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Dosimetric characterization of flexisource HDR ^{192}Ir brachytherapy source using GATE/GEANT4 Monte Carlo code

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ABSTRACT

Aim: The aim of this study is to validate the dosimetric parameters of High Dose Rate ^{192}Ir Flexi-source (mHDR v1 model) using GATE (version 9.1) Geant4-based Monte Carlo code, which is widely used in clinical applications for brachytherapy. This validation serves as a preliminary step toward investigating the issues related to tissue heterogeneities in brachytherapy dosimetry.

Methods: In this study, the geometry of the ^{192}Ir Flexi-source mHDR-v1 was simulated within a water sphere using GATE Monte Carlo code. The dosimetric parameters, including air kerma strength Sk, dose rate constant λ, radial dose function g(r), and anisotropy function F (r, θ), were computed in accordance with the TG- 43U1 and ESTRO guidelines, and the results were compared with available literature and clinical data for validation.

Results: The dose rate constant obtained was 1.078 cGy h^{-1} U^{-1} ± 0.012 cGy h^{-1} U^{-1}, showing a relative difference of 2.79% compared to the reference value. The radial dose function, starting from 0.25 cm to 15 cm, showed excellent agreement with a maximum of 3.43% at 15 cm. For the anisotropy function F (r, θ), the agreements were within 4.45% for 5<θ<175, and within 13.29% for all θ values.

Conclusion: Results from this study demonstrate that the validation of the Flexi-source HDR ^{192}Ir source is achievable using the GATE based Monte Carlo simulation. Consequently, the GATE code can be employed to explore challenges associated with tissue heterogeneities in brachytherapy dosimetry for ^{192}Ir Flexi-source.

Keywords: brachytherapy, HDR, GATE, flexisource, ^{192}Ir, TG-43U1.

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INTRODUCTION

Brachytherapy High dose rate is a widely used and accepted treatment modality for several types of cancer. In practice, the planning system software calculates the dose distribution based on the American Association of Medical Physicist's Task Group No. 43. The clinical use of such a technique requires the accurate determination of all relevant dosimetric data, which is essentially required by the software [1]. Despite its efficiency, this formalism has some limitations [2]. If we were made entirely of water, TG-43U1 would be perfectly accurate. This is not the case in clinical routine because the human body is composed of biological tissues of different densities (heterogeneity of the medium).

The Monte Carlo method is a statistical sampling technique that has been successfully applied over the years to a wide range of scientific problems, notably in physics to simulate the interaction of radiation with matter [3]. The primary benefit of using Monte Carlo (MC) simulations instead of experimental measurements lies in MC's ability to acquire dose data even in situations where experimental measurements would be very difficult. The use of these methods in radiotherapy dosimetry has grown almost exponentially over the last few decades. Since the 1990s, MC simulations have played an important role in the characterisation of brachytherapy equipment. They are used to calculate dosimetry parameters such as air kerma strength, dose rate constant, radial dose and anisotropy functions. but whose applications can also be extended to dosimetric calculations in external beam radiotherapy, brachytherapy modelling, radiography and other fields [4, 5]. The use of Monte Carlo simulation codes can take into account all factors that may lead to inaccuracies in the estimation of absorbed dose to organs during brachytherapy treatment, and help to understand and optimise clinical protocols. Several studies have initiated the dosimetric characterization of the ^{192}Ir Flexisource using various Monte Carlo simulation codes, such as GEANT4, EGS, and MCNPX [5, 6].

In this study, we validate the dosimetric parameters of the FlexiSource ^{192}Ir using the GATE Geant4-based Monte Carlo code according to the recommendations of the American Association of Physicist in Medicine (AAPM) and the European Society for Radiotherapy and Oncology (ESTRO) [7, 8]. The results were compared with reference data. Our research is part of the study of the impact of tissue heterogeneities on dose distribution in brachytherapy and is an important step towards this goal.

The primary benefit of using Monte Carlo (MC) simulations instead of experimental measurements lies in MC's ability to acquire dose data even in situations where experimental measurements would be exceedingly challenging.

