Original Article

Monte Carlo Study on Dose Distributions Around ^{192}Ir, ^{169}Yb, and ^{125}I Brachytherapy Sources Using EGSnrc-based egs_brachy User-code

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Abstract

Introduction: As per the recommendations of the American Association of Physicists in Medicine Task Group 43, Monte Carlo (MC) investigators should reproduce previously published dose distributions whenever new features of the code are explored. The purpose of the present study is to benchmark the TG-43 dosimetric parameters calculated using the new MC user-code egs_brachy of EGSnrc code system for three different radionuclides ^{192}Ir, ^{169}Yb, and ^{125}I which represent high-, intermediate-, and low-energy sources, respectively. **Materials and Methods:** Brachytherapy sources investigated in this study are high-dose rate (HDR) ^{192}Ir VariSource (Model VS2000), ^{169}Yb HDR (Model 4140), and ^{125}I -low-dose-rate (LDR) (Model OcuProsta). The TG-43 dosimetric parameters such as air-kerma strength, S_k, dose rate constant, Λ, radial dose function, g(r) and anisotropy function, $F(r;\theta)$ and two-dimensional (2D) absorbed dose rate data (along-away table) are calculated in a cylindrical water phantom of mass density 0.998 g/cm^3 using the MC code egs_brachy. Dimensions of phantom considered for ^{192}Ir VS2000 and ^{169}Yb sources are 80 cm diameter ×80 cm height, whereas for ^{125}I OcuProsta source, 30 cm diameter ×30 cm height cylindrical water phantom is considered for MC calculations. **Results:** The dosimetric parameters calculated using egs_brachy are compared against the values published in the literature. The calculated values of dose rate constants from this study agree with the published values within statistical uncertainties for all investigated sources. Good agreement is found between the egs_brachy calculated radial dose functions, g(r), anisotropy functions, and 2D dose rate data with the published values (within 2%) for the same phantom dimensions. For ^{192}Ir VS2000 source, difference of about 28% is observed in g(r) value at 18 cm from the source which is due to differences in the phantom dimensions. **Conclusion:** The study validates TG-43 dose parameters calculated using egs_brachy for ^{192}Ir, ^{169}Yb, and ^{125}I brachytherapy sources with the values published in the literature.

Keywords: Brachytherapy, egs_brachy, EGSnrc code system, Monte Carlo, TG-43 dosimetry

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Introduction

As per the American Association of Physicists in Medicine (AAPM) Task Group 43 (TG-43) recommendations, Monte Carlo (MC) investigators should reproduce previously published dose distributions for at least one widely used brachytherapy source model whenever new features of the code are explored.[1,2] egs_brachy[3,4] is a new user-code of EGSnrc code system[5] designed especially for brachytherapy applications. To the best of our knowledge, TG-43 dosimetry parameters are investigated for two high-dose rate (HDR) sources ^{192}Ir MicroSelectron V2 and BEBIG ^{60}Co (model Co0.A86) using egs_brachy code.[3,6] Recently, TG-43 parameters are calculated by Safigholi *et al*.[7] for low-energy (≤50 keV) photon-emitting low-dose rate (LDR) brachytherapy

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sources (40 numbers) using egs_brachy to update the Carleton Laboratory for Radiotherapy Physics TG-43 dosimetry database. TG-43 parameters vary significantly with different source designs and encapsulation materials due to the existence of high-dose gradient region around it. Hence, it is important to benchmark the dosimetry dataset of a given brachytherapy source model before carrying out further studies using a new MC code.

The purpose of the present study is to benchmark the TG-43 dosimetric parameters calculated using the new user-code egs_brachy[3,4] for three different radionuclides ^{192}Ir, ^{169}Yb, and ^{125}I which represent high-, intermediate-, and low-energy sources, respectively. The brachytherapy sources for which TG-43 parameters are not available using egs_brachy[3,4] MC code are chosen for benchmarking and the sources considered for the investigation are HDR ^{192}Ir (Model VS2000),[8] HDR ^{169}Yb (Model 4140)[9] and LDR ^{125}I (Model OcuProsta).[10] Thus, this study covers a range of photon energies relevant in brachytherapy.

^{192}Ir HDR VS2000[8] source is widely in use for clinical applications and differs significantly from other commercially available ^{192}Ir HDR brachytherapy sources in their dimensions such as active length, active diameter, and the encapsulation materials. It consists of two active sources of 2.5 mm each, as compared to the single source of typical active length of about 3.5 mm; the active diameter of VS2000 sources is 0.35 mm as compared to the typical active diameter of 0.6 mm. Alloy of Nickel and Titanium is used as the encapsulation material in VS2000 whereas stainless steel is used in other brachytherapy sources. For VS2000[8] source, Angelopoulos *et al*.[8] calculated TG-43 dosimetric parameters in a 30 cm diameter spherical water phantom using an egs_brachy analytical MC code.[11-13] In another study, Taylors and Rogers[14] calculated the TG-43 dosimetric parameters in a rectilinear water phantom of dimensions of 80 cm × 80 cm × 80 cm for ^{192}Ir VS2000[8] and ^{169}Yb 4140[9] sources using the MC code BrachyDose.[15,16] Medich *et al*.[9] calculated TG-43 dosimetric parameters in a 40 cm diameter spherical water phantom for ^{169}Yb (model 4140) source using MCNP5 MC code.[17]

