Original Article

Investigation of TG-43 Dosimetric Parameters for ^{192}Ir Brachytherapy Source Using GATE Monte Carlo Code

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Abstract

Purpose: According to the revised Task Group number 43 recommendations, a brachytherapy source must be validated against a similar or identical source before its clinical application. The purpose of this investigation is to verify the dosimetric data of the high dose rate (HDR) BEBIG ^{192}Ir source (Ir2.A85-2). **Materials and Methods:** The HDR ^{192}Ir encapsulated seed was simulated and its main dosimetric data were calculated using Geant4 Application for Tomographic Emission (GATE) simulation code. Cubic cells were used for the calculation of dose rate constant and radial dose function while for anisotropy function ring cells were used. DoseActors were simulated and attached to the respective cells to obtain the required data. **Results:** The dose rate constant was obtained as 1.098 ± 0.003 cGy.h $-$ ^{1}.U $-$ ^{1}, differing by 1.0% from the reference value reported by Granero *et al*. Similarly, the calculated values for radial dose and anisotropy functions presented good agreement with the results obtained by Granero *et al*. **Conclusion:** The results of this study suggest that the GATE Monte Carlo code is a valid toolkit for benchmarking brachytherapy sources and can be used for brachytherapy simulation-based studies and verification of brachytherapy treatment planning systems.

Keywords: BEBIG ^{192}Ir source, GATE code, Monte Carlo simulation, TG-43U1 report

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Introduction

A well-known technique for treating several cancers, including breast, prostate, skin, cervix, and head and neck, is brachytherapy using high dose rate (HDR) sources.[1] HDR brachytherapy has been considered a suitable modality for outpatient cancer treatment compared to low dose rate brachytherapy. HDR brachytherapy with ^{192}Ir sources was used widely in the past because manufacturers could only produce small size ^{192}Ir HDR sources. Recent technical improvements have provided the opportunity to produce miniaturized ^{60}Co sources similar to the ^{192}Ir source for the use in HDR brachytherapy. Comparative investigations have reported similar outcomes for HDR brachytherapy using ^{60}Co and ^{192}Ir sources.[1-3]

Based on the recommendation of the revised task group number 43 (TG-43U1) report,[4] a brachytherapy source requires dosimetric verification in a water phantom either experimentally or by Monte Carlo (MC) simulation before its clinical application. The verified characteristics of the source can then be used as the input in the HDR treatment planning system.[5,6] In the MC platform, the source geometry and physical interactions of radiation with matter, including the process of dose absorption, can be simulated accurately. In addition, MC can calculate the dose at points where conducting an experimental measurement is very difficult or even impossible.[5]

A few simulation-based studies have investigated the dosimetric data of the BEBIG ^{192}Ir HDR (Ir2.A85-2) source. Our literature review showed that there had been only two MC studies on the dosimetric verification of this source model. According to the

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American Association of Physicists in Medicine and European Society for Radiotherapy and Oncology[7] report, the only reference of the consensus data for this source is the results of a study conducted by Granero *et al.*[6] using GEometry ANd Tracking (GEANT4) MC code. They compared their results with the dosimetric characteristics of a very similar ^{192}Ir source, BEBIG GmbH model GI192M11 (Eckert and Ziegler Company). The second simulation-based study was performed by Sadeghi *et al.*[8] using MCN-Particle (MCNP5) transport code. The lack of necessary validation data can be fulfilled by performing more practical and theoretical investigations to assure that the proposed BEBIG iridium source is eligible for the clinical applications.

Therefore, the present study validated the dosimetric parameters of the BEBIG HDR ^{192}Ir source (model Ir2.A85-2) using the GATE MC simulation toolkit.

Materials and Methods

GATE simulation toolkit

The Geant4 Application for Tomography Emission (GATE) (http://www.opengatecollaboration.org/) is a Geant4-based open access simulation code which does not require any prior C++ knowledge. In this toolkit user write very intuitive codes to introduce the geometries, materials, detectors, scoring bodies (DoseActors), and the physics of radiation interactions with mater and dose deposition. The code was initially developed for application in nuclear medicine, but over the time, its application range has been expanded. To date, the GATE code has been successfully implemented in the simulation of emission tomography (positron emission tomography and single-photon emission computed tomography), optical imaging, computed tomography, radiotherapy including brachytherapy and particle therapy. In addition, GATE is able to simulate time-dependent events such as detector movement and rotation, patient breathing, and radioactive source decay.[9-19] In Gate, a DoseActor is an important parameter that should be defined for energy/dose deposition. Different actors can collect the data during simulation like the number of particles, energy, and dose deposition in a given volume, etc., The output files can be in the formats of ASCII File (.txt), Root file (.root), Analyze (.hdr/.img), and MetaImage (.mhd/.raw), but Meta Header (mhd) is recommended.[20]

