Original Article

Monte Carlo Determination of Dosimetric Parameters of a New ^{125}I Brachytherapy Source According to AAPM TG-43 (U1) Protocol

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Abstract

Background: ^{125}I is one of the important sources frequently used in brachytherapy. Up to now, several different commercial models of this source type have been introduced to the clinical radiation oncology applications. Recently, a new source model, IrSeed-125, has been added to this list. The aim of the present study is to determine the dosimetric parameters of this new source model based on the recommendations of TG-43 (U1) protocol using Monte Carlo simulation.

Methods: The dosimetric characteristics of Ir-125 including dose rate constant, radial dose function, 2D anisotropy function and 1D anisotropy function were determined inside liquid water using MCNPX code and compared to those of other commercially available iodine sources.

Results: The dose rate constant of this new source was found to be 0.983+0.015 $cGyh^{-1}U^{-1}$ that was in good agreement with the TLD measured data (0.965 $cGyh^{-1}U^{-1}$). The 1D anisotropy function at 3, 5, and 7 cm radial distances were obtained as 0.954, 0.953 and 0.959, respectively.

Conclusion: The results of this study showed that the dosimetric characteristics of this new brachytherapy source are comparable with those of other commercially available sources. Furthermore, the simulated parameters were in accordance with the previously measured ones. Therefore, the Monte Carlo calculated dosimetric parameters could be employed to obtain the dose distribution around this new brachytherapy source based on TG-43 (U1) protocol.

Keywords: Brachytherapy, dosimetric characteristics, IrSeed-125, Monte Carlo simulation, TG-43 (U1)

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Introduction

Interstitial brachytherapy is a common method in treating various cancers, such as prostate.[1–4] ^{125}I is one of the most favorable sources used in prostate brachytherapy.[5–7] One of the main advantages of this source is the emission of gamma rays with the mean energy of 28 keV, which plays a major role in local control of the tumor, protection of healthy tissues around the tumor, and reduction of the treatment team exposure.

Wide application of ^{125}I in brachytherapy has been resulted in the development of several commercial models from this radioactive material, including Amersham 6711, Amersham 6702, Inter-source125, Best Medical Model 2301, PharmaSeed BT-125, IsoAid Advantage, I125-SL, etc.[8–11] These sources are different in their physical and geometrical features, such as source length, effective source length, type of the material used as wire, and kind of entrance window. Recently, a new ^{125}I brachytherapy source named IrSeed-125 is added to the mentioned commercial sources[12] (Atomic Energy Organization of Iran).

According to the recommendation of AAPM TG-43 (U1) protocol, determining the dosimetric characteristics of each new brachytherapy source is quite essential prior to using it in clinical applications. Several studies have been conducted to determine the dosimetric parameters of the commercially developed brachytherapy sources.[5,10,13–17] In our previous study,[12] the dosimetric characteristics of Irseed-125 were experimentally determined using thermoluminescent dosimetry (TLD-100 (LiF:Mg)). However, there is no study about Monte Carlo evaluation of dosimetric parameters of this new brachytherapy source. The aim of the present study is the Monte Carlo determination of the dosimetric parameters of IrSeed-125 according to the TG-43 (U1) protocol and recommendations of AAPM on calibration of photon sources[18–20] and comparing the simulated parameters to those of other commercially available sources.

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Materials and Methods

Physical characteristics of IrSeed-125 source

Schematic diagram of IrSeed-125 encapsulated source is shown in Figure 1. The physical length of this source is 4.7 mm. In addition, its active length, which is defined as the length of ^{125}I radioactive layer deposited on the X-ray marker, is equal to 3.2 mm. ^{125}I is uniformly deposited on a silver cylindrical core with 0.025 cm radius and 3.2 mm length. Thickness of the active layer on the silver core is equal to 1 µm. The source clad is made of titanium with 0.06 mm thickness (top and bottom), and 0.4 mm radius at the both semispherical ends. The external diameter of the source clad is equal to 0.8 mm. The space between the core and clad is filled with air. Physical characteristics of the materials used in this brachytherapy source are listed in Table 1. ^{125}I is a radioactive