OcuProsta is an indigenous model of ^{125}I brachytherapy source designed and fabricated by Radiopharmaceuticals Division of Bhabha Atomic Research Centre for brachytherapy applications.[10,18-20] This source is clinically used in permanent prostate implant.[20] It consists of 0.5 mm diameter and 3.0 mm long silver rod coated with palladium on which ^{125}I is adsorbed and encapsulated in a hollow cylindrical 0.05 mm thick titanium tube. The external dimensions of the seed are 0.8 mm diameter and 4.75 mm length. Sharma *et al*.[10] calculated TG-43 parameters in a 30 cm diameter spherical water phantom for this source using MCNP Version 3.1[21] MC code. The authors have calculated radial dose functions up to a distance of 5 cm and anisotropy function at r = 1, 2, 3, and 5 cm for polar angles from 0° to 90° at 10° interval. In another study, Sahoo *et al*.[22] reported dose rate constant and radial dose functions (up to a distance of 10 cm) for this source using DORZnrc user-code[23] of EGSnrc code system.[5]

In the present study, TG-43 dosimetric parameters such as air-kerma strength, S_k, dose rate constant, Λ, radial dose function, g(r) and anisotropy function, $F(r,\theta)$ and two-dimensional (2D) absorbed dose rate data (along-away table) are calculated for ^{192}Ir HDR VariSource VS2000,[8] ^{169}Yb HDR 4140[9], and ^{125}I LDR OcuProsta[10] brachytherapy sources using the new user-code egs_brachy[3,4] of the EGSnrc code system.[5] Statdose[24] and 3ddose_tools[25] user-codes of EGSnrc code system are used for analyzing the dose distributions obtained from the egs_brachy MC code. The TG-43 parameters calculated using egs_brachy are compared with the published data.[10,14,22] For OcuProsta source, $F(r,\theta)$ are calculated for additional radial distances r = 0.25, 0.5, 7.5, and 10 cm for polar angles 0°–90° at an interval of 2°–5°. 2D-dose rate data (along-away table) is also calculated in this study which is not available for this source.

Materials and Methods

Egs_brachy Monte Carlo code

MC-based EGSnrc code system[5] consists of several user-codes[23] dedicated to address specific applications. egs_brachy[3,4] is a fast and versatile new user-code of EGSnrc code system designed especially for brachytherapy applications. egs_brachy is a modern EGSnrc application which employs C++ class library (egs++)[26] for modeling geometries and particle sources.

Brachytherapy sources

Brachytherapy sources investigated in this study were HDR ^{192}Ir VariSource (Model VS2000),[8] ^{169}Yb HDR (Model 4140)[9] and ^{125}I LDR (Model OcuProsta).[10] The geometry, dimensions, and material details of the above sources were taken from the published studies.[8-10] The photon energy spectra of ^{192}Ir and ^{169}Yb needed for the MC calculations were taken from literature.[9,27] For ^{125}I source, the photon spectrum was taken from AAPM TG-43U1.[2]

Monte Carlo calculations

In the MC calculations of absorbed dose to water, the brachytherapy source was positioned at the center of the water phantom of mass density 0.998 g/cm^3. For ^{192}Ir VS2000[8] and ^{169}Yb 4140[9] sources, a cylindrical water phantom of dimensions 80 cm diameter and 80 cm height was simulated which was consistent with the recommendation of AAPM and ESTRO Report for photon-emitting brachytherapy sources with an average energy higher than 50 keV.[28,29] For OcuProsta[10] source, a cylindrical water phantom of dimensions 30 cm diameter and 30 cm height was considered which was consistent with the AAPM TG-43U1 recommendations.[2] The geometric center of the active part of the source was taken as the origin. The water phantom was divided into a number of cylindrical voxels with different sizes. For high-dose gradients regions, small voxel sizes were adapted. Absorbed dose was scored in voxels of dimensions 0.1 mm × 0.1 mm for distance $r \leq 1$ cm, 0.5 mm × 0.5 mm voxels for $1 < r \leq 5$ cm, 1 mm × 1 mm voxels for $5 < r \leq 10$ cm, and 2 mm × 2 mm voxels for $10 < r \leq 20$ cm. For S_k calculations, the source was immersed at the center of a 50 cm diameter vacuum sphere. Air-kerma per history was calculated in a voxel of dimension 0.1 cm × 0.1 cm × 0.05 cm filled with air (40% humidity, as recommended by TG-43U1[2]) located at a distance of 10 cm from the transverse axis of the source.

The PEGS4 dataset needed for MC calculations is based on the XCOM[30] compilations. For the investigated sources, charged particle equilibrium was assumed and collision-kerma was considered as absorbed dose since the range of secondary electrons is short.[4] The photon fluence spectrum scored using track length estimator was converted to collision-kerma to water by using the mass energy-absorption coefficients of water. Up to 8×10^9 photon histories were simulated. Uncertainties were calculated with the default history-by-history method used in EGSnrc code system.[31] As per the recommendations of AAPM TG-268,[32] Table 1 summarizes the parameters used in the MC calculations.

