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Effect of marker material on the dosimetric parameters of I-125 source (model 6711): Monte Carlo simulation

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HIGHLIGHTS

- Validation of the I-125 (model 6711) seed according to the TG-43U1 recommendation by GEANT4.
- Simulation of new seeds containing Ag+Al_2O_3 markers with different ratio of Ag and Al_2O_3.
- Similarity between calculated dosimetric parameters of the I-125 seed (6711) and the new sources.

ABSTRACT

Low energy I-125- seeds are considered as a common source in different brachytherapy techniques for treatment of different cancers. In this study, at first, we simulated and validated I-125 (model 6711) seed according to the TG-43U1 recommendation, by GEANT4 Monte Carlo toolkit. Moreover, we simulated new seeds containing cylindrical Ag+Al_2O_3 markers with different ratio of Ag and Al_2O_3 in the final composition of the marker and compared the radial dose functions and anisotropy functions of the sources. For validation and evaluation purposes, the radial dose function and anisotropy function were calculated at various distances from the center of the different simulated sources. The source validation results show that GEANT4 Monte Carlo toolkit produces accurate results for dosimetric parameters of the I-125 seed by choosing the appropriate physics list. On the other hand, results show a similarity between calculated dosimetric parameters of the I-125 seed (6711) and other sources, with a percentage difference of about 5%.

KEYWORDS
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GEANT4

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1 Introduction

Brachytherapy is a type of internal radiation therapy, in which an encapsulated radiation source is positioned within or close to a region inside the patient's body to maximize doses to cancer cells while minimizing damage to normal tissues (Russell and Blasko, 1993). Although in some cases beta emitters are used in this method (Rajabi and Taherparvar, 2019), the low-energy photon emitting radioisotopes such as I-125, Pd-103, and Cs-131 are widely used in brachytherapy for treatment of different cancer, such as prostate cancer, eye malignant tumors, cervix cancers, and malignant brain tumors (Rajabi and Taherparvar, 2019; Ghiassi-Nejad et al., 2001; Taherparvar and Fardi, 2022, 2021). I-125 is the most commonly used form of local treatment brachytherapy with a half-life of 59.431 days. It decays by electron capture to the excited state of Te-125 (Ghiassi-Nejad et al., 2001). According to the American Association of Physicists in Medicine (AAPM), determination of dosimetric parameters of brachytherapy sources is essential. These dosimetric parameters consist of dose rate constant (Λ), radial dose function ($g(r)$), anisotropy function ($F(r, \theta)$). Today, different Monte Carlo simulation codes, such as GEANT4, MCNP, GATE, FLUKA, etc., have been used for determination of dosimetric parameters of the brachytherapy sources. In this study, we simulated I-125 seed model 6711 by GEANT4 Monte Carlo toolkit. The sources have been validated by comparing our simulation results with with available data in the literatures, according to TG-43U1 protocol (Meigooni, 1995). In the I-125 seed models, the materials and geometry of the active core varies from company to company. Since Ag+Al_2O_3 rod is a good carrier for an Iodine radioisotope and the distribution of the

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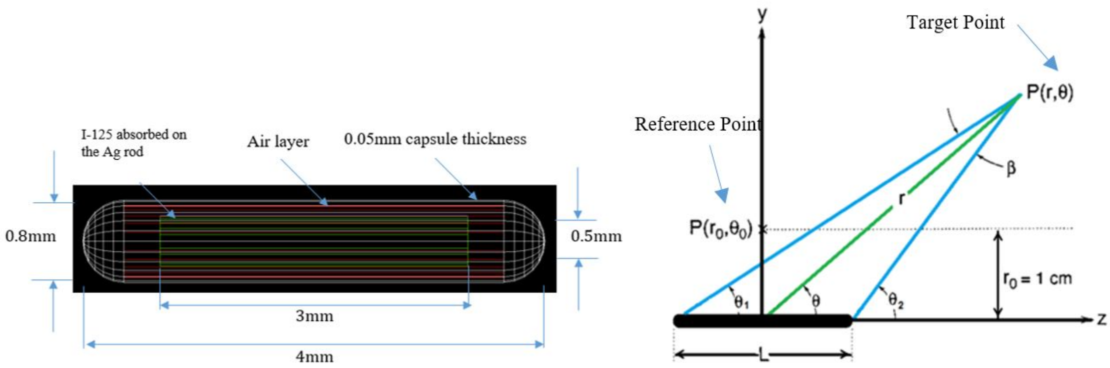