^{192}Ir source geometry

The modeling and validation process of the BEBIG HDR ^{192}Ir seed (Ir2.A85-2 model, Eckert and Ziegler BEBIG Company, Germany) was carried out in the present study. The active core of the source (22.42 g/cm^3) with 0.6 mm diameter and 3.5 mm length was simulated at the center of a 40 cm diameter spherical water phantom (1.0 g/cm^3). After that, the 0.05 mm thick air layer around the active core and the 0.1 mm thick external encapsulation shell made of 316L stainless steel (8.03 g/cm^3) were also modeled. Two disks from 316 L stainless steel material with identical diameters of 0.9 mm and different heights of 0.72 mm and 0.68 mm were simulated, respectively, at the left and right sides of the active core. Finally, the simulation of a 304 stainless steel (5.75 g/cm^3) cable with the diameter of 0.9 mm and length of 2 mm was also performed at the left end of the brachytherapy seed [Figure 1].[6]

The features and full methodology of the commands written in the GATE simulation code are explained in detail elsewhere.[21]

Calculation of dosimetric parameters

The dose rate constant (Λ) is defined as the ratio of the dose rate (D) of the source in water at a point located 1.0 cm away from the source center on the bisector plane of the source longitudinal axis, to the quantity called air-kerma strength (S_k).[4]

$$\Lambda = \dot{D}\left(r_0,\theta_0\right) / S_k \tag{1}$$

The dose rate calculation was performed in the spherical water phantom, which was located within a 100 cm × 100 cm × 100 cm air rectangular medium in the GATE environment. A cubic cell (0.5 mm × 0.5 mm × 0.5 mm) was simulated at a point 1.0 cm away from the center of the source on the plane perpendicular to the long axis of the source. DoseActors, which store the dose distribution in three dimensions, were also defined and attached to the respective cubic cells.[20]

Air-kerma strength was calculated in an air sphere phantom with a density of 0.0012 g/cm^3 and a radius of 2 m. The air kerma rate was calculated in the distance of 100 cm for several times and the average value was reported as the air kerma strength in this study. The simulation world (medium) was defined as a cubic vacuum (6 m × 6 m × 6 m) with 0.000001 mg/cm^3 density.

For fast and efficient air-kerma rate calculation, the track length estimator DoseActors (TLEDoseActors) were simulated and connected to the respective air ring cells.[6] The details of the gamma-energy spectrum for the ^{192}Ir source were taken from the National Nuclear Data Center database[22] and included in the GATE dataset. The emitted beta particles and electrons do not significantly contribute to the absorbed dose as they are absorbed by the stainless steel capsule of the ^{192}Ir source. Therefore, their contributions to the absorbed dose and air-kerma rate were neglected.[23] The physics list was chosen as the emstandard_opt3 to include all the necessary radiation interactions with matter in dosimetry and radiotherapy with high precision.[24] "A cutoff energy of 10 keV for photons was used because the contribution to the absorbed dose of photons with energy lower than 10 keV is negligible".[25]

The radial dose function was calculated from 0.25 to 10 cm from the source center by defining cubic cells in the simulation

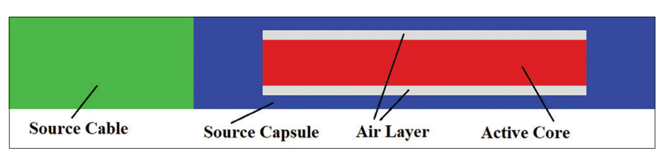

Figure 1: Cross-section of the BEBIG high dose rate ^{192}Ir source (Ir2.A85-2), modeled by GATE Monte Carlo code

codes. Finally, the anisotropy function was calculated at radial distances ranging from 1.0 to 10 cm from the source center and angles ranging from 0° to 170°. Water rings were used for the calculation of the anisotropy functions. The sizes of the cells were selected based on the recommendation by references.[26,27]

Up to 2×10^9 histories were selected as the total number of particles for the whole steps of the simulation and executed through the online Virtual Imaging Platform cluster.[28] The required parameters calculation results were collected and read out by amide (amide. exe 1.0.4) software, as an open-source medical imaging data examiner software.[29]

Results

The dose rate constant for the BEBIG HDR ^{192}Ir source (Ir2.A85-2 model) was determined to be 1.098 ± 0.003 cGy.h − 1.U − 1. Table 1 compares the calculated dose rate constant in this study with those obtained by Granero *et al*.[6] and Sadeghi *et al*.[8]

The obtained radial dose functions matched significantly the reference values. The mean relative difference was 0.45%, for the point 6 cm away from the source center, with the highest discrepancy of 1.4% [Table 2 and Figure 2].