Results and Discussion

Air-kerma strength, S_k

The MC-calculated air-kerma per history obtained at 10 cm was corrected to give the air-kerma per history at a point of 1 m. The values of S_k calculated for ^{192}Ir VS2000, ^{169}Yb 4140, and ^{125}I OcuProsta sources are $1.202 \pm 0.0014 \times 10^{-13}$, $2.184 \pm 0.0019 \times 10^{-14}$, and $4.138 \pm 0.0017 \times 10^{-14}$ Gy cm^2/history, respectively.

Dose rate constant, Λ

The dose rate constant (Λ) was calculated by dividing the absorbed dose to water per history at reference position (1 cm, 90°) in the water phantom to the S_k per history. The values of Λ for ^{192}Ir VS2000, ^{169}Yb 4140 and ^{125}I OcuProsta sources are 1.099 ± 0.003, 1.186 ± 0.003, and 0.962 ± 0.003 cGyh^{-1}U^{-1}, respectively. The egs_barchy-calculated values of dose rate constants are in excellent agreement with the published values[8-10,14,22] within statistical uncertainties for all investigated sources.

Table 1: Summary of parameters used for Monte Carlo calculations as per the recommendations of American Association of Physicists in Medicine task group-286

Item name	Descriptions	References
Code, version/release date	egs_brachy, 2017 version/September 15, 2017	[3,4]
Validation	Validated for ^{192}Ir MicroSelectron V2, BEBIG ^{60}Co and about 40 numbers of LDR brachytherapy sources	[3,6,7]
Timing	About 7680 total CPU hours on Intel (R) Xeon (R) 32 CPUs with clock speeds of 2.6 GHz	
Source description	^{192}Ir HDR (Model VS2000): It consists of two active sources made of iridium (ρ=22.42 g/cm^3) of 2.5 mm long and 0.35 mm diameter each. The uniformly distributed radioactive iridium core is encapsulated in a nickel and titanium alloy (ρ=6.95 g/cm^3). Photons are uniformly distributed in the active iridium core and the photon emission is isotropic	[8-10]
	^{169}Yb HDR (Model 4140): It consists of a 0.73 mm diameter and 3.6 mm long ytteribum oxide rod (ρ=6.9 g/cm^3) enclosed in a stainless steel capsule (ρ=7.8 g/cm^3). Photons are uniformly distributed in the active core and the photon emission is isotropic	
	^{125}I LDR (Model OcuProsta): It consists of 0.5 mm diameter and 3 mm long silver rod (ρ=10.5 g/cm^3) coated with palladium on which ^{125}I is adsorbed and encapsulated in a hollow cylindrical 0.05 mm thick titanium tube. Photons are uniformly distributed in 0.003 cm thick layer of NaI (ρ=3.67 g/cm^3) which is coated on the surface of ^{103}Pd core and the photon emission is isotropic	
Cross-sections	Photon cross-sections and mass-energy absorption coefficients are calculated using XCOM database	[30]
Transport parameters	Rayleigh scattering, bound Compton scattering, photoelectric absorption, and fluorescent emission of characteristic X-rays processes are simulated in all the calculations	
	For ^{192}Ir VS2000 and ^{169}Yb HDR 4140 sources, PCUT=10 keV and ECUT=1.5 MeV used in all calculations	
	For ^{125}I OcuProsta source, PCUT=1 keV and ECUT=1 MeV in all calculations, except S_k calculations for which PCUT=5 keV	
VRT and AIET	No variance reduction technique is used in this study	
Scored quantities	Dose to medium is scored using track length estimator	
Number of histories/statistical uncertainties	Up to 8×10^9 photon histories are simulated/1σ statistical uncertainties on the calculated values are <1% for r <10 cm, <2% for r=10–15 cm and <3% for r=10-20 cm	
Statistical methods	Uncertainties are calculated with the default history-by-history method used in EGSnrc	[31]
Postprocessing	TG-43 parameters are calculated using the TG-43 formalism and the results are reported without using any kind of filtrations	[1,2]

LDR: Low-dose rate, CPU: Central processing unit, TG-43: Task group 43, PCUT: Photon cutoff energy, ECUT: Electron cutoff energy

Table 2: Radial dose function, *g* (*r*), of ^{192}Ir VS2000 and ^{169}Yb 4140 high-dose-rate brachytherapy sources