Figure 1: I-125 seed in GEANT4 (a), the geometry conventions for dose rate calculations (b), r: denotes the distance in centimeters from the center of the source, θ_1 (θ_2): denotes the polar angle between the point of interest and the beginning (end) of the source.

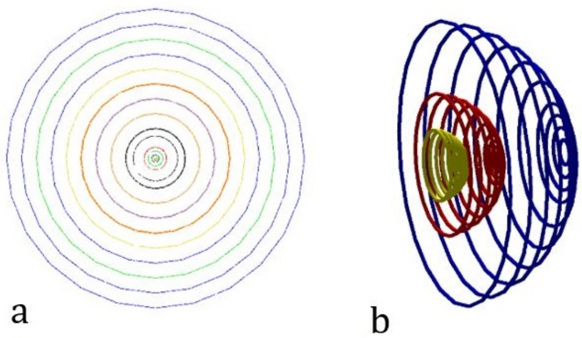


Figure 2: Geometric system used to calculate $g(r)$ (a) and $F(r,\theta)$ (b) in the GEANT4.

source on it is relatively uniform, the $Ag+Al_2O_3$ has been suggested as a good compound for seed marker (Babaheidari and Shamsaee, 2014). Hereby, in this study by validation of the I-125 (model 6711) seed according to the TG-43U1 recommendation by GEANT4 toolkit, we evaluate the effect of $Ag+Al_2O_3$ markers on the dosimetric parameters of the new source. Furthermore, effect of different ratio of Ag and Al_2O_3 in the composition of the marker material were evaluated by calculation of the radial dose functions and anisotropy functions of the sources.

2 Materials and Methods

2.1 Source characteristics

At first, we simulated I-125 (model 6711) seed (named Seed 1), as shown in Fig. 1. The seed consists of a silver cylindrical marker with 0.025 cm radius and 3.2 mm length. I-125 radioisotope is uniformly deposited on the silver marker with the 1 m thickness. The marker is encapsulated within a titanium tube of 0.47 cm in length, 0.08 cm diameter, 0.006 cm thickness on top and bottom, and 0.4 mm radius at both semispherical ends. The space between the titanium and marker was filled with air. In separate simulations, Ag was replaced with Ag+ Al_2O_3 markers with different percentages consist of: 15%Ag + 85% Al_2O_3 (Seed 2), 25%Ag + 75% Al_2O_3 (Seed 3), and 35%Ag + 65% Al_2O_3 (Seed 4). All simulations with theses seeds were repeated and results were compared. Simulations were performed by using GEANT4 Monte Carlo toolkit to determine the dosimetric parameters of the seeds in the center of a water phantom. The photon energy spectrum used in the simulations for all seeds are shown in Table 1 (according to TG-43U1 protocol). The radial dose functions and anisotropy functions were calculated by calculation of dose deposition in the specific scoring rings, according to the TG-43U1, as shown in Fig. 2 (Ghiassi-Nejad et al., 2001).

Table 1: Photon spectrum of I-125 (Taherparvar and Fardi, 2021).

Energy (keV)	Intensity
3.77000	0.150
27.2017	0.397
27.4723	0.741
31.0000	0.257
35.4919	0.067

2.2 Dosimetric parameters

According to the AAMP recommendations (Fardi and Taherparvar, 2019), the dose-rate at point (r,θ) (as can be seen in Fig. 1-b) could be acquired as follows:

$$\dot{D}(r,\theta) = S_k.\Lambda.\frac{G_1(r,\theta)}{G_1(r_0,\theta_0)}.G_1(r).F(r,\theta) \qquad (1)$$

