOSRZnrc [8] user code. The radial dose func-

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tion and anisotropy function are calculated from the dose rate table of Polar coordinate system with TG-43U1 [1] formalism.

Material and methods

The specifications of the source geometry and materials are taken from Islam *et al.* [9]. The BEBIG ^{60}Co HDR source consists of pure cobalt metal (density of 8.9 g cm^{-3}), and is kept inside the source cylinder having diameter 0.05 cm and length 0.35 cm. Radioactive ^{60}Co material is uniformly distributed inside it. The source core is encapsulated with an AISI 316L stainless steel capsule with 0.1 cm in outer diameter and 0.07 cm in inner diameter. The capsule is 0.5 cm long and connected to a 0.2 cm long steel cable. The capsule thickness is 0.075 cm for both longitudinal side of the ^{60}Co core and the steel thickness of axial side is 0.015 cm. There is an air gap of 0.01 cm around the axial side of the active source core. The rounded source tip of the real source geometry is modeled as flat with uniform thickness of 0.075 cm stainless steel, because a rounded tip cannot be simulated in DOSRZnrc [5]. The diameter of the source cable is modeled as same as the diameter of source capsule for simplicity. However, this simplification will not notably affect the dosimetry. Figure 1A shows the geometry of the real BEBIG ^{60}Co HDR source, and Figure 1B shows the model of it used in the Monte Carlo calculations.

The DOSRZnrc [8] is a user code for absorbed dose calculation of EGSnrc [3] based Monte Carlo transport code system. This code is used for the calculation of absorbed dose rate distribution around the new BEBIG ^{60}Co source. Two photon energies, 1.17 and 1.33 MeV are considered for ^{60}Co source, and in each disintegration two photons/(Bq s) are generated on average. The photon energy spectrum file (bareco60.spectrum) [8] has been used for these simulations. For the absorbed dose rate calculation, the source is positioned at the centre of a cylindrical unbounded water phantom of dimensions 200 cm (diameter) × 200 cm (height). The density of water considered is 0.998 g/cm^3 at 22°C [1]. In order to provide adequate spatial resolution, the cells are 0.01 cm thickness for $r < 2$ cm, 0.05 cm for $2 < r < 5$ cm, 0.1 cm for $5 < r < 10$ cm and 0.2 cm for $r > 10$ cm from the source [2,10]. The dose rate values are calculated in different positions of the water phantom with polar and Cartesian co-ordinates for different position of the water phantom. The true dose rate is calculated for all points of interest, and these values are used to calculate TG-43U1 parameters [1] e.g., radial dose function and anisotropy function. Up to 5×10^9 primary photon histories are simulated to obtain dose rate data. The cut-off energy for photon and electron transport are 0.001 MeV, and 0.521 MeV, respectively, as maintained in the dose rate calculations for all radial distances. XCOM photon cross-section library is used in subsequent simulations. Consequently, photoelectric effect, pair production, Rayleigh scattering and bound Compton scattering are included in simulation. No variance reduction techniques are used in the simulations. The contribution of primary electron to the dose is not considered, i.e. no beta spectrum is simulated. The value of air-kerma strength, S_k/A (= $3.039 \times 10^{-7} \pm 0.41\%$ U Bq^{-1}) and dose rate constant, Λ (= $1.097 \pm 0.12\%$ cGy h^{-1} U^{-1}) are taken from Islam *et al.* [9]. The authors calculated the air-kerma per initial particle at 100 cm distance from the center of the source as per AAPM TG-43U1 recommendations [1]. The mass energy-absorption coefficient for dry air was taken from the latest NIST compilation [11]. The photon fluency spectrum at 5 keV intervals was scored along the transverse axis for the point of 100 cm distance. The user-code FLURZnrc [3] was used to calculate the differential fluency spectrum in the calculation grid per initial photon in the simulation. To estimate the air-kerma strength, the source is kept in an unbounded cylindrical air phantom, and the kerma was scored for a 0.2 cm thick and 0.1 cm high cylindrical ring cell, located along the transverse source axis.

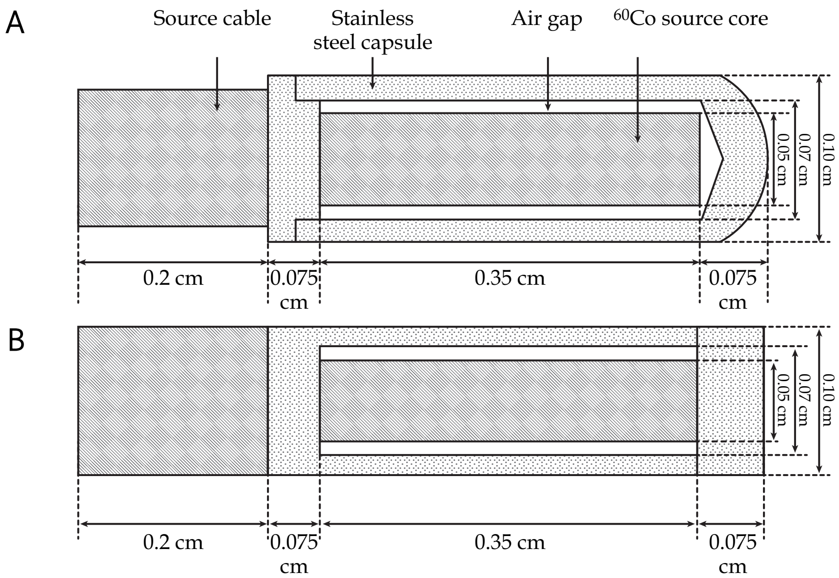

Fig. 1. A) Schematic diagram of the new BEBIG ^{60}Co HDR source and **(B)** the model diagram of the source used in Monte Carlo simulations