Distance *r* (cm)	^{192}Ir VS2000			^{169}Yb 4140		
	This study	Published[14]	Difference (%)	This study	Published[14]	Difference (%)
0.25	0.990	0.991	−0.10	0.932	0.927	0.54
0.3	0.990	0.993	−0.30	0.940	0.934	0.64
0.4	0.995	0.995	0.00	0.949	0.945	0.42
0.5	0.999	0.997	0.20	0.958	0.955	0.31
0.6	0.999	0.997	0.20	0.967	0.966	0.10
0.7	1.000	0.997	0.30	0.977	0.975	0.21
0.75	1.000	0.999	0.10	0.979	0.978	0.10
0.8	1.000	1.000	0.00	0.986	0.982	0.41
0.9	1.000	0.998	0.20	0.993	0.993	0.00
1	1.000	1.000	0.00	1.000	1.000	0.00
1.25	1.006	1.004	0.20	1.020	1.021	−0.10
1.5	1.006	1.005	0.10	1.041	1.040	0.10
1.75	1.007	1.007	0.00	1.061	1.057	0.38
2	1.011	1.010	0.10	1.077	1.074	0.28
2.5	1.012	1.011	0.10	1.107	1.101	0.54
3	1.014	1.012	0.20	1.130	1.119	0.98
3.5	1.011	1.014	−0.30	1.143	1.137	0.53
4	1.011	1.013	−0.20	1.152	1.147	0.44
4.5	1.010	1.013	−0.30	1.168	1.157	0.95
5	1.008	1.011	−0.30	1.160	1.161	−0.09
6	1.001	1.003	−0.20	1.165	1.158	0.60
7	0.992	0.994	−0.20	1.151	1.140	0.96
8	0.979	0.982	−0.31	1.120	1.111	0.81
9	0.963	0.966	−0.31	1.076	1.084	−0.74
10	0.947	0.949	−0.21	1.053	1.047	0.57
11	0.926	0.930	−0.43	1.017	1.004	1.29
12	0.906	0.908	−0.22	0.972	0.960	1.25
13	0.886	0.884	0.23	0.928	0.913	1.64
14	0.859	0.858	0.12	0.882	0.867	1.73
15	0.832	0.834	−0.24	0.806	0.820	−1.71
16	0.797	0.805	−0.99	0.790	0.776	1.80
17	0.768	0.777	−1.16	0.719	0.732	−1.78
18	0.758	0.749	1.20	0.696	0.686	1.46
19	0.720	0.721	−0.14	0.652	0.644	1.24
20	0.688	0.694	−0.86	0.610	0.599	1.84

The calculated data are based on a cylindrical liquid water phantom of dimensions 80 cm diameter×80 cm height

Radial dose function, g(r)

Radial dose function, g(r), calculated for ^{192}Ir VS2000 and ^{169}Yb 4140 sources for distances r = 0.25–20 cm were presented in Table 2 along with the corresponding published values.[14] For ^{125}I OcuProsta source, g(r) values are calculated up to a distance of 10 cm and are presented in Figure 1 along with the corresponding published values.[10,22] g(r) values for ^{192}Ir VS2000 source were found to be in good agreement with the published values[14] with a maximum deviation of about 1.2% at a distance r = 18 cm. However, significant differences in g(r) values were observed beyond r = 8 cm which increases gradually with r when compared with the g(r) values (a maximum difference of about 28% at r = 18 cm) calculated by Angelopoulos *et al*.[8] This is due to the fact that Angelopoulos *et al*.[8] considered spherical water phantom of 40 cm diameter in their study whereas in the present study a cylindrical phantom of 80 cm diameter ×80 cm height is considered. The phantom dimensions significantly affect g(r) values only near the phantom boundaries. This effect is due to the reduction of scatter contribution to overall dose at the edges of the phantom.

For ^{169}Yb 4140 and ^{125}I OccuProsta sources, excellent agreement is found between the g(r) values calculated using egs_brachy and the published values.[14,22] A maximum deviations of about 1.8% at a distance r = 20 cm and 0.68% at a distance r = 10 cm are observed for ^{169}Yb 4140 and ^{125}I OcuProsta sources, respectively.

Table 3: Anisotropy function, $F(r,\theta)$, of ^{192}Ir VS2000 high-dose-rate brachytherapy source