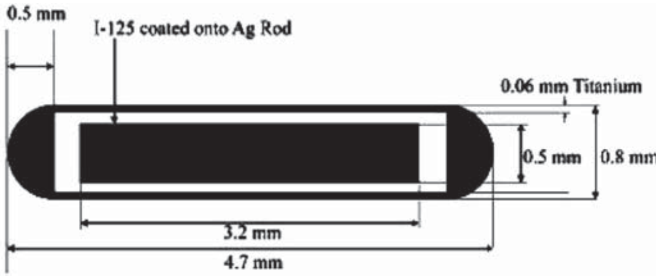

Figure 1. Geometric diagram of the IrSeed-125 brachytherapy source.

Table1. Physical properties of the source constituent elements.

Material	Atomic Number (Z_{eff})	Mass Density (g/cm^3)	Simulated Physical State
Titanium (Ti)	22	4.5	Solid
Silver (Ag)	47	10.49	Solid
Iodine (I-125)	53	4.933	Solid
Air	7.62	0.00120	Gas

source with 59.4 d half-life, which decays to ^{125}Te through electron capture. During this process, gamma rays are emitted from the excited state of ^{125}Te with the maximum and mean energy of 35 and 28 keV, respectively

Monte Carlo simulation

Monte Carlo simulation is one of the powerful and valuable instruments in dosimetry of brachytherapy sources.[19] In general; various Monte Carlo codes exist for dosimetry in brachytherapy field. In this study, Monte Carlo MCNPX code was used to determine the dosimetric characteristics of IrSeed-125 source. This code has a large number of features making it appropriate for using in brachytherapy. This code is able to transport the photons and electrons in the energy range of 1 keV to 100 MeV,[21] which is a significant feature considering, the fact that low energy sources utilized in brachytherapy. In addition, using this code, the complex geometry of the sources used in brachytherapy can be accurately modeled. To determine the dosimetric parameters of Irseed-125, the source was located at the center of a spherical water phantom with 20 cm radius and dose rate constant, Λ, radial dose function, g(r), 2D anisotropy function, F(r,θ), as well as 1D anisotropy function, $\varphi_{an}(r)$ were calculated. According to TG-43 (U1) recommendations, pure and degassed water with a mass density of 0.998 g/cm^3 at 22°C was considered as a reference dosimetry media.

In general, many standard tallies are used by the MCNP code to determine the mentioned parameters. In this study, *F8 tally (deposited energy) was used for close distances to the source, while the F6 tally (track length estimate of energy deposition) was employed for far distances due to the existence of the electronic equilibrium condition. It should be mentioned that the updated ENDF/B-VI.8 library which is based on the EPDL97 library[22] was used to allow compatible and consistent transport of photon, electron and coupled photon-electron. Note that EPDL97 data is available online in ENDF format as part of ENDF/B-VI Atomic data.[23] Moreover, the detailed physics treatment involving coherent scattering, fluorescent photons followed by photoelectric absorption, and Auger electrons were taken into account in all calculations by manipulating photon and electron physics cards.[21] Fluorescent X-rays were generated and transported assuming an isotropic emission. Both photon and electron were fully transported during calculations in order to be close to the actual conditions.

According to the TG-43 (U1) protocol, dose rate constant, Λ, is defined as the dose rate at the reference point, $(1,\frac{\pi}{2})$, and per air kerma strength of the source (Eq. 1).