MATERIAL AND METHOD

TG-43 dosimetry formalism for brachytherapy

2D Dose-rate formalism:

The aim of the TG-43U1 dosimetry Protocol is to define a formalism expressed as a mathematical equation, allowing the calculation of dose distributions and dose rates around radioactive sources used in clinical routine. The calculation of the dose around an encapsulated brachytherapy source adopted by the AAPM is as follows:

$$D(r,\vartheta) = S_k \Lambda \frac{G_l(r,\vartheta)}{G_l(r,\vartheta_0)} gLF(r,\vartheta) \quad (1)$$

- r: the radial distance from the center of the source
- ϑ: the polar angle
- Sk: the air Kerma strength in a unit of U, 1 U=1 μ Gy cm^2 h−1
- Λ: the dose rate constant in water, expressed in cGy. h−1.U −1
- GL(r, ϑ): is the Geometry function

The Air-kerma strength:

The air Kerma Strength (S_K) is quantified as the rate of air kerma, , in a vacuum at a given distance (d) on the transverse plane of the source. The resulting value is multiplied by d and expressed in $cGycm^{-1}h^{-1}$ units. This quantity is measured in a vacuum at a distance of 1 m from the center of the radioactive source. The index δ designates an energy cutoff to exclude the low energy contaminating photons that would increase the air kerma rate without contributing significantly to the tissue dose.

$$S_k = K\ddot{y}\delta.d^2 \quad (2)$$

To perform the calculations, a water sphere phantom with a radius of 20 cm is simulated in a rectangular vacuum with dimensions of 4 m^3 × 4 m^3 × 4 m^3 .In this study, the Gate v9.1 software is utilized to obtain results in MeV. Subsequently, a conversion is performed to calculate the air kerma in Gray (Gy) units. Figure 1 illustrates the output dose distribution for Air-kerma strength calculation.

Fig. 1. Dose Distribution from simulation output generated by GATE: calculating Sk by placing a ring (dose actors) at 1 m from the source

The dose rate constant:

The dose rate constant is defined as the dose rate in water at the reference point (r_0=1 cm) on and along the transverse axis (ϑ_0 = 90), divided by the unit power of kerma: This study aims to determine the dose rate constant according to TG43-U1 guidelines. The constant is obtained by dividing the dose rate at the reference point D(ϑ_0, r0) in the transverse plane of the source by the air Kerma Strength (S_K).

$$\Lambda = \frac{D(r_0, \theta_0)}{S_k} \quad (3)$$

The dose at a given reference point within a 3 m^3 rectangular volume is calculated using a water filled spherical object reduced to a size of 40 cm within the rectangular volume. This calculation uses a dose actor with a resolution of 1 mm^3, facilitated by the use of Gate software.

The radial dose function:

The radial dose function, gL(r), takes into account the variation of the dose on the transverse axis due to the scattering and attenuation of photons by the medium (water) as well as the self absorption of the beam by the encapsulation and by the radioactive source itself. The radial dose function gL(r) is defined by:

$$gL(r) = \frac{D\ (r,\ \theta_0}{D\ (r_0,\ \theta_0} \frac{GL\ (r_0,\ \theta_0)}{GL\ (r,\ \theta_0)} \quad (4)$$

The radial function values were determined by analyzing the 3D MHD type image obtained from the simulation. GNU Octave (7.1.0) was employed to position rings with different thicknesses (0.25 mm-0.5 mm and 1 mm) at radial distances between 0.25 cm and 15 cm in order to optimize the impact of voxel size on the absorbed dose quantity, according to the recommendations outlined in the investigation conducted [9-14].

The anisotropy function:

The anisotropy function is given by the following formula:

$$F(r,\ \theta) = \frac{D\ (r,\ \theta_0}{D\ (r,\ \theta_0)} \frac{GL\ (r,\ \theta_0)}{GL(r,\ \theta)} \quad (5)$$

It describes the variation of the dose rate as a function of the polar angle on the transverse axis. Thus, it represents the influence of the encapsulation and the attenuating medium (water) at a distance r when moving from the transverse axis ($\vartheta_0 = 90°$) to an angle ϑ.