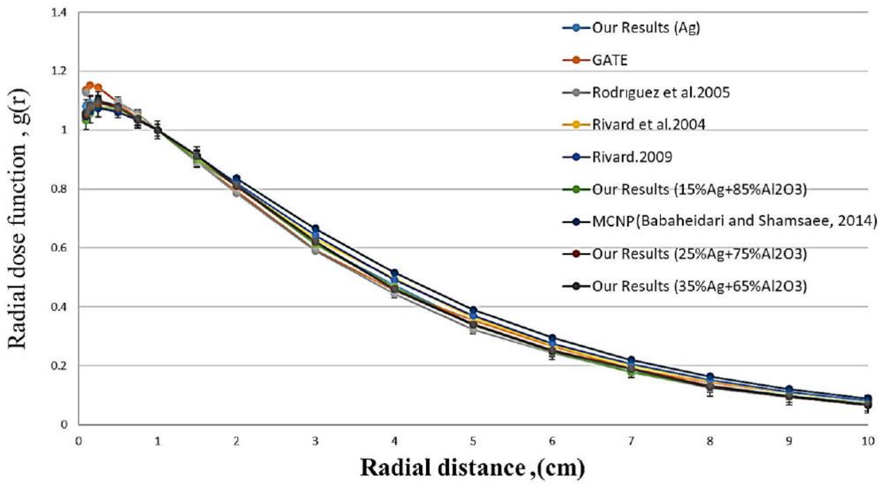


Figure 3: Comparison of the radial dose function obtained by GEANT4 simulation results for I-125 with Ag and different combinations of $Ag+Al_2O_3$ with different percentages markers and other experimental and theoretical results.

where $\dot{D}(r,\theta)$ is the dose rate at the distance r (cm) from the capsule center, θ is the polar angle defining the P point, S_k is the air-kerma strength, Λ is the dose rate constant, $G(r,\theta)$ and $G(r_0,\theta_0)$ are the geometry factors around the source and reference point, respectively. The dose rate constant (Λ) is equal to the dose rate at the reference point ($r_0 = 1$ cm, $\theta_0 = \frac{\pi}{2}$) divided by source air kerma strength.

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_k} \tag{2}$$

To calculate the radial dose function, $g(r)$, rings with 0.4 mm thicknesses were located at 0.1 to 10 cm distance from the source along its transverse axis. Then, $g(r)$ was calculated as follows:

$$g(r) = \frac{\dot{D}(r,\theta_0)\, G(r_0,\theta_0)}{\dot{D}(r_0,\theta_0)\, G(r,\theta_0)} \tag{3}$$

The geometric systems used to calculate $g(r)$ are shown in Fig. 2-a. The anisotropy function of I-125 source was calculated (according to Eq. (4)) at distances of 0.5 ,1 and 5 cm from the source center using rings with 0.4 mm thicknesses at different angles. The geometric systems used to calculate $F(r,\theta)$ are shown in Fig. 2-b.

$$F(r,\theta) = \frac{\dot{D}(r,\theta)\, G(r,\theta_0)}{\dot{D}(r,\theta_0)\, G(r,\theta)} \tag{4}$$

2.3 Monte Carlo simulation

Simulations were performed using GEANT4 version 10.5, Monte Carlo toolkit to determine the dosimetric parameters of seeds 1 to 4 in a 20 cm radius spherical water phantom according to the recommendation of the AAPM. GEANT4 (derived from Geometry and Tracking) is written in the C++ programming language with extensive libraries, which contain a differential cross-section of different particles in different areas in the energy range of several eV to PeV.

At first, I-125 (model 6711) seed (Seed 1) was located in the center of the phantom and radial dose function and 2D anisotropy function were calculated. According to TG-43 (U1) recommendations, reference dosimetry media was considered degassed water with a mass density of 0.998 g.cm^{-3}. On the other hand, since $Ag+Al_2O_3$ rod is a good carrier for an Iodine radioisotope and the distribution of the source on it is relatively uniform, the effects of the marker materials consist of different percentages different combinations of Ag and Al_2O_3 (with different ratio of Ag 15%, 25%, and 35%) on the radial dose function and 2D anisotropy function were investigated in this study.