$$\Lambda=\frac{\dot{D}(1,\frac{\pi}{2})}{S_k} \quad (1)$$

To determine the dose rate constant, first the source's air kerma rate, $\dot{K}(d)$ was calculated within an air filled spherical scoring cell with radius of 2 mm that was located at 50 cm distance from the source center along its transverse axis.[10] In order to suppress the effects of photon attenuation and scattering in the air, the intervening medium between the source and air-filled scoring cell was considered as a vacuum. It should be mentioned that the characteristic X-rays emitted from source clad and other low energy X-rays were also excluded from calculations by setting particle cutoff energy to 5 keV, as recommended by TG-43 (U1) protocol. Then, air kerma strength was calculated using the following Equation:

$$S_k=\dot{K}(d)d^2 \quad \& \quad d=50\text{ cm} \quad (2)$$

Having S_k and determining the dose rate at 1 cm distance from the source center along its transverse axis ($\dot{D}(1,\frac{\pi}{2})$), the dose rate constant was calculated using Eq. 1. 5×10^8 particles were followed to obtain statistical uncertainty of 0.28% and 1.5% for dose rate, as well as air kerma strength, respectively (statistical uncertainty is reported as 1σ).

Considering the geometric symmetry of the source, 2D anisotropy function (Eq. 3), F(r,θ), was calculated at 0 to 90º angles relative to the source longitudinal axis, with 10º increments, for 0.5, 1, 2, 3, 5, and 7 cm radial distances. Spherical scoring cells with 0.4 mm radius were used to calculate F(r,θ). Statistical uncertainties related to F(r,θ) ranged from 0.7% to 2.6% (reported as 1σ) after following 5×10^8 primary particles.

$$F(r,\theta)=\frac{\dot{D}(r,\theta)G(r,\frac{\pi}{2})}{\dot{D}(r,\frac{\pi}{2})G(r,\theta)} \quad (3)$$

To determine the radial dose function, g(r), scoring cells with 0.4 mm radius were located at 0.1 to 7 cm distance from the source center along its transverse axis. Then, g(r) was calculated according to Eq. 4. 5×10^8 primary particles were followed to reduce the statistical uncertainty to 0.18% and 1.8% (reported as 1σ) for 0.1 and 7 cm distances, respectively.

$$g(r)=\frac{\dot{D}(r,\frac{\pi}{2})G(1,\frac{\pi}{2})}{\dot{D}(1,\frac{\pi}{2})G(r,\frac{\pi}{2})} \quad (4)$$

It should be mentioned that the geometry function, G(r,θ), was computed using line source approximation, according to the following Equation:[15,19]

$$G(r,\theta)=\begin{cases}(r^2-L^2/4)^{-1} & \text{if } \theta=0\\ \dfrac{\tan^{-1}(\frac{x+L/2}{y})-\tan^{-1}(\frac{x-L/2}{y})}{Ly} & \text{if } \theta\neq 0\end{cases} \quad (5) \quad \text{Line source approximation}$$

Where L is the source active length and was assumed to be 3.2 mm.

The energy spectrum of ^{125}I gamma rays was obtained using the data reported by NCRP58.[24] Also, according to the recommendations of TG-43 (U1) protocol, humidity of the air between the cylindrical core and the source clad was considered to be 40% (Hydrogen: 0.0732%, Carbon: 0.0123%, Nitrogen: 75.0325%, Oxygen: 23.6077%, and Argon: 1.2743%, (data are in percent mass)) in all of the simulations.

Results

The dose rate constant, Λ, at (1 cm, $\frac{\pi}{2}$) reference point was calculated inside a water phantom and its value was calculated as 0.983+0.015 $cGyh^{-1}U^{-1}$. This value was in good agreement with our previously TLD measured Λ of 0.965 $cGyh^{-1}U^{-1}$.[12] The difference between the measured and calculated data was about 1.8%.

Comparison of the dose rate constant of Irseed-125 source to that of other commercial sources is shown in Table 2. As it can be seen, there is a good agreement between the simulated dose rate constant of the Irseed-125 and that of other commercially available sources.

The values of the simulated radial dose function of Irseed-125 at various distances from the source center are reported in Table 3. The comparison between the measured and simulated radial dose function is shown in Figure 2. As it can be seen in Figure 2, the results of Monte Carlo simulation are in accordance with TLD measured data. The mean difference between the simulated and measured radial dose function was about 6%.