The calculation of the anisotropy function was performed from 0.25 cm to 10 cm from the source center, spanning angles from 0° to 170° [Table 3 and Figure 3]. The comparison of the obtained results with the data from Granero *et al*.[6] showed fine agreement with an overall mean difference of 0.9%. The largest variation occurred at the angles equal or smaller than 20° and larger than 160°. However, the difference of over 8% was recorded at a radial distance of 2 cm and an angle of 20°.

Discussion

The calculation of BEBIG HDR ^{192}Ir brachytherapy source dosimetric data was conducted successfully with the GATE toolkit. The calculated dose rate constant for the BEBIG HDR ^{192}Ir source (Ir2.A85-2 model) in this study presented better than 1.35% agreement with the available references [Table 1].[6,8] The calculated dose rate constant (1.098 ± 0.003 cGy.h − 1.U − 1) using the GATE MC code is 1.0% different from the reference value (1.109 ± 0.011 cGy.h − 1.U − 1) due to using similar MC codes (GATE versus Geant4 MC). There is a larger difference of 1.35% in dose rate constant when a different MC code is used.[8] While similar cutoff energies for electrons and photons, photon yields, and energy spectra have been used for all studies, the causes of the slight difference with the reference could be due to simplifying of the source geometry and the use of different MC codes.

In contrast, studies on other brachytherapy sources using GATE-related MC codes reported relatively higher differences in acquiring dose rate constants. Guerrero *et al*.[5] found that

Table 1: The BEBIG ^{192}Ir dose rate constant calculated in this study and two other studies

MC code	Λ (cGyh⁻¹U⁻¹)	Relative differences with this study (%)
Geant4 (Granero *et al*.[6])	1.109±0.011	1.00
MCNP5 (Sadeghi *et al*.[8])	1.113±0.033	1.35
GATE (This study)	1.098±0.003	-

MC: Monte Carlo, Geant4: GEometry and tracking, MCNP5: MC N-particle, GATE: Geant4 application for emission tomography

Table 2: Comparison of radial dose function for BEBIG ^{192}Ir high dose rate source (Ir2.A85-2 model)

	gL (*r*)		
r (cm)	This study	Granero *et al*.[6]	Sadeghi *et al*.[8]
0.25	0.983	0.990	-
0.5	0.985	0.996	0.995
0.75	1.007	0.998	-
1.0	1.000	1.000	1.000
1.5	1.008	1.003	1.002
2.0	1.015	1.004	1.005
3.0	0.999	1.005	1.006
4.0	1.009	1.004	0.999
5.0	1.009	0.999	0.990
6.0	1.005	0.992	0.978
8.0	0.981	0.968	0.936
10.0	0.943	0.935	0.878

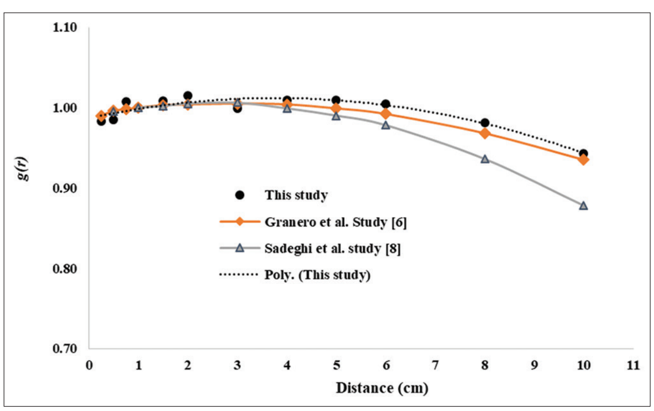

Figure 2: Graphical comparison of radial dose functions in this study with other studies

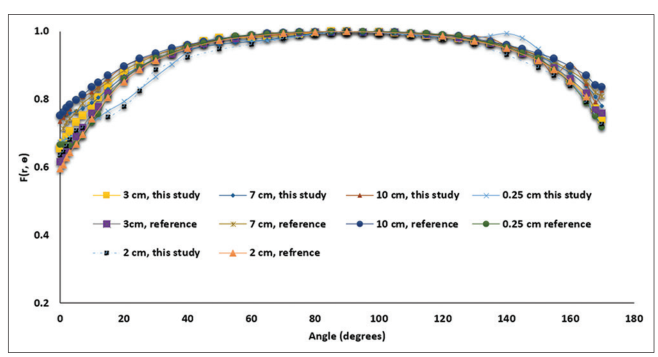

Figure 3: Graphical comparison of anisotropy functions in this study with a reference study for distances of 0.25, 2.0, 3.0, 7.0, and 10 cm