We used G4PSEnergyDeposit and G4PSDoseDeposit classes, which are the standard classes in GEANT4 to llcluclac energy and dose deposition in the predefined rings. The G4EmStandardPhysics_option3 was used to simulate different physical processes such as elastic scattering, ionization, electronic excitation, and lna vibrational excitation for photons without using any reduction techniques. The number of primary particles included 5×10^8 and the mean statistical uncertainty for the dose calculations were about 2%.

3 Results and Discussion

3.1 Radial dose function

Values of the radial dose function for source in the water phantom for four simulated seeds, which were calculated for distances from 0.1 to 10 cm from the source center, are indicated in Fig. 3 and Table 2. These results. The comparison between the theoretical and experimental radial dose function show that the mean difference between Seed1 and those of Fardi et al. (Taherparvar and Fardi, 2021), Rodrguez (Rodríguez et al., 2005), Rivard et al. (Rivard et al., 2004), Rivard (Rivard, 2009), and Eslami et al. (by MCNP) (Babaheidari and Shamsaee, 2014) were about 4%, 3%, 4.6%, 5.8%, and 5%, respectively, which show a good agreement. On the other hand, the mean difference between Seed2, Seed3, and Seed4 results and

Table 2: Radial dose function of I-125 seed sources obtained from different study.

Radial distance (cm)	Our Results (Seed 1)	GATE (Ag)	(Rodríguez et al., 2005) (Ag)	(Rivard et al., 2004) (Ag)	(Rivard, 2009) (Ag)	Our Results (Seed2)	MCNP ($Ag+Al_2O_3$)	Our Results (Seed3)	Our Results (Seed4)
0.1	1.080	1.136	1.1278	1.055	1.036	1.033	1.046	1.054	1.061
0.15	1.092	1.152	-	1.078	1.057	1.055	1.065	1.078	1.085
0.25	1.095	1.145	-	1.082	1.074	1.076	1.075	1.092	1.1
0.5	1.073	1.092	1.096	1.071	1.066	1.073	1.061	1.076	1.081
0.75	1.036	1.041	1.0575	1.042	-	1.036	1.035	1.038	1.04
1	1	1	1	1	1	1	1	1	1
1.5	0.892	0.892	0.8923	0.908	0.913	0.90	-	0.91	0.912
2	0.813	0.794	0.7862	0.814	0.82	0.810	0.837	0.81	0.813
3	0.613	0.594	0.5899	0.632	0.643	0.614	0.666	0.622	0.623
4	0.473	0.456	0.4443	0.496	0.491	0.467	0.516	0.461	0.458
5	0.340	0.355	0.3224	0.364	0.37	0.337	0.39	0.341	0.338
6	0.250	0.267	0.2443	0.27	0.276	0.248	0.295	0.252	0.25
7	0.179	0.191	0.1792	0.199	0.205	0.178	0.22	0.189	0.19
8	0.134	0.143	0.1244	0.149	0.151	0.129	0.164	0.131	0.128
9	0.097	0.108	0.0937	0.109	0.111	0.097	0.121	0.095	0.097
10	0.071	0.079	0.0702	0.083	0.082	0.071	0.089	0.067	0.069

Table 3: Anisotropy function calculated for the I-125 seed for 0.5 cm, 1 cm, and 5 cm.