Moreover, the simulated radial dose function was quantitatively determined through fitting a 5th order polynomial function to the simulated values (Adjusted-R^2=1):

$$g(r)=a_0+a_1r+a_2r^2+a_3r^3+a_4r^4+a_5r^5 \quad (6)$$

Where a_0, a_1, a_2, a_3, a_4, and a_5 coefficients of the radial dose function were obtained as 1.0808, 0.01485, -1.257×10^{-1}, 3.53×10^{-2}, -4.18×10^{-3}, and 1.8429×10^{-4}, respectively.

Figure 3, shows the comparison between the simulated radial dose function of the source under study and that of other commer-

Table 2. Comparison of the IrSeed-125 dose rate constant to that of some other commercially available sources.

Source model	Method	Medium	Dose rate constant ($cGy\ h^{-1}U^{-1}$)
IrSeed125 (This Work)	Monte Carlo Simulation	Water	0.983
IrSeed125 (Lohrabian, et al. 2013)	Measurement	Plexiglass	0.965
InterSource125 (Meigooni, et al. 2002)	Monte Carlo Simulation	Water	1.013
BestModel2301 (Sowards and Meigooni, 2002)	Monte Carlo Simulation	Water	1.01
I125-SL (Wallace, 2000)	Measurement	Plastic phantom	0.95
Model6711 (Williamson, 1991)	Monte Carlo Simulation	Water	0.877
Model6702 (Williamson, 1991)	Monte Carlo Simulation	Water	0.932
BT-125-1 (Solberg, et al. 2002)	Monte Carlo Simulation	Water	0.955
ADVANTAGE (Solberg, et al. 2002)	Monte Carlo Simulation	Water	0.962
Model6702 (Rivard, et al. 2004)	Average of Monte Carlo Simulation And Measurement	Water	1.036
Model6711 (Rivard, et al. 2004)	Average of Monte Carlo Simulation And Measurement	Water	0.965
BestModel2301 (Rivard, et al. 2004)	Average of Monte Carlo Simulation And Measurement	Water	1.018
BestModel2301 (Meigooni, et al. 2000)	Measurement	Solid Water	0.961

Table 3. Simulated radial dose function of IrSeed-125 source at various distances from source center.

Distance, r (cm)	Simulated g(r), Liquid water	Distance, r (cm)	Simulated g(r), Liquid water
0.1	1.071	1.8	0.865
0.2	1.083	2.0	0.830
0.3	1.078	2.5	0.738
0.4	1.074	3.0	0.657
0.5	1.063	3.5	0.575
0.6	1.053	4.0	0.505
0.7	1.041	4.5	0.441
0.8	1.028	5.0	0.384
0.9	1.014	5.5	0.327
1.0	1.000	6.0	0.283
1.2	0. 967	6.5	0.230
1.4	0.934	7.0	0.182
1.6	0.900		

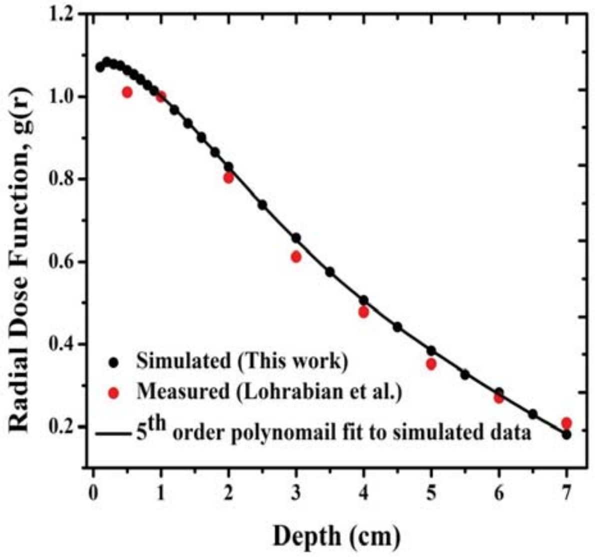

Figure 2. Comparison of the simulated and measured radial dose functions for Irseed-125 source.