θ (deg)	distance *r* (cm)										
	0.25	0.5	1	2	3	4	5	7.5	10	12.5	15
0	-	-	0.524	0.536	0.577	0.605	0.638	0.670	0.741	0.791	0.767
1	-	-	0.530	0.536	0.571	0.612	0.639	0.692	0.741	0.791	0.769
2	-	-	0.541	0.558	0.584	0.624	0.672	0.709	0.752	0.805	0.814
3	-	-	0.571	0.584	0.624	0.663	0.695	0.712	0.767	0.809	0.824
5	-	-	0.643	0.657	0.667	0.716	0.722	0.780	0.783	0.842	0.843
7	-	-	0.705	0.715	0.712	0.775	0.795	0.810	0.813	0.858	0.842
10	-	-	0.780	0.784	0.808	0.818	0.826	0.834	0.837	0.889	0.875
12	-	-	0.805	0.809	0.822	0.838	0.854	0.870	0.875	0.926	0.868
15	-	-	0.840	0.847	0.856	0.890	0.896	0.896	0.903	0.839	0.913
20	-	-	0.892	0.883	0.886	0.898	0.909	0.927	0.947	0.959	0.924
25	-	0.941	0.914	0.916	0.918	0.925	0.952	0.940	0.957	0.967	0.916
30	-	0.955	0.937	0.931	0.944	0.957	0.967	0.942	0.966	0.985	0.931
35	-	0.950	0.960	0.946	0.957	0.959	0.973	0.959	0.969	0.993	0.935
40	-	0.980	0.972	0.963	0.971	0.978	0.994	0.979	0.980	0.994	0.943
45	-	0.996	0.973	0.978	0.975	0.964	0.987	0.981	0.989	1.011	0.953
50	-	0.997	0.984	0.978	0.970	0.994	0.999	0.981	0.996	1.015	0.962
55	0.996	0.997	0.994	0.984	0.988	0.991	0.996	0.983	0.993	1.015	0.947
60	0.997	1.004	0.986	0.996	0.988	0.991	1.012	0.979	0.985	1.016	0.968
65	0.997	1.006	0.995	0.996	0.989	0.993	1.010	0.976	0.994	1.013	0.949
70	0.998	0.996	1.006	0.987	0.984	1.000	1.003	0.987	1.006	1.005	0.949
75	0.998	1.010	1.002	0.999	0.990	0.998	0.999	1.003	1.000	1.009	0.969
80	0.999	1.009	1.001	0.994	1.014	0.997	0.998	1.000	0.999	1.012	0.975
85	0.999	0.991	1.000	1.006	1.003	1.001	1.000	1.016	0.999	1.013	0.981
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	0.996	1.000	1.012	0.990	1.006	1.002	1.000	1.000	1.003	0.996
100	0.999	1.008	1.002	1.000	1.004	1.008	1.000	0.994	0.992	1.004	0.968
105	0.999	1.006	1.000	0.990	0.989	1.003	1.000	1.006	1.021	0.996	0.968
110	0.999	1.001	1.003	0.999	0.988	0.997	0.998	1.012	1.014	0.998	0.954
115	0.998	1.008	0.991	0.990	0.980	0.995	0.996	1.015	1.004	0.998	0.968
120	0.997	1.000	0.993	0.987	0.991	0.999	0.994	0.983	0.995	0.994	0.978
125	0.995	0.980	0.994	0.978	0.980	0.997	0.992	0.993	1.004	0.989	0.959
130	-	1.006	0.979	0.972	0.975	0.994	0.985	0.980	0.991	0.987	0.943
135	-	1.008	0.973	0.980	0.971	0.968	0.975	0.973	0.991	0.986	0.949
140	-	0.995	0.971	0.961	0.963	0.972	0.987	0.961	0.974	0.981	0.935
145	-	0.969	0.964	0.950	0.950	0.951	0.969	0.980	0.983	0.979	0.933
150	-	0.982	0.933	0.940	0.930	0.951	0.964	0.967	0.969	0.981	0.912
155	-	0.989	0.921	0.906	0.912	0.926	0.951	0.938	0.934	0.966	0.919
160	-	-	0.895	0.894	0.891	0.902	0.919	0.890	0.919	0.957	0.906
165	-	-	0.835	0.840	0.843	0.865	0.867	0.870	0.908	0.907	0.866
168	-	-	0.808	0.804	0.833	0.853	0.859	0.850	0.891	0.903	0.856
170	-	-	-	0.762	0.801	0.809	0.838	0.843	0.886	0.894	0.877
173	-	-	-	0.724	0.731	0.739	0.752	0.819	0.840	0.865	0.827
175	-	-	-	-	0.644	0.702	0.718	0.756	0.775	0.802	0.788
177	-	-	-	-	-	0.634	0.673	0.708	0.740	0.794	0.793
178	-	-	-	-	-	-	-	0.662	0.719	0.781	0.755
179	-	-	-	-	-	-	-	0.608	0.682	0.685	0.740
180	-	-	-	-	-	-	-	0.546	0.621	0.644	0.686

The calculated data are based on a cylindrical liquid water phantom of dimensions 80 cm diameter ×80 cm height

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

For ^{192}Ir VS2000, ^{169}Yb 4140 sources, $F(r,\theta)$ were calculated at radii of 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 7.5, 10, 12.5, and 15 cm for polar angles from 0° to 180° with varying intervals. For ^{125}I OcuProsta source, $F(r,\theta)$ were calculated for polar angles 0° to 90° at radii of 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 7.5,

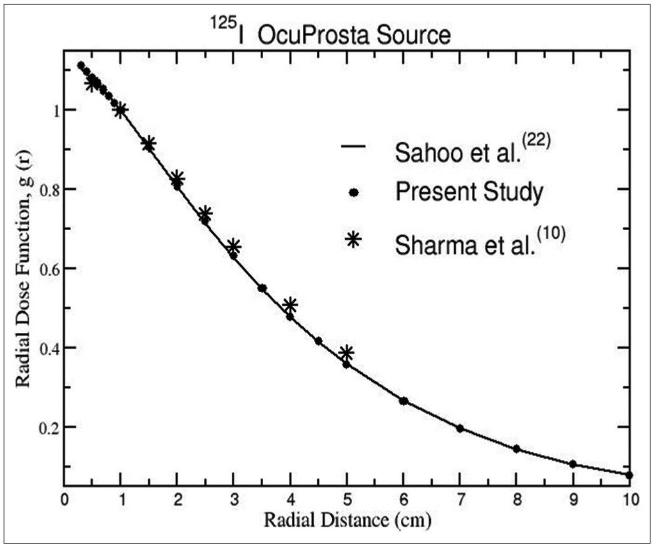

Figure 1: Radial dose function, g(r), of ^{125}I LDR OcuProsta brachytherapy source for radial distances 0.25–10 cm. The calculated data are based on a cylindrical liquid water phantom of dimensions 30 cm diameter ×30 cm height

and 10 cm because of the symmetry of the source. Tables 3-5 present the *F(r,*θ*)* values for ^{192}Ir VS2000, ^{169}Yb 4140, and ^{125}I OcuProsta sources, respectively. For ^{192}Ir VS2000 and ^{169}Yb 4140 sources, values of *F(r,*θ*)* are in good agreement with the published values[14]

For ^{125}I OcuProsta source, the values of *F(r,*θ*)* are in good agreement with the published values.[10] Figure 2a and b presents the values of *F(r,*θ*)* at different polar angles along with the corresponding published values[10] at radial distances r = 1 and 5 cm, respectively.