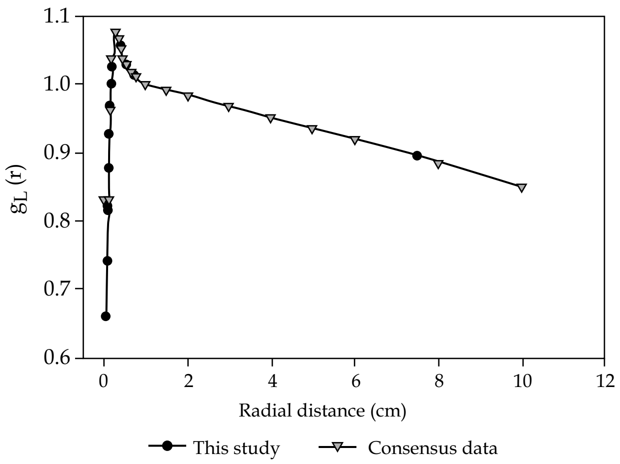

Fig. 2. Comparison of radial dose functions for BEBIG ^{60}Co HDR source; simulated with electron cutoff energy 2 MeV and 0.521 MeV

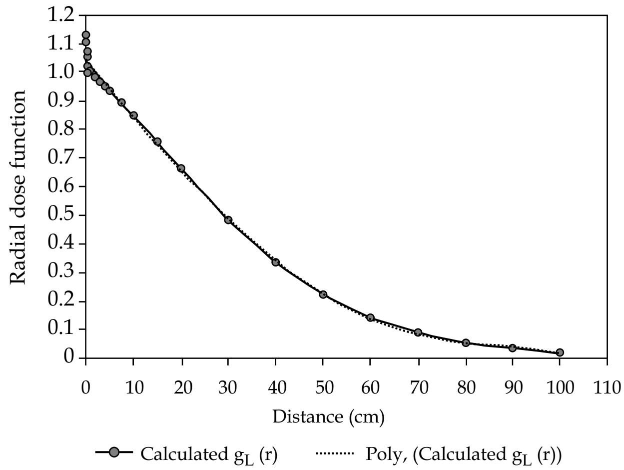

Fig. 3. Comparison of radial dose functions for BEBIG ^{60}Co HDR source with this study and consensus data set [2,5]

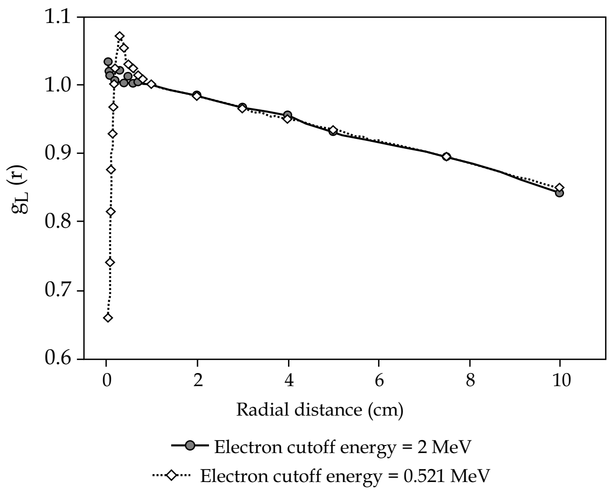

Fig. 4. The polynomial fit curve with radial dose function for BEBIG ^{60}Co HDR source from 0.06 cm to 100 cm

Table 1. Radial dose function for the BEBIG ^{60}Co source (model Co0.A86)

Distance r, cm	Radial dose function, $g_L(r)$
0.06	0.6585
0.08	0.7405
0.1	0.8140
0.12	0.8763
0.14	0.9276
0.16	0.9677
0.18	1.0017
0.20	1.0185
0.30	1.0715
0.40	1.0532
0.50	1.0302
0.60	1.0217
0.70	1.0148
0.80	1.0086
1	1
2	0.9812
3	0.9659
4	0.9504
5	0.9347
7.5	0.8951
10	0.8485
15	0.7587
20	0.6619
30	0.4838
40	0.3357
50	0.2224
60	0.1417
70	0.0889
80	0.0562
90	0.0347
100	0.0201

Table 2. Calculated 5th order polynomial coefficient values of radial dose function from 0.06 cm to 100 cm of radial distances