$$r_y = L.sin(\phi),\ r_x = L.cos(\phi) \quad (6)$$

With: $L = \sqrt{r^2 - z^2}$

The anisotropic function was calculated using the Gate Monte Carlo code by calculating the dose at different distances from the source, considering angles from 0° to 180°. To improve the accuracy of the results, three different dose actor sizes (1 mm^3, 0.5 mm^3 and 0.25 mm^3) were used. The 3D data generated were then analysed using Gnu Octave version 7.1.0 To calculate the anisotropy function, the rings were used with a different size for each angle to avoid statistical fluctuations. To achieve this, the plan (y, x) is adjusted according to the following equation, as shown in figure 2:

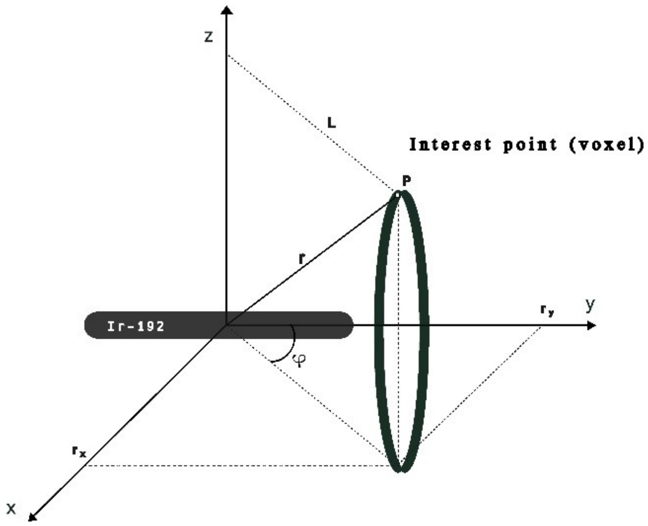

Fig. 2. Geometric system used to calculate the absorbed dose (within a ring) and determine g(r) and F(r, θ)

Flexisource HDR ^{192}Ir source

The brachytherapy source used in this study is a FlexiSource (Nucletron B.V. Veenendaal, The Netherlands), it's made of a 3.50 mm long, 0.60 mm diameter ^{192}Ir radioactive core enclosed in a 0.85 mm diameter AISI-304 stainless steel capsule (density 7.8 g/cm^3). The end of the encapsulation has a conical section of 0.108 mm thickness with a half angle of 23.6 and a radius of 0.17 mm. full geometry of the source is presented in figure 3. ^{192}Ir is a radioactive isotope of iridium, with a half life of 73.827 days. It decays by emitting beta (β) particles and gamma (γ) radiation. About 96% of ^{192}Ir decays occur via emission of β and γ radiation, leading to ^{192}Pt.

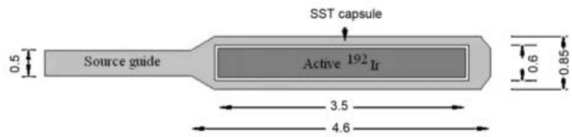

Fig. 3. Geometry of Flexisource ^{192}Ir brachytherapy source (mHDR v1 model)

Monte carlo code and the simulation configuration

GATE version 9.1, an advanced and user friendly extension of the Geant4 toolkit, has been used to simulate the brachytherapy Flexisource ^{192}Ir. This simulation follows the AAPM TG-43U1 recommendations [2], with the source geometry as previously mentioned attached to a 5 mm cable (Figure 4). The simulation involved the source positioning at the center of a 20 cm radius water sphere.

The physics modules used in this work were emstandard optphysics which contains a combination of models for each electro magnetic physics process deemed to offer the best performance in term of precision at the cost of CPU efficiency [8].

The number of photons generated was 2×10^9, which reduces the statistical uncertainty with a voxel size of 1 mm. The cuts were 1 keV for the photon energies and 1 mm for the electron paths. The energy spectrum of Ir-192 used is obtained from the NIST Database [9], with gamma emissions ranging from 61.49 keV to 1378.20 keV. The β spectrum was not considered, as its contribution to the dose rate at distances greater than 1 mm from the source is negligible due to attenuation by the encapsulation.

Dose calculations employed three actors representing different sizes (small, medium, and large) at varying distances from the source for enhanced accuracy. The result of the simulation was a Dose Map, providing an image representation of the spatial distribution of the dose distrubition in 3D. The value of each voxel in the image corresponds to the dose at the point of interest.