Along and away two-dimensional dose rate distribution

For ^{125}I OcuProsta source absorbed dose per unit air-kerma strength was calculated up to a distance of 10 cm and presented in Table 6. The 2D-dose rate values for ^{192}Ir VS 2000 and ^{169}Yb 4140 sources agree well with the published data[14] within 2%. It may be noted that, for ^{125}I OcuProsta source, 2D along-away table is not available for comparison.

Uncertainties

The uncertainties associated with the estimated quantities are only statistical. It does not include Type B uncertainty related to cross-section, source geometry, source material, and size of the voxel. However, to minimize the uncertainty that may arise due to dimensions of voxel, distance-specific voxel dimensions were chosen as recommended by Taylor *et al*.[15] In this study, 1 σ statistical uncertainties on the calculated dosimetry values are <1% at distances r < 10 cm, <2% at distances r = 10–15 cm, and <3% at distances r = 10–20 cm.

Conclusion

In this study, TG-43 dosimetric parameters were calculated for ^{192}Ir VS2000, ^{169}Yb 4140, and ^{125}I Ocuprosta brachytherapy sources using the new egs_brachy user-code of the EGSnrc code system. The calculated dosimetric parameters are in good agreement with the published data. The present study validates the new user-code egs_brachy with the published dose distributions. This study thus demonstrates the ability of egs_brachy MC code to handle the transport of photons and electrons accurately at brachytherapy photon energies such as ^{192}Ir, ^{169}Yb, and ^{125}I. The study also demonstrates the capability of the egs_brachy to model the complex geometry of sources accurately. For example, the simulation of VS2000 which consists of two cylindrical sources having spherical caps at both ends, which is not possible using user-code such as DOSRZnrc due to the limitations associated with it.

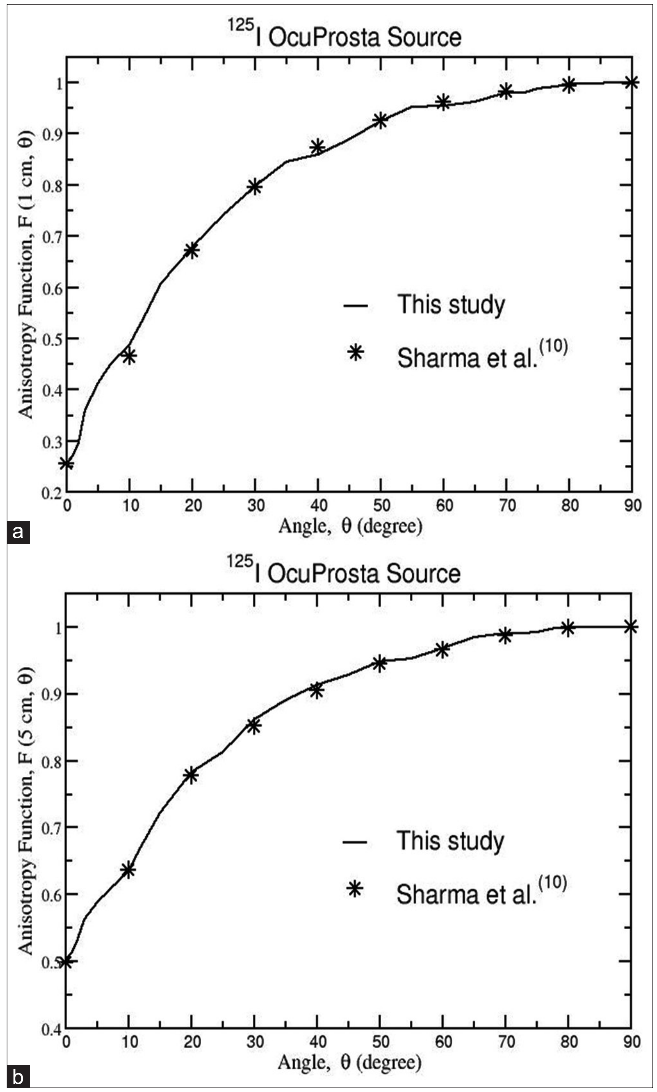

Figure 2: (a) Anisotropy function, *F(r,*θ*),* of ^{125}I LDR OcuProsta brachytherapy source at a radial distance of 1 cm. The calculated data are based on a cylindrical liquid water phantom of dimensions 30 cm diameter × 30 cm height. (b) Anisotropy Function, *F(r,*θ*),* of ^{125}I LDR OcuProsta brachytherapy source at a radial distance of 5 cm. The calculated data are based on a cylindrical liquid water phantom of dimensions 30 cm diameter × 30 cm height

Table 4: Anisotropy function, $F(r,\theta)$, of ^{169}Yb 4140 high-dose rate brachytherapy source