Polynomial coefficient	Value
a_0	1.0409
a_1	–0.0208
a_2	8×10^{-5}
a_3	-8×10^{-7}
a_4	3×10^{-8}
a_5	-2×10^{-10}

Results

In the present work, the radial dose functions are calculated for the distance of 0.06 cm to 100 cm from the source centre for BEBIG ^{60}Co HDR source considering electron cut-off energy 0.521 MeV and 2 MeV. Figure 2 shows the com-

Table 3. Anisotropy functions $F(r, \theta)$ for new BEBIG ^{60}Co HDR source (model Co0.A86). The origin is chosen at the center of the ^{60}Co core and the simulated angle values are increased from the source tip to the cable side of the source

Theta, deg	Radial distance, cm							
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1
1		0.5989	0.7406	0.9558	0.9587	0.9745	0.9581	0.9561
2		0.6130	0.7609	0.9601	0.9608	0.9765	0.9610	0.9568
3		0.6220	0.7813	0.9627	0.9639	0.9796	0.9641	0.9586
4		0.6339	0.7886	0.9667	0.9654	0.9829	0.9656	0.9632
5		0.6407	0.8061	0.9696	0.9689	0.9848	0.9667	0.9650
7		0.6499	0.8251	0.9744	0.9737	0.9875	0.9690	0.9663
10		0.6717	0.8658	0.9841	0.9815	0.9922	0.9727	0.9710
12		0.6947	0.8881	0.9930	0.9868	0.9964	0.9750	0.9766
15	0.6300	0.7323	0.9164	1.0035	0.9919	0.9996	0.9816	0.9850
20	0.6921	0.8047	0.9579	1.0150	0.9955	1.0000	0.9885	0.9937
25	0.7548	0.8649	0.9804	1.0162	0.9936	0.9960	0.9929	0.9974
30	0.8071	0.8979	0.9869	1.0139	0.9930	0.9945	0.9941	0.9968
35	0.8496	0.9103	0.9849	1.0094	0.9917	0.9921	0.9954	0.9951
40	0.8842	0.9399	0.9821	1.0048	0.9920	0.9916	0.9944	0.9961
45	0.9087	0.9551	0.9887	0.9999	0.9913	0.9912	0.9941	0.9967
50	0.9294	0.9686	0.9896	0.9956	0.9911	0.9915	0.9942	0.9956
55	0.9528	0.9758	0.9900	0.9944	0.9913	0.9921	0.9943	0.9966
60	0.9662	0.9828	0.9921	0.9947	0.9923	0.9927	0.9952	0.9978
65	0.9820	0.9881	0.9993	0.9939	0.9936	0.9955	0.9962	0.9973
70	0.9904	0.9933	0.9933	0.9944	0.9952	0.9971	0.9970	0.9977
75	0.9992	0.9970	1.0036	0.9954	0.9981	0.9969	0.9987	0.9984
80	0.9862	0.9910	0.9940	0.9976	0.9999	0.9977	0.9996	0.9995
85	1.0064	1.0015	0.9961	0.9991	1.0002	0.9993	1.0001	0.9997
90	1	1	1	1	1	1	1	1
95	1.0002	0.9957	0.9976	0.9994	0.9996	0.9992	0.9994	0.9997
100	1.0002	0.9947	0.9962	0.9979	0.9996	0.9977	0.9991	0.9996
105	0.9922	0.9907	0.9907	0.9968	0.9986	0.9967	0.9987	0.9993
110	0.9862	0.9877	0.9877	0.9967	0.9976	0.9957	0.9987	0.9986
115	0.9801	0.9817	0.9847	0.9964	0.9966	0.9947	0.9977	0.9977
120	0.9711	0.9777	0.9817	0.9977	0.9960	0.9947	0.9962	0.9966
125			0.9777	0.9972	0.9960	0.9937	0.9955	0.9966
130			0.9747	0.9973	0.9949	0.9926	0.9949	0.9954
135			0.9907	0.9963	0.9947	0.9927	0.9947	0.9954
140			0.9937	0.9959	0.9944	0.9927	0.9956	0.9966
145			0.9907	0.9939	0.9936	0.9907	0.9960	0.9969
150			0.9817	0.9897	0.9909	0.9883	0.9949	0.9974
155					0.9841	0.9847	0.9915	0.9960
160					0.9751	0.9757	0.9857	0.9919
165							0.9777	0.9817
168							0.9705	0.9696
170							0.9647	0.9588
173							0.9547	0.9460
175							0.9407	0.9302
176							0.9307	0.9249
177							0.9207	0.9213
178							0.9147	0.9172
179							0.9107	0.9148

Table 3. Cont.