RESULTS

Dose rate constant

The simulation of dose rate constant give's maximum deviation of 2.79% compared to Granero et al data [11]. This demonstrates a notable alignment with established litterature. The corresponding findings are detailed in table 1.

Tab. 1. Dose rate constant comparison with other published data

Author	Method	λ(cGyh⁻¹U⁻¹)
Safigholi et al [13]	10 cm^3 x 10 cm^3 x 0.05 cm^3 voxel at 100 cm	1.1101
Taylor, Rogers [14]	10 cm^3 x 10 cm^3 x 0.05 cm^3 voxel at 100 cm	1.116
Granero et al [11]	extrap	1.109
Perez-Calatayud et al [12]	Consensus Value	1.113
This study	10 cm^3 x 10 cm^3 x 0.05 cm^3 voxel at 100 cm	1.078

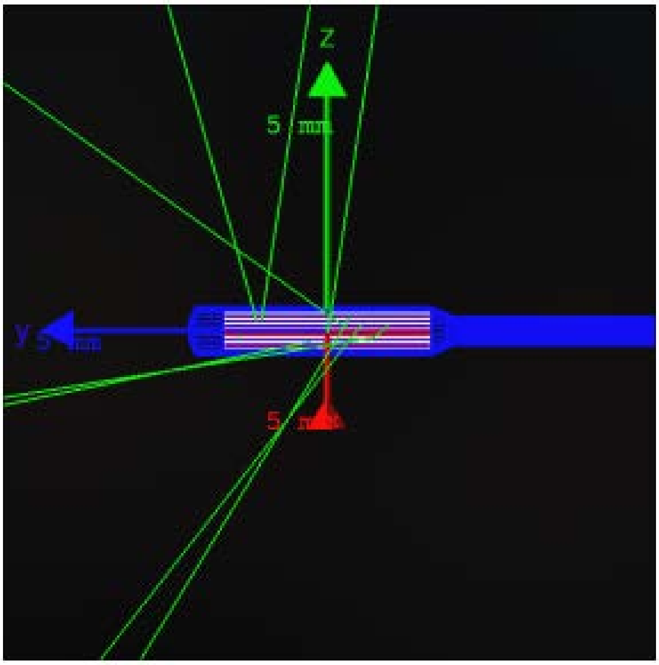

Fig. 4. Geometry used to simulate the ^{192}Ir Flexisource with GATE v9.1

Radial dose function

In our investigation, the results of radial dose function indicated a good agrement with established data, with a maximum relative difference of 3.43% at 15 cm from the radiation source. Table 2 and figure 5 present the radial dose function values derived from our study and comparison with the reference data.

Tab. 2. Radial dose function results with granero's study as a reference

R(cm)	This study	Granero et al [11]	Relative Difference %
0.25	1.01	0.99	2.38
0.5	1.01	1	1.36
0.75	1.01	1	0.99
1	1	1	0
1.5	1.02	1	1.97
2	1.02	1	1.55
3	1.02	1.01	1.55
4	1	1	0.12
5	1	1	0.48
6	1.02	0.99	2.83
7	1	0.98	1.54
8	0.98	0.97	1.39
10	0.96	0.93	2.38
12	0.9	0.89	1.12
15	0.85	0.82	3.43

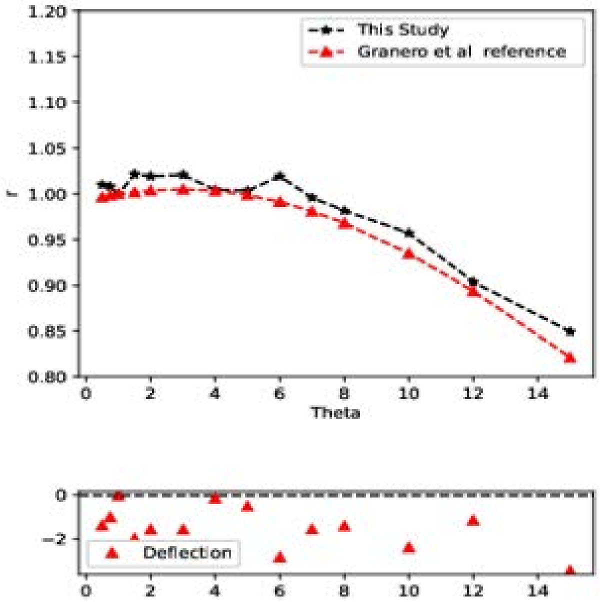

Fig. 5. The radial dose function, gL(r) for HDR ^{192}Ir Flexisource calculated by GATE, Data from granero et al are also included, Relative difference(%) to the reference is indicated [11]