θ (°)	Distance *r* (cm)										
	0.25	**0.50**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**7.50**	**10.00**	**12.50**	**15.00**
0	-	0.555	0.558	0.609	0.660	0.696	0.726	0.774	0.802	0.833	0.850
1	-	0.556	0.558	0.609	0.657	0.696	0.725	0.774	0.814	0.832	0.850
2	-	0.555	0.558	0.612	0.662	0.698	0.726	0.780	0.813	0.833	0.850
3	-	0.556	0.559	0.616	0.666	0.703	0.731	0.783	0.813	0.835	0.851
5	-	0.560	0.571	0.628	0.676	0.712	0.737	0.791	0.812	0.838	0.855
7	-	0.571	0.589	0.644	0.690	0.724	0.749	0.801	0.825	0.846	0.860
10	-	0.598	0.620	0.671	0.715	0.746	0.768	0.812	0.832	0.854	0.869
12	-	0.621	0.642	0.691	0.731	0.758	0.779	0.824	0.843	0.862	0.878
15	-	0.658	0.676	0.719	0.754	0.783	0.798	0.837	0.852	0.871	0.883
20	-	0.716	0.728	0.764	0.795	0.816	0.829	0.859	0.876	0.889	0.898
25	-	0.769	0.777	0.804	0.828	0.844	0.855	0.886	0.892	0.905	0.912
30	-	0.814	0.819	0.839	0.857	0.872	0.880	0.901	0.912	0.921	0.927
35	-	0.851	0.849	0.868	0.885	0.894	0.900	0.922	0.926	0.935	0.938
40	-	0.883	0.884	0.895	0.908	0.915	0.917	0.935	0.939	0.945	0.951
45	-	0.909	0.909	0.916	0.930	0.937	0.940	0.956	0.952	0.958	0.960
50	-	0.931	0.931	0.937	0.946	0.951	0.953	0.963	0.965	0.968	0.972
55	0.963	0.951	0.950	0.952	0.959	0.962	0.964	0.973	0.971	0.976	0.979
60	0.973	0.963	0.960	0.967	0.974	0.976	0.976	0.984	0.983	0.982	0.984
65	0.981	0.976	0.979	0.978	0.984	0.984	0.985	0.994	0.989	0.990	0.990
70	0.988	0.985	0.986	0.986	0.991	0.992	0.994	1.002	0.995	0.995	0.994
75	0.994	0.991	0.991	0.993	0.997	0.997	0.998	1.004	0.996	0.998	0.999
80	0.997	0.998	0.997	0.997	1.000	1.000	1.000	1.004	1.002	1.003	1.002
85	0.998	1.000	1.000	0.997	1.003	1.004	1.000	1.004	0.995	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	0.998	0.999	1.002	0.998	1.001	1.002	1.001	1.003	0.999	1.002	1.000
100	0.997	0.997	0.995	0.994	0.999	1.001	0.999	1.001	1.000	1.001	0.996
105	0.993	0.990	0.992	0.990	0.994	0.994	0.991	0.996	0.993	0.996	0.998
110	0.989	0.984	0.985	0.983	0.988	0.992	0.991	0.995	0.989	0.994	0.992
115	0.981	0.975	0.974	0.975	0.980	0.981	0.978	0.989	0.988	0.988	0.988
120	0.973	0.960	0.964	0.966	0.971	0.973	0.969	0.979	0.974	0.981	0.981
125	0.963	0.946	0.947	0.949	0.957	0.961	0.959	0.970	0.967	0.971	0.975
130	-	0.928	0.927	0.932	0.942	0.947	0.950	0.960	0.959	0.963	0.967
135	-	0.904	0.902	0.911	0.923	0.929	0.933	0.943	0.946	0.952	0.955
140	-	0.877	0.880	0.888	0.902	0.910	0.915	0.929	0.932	0.940	0.946
145	-	0.843	0.843	0.859	0.878	0.888	0.894	0.912	0.918	0.926	0.931
150	-	0.805	0.805	0.827	0.847	0.861	0.871	0.894	0.903	0.910	0.919
155	-	0.754	0.760	0.789	0.816	0.832	0.845	0.872	0.881	0.895	0.902
160	-	-	0.708	0.744	0.775	0.798	0.813	0.847	0.860	0.877	0.888
165	-	-	0.644	0.690	0.730	0.755	0.776	0.818	0.837	0.856	0.872
168	-	-	0.596	0.652	0.698	0.731	0.752	0.801	0.821	0.845	0.859
170	-	-	0.560	0.625	0.673	0.710	0.736	0.787	0.808	0.835	0.850
173	-	-	0.505	0.583	0.639	0.679	0.711	0.763	0.797	0.823	0.840
175	-	-	0.472	0.557	0.618	0.661	0.693	0.759	0.786	0.815	0.835
177	-	-	0.457	0.537	0.599	0.644	0.677	0.742	0.778	0.808	0.827
178	-	-	0.455	0.532	0.594	0.639	0.672	0.740	0.777	0.805	0.825
179	-	-	0.451	0.528	0.590	0.636	0.671	0.736	0.772	0.803	0.821
180	-	-	0.454	0.527	0.589	0.633	0.665	0.733	0.774	0.802	0.819

The calculated data are based on a cylindrical liquid water phantom of dimensions 80 cm diameter×80 cm height

Table 5: Anisotropy function, *F(r,θ)*, of ^{125}I OcuProsta low-dose rate brachytherapy source