Theta, deg	Radial distance, cm							
	2	3	4	5	7.5	10	15	20
1	0.9575	0.9291	0.9440	0.9246	0.9378	0.9329	0.9565	0.9517
2	0.9598	0.9370	0.9446	0.9306	0.9406	0.9379	0.9586	0.9557
3	0.9633	0.9406	0.9451	0.9338	0.9445	0.9422	0.9605	0.9588
4	0.9645	0.9417	0.9462	0.9393	0.9497	0.9459	0.9621	0.9620
5	0.9651	0.9438	0.9474	0.9441	0.9542	0.9517	0.9662	0.9676
7	0.9695	0.9474	0.9494	0.9511	0.9599	0.9580	0.9691	0.9737
10	0.9748	0.9548	0.9554	0.9572	0.9656	0.9656	0.9720	0.9779
12	0.9784	0.9634	0.9619	0.9665	0.9702	0.9698	0.9744	0.9804
15	0.9830	0.9712	0.9732	0.9715	0.9742	0.9754	0.9784	0.9844
20	0.9901	0.9788	0.9803	0.9778	0.9811	0.9798	0.9814	0.9876
25	0.9942	0.9865	0.9875	0.9856	0.9868	0.9841	0.9865	0.9899
30	0.9958	0.9899	0.9902	0.9889	0.9902	0.9900	0.9897	0.9928
35	0.9952	0.9922	0.9936	0.9924	0.9941	0.9928	0.9929	0.9941
40	0.9949	0.9939	0.9949	0.9959	0.9955	0.9946	0.9946	0.9949
45	0.9952	0.9956	0.9973	0.9970	0.9967	0.9962	0.9978	0.9960
50	0.9958	0.9970	0.9986	0.9977	0.9978	0.9967	0.9989	0.9971
55	0.9960	0.9980	0.9981	0.9992	0.9981	0.9973	0.9994	0.9979
60	0.9966	0.9989	0.9983	0.9989	0.9985	0.9978	1.0000	0.9989
65	0.9976	0.9991	0.9981	0.9990	0.9991	0.9978	0.9993	0.9992
70	0.9986	0.9998	0.9986	0.9982	0.9987	0.9990	1.0000	0.9995
75	0.9992	1.0000	0.9987	0.9983	0.9987	0.9991	1.0000	0.9997
80	1.0001	1.0002	0.9995	0.9997	1.0000	1.0000	1.0000	0.9997
85	0.9998	1.0002	1.0000	0.9995	0.9998	0.9996	1.0000	1.0000
90	1	1	1	1	1	1	1	1
95	0.9997	0.9999	1.0000	1.0005	1.0003	1.0000	0.9990	0.9992
100	0.9998	0.9998	0.9999	0.9997	1.0004	1.0000	0.9990	0.9994
105	0.9995	0.9999	1.0004	0.9987	1.0004	1.0000	0.9995	0.9994
110	0.9991	0.9994	0.9999	0.9981	1.0000	0.9992	0.9995	0.9994
115	0.9982	0.9990	0.9999	0.9978	0.9998	0.9986	0.9995	0.9988
120	0.9977	0.9990	0.9996	0.9973	0.9995	0.9978	0.9989	0.9986
125	0.9972	0.9985	0.9999	0.9968	0.9991	0.9984	0.9994	0.9983
130	0.9970	0.9981	0.9996	0.9963	0.9984	0.9977	0.9997	0.9979
135	0.9961	0.9969	0.9987	0.9946	0.9974	0.9971	0.9986	0.9977
140	0.9961	0.9947	0.9988	0.9927	0.9954	0.9968	0.9986	0.9968
145	0.9960	0.9930	0.9980	0.9897	0.9934	0.9958	0.9962	0.9960
150	0.9973	0.9893	0.9957	0.9857	0.9914	0.9924	0.9932	0.9939
155	0.9960	0.9841	0.9931	0.9809	0.9874	0.9866	0.9873	0.9917
160	0.9936	0.9726	0.9864	0.9748	0.9824	0.9764	0.9760	0.9877
165	0.9856	0.9605	0.9752	0.9637	0.9751	0.9661	0.9616	0.9803
168	0.9799	0.9499	0.9621	0.9541	0.9673	0.9583	0.9509	0.9691
170	0.9716	0.9384	0.9522	0.9451	0.9603	0.9496	0.9420	0.9609
173	0.9617	0.9213	0.9406	0.9320	0.9513	0.9413	0.9312	0.9529
175	0.9469	0.9129	0.9330	0.9220	0.9442	0.9328	0.9222	0.9450
176	0.9293	0.9069	0.9280	0.9145	0.9383	0.9248	0.9163	0.9384
177	0.9241	0.9030	0.9240	0.9118	0.9323	0.9184	0.9096	0.9330
178	0.9192	0.8980	0.9200	0.9073	0.9269	0.9124	0.9024	0.9286
179	0.9154	0.8930	0.9130	0.9038	0.9185	0.9051	0.8933	0.9231