Angle (θ)	5	10	15	20	30	40	50	60	70	80
$F(0.5,\theta)$; GATE (Ag)	0.353	0.438	0.557	0.658	0.838	0.945	1.007	1.027	1.039	0.998
$F(0.5,\theta)$; GEANT (Seed1)	0.366	0.448	0.571	0.689	0.846	0.959	1.014	1.026	1.038	0.994
$F(0.5,\theta)$; GEANT (Seed2)	0.352	0.420	0.527	0.633	0.794	0.896	0.958	0.983	1.006	0.992
$F(0.5,\theta)$; GEANT (Seed3)	0.348	0.425	0.538	0.651	0.816	0.919	0.973	0.999	1.02	1.002
$F(0.5,\theta)$; GEANT (Seed4)	0.349	0.427	0.54	0.66	0.828	0.927	0.978	1.003	1.02	1.018
$F(1,\theta)$; GATE (Ag)	0.478	0.502	0.611	0.689	0.825	0.919	0.985	1.004	1.022	1.023
$F(1,\theta)$; GEANT (Seed1)	0.451	0.534	0.632	0.721	0.837	0.931	0.992	1.025	1.040	1.0251
$F(1,\theta)$; GEANT (Seed2)	0.425	0.495	0.582	0.657	0.786	0.885	0.945	0.985	1.012	1.011
$F(1,\theta)$; GEANT (Seed3)	0.449	0.501	0.594	0.679	0.802	0.895	0.957	0.99	1.019	1.035
$F(1,\theta)$; GEANT (Seed4)	0.453	0.501	0.605	0.634	0.814	0.904	0.967	0.997	1.018	1.033
$F(5,\theta)$; GATE (Ag)	0.684	0.720	0.756	0.823	0.841	0.905	0.962	0.948	0.998	0.952
$F(5,\theta)$; GEANT (Seed1)	0.593	0.664	0.761	0.821	0.870	0.953	1.022	1.002	1.027	0.979
$F(5,\theta)$; GEANT (Seed2)	0.535	0.643	0.712	0.760	0.837	0.914	0.981	1.004	1.033	0.986
$F(5,\theta)$; GEANT (Seed3)	0.620	0.626	0.703	0.789	0.827	0.928	0.948	1.014	1.020	0.973
$F(5,\theta)$; GEANT (Seed4)	0.63	0.646	0.706	0.797	0.842	0.934	0.957	1.008	1.005	0.986

I-125 seed (Seed1) were about 1.2%, 1.7%, and 4.9%, respectively.

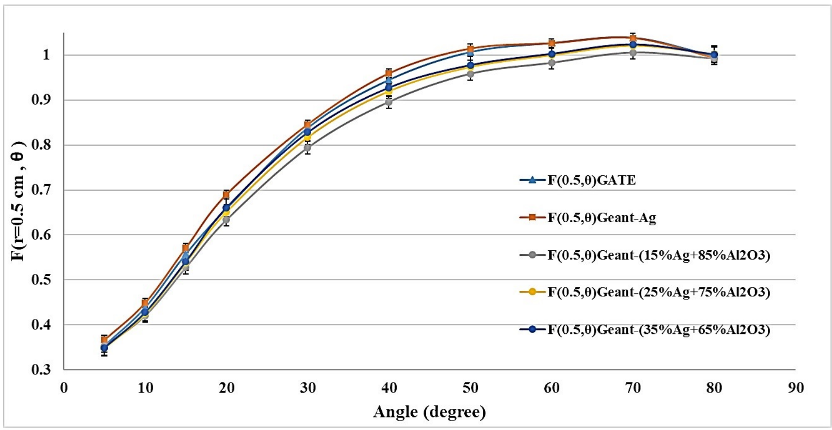
3.2 Anisotropy function

The anisotropy function of the seeds were calculated at distances of 0.5, 1, and 5 cm from the source center using rings with 0.4 mm thicknesses at different angles relative to the source axis (Fig. 2-b). Table 3 shows the calculated anisotropy function values at different radial distances for angles between 5° and 80°, respectively. Also, a comparison of the anisotropy function of the four simulated sources and Fardi et al. (Taherparvar and Fardi, 2021) results are shown in Fig. 4, at radial distances of 0.5 cm (Fig. 4-a), 1 cm (Fig. 4-b), and 5 cm (Fig. 4-c). The mean difference between GEANT4 results and those of GATE for I-125 seed (6711) is about 1.7%, 2.7%, and 4.8% at radial distances of 0.5 cm, 1 cm, and 5 cm distance, respectively. A comparison of the calculation with the obtained results shows a good agreement between our simulation results and other report.