Table 3: Anisotropy functions for BEBIG ^{192}Ir high dose rate source (Ir2.A85-2 model) in this study

Θ (°)	*r* (cm)							
	0.25	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**7.00**	**10.00**
0	0.674	0.591	0.636	0.655	0.646	0.695	0.758	0.734
1	0.679	0.602	0.651	0.672	0.663	0.704	0.757	0.747
2	0.684	0.612	0.663	0.689	0.679	0.713	0.758	0.759
3	0.690	0.623	0.681	0.707	0.694	0.722	0.759	0.771
5	0.701	0.655	0.709	0.733	0.732	0.739	0.765	0.801
7	0.713	0.666	0.716	0.751	0.740	0.755	0.773	0.807
10	0.732	0.694	0.742	0.781	0.760	0.779	0.790	0.821
12	0.746	0.719	0.744	0.805	0.784	0.792	0.805	0.836
15	0.766	0.720	0.748	0.839	0.823	0.813	0.830	0.861
20	0.793	0.756	0.778	0.879	0.855	0.865	0.868	0.897
25	0.830	0.857	0.824	0.900	0.888	0.889	0.896	0.917
30	0.867	0.880	0.887	0.916	0.915	0.905	0.917	0.931
35	0.903	0.894	0.890	0.936	0.934	0.921	0.933	0.945
40	0.940	0.905	0.893	0.956	0.950	0.936	0.945	0.959
45	0.969	0.914	0.904	0.972	0.963	0.949	0.956	0.970
50	0.981	0.923	0.948	0.980	0.974	0.961	0.963	0.977
55	0.976	0.931	0.951	0.982	0.982	0.973	0.967	0.982
60	0.972	0.939	0.963	0.983	0.988	0.982	0.970	0.985
65	0.974	0.950	0.970	0.985	0.991	0.987	0.976	0.988
70	0.979	0.963	0.978	0.989	0.994	0.991	0.982	0.992
75	0.986	0.977	0.986	0.993	0.997	0.994	0.988	0.995
80	0.993	0.989	0.993	0.997	0.998	0.997	0.994	0.998
85	0.998	0.998	0.998	1.000	1.000	0.999	0.998	1.000
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
95	0.999	0.999	0.999	1.000	0.999	0.999	0.999	1.000
100	0.997	0.993	0.997	0.999	0.997	0.997	0.998	0.999
105	0.994	0.985	0.993	0.996	0.993	0.995	0.995	0.998
110	0.990	0.973	0.989	0.993	0.989	0.991	0.992	0.996
115	0.987	0.960	0.983	0.988	0.984	0.987	0.989	0.994
120	0.984	0.946	0.976	0.984	0.979	0.983	0.984	0.991
125	0.981	0.932	0.969	0.978	0.974	0.978	0.980	0.988
130	0.981	0.918	0.961	0.973	0.969	0.974	0.975	0.985
135	0.988	0.901	0.949	0.965	0.965	0.969	0.968	0.980
140	0.994	0.882	0.931	0.953	0.958	0.962	0.959	0.959
145	0.981	0.863	0.914	0.938	0.945	0.949	0.946	0.944
150	0.948	0.844	0.894	0.917	0.924	0.928	0.928	0.926
155	0.902	0.822	0.871	0.890	0.895	0.901	0.905	0.873
160	0.853	0.795	0.840	0.858	0.861	0.870	0.878	0.905
165	0.799	0.762	0.792	0.813	0.817	0.834	0.840	0.846
168	0.754	0.733	0.754	0.774	0.779	0.804	0.808	0.792
170	0.716	0.707	0.727	0.741	0.747	0.778	0.781	0.826

the GEANT4 MC code underestimated the dose rate about 10% near the BEBIG ^{60}Co source compared to PENELOPE code. Chatzipapas *et al*.[30,31] explored the dosimetric data of two HDR ^{192}Ir brachytherapy sources using GATE simulation code and reported a discrepancy of as large as 6% in dose rate constant compared with the theoretical method. Thiam *et al.*[32] investigation using GATE/GEANT4 code for validation of ^{125}I source (model 6711) resulted in a 2.6% difference in dose rate constant from the TG-43 consensus data on this source model. Similarly, Fardi and Taherparver[33] reported a 5.5% difference between their calculated dose rate constant and the reference for the IrSeed-125 (the new design of iodine-125 source, which is known as IrSeed-125, and is produced in Nuclear Science and Technology Research Institute of Atomic Energy Organization of Iran for the use in interstitial brachytherapy applications)[34] by GATE MC code. Joya *et al*.[21] recently validated the BEBIG HDR ^{60}Co brachytherapy source using the GATE MC code and reported a 2.01% difference in the dose rate constant value compared to the consensus data on this source. Overall, a good result for calculating the dose rate constant was achieved in this study.