Anisotropy function

The anisotropy function was simulated for angles ranging from 0° to 180° at distances from 0.25 cm to 15 cm. Table 3 and figures 6-9 shows the results of the anisotropy function. For angles θ<15° and θ>175°, the maximum relative difference was found up to 13.29% at r=3 cm for θ=0°. For angles in the range 15°<θ<175°, the maximum difference observed was 3%. This shows good agreement with the reference data.

Tab. 3. Anisotropy Function Values Ranging from 0.25 cm to 15 cm for ^{192}Ir HDR Flexisource

	Distace (cm)															
Θ deg	0.25	0.5	0.75	1	1.5	2	3	4	5	6	7	8	9	10	12	15
0		0.681	0.622	0.637	0.579	0.663	0.55	0.591	0.614	0.698	0.779	0.77	0.664	0.815	0.742	0.733
2		0.677	0.628	0.645	0.625	0.667	0.641	0.683	0.742	0.75	0.717	0.775	0.759	0.801	0.826	0.833
4		0.661	0.647	0.641	0.653	0.667	0.682	0.725	0.714	0.745	0.756	0.766	0.779	0.801	0.842	0.808
6		0.685	0.676	0.682	0.684	0.7	0.693	0.721	0.783	0.76	0.772	0.79	0.802	0.812	0.843	0.847
8		0.713	0.695	0.701	0.703	0.721	0.734	0.764	0.756	0.812	0.827	0.81	0.808	0.832	0.852	0.859
10		0.728	0.712	0.716	0.709	0.78	0.779	0.793	0.808	0.802	0.833	0.817	0.831	0.855	0.864	0.855
15		0.816	0.811	0.831	0.801	0.787	0.821	0.85	0.842	0.861	0.857	0.858	0.866	0.864	0.897	0.898
20		0.835	0.868	0.827	0.854	0.837	0.868	0.88	0.893	0.9	0.891	0.899	0.883	0.908	0.912	0.916

25		0.913	0.908	0.907	0.892	0.898	0.9	0.881	0.882	0.929	0.923	0.894	0.911	0.924	0.922	0.932
30		0.936	0.917	0.938	0.909	0.908	0.92	0.929	0.932	0.923	0.916	0.937	0.93	0.942	0.956	0.921
40		0.978	0.958	0.972	0.944	0.928	0.952	0.962	0.965	0.96	0.957	0.957	0.957	0.958	0.947	0.946
50		0.975	0.988	0.963	0.981	0.957	0.951	0.992	0.989	0.97	0.969	0.983	0.952	0.992	0.982	0.971
60	0.988	0.991	0.983	0.982	0.979	0.992	0.983	1.001	1.005	0.981	0.991	0.995	0.991	0.989	1.01	0.978
70	1.033	0.991	1.003	0.988	1	0.987	0.983	1.014	0.97	1.001	0.994	1	1.002	0.992	1.008	0.992
80	0.982	1.005	1.013	0.996	0.999	1.001	0.994	1.006	0.988	1.005	1	0.999	0.993	1.011	1.014	0.995
90	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
100	0.98	0.998	1.014	0.999	0.992	1.002	0.99	1.007	0.985	1	1.002	0.994	0.991	1.008	0.999	0.986
110	1.038	0.993	1.016	0.986	0.992	0.99	0.984	1.002	1.003	0.983	1.005	0.993	1.009	1.01	1.018	0.982
120	0.984	0.984	0.992	0.994	0.975	0.985	0.975	0.99	0.999	0.99	0.997	0.975	0.999	0.991	0.996	0.977
130		0.974	0.993	0.969	0.983	0.962	0.952	0.994	0.966	0.958	0.982	0.98	0.977	0.991	0.993	0.978
140		0.986	0.958	0.974	0.945	0.931	0.953	0.95	0.966	0.962	0.959	0.962	0.963	0.962	0.956	0.949
150			0.919	0.94	0.905	0.898	0.93	0.948	0.929	0.926	0.924	0.924	0.935	0.927	0.95	0.946
155			0.877	0.899	0.894	0.899	0.904	0.89	0.904	0.932	0.937	0.898	0.902	0.925	0.93	0.906
160				0.839	0.855	0.842	0.868	0.875	0.859	0.902	0.895	0.903	0.889	0.91	0.913	0.902
165				0.831	0.801	0.799	0.824	0.847	0.84	0.854	0.854	0.874	0.875	0.864	0.891	0.869
170				0.704	0.716	0.776	0.759	1.7366	0.818	0.815	0.819	0.818	0.825	0.859	0.851	0.884
172				0.688	0.697	0.7	0.755	0.767	0.774	0.812	0.792	0.815	0.822	0.83	0.856	0.844
174				0.679	0.68	0.671	0.698	0.743	0.758	0.768	0.776	0.777	0.801	0.811	0.84	0.851
176				0.651	0.676	0.652	0.678	0.714	0.743	0.747	0.768	0.785	0.768	0.793	0.795	0.834
178					0.628	0.603	0.667	0.687	0.704	0.735	0.748	0.749	0.781	0.791	0.806	0.811
180					0.64	0.566	0.597	0.556	0.685	0.697	0.694	0.668	0.704	0.684	0.763	0.739