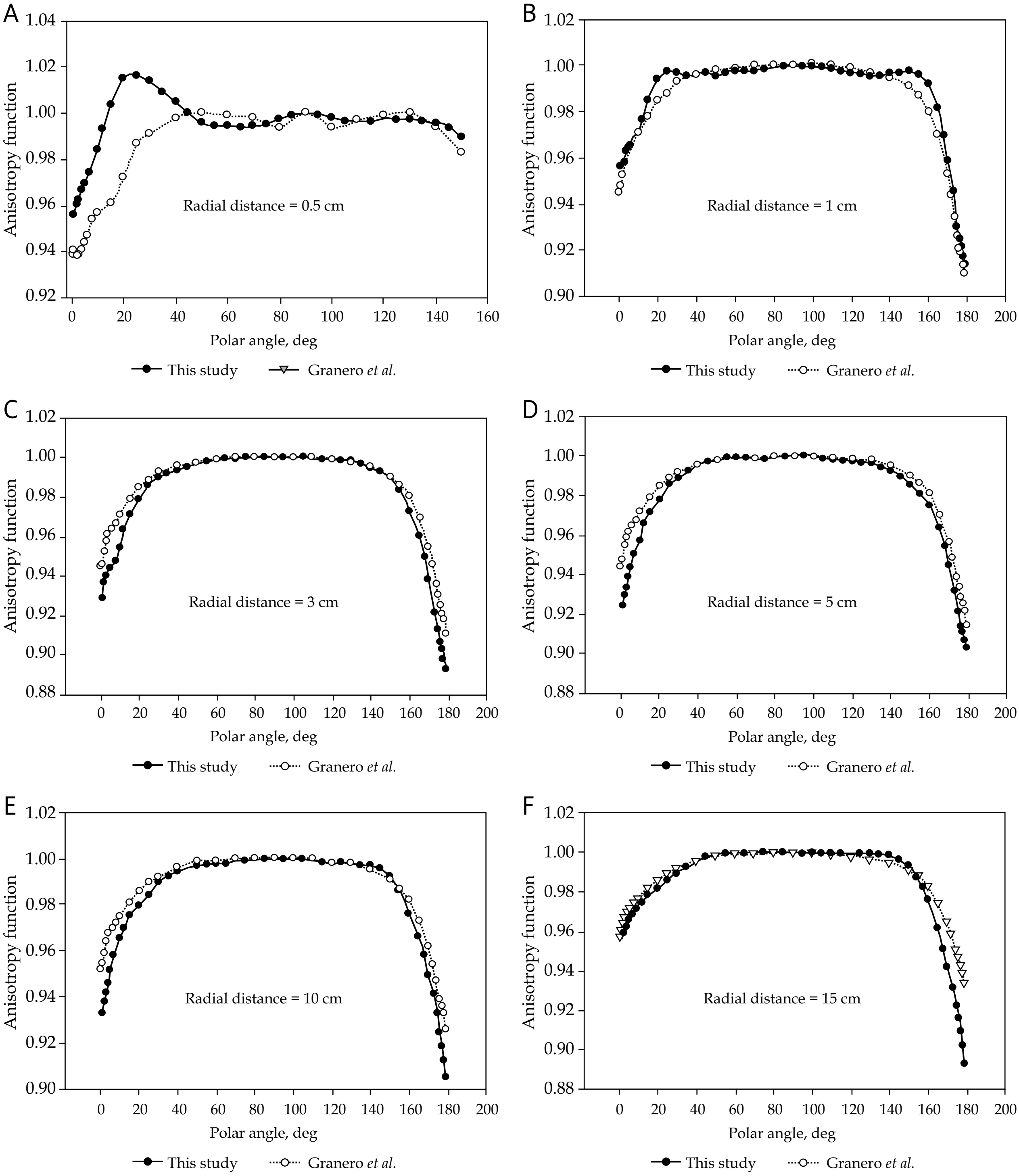

Fig. 5. Comparison of anisotropy functions for BEBIG ^{60}Co HDR source at different distances from the center of active source. **A)** 0.50 cm, **B)** 1.00 cm, **C)** 3.00 cm, **D)** 5.00 cm, **E)** 10.00 cm, **F)** 15.00 cm with the literature data from Granero *et al.* [7]

parison for radial dose functions for different cutoff energies of electron. The radial dose function (Fig. 2) values (in case of electron cutoff energy 0.521 MeV) from 0.06 cm to 0.18 cm are lower than the values simulated with electron cutoff energy 2 MeV, and the values from 0.2 cm to 0.8 cm are 2.36% (average) higher than the values of other radial dose function with ECUT = 2 MeV. The radial dose function data are presented in Table 1. Figure 3 shows the graphical comparison of the radial dose function with consensus data set [2, 5]. Figure 4 shows the polynomial curve along with the data points to present the radial dose function for BEBIG ^{60}Co HDR source. The polynomial coefficient values are shown in Table 2. Table 3 present the anisotropy function values. The anisotropy functions for BEBIG ^{60}Co HDR

Table 4. Along away dose rate data for BEBIG ^{60}Co HDR source (cGy h^{-1} U^{-1}). The origin is chosen at the center of the ^{60}Co core and the negative values of distance are placed on the side from origin to the source tip and the positive values for other side