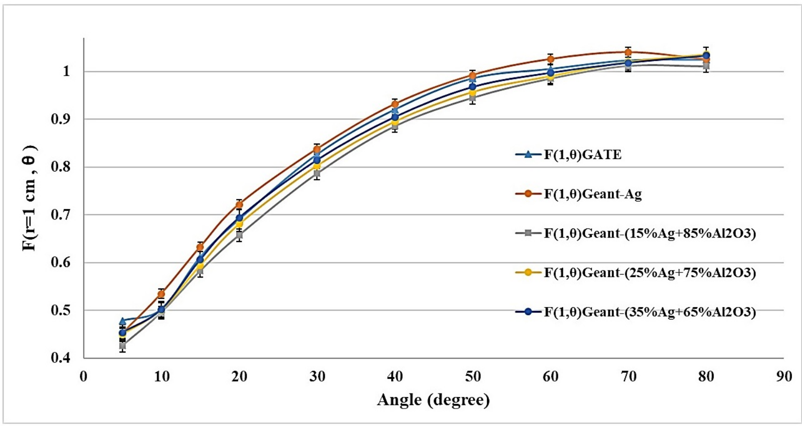
Furthermore, the average difference between results of the anisotropy function of the I-125 seed with Ag marker and I-125 seed with $15\%Ag+85\%Al_2O_3$ marker (Seed2) in our simulation is about 5.2%, 5.3%, and 3.9% at 0.5 cm, 1 cm, and 5 cm distances, respectively. The mean difference between Seed2 and Seed1 is about 1.8%, 1.9% and 3.5% at radial distances of 0.5 cm, 1cm, and 5 cm distance, respectively. In addition to, the mean difference between Seed3 and Seed1 is about 2.3%, 2.8% and 3.3% at radial distances of 0.5 cm, 1 cm, and 5 cm distance, respectively.

4 Discussion and conclusion

Dosimetric parameters of the I-125 (model 6711) brachytherapy source have been investigated according to the TG-43U1 recommendation by using GEANT4 toolkit. Our results along with a comparison with other commercial source models show good consistency between simulated I-125 source (model 6711) results and other simulation results of seed's dosimetric parameters in the literature. It is noted that a little more differences between our simulation results and reported experimental data could be due to the experimental errors in the measurements, imprecision of dosimeter positioning during the experiment, and uncertainty sources in a measurement proce-



a)



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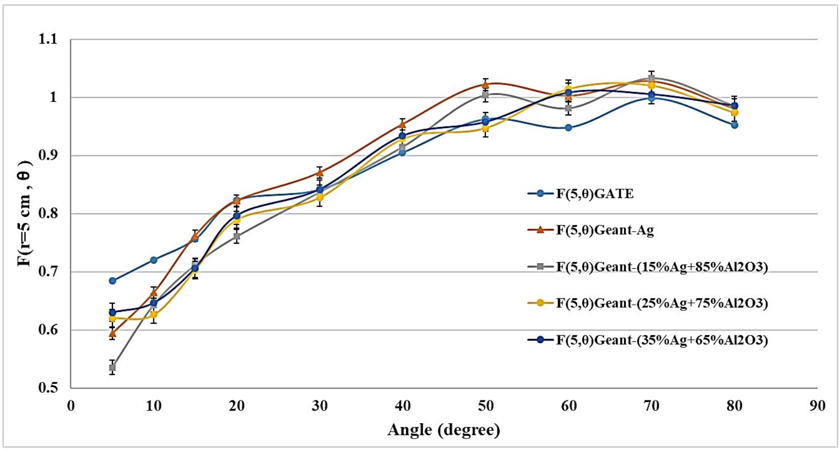

c)

Figure 4: Anisotropy function obtained by GEANT4 results and other results for 0.5 cm (a), 1 cm (b), and 5 cm (c).

dure. Furthermore, since $Ag+Al_2O_3$ rod has been recently introduced as a good carrier for Iodine radioisotope with relatively uniform distribution, we evaluated effect of the $Ag+Al_2O_3$ on the dosimetric parameters of new Iodine seed. In addition to, we assess effect of different ratio of Ag and Al_2O_3 in the final composition of the marker on the radial dose functions and anisotropy functions of the seeds. Our results show the similarity between model 6711 and simulated new seeds containing cylindrical $Ag+Al_2O_3$ markers in the same protocol. So that, results indicate mean difference of less than 5% in calculating the radial dose function and less than 6% in estimating the anisotropy functions.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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