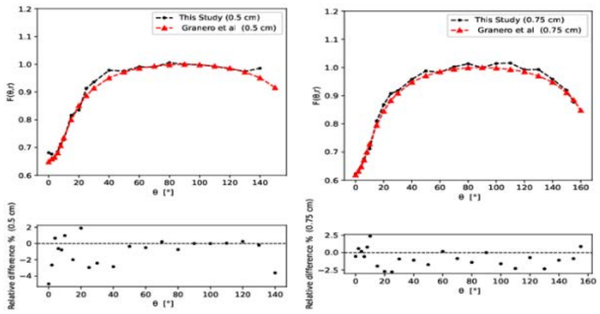

Fig. 6. 2D Anisotropy Function F (r, θ) for HDR ^{192}Ir Flexisource for Distances of 0.5 cm and 0.75 cm at Angles 0−180◦. Relative difference are also indicated for comparaison

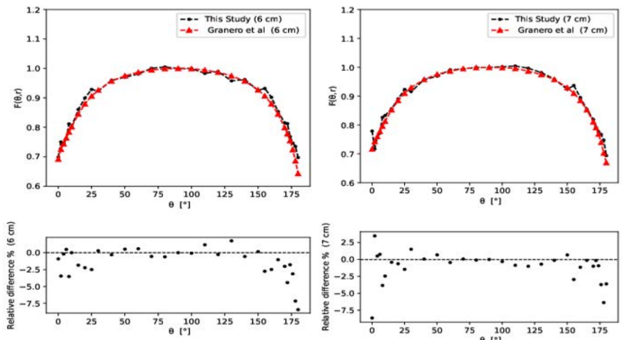

Fig. 7. 2D Anisotropy Function F (r, θ) for HDR ^{192}Ir Flexisource for Distances of 6 cm and 7 cm at Angles 0˚−180˚. Relative difference are also indicated for comparaison

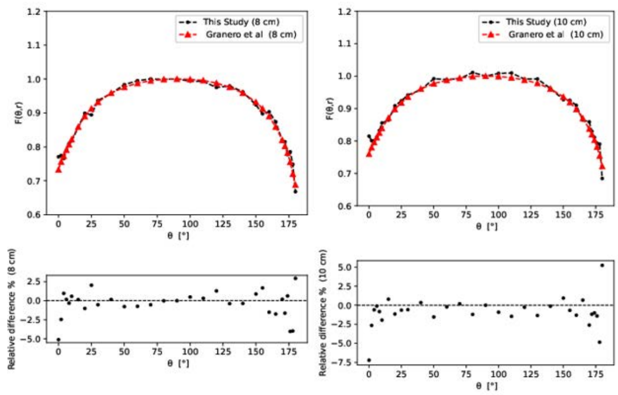

Fig. 8. 2D Anisotropy Function F (r, θ) for HDR ^{192}Ir Flexisource for Distances of 8 cm and 10 cm at Angles 0˚−180˚. Relative difference are also indicated for comparaison