Along cm	Away, cm									
	0.2	0.25	0.3	0.4	0.5	0.6	0.7	0.8	1	1.5
–20	1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.60E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03
–15	3.60E-03	3.10E-03	3.20E-03	3.40E-03	3.30E-03	3.30E-03	3.30E-03	3.40E-03	3.40E-03	3.40E-03
–13	5.50E-03	5.30E-03	5.20E-03	5.20E-03	5.20E-03	5.30E-03	5.10E-03	5.30E-03	5.20E-03	5.20E-03
–10	8.60E-03	8.61E-03	8.50E-03	8.30E-03	8.30E-03	8.40E-03	8.60E-03	8.70E-03	8.60E-03	8.60E-03
–7.5	1.56E-02	1.57E-02	1.58E-02	1.63E-02	1.57E-02	1.62E-02	1.57E-02	1.57E-02	1.61E-02	1.60E-02
–5	3.78E-02	3.78E-02	3.79E-02	3.76E-02	3.78E-02	3.77E-02	3.78E-02	3.81E-02	3.81E-02	3.67E-02
–4	5.79E-02	5.79E-02	5.80E-02	5.93E-02	5.95E-02	5.98E-02	6.09E-02	6.03E-02	5.95E-02	5.63E-02
–3	1.08E-01	1.08E-01	1.08E-01	1.08E-01	1.10E-01	1.11E-01	1.09E-01	1.08E-01	1.06E-01	9.36E-02
–2	2.47E-01	2.47E-01	2.46E-01	2.51E-01	2.49E-01	2.44E-01	2.40E-01	2.31E-01	2.17E-01	1.73E-01
–1.5	4.47E-01	4.53E-01	4.55E-01	4.48E-01	4.32E-01	4.18E-01	4.00E-01	3.80E-01	3.38E-01	2.42E-01
–1	1.05E+00	1.04E+00	1.02E+00	9.71E-01	8.99E-01	8.25E-01	7.51E-01	6.77E-01	5.52E-01	3.36E-01
–0.8	1.67E+00	1.62E+00	1.55E+00	1.43E+00	1.28E+00	1.12E+00	9.90E-01	8.73E-01	6.76E-01	3.79E-01
–0.6	2.97E+00	2.79E+00	2.63E+00	2.23E+00	1.88E+00	1.57E+00	1.32E+00	1.12E+00	8.09E-01	4.19E-01
–0.4	6.55E+00	5.75E+00	4.97E+00	3.69E+00	2.80E+00	2.17E+00	1.72E+00	1.39E+00	9.57E-01	4.54E-01
–0.25	1.33E+01	1.02E+01	8.06E+00	5.22E+00	3.62E+00	2.65E+00	2.00E+00	1.59E+00	1.04E+00	4.75E-01
–0.2	1.59E+01	1.21E+01	9.20E+00	5.77E+00	3.87E+00	2.80E+00	2.09E+00	1.63E+00	1.06E+00	4.79E-01
0	2.32E+01	1.66E+01	1.19E+01	6.88E+00	4.39E+00	3.06E+00	2.25E+00	1.72E+00	1.10E+00	4.87E-01
0.2	1.55E+01	1.21E+01	9.06E+00	5.68E+00	3.85E+00	2.76E+00	2.08E+00	1.63E+00	1.06E+00	4.78E-01
0.25	1.30E+01	1.00E+01	7.94E+00	5.19E+00	3.62E+00	2.61E+00	2.00E+00	1.58E+00	1.04E+00	4.73E-01
0.4	6.38E+00	5.73E+00	4.89E+00	3.67E+00	2.79E+00	2.17E+00	1.72E+00	1.39E+00	9.54E-01	4.54E-01
0.6	3.00E+00	2.85E+00	2.63E+00	2.24E+00	1.88E+00	1.57E+00	1.32E+00	1.12E+00	8.11E-01	4.18E-01
0.8	1.68E+00	1.64E+00	1.56E+00	1.41E+00	1.27E+00	1.12E+00	9.87E-01	8.73E-01	6.71E-01	3.77E-01
1	1.07E+00	1.05E+00	1.03E+00	9.62E-01	8.98E-01	8.27E-01	7.49E-01	6.78E-01	5.51E-01	3.36E-01
1.5	4.67E-01	4.64E-01	4.59E-01	4.48E-01	4.36E-01	4.19E-01	4.00E-01	3.79E-01	3.36E-01	2.42E-01
2	2.57E-01	2.56E-01	2.55E-01	2.55E-01	2.50E-01	2.46E-01	2.39E-01	2.32E-01	2.16E-01	1.72E-01
3	1.13E-01	1.12E-01	1.11E-01	1.12E-01	1.11E-01	1.11E-01	1.11E-01	1.09E-01	1.05E-01	9.41E-02
4	6.34E-02	6.31E-02	6.28E-02	6.24E-02	6.14E-02	6.10E-02	6.08E-02	6.15E-02	6.06E-02	5.67E-02
5	3.82E-02	3.84E-02	3.85E-02	3.88E-02	3.93E-02	3.88E-02	3.91E-02	3.90E-02	3.85E-02	3.72E-02
7.5	1.64E-02	1.68E-02	1.72E-02	1.63E-02	1.64E-02	1.65E-02	1.63E-02	1.66E-02	1.65E-02	1.61E-02
10	9.30E-03	9.40E-03	8.80E-03	9.00E-03	9.10E-03	8.70E-03	9.00E-03	9.10E-03	9.00E-03	8.80E-03
12.5	5.60E-03	5.50E-03	5.40E-03	5.60E-03	5.70E-03	5.50E-03	5.60E-03	5.40E-03	5.40E-03	5.40E-03
15	3.60E-03	3.60E-03	3.60E-03	3.60E-03	3.60E-03	3.50E-03	3.60E-03	3.50E-03	3.60E-03	3.60E-03
20	1.50E-03	1.60E-03	1.70E-03	1.80E-03	1.70E-03	1.70E-03	1.80E-03	1.70E-03	1.70E-03	1.70E-03