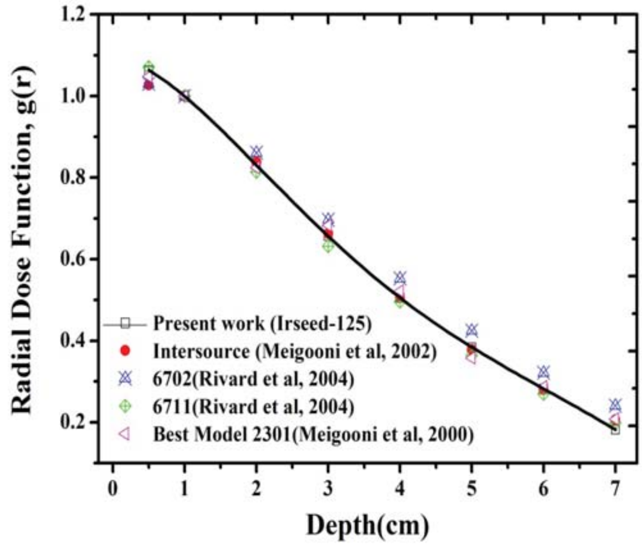

Figure 3. Comparison between the simulated radial dose function of the Irseed-125 and other commercial sources.

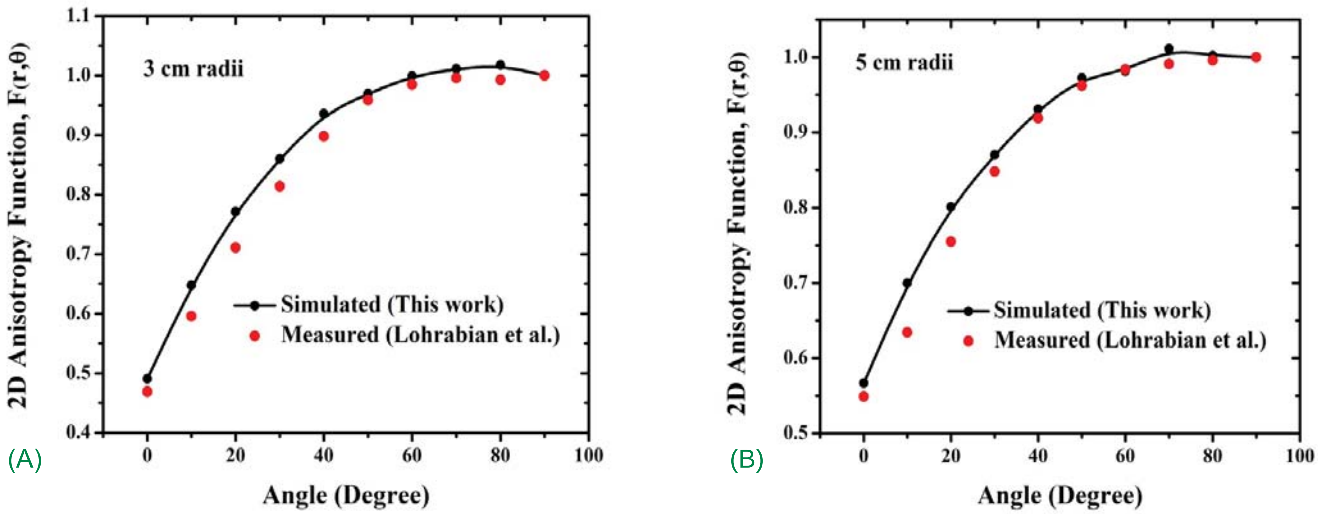

Figure 4. Comparison between the simulated and measured 2D anisotropy function of Irseed-125 at two radial distances; **A)** 3 cm and **B)** 5 cm.

cial sources. According to Figure 3, there is a great agreement between the simulated radial dose function of Irseed-125 and those reported for other commercial ^{125}I sources.

Simulated and measured 2D anisotropy functions of Irseed-125 at two radial distances of 3 and 5 cm have been compared in Figure 4. As it can be seen in this Figure, the results of simulation are in accordance with the experimentally measured data (the mean difference of about 3.7% and 2.7% for 3 cm and 5 cm distances, respectively). This fact shows that the source geometry is accurately modeled by the Monte Carlo MCNPX code.