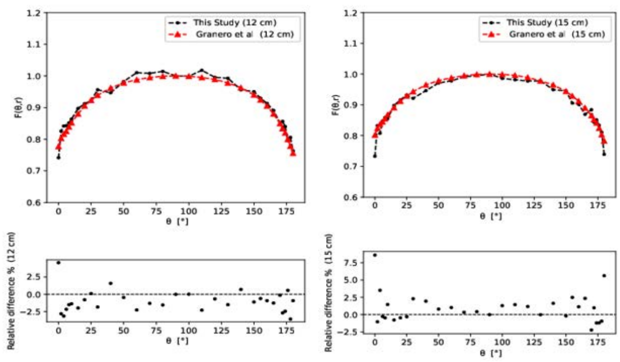

Fig. 9. 2D Anisotropy Function F (r, θ) for c Flexisource for Distances of 12 cm and 15 cm at Angles 0˚−180◦. Relative difference are also indicated for comparaison

DISCUSSION

In the present study, we employed the advanced Gate Monte Carlo (MC) code to simulate the TG-43U1 dosimetry parameters for the Flexisource HDR ^{192}Ir brachytherapy source. This was based on ^{192}Ir photon spectra from the National Nuclear Data Center (NNDC) [10]. A comparative analysis with existing literature indicates a good agreement, affirming the accuracy and reliability of our simulation.

According to TG-43U1 guidelines, a combination of Monte Carlo simulations and practical experiments is recommended for establishing TG-43U1 dosimetry parameters in brachytherapy sources [1]. This work aligns with this, adding to the consensus derived from studies by Granero et al. [11, 13, 14].

This research introduces a new feature by simulating TG-43U1 dosimetry parameters with new setups, enriching existing datasets. Our model's accuracy, bench marked against prior data, demonstrates its validity and can help medical physicists in their later Monte Carlo works. Employing GATE, a simplified version of the Geant 4 MC code, we provide a more accessible approach for subsequent Monte Carlo studies [15].

Variations in dosimetry calculations may originate from differences in source spectra and cross sections. A prior study highlighted up to 3.1% differences in Dose rate constant Λ values due to variations in ^{192}Ir spectra [16]. Also, the attenuation coefficient for Compton scattering in water shows differences when using the Geant4 "g4em-standard opt4" physics model, as in our study, compared to the XCOM photon cross sections used by Taylor and Rogers [14].

The accuracy of gL(r) and F (r, θ) functions in proximity to the source (where r is less than or equal to 2 mm) is not precise and therefore not presented. This is due to the potential absence of electronic equilibrium and the neglect of dose contribution from the beta spectrum of ^{192}Ir.

In this investigation, we conducted a comparative analysis with the results presented by Granero et al. which indicates a maximum difference of 3.43 % in the values of gL(r), and this variation is attributed to the incorporation of new cross sections. In the process of calculating F (r, θ), we simulated fewer photons due to the extensive time requirements, leading to relatively high statistical uncertainties. The larger differences observed in F (r, θ) at θ angles near 0° and 180° can be attributed to the reduced voxel size close to the source's axis [14]. Future studies could potentially reduce these uncertainties by incorporating a greater number of simulation histories.

The Flexisource ^{192}Ir's cable, composed of stainless steel, also impacts the dose distribution around the source. It absorbs and scatters radiation, creating an inhomogeneous dose distribution, which is a critical consideration in practical applications.

CONCLUSION

This study validates the Flexisource HDR ^{192}Ir using GATE based Monte Carlo simulations. It reveals a good agreement with reference values in dose rate constant, radial dose function gL(r) and anisotropy function F (r, θ) simulations.

These findings affirm the effectiveness of GATE based Monte Carlo simulation in brachytherapy dosimetry for the ^{192}Ir Flexisource. They also demonstrate its potential for addressing challenges related to tissue heterogeneities in brachytherapy dosimetry.

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