source are compared with GEANT4 Monte Carlo based published value for different radial distances by Granero *et al.* [2,7]. Good agreement with the published data was observed except the values less than 40° angle at 0.5 cm distance. This location is the corner of the source tip. Figure 5 shows the graphical comparison of the anisotropy functions for different distances. Along-away 2D dose rate data is presented in Table 4 for TPS quality assurance purposes. The statistical uncertainties (Type A) on the calculation are estimated have a coverage factor k = 1. This is depending on the location of calculation points, calculating grid size, and number of histories simulated. The uncertainties were obtained 0.1% at r < 0.2 cm, 0.3% at 0.2 < r ≤ 1 cm and 0.7% at 1 < r cm on average.

Discussions

The radial dose function for BEBIG ^{60}Co HDR source was calculated from 0.06 cm to 100 cm of radial distances. The values of the function from 0.06 cm to 0.16 cm are low and these values gradually increased up to 0.3 cm radial distance. However, it sharply decreased with longer distances.

Table 4. Cont.

Along cm	Away, cm								
	2	3	4	5	7.5	10	12.5	15	20
–20	1.70E-03	1.70E-03	1.70E-03	1.60E-03	1.50E-03	1.30E-03	1.20E-03	1.00E-03	7.00E-04
–15	3.50E-03	3.50E-03	3.40E-03	3.20E-03	2.80E-03	2.40E-03	1.90E-03	1.60E-03	1.00E-03
–13	5.20E-03	5.20E-03	5.00E-03	4.80E-03	4.00E-03	3.20E-03	2.50E-03	1.90E-03	1.20E-03
–10	8.70E-03	8.30E-03	7.90E-03	7.20E-03	5.60E-03	4.30E-03	3.20E-03	2.40E-03	1.40E-03
–7.5	1.58E-02	1.48E-02	1.31E-02	1.17E-02	8.30E-03	5.70E-03	4.00E-03	2.80E-03	1.60E-03
–5	3.51E-02	2.99E-02	2.44E-02	2.00E-02	1.18E-02	7.30E-03	4.80E-03	3.30E-03	1.70E-03
–4	5.18E-02	4.15E-02	3.21E-02	2.45E-02	1.34E-02	8.00E-03	5.10E-03	3.40E-03	1.70E-03
–3	8.15E-02	5.85E-02	4.13E-02	3.00E-02	1.50E-02	8.50E-03	5.40E-03	3.60E-03	1.80E-03
–2	1.34E-01	8.16E-02	5.21E-02	3.56E-02	1.63E-02	9.00E-03	5.50E-03	3.60E-03	1.80E-03
–1.5	1.73E-01	9.46E-02	5.75E-02	3.80E-02	1.68E-02	9.20E-03	5.60E-03	3.70E-03	1.80E-03
–1	2.17E-01	1.06E-01	6.18E-02	3.99E-02	1.73E-02	9.30E-03	5.60E-03	3.70E-03	1.80E-03
–0.8	2.33E-01	1.11E-01	6.32E-02	4.05E-02	1.73E-02	9.30E-03	5.70E-03	3.70E-03	1.80E-03
–0.6	2.48E-01	1.14E-01	6.45E-02	4.10E-02	1.75E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
–0.4	2.62E-01	1.17E-01	6.54E-02	4.12E-02	1.75E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
–0.25	2.66E-01	1.18E-01	6.57E-02	4.14E-02	1.76E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
–0.2	2.68E-01	1.19E-01	6.58E-02	4.15E-02	1.78E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
0	2.71E-01	1.19E-01	6.57E-02	4.14E-02	1.76E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
0.2	2.68E-01	1.18E-01	6.53E-02	4.13E-02	1.76E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
0.25	2.67E-01	1.18E-01	6.52E-02	4.13E-02	1.75E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
0.4	2.61E-01	1.17E-01	6.52E-02	4.12E-02	1.76E-02	9.40E-03	5.70E-03	3.70E-03	1.80E-03
0.6	2.49E-01	1.15E-01	6.44E-02	4.08E-02	1.74E-02	9.30E-03	5.70E-03	3.70E-03	1.80E-03
0.8	2.34E-01	1.11E-01	6.31E-02	4.04E-02	1.74E-02	9.30E-03	5.60E-03	3.70E-03	1.80E-03
1	2.17E-01	1.07E-01	6.14E-02	3.98E-02	1.72E-02	9.30E-03	5.60E-03	3.70E-03	1.80E-03
1.5	1.73E-01	9.44E-02	5.73E-02	3.80E-02	1.68E-02	9.20E-03	5.60E-03	3.70E-03	1.80E-03
2	1.34E-01	8.14E-02	5.22E-02	3.54E-02	1.64E-02	9.00E-03	5.60E-03	3.60E-03	1.80E-03
3	8.13E-02	5.81E-02	4.14E-02	3.01E-02	1.50E-02	8.50E-03	5.30E-03	3.60E-03	1.80E-03
4	5.22E-02	4.10E-02	3.22E-02	2.46E-02	1.35E-02	8.00E-03	5.10E-03	3.50E-03	1.70E-03
5	3.48E-02	2.97E-02	2.44E-02	2.00E-02	1.18E-02	7.40E-03	4.80E-03	3.30E-03	1.70E-03
7.5	1.59E-02	1.48E-02	1.34E-02	1.18E-02	8.20E-03	5.70E-03	4.00E-03	2.90E-03	1.50E-03
10	8.80E-03	8.30E-03	7.80E-03	7.20E-03	5.70E-03	4.30E-03	3.20E-03	2.40E-03	1.40E-03
12.5	5.40E-03	5.30E-03	5.00E-03	4.80E-03	3.90E-03	3.20E-03	2.50E-03	1.90E-03	1.20E-03
15	3.50E-03	3.40E-03	3.40E-03	3.30E-03	2.90E-03	2.40E-03	1.90E-03	1.60E-03	1.20E-03
20	1.80E-03	1.70E-03	1.70E-03	1.70E-03	1.50E-03	1.40E-03	1.20E-03	1.00E-03	7.00E-04