The values of the simulated 2D anisotropy function for Ir-Seed-125 source at various radial distances as a function of θ angle relative to the source longitudinal axis are shown in Table 4. Furthermore, comparison of the simulated 2D anisotropy function of Irseed-125 to that of other commercially available sources at different radial distances is presented in Figure 5.

As it can be seen in Figure 5, within the angular range of 20º to 90º, there is a good agreement between the obtained data and those related to other commercial sources. On the other hand, the rather great difference among calculated data at angles less than 20º might be due to differences in designing the source geometry, source encapsulation, and distribution of the radioactive material on the source core.

The 1D anisotropy function, $\varphi_{an}(r)$, of the source under study and that of other commercial sources as a function of distance to the source center are reported in Table 5. It should be mentioned that the 1D anisotropy function at different radial distances was computed using the following Equation:[19]

$$\varphi_{an}(r)=\frac{\int_0^\pi \dot{D}(r,\theta)\sin\theta \, d\theta}{2\dot{D}(r,\frac{\pi}{2})} \quad (7)$$

The reported data in Table 5 also confirms that the 1D anisotropy function of Irseed-125 at various radial distances is comparable to that of other commercially available sources.

Table 4. Simulated 2D anisotropy function for IrSeed-125 source at different radial distances from source center as a function of θ angle.

Degrees	Anisotropy function, F(r,θ)					
	r=0.5 cm	r=1 cm	r=2 cm	r=3 cm	r=5 cm	r=7 cm
0	0.267	0.334	0.431	0.490	0.567	0.631
5	- - -	0.494	0.562	0.599	0.656	0.689
10	0.471	0.533	0.616	0.647	0.700	0.717
15	- - -	0.632	0.689	0.717	0.747	0.762
20	0.670	0.717	0.749	0.771	0.801	0.826
30	0.850	0.843	0.856	0.860	0.870	0.861
40	0.955	0.933	0.934	0.936	0.931	0.905
50	1.013	0.992	0.982	0.969	0.972	0.973
60	1.032	1.030	1.012	0.999	0.981	0.971
70	1.021	1.044	1.020	1.011	1.011	1.001
80	0.999	1.030	1.028	1.018	1.002	1.016
90	1.000	1.000	1.000	1.000	1.000	1.000
$\varphi_{an}(r)$	0.991	0.967	0.959	0.954	0.953	0.959