Theta (deg)	Distance (*r*)									
	0.25	0.5	0.75	1	2	3	4	5	7.5	10
0	0.199	0.209	0.233	0.256	0.370	0.437	0.501	0.504	0.634	0.696
1	0.226	0.251	0.268	0.272	0.395	0.450	0.509	0.514	0.655	0.723
2	0.245	0.270	0.288	0.298	0.411	0.509	0.515	0.534	0.671	0.728
3	0.285	0.337	0.347	0.361	0.454	0.470	0.522	0.563	0.687	0.723
5	0.320	0.352	0.409	0.412	0.486	0.495	0.561	0.589	0.706	0.730
7	0.349	0.391	0.434	0.448	0.507	0.523	0.605	0.607	0.721	0.747
10	0.381	0.443	0.468	0.469	0.557	0.592	0.685	0.635	0.739	0.767
12	0.424	0.456	0.522	0.522	0.593	0.634	0.710	0.671	0.755	0.781
15	0.475	0.511	0.586	0.607	0.679	0.672	0.751	0.723	0.775	0.809
20	0.585	0.629	0.667	0.678	0.734	0.740	0.794	0.782	0.824	0.838
25	0.665	0.715	0.736	0.742	0.781	0.786	0.828	0.813	0.870	0.859
30	0.727	0.782	0.782	0.798	0.828	0.825	0.868	0.862	0.889	0.890
35	0.769	0.827	0.837	0.846	0.863	0.862	0.901	0.890	0.910	0.904
40	0.804	0.847	0.851	0.860	0.900	0.894	0.921	0.912	0.931	0.933
45	0.836	0.870	0.879	0.888	0.924	0.913	0.941	0.929	0.946	0.944
50	0.864	0.893	0.916	0.924	0.941	0.938	0.966	0.949	0.961	0.962
55	0.871	0.937	0.947	0.952	0.942	0.945	0.971	0.952	0.972	0.962
60	0.889	0.935	0.952	0.954	0.970	0.960	0.981	0.968	0.981	0.987
65	0.909	0.945	0.959	0.962	0.987	0.981	0.989	0.985	0.989	0.986
70	0.933	0.960	0.979	0.980	0.991	0.994	0.997	0.990	0.990	0.989
73	0.956	0.968	0.981	0.985	0.993	1.000	0.999	0.990	0.990	0.990
75	0.972	0.976	0.985	0.987	0.997	1.000	1.000	0.992	0.990	0.990
78	0.979	0.984	0.995	0.992	0.998	1.000	0.999	0.997	0.992	0.991
80	0.982	0.987	0.999	0.997	0.995	1.000	1.000	0.999	0.993	0.996
82	0.987	0.990	1.000	0.999	0.993	1.000	0.999	1.000	0.994	0.997
84	0.990	0.990	0.999	0.999	0.996	1.000	0.997	0.999	0.999	0.992
85	0.992	0.992	1.000	0.999	0.999	1.000	1.000	1.000	1.000	1.000
86	0.998	0.999	1.001	0.999	0.998	1.000	1.000	1.000	1.000	0.999
87	0.999	0.999	0.999	0.999	0.998	0.999	1.000	1.000	1.000	0.999
88	0.999	0.992	0.999	1.000	0.999	1.000	1.000	1.000	0.999	1.001
89	1.000	0.996	0.998	0.997	0.999	1.000	1.000	1.000	1.000	1.000
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

The calculated data are based on a cylindrical liquid water phantom of dimensions 30 cm diameter × 30 cm height

Table 6: Dose rate (2D along away) data per unit air-kerma strength (cGyh^{-1} U^{-1}) for ^{125}I OcuProsta low-dose-rate brachytherapy source

Along (cm)	Away (cm)										
	0.25	0.5	0.75	1	1.5	2	3	4	5	7.5	10
0	13.477	4.075	1.799	0.962	0.389	0.196	0.068	0.029	0.014	0.003	0.001
0.25	7.332	3.203	1.544	0.903	0.378	0.192	0.068	0.029	0.014	0.003	0.001
0.5	2.668	1.861	1.143	0.738	0.341	0.181	0.065	0.028	0.014	0.003	0.001
0.75	1.069	1.008	0.770	0.558	0.294	0.165	0.062	0.027	0.014	0.003	0.001
1	0.564	0.600	0.518	0.410	0.243	0.145	0.058	0.026	0.013	0.003	0.001
1.5	0.215	0.246	0.244	0.219	0.157	0.106	0.048	0.023	0.012	0.003	0.001
2	0.108	0.122	0.127	0.122	0.099	0.074	0.039	0.020	0.011	0.002	0.001
3	0.040	0.042	0.044	0.045	0.041	0.035	0.023	0.013	0.008	0.002	0.001
4	0.019	0.018	0.019	0.019	0.019	0.017	0.013	0.009	0.005	0.002	0.001
5	0.009	0.009	0.009	0.009	0.009	0.009	0.007	0.005	0.004	0.001	---
7.5	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	---
10	0.001	0.001	0.001	0.001	0.001	0.001	---	---	---	---	---

The calculated data are based on a cylindrical liquid water phantom of dimensions 30 cm diameter × 30 cm height. "---"Negligible dose rate values

Ethical approval

This article does not contain any studies with human participants or animals performed.

Informed consent

Informed consent was obtained from all individual participants included in this study.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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