The radial dose function, $g_L(r)$ considers the dose reduction as a result of photon attenuation and scattering from water in the transverse plane. As shown in Table 2 and Figure 2, the radial dose function was calculated from 0.25 cm to 10 cm from the source center in this study. There is an excellent agreement between the radial dose function values in this study and the corresponding consensus data.[6] The results showed the trend of radial dose fall for the BEBIG HDR ^{192}Ir source (Ir2.A85-2 model) experienced a slower fall-off up to 10 cm. A complex pattern of variations was observed up to the distance of 3 cm, while beyond that point, the GATE MC code slightly overestimated the radial dose functions compared with the reference data calculated by Granero *et al*.[6] Whereas obtained data by Sadeghi *et al*.[8] using MCNP code well matched with the reference data[6] at close distances, but the underestimation started at radial distance of about 3 cm and the difference reached 6% at 10 cm from the source center. The excellent agreement of radial dose function in this study with reference[6] indicates that using the GATE MC code, the ^{192}Ir source geometry can be appropriately simulated, and its radial dose function can be calculated accurately. In contrast, other studies using the GATE MC code reported higher discrepancies. The maximum relative differences of as higher as 15% and 5% for radial dose functions were reported by Thiam *et al.*[32] and Fardi and Taherparver,[33] respectively, for various sources.

The anisotropy function, $F(r, \theta)$, calculates the anisotropic distribution of dose around the source, including absorption and scattering by water. Anisotropy is equal to 1.0 in the central transverse plane, but at points, out of this plane, its values decrease with (i) increasing the radial distance, (ii) when the angle approaches 0° or 180°, (iii) with increasing the capsule thickness, and (iv) with photon energy reduction.[4,35] The obtained anisotropy function values for the BEBIG HDR ^{192}Ir source (Ir2.A85-2 model) for different points showed good agreements with the reference data,[6] [Table 3 and Figure 3]. The anisotropy function shows the variation of dose in different angles on the longitudinal plane which is normalized to the dose at 90° in that radial distance from the source center. The maximum observed discrepancy of 8% at the radial distance of 2 cm and angle of 20° in this study is comparable with the maximum relative difference of 7% reported by Sadeghi *et al*.[8] For an ideal point or spherical source, the anisotropy function values should be 1.0 at all distances at all angles. However, the anisotropy function value for a cylindrical source is <1.0 for the angles close to the 0° and 180° and approaches to 1.0 as the angles get closer to the 90°. Different factors such as the capsule oblique radiation filtration are the cause of the lower absorbed dose at points close to the source's longitudinal axis.[36] Selvam and Bhola,[37] in a study, reported that the cause of, respectively, 9% and 14% overestimation in radial dose function and anisotropy function for HDR BEBIG ^{60}Co brachytherapy source was the simulation of 5 mm cable instead of 1 mm stainless steel cable. Similarly, according to Guerrero *et al*.,[5] geometry simplification can cause differences of up to 0.7% and 2% in radial dose function and anisotropy function. Based on the studies, dose scoring volumes effects,[32] variation in materials density, the application of different physics lists and different cross-sections, energy cut-off for electrons and photons, and different MC codes are the potential causes of discrepancies in dosimetric parameters calculation for brachytherapy sources.[5,8,36,37]

Overall, the results of this study showed an excellent agreement with the reference data provided by Granero *et al*.[6] and with the result of the other study by Sadeghi *et al*.[8] on the validation of HDR BEBIG ^{192}Ir brachytherapy source. Therefore, it can be concluded that the GATE MC code is a reliable platform for the simulation and validation of brachytherapy sources along with the other MC codes.

Conclusion

The calculation of BEBIG HDR ^{192}Ir brachytherapy source dosimetric data was conducted successfully using the GATE toolkit. Excellent agreement was obtained in the dose rate constant, the radial dose function, and the anisotropy functions compared to the consensus data and the published references on this source by Granero *et al*.[6] and Sadeghi *et al*.,[8] respectively. The results of this study confirmed that the GATE MC code can be a useful toolkit for the application in brachytherapy and can be used for brachytherapy simulation-based studies and the verification of brachytherapy treatment planning systems.

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Conflicts of interest

There are no conflicts of interest.

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