The radial dose function values are compared with the values of consensus data set reported by Selvam *et al.* [2,5] using EGSnrc code system, and it is in good agreement with the published data for the range. The data for < 0.1 cm is not available in consensus data set, and extrapolated value is included for 0 distances which is the same as the value of 0.1 cm. In this study, the obtained values are strictly fall-off to < 0.1 cm distances.

The equation for radial dose function, $g_L(r) = a_0 + a_1r + a_2r^2 + a_3r^3 + a_4r^4 + a_5r^5$ corrects a typographical error in the original TG-43U1 protocol [12]. Here, $g_L(r)$ is denoted the radial dose function for the point r and a_0, a_1, a_2, a_3, a_4, a_5 is polynomial coefficients up to 5th order. While table lookup via linear interpolation or any appropriate mathematical model fit to the data may be used to evaluate $g_X(r)$, some commercial treatment planning systems currently accommodate a fifth-order polynomial fit to the tabulated $g(r)$ data. Since this type of polynomial fit may produce erroneous results with large errors outside the radial range used to determine the fit, alternate fitting equations have been proposed which are less susceptible to this effect. The parameters a_0 through a_5 are fitted, so that the calculated radial dose function from the polynomial curve within ± 2% compared with original data in Table 1 to the radial distance

0.2 cm to 60 cm. The electron cutoff energy influenced dosimetry at the close region of the source due to considering the contribution of betas. In case of catheter based interstitial brachytherapy, higher values of radial dose function (2.36% from 0.2 cm to 0.8 cm of radial distances) may significant affect in radial dose distribution in clinical relevant situation.

The anisotropy functions are calculated with varying radial distances and angles. Some of the points in the table are data blank, which are situated within the source encapsulation or in the source core. The anisotropy functions for BEBIG ^{60}Co HDR source are compared with GEANT4 Monte Carlo based published value for different radial distances by Granero *et al.* [7]. The significant difference is noted with 0.5 cm of radial distance including polar angle less than 40^{o}, which could be mainly derived from the influence of geometry model (the tips of the source and encapsulation). In this case, our results are quite high in the longitudinal edge region of the source encapsulation. The authors calculated kerma to approximate the dose for the points where electronic equilibrium exists, and the cutoff energy of 10 keV was used for both photons and electrons.

The along-away 2D dose rate data are presented for 20 cm apart from the source center. Selvam *et al.* [5] reproduced the Granero *et al.* [7] study using the EGSnrc code, obtaining only an away-along table. The comparison of away-along tables from both studies reveals that at y = 0.25 cm and z = –0.25, z = 0, and z = 0.25 cm the Granero *et al.* [7] data are underestimated [2]. The published values by Selvam *et al.* [5] are in good agreement with the values obtained from this study. But the values reported by Granero *et al.* [7] are 6.5%, 8.5% and 5.2% lower than the values obtained from this study, respectively.

Conclusions

In this study, the dosimetric data for new BEBIG ^{60}Co source (model Co0.A86) is obtained for an unbounded liquid water phantom. Electron contribution is considered with appropriate cutoff energy for absorbed dose calculations throughout the study using EGSnrc-based DOSRZnrc user code.

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