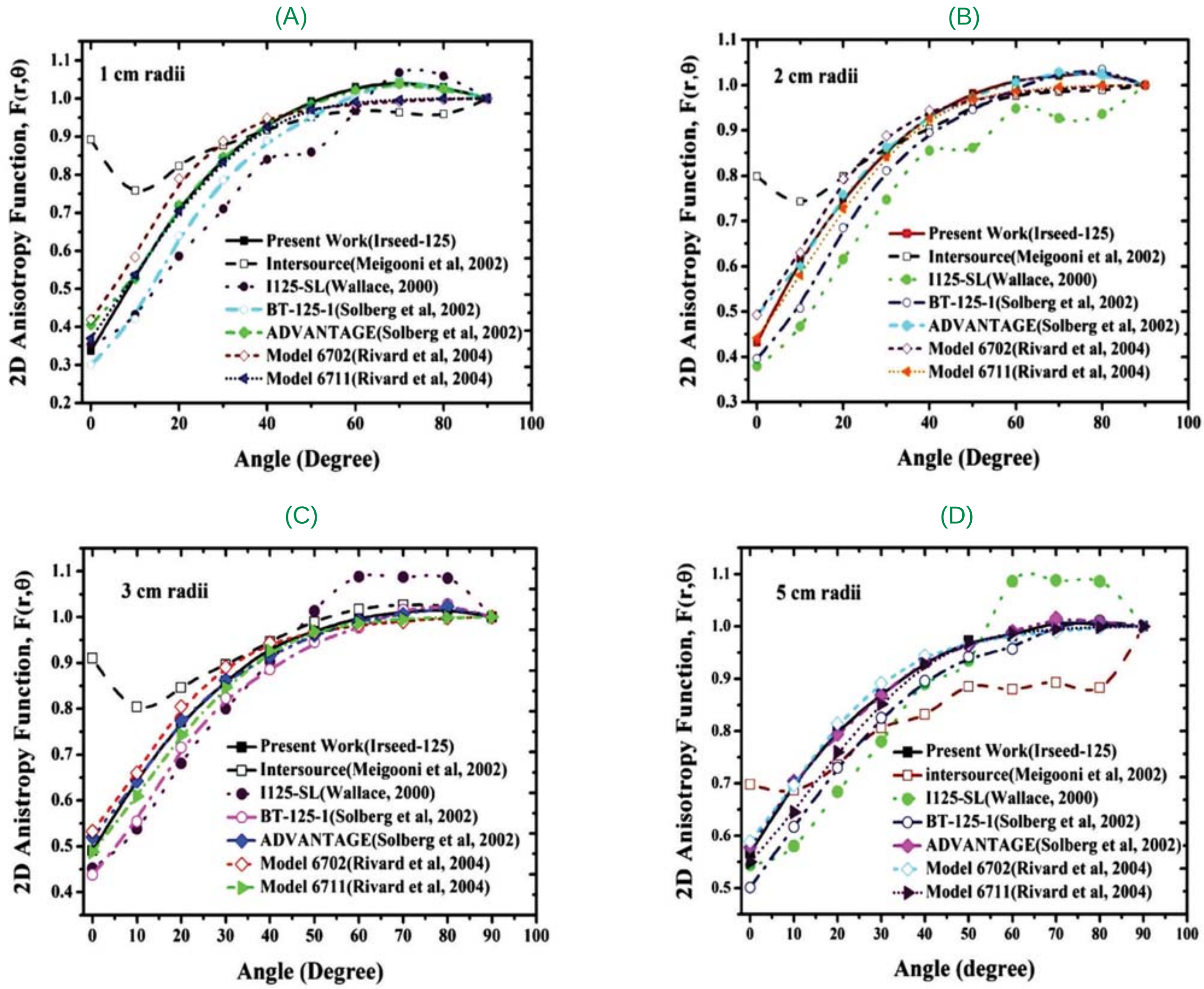

Figure 5. Comparison between the simulated 2D anisotropy function of the Irseed-125 and other commercially available sources at different radial distances; **A)** 1 cm; **B)** 2 cm; **C)** 3 cm; and **D)** 5 cm.

Table 5. Comparison of the 1D anisotropy functions of the IrSeed-125 at different radial distances with other commercially available sources.

Source Model	1D Anisotropy Function, $\varphi_{an}(r)$				
	r = 1 cm	r = 2 cm	r = 3 cm	r = 5 cm	r = 7 cm
IrSeed[125] (Present Work)	0.967	0.959	0.954	0.953	0.959
IrSeed[125] (Lohrabian, et al. 2013)	0.938	0.940	0.942	0.944	- - -
InterSource[125] (Meigooni, et al. 2002)	0.959	0.947	0.983	0.949	0.965
BestModel2301 (Sowards and Meigooni, 2002)	0.986	0.976	0.968	0.969	0.969
I125-SL (Wallace, 2000)	0.927	0.875	0.982	0.968	- - -
Model6711 (Nath, et al. 1995)	0.944	0.936	0.893	0.884	0.901
BT-125-1 (Solberg, et al. 2002)	0.948	0.946	0.943	0.940	0.937
ADVANTAGE (Solberg, et al. 2002)	0.968	0.964	0.955	0.959	0.955
Model6702 (Rivard, et al. 2004)	0.960	0.952	0.951	0.954	- - -
Model6711 (Rivard, et al. 2004)	0.944	0.941	0.942	0.944	- - -
BestModel2301 (Rivard, et al. 2004)	0.945	0.987	0.968	0.969	0.969
Model6702 (Nath, et al. 1995)	0.968	0.928	0.897	0.959	0.907
BestModel2301 (Meigooni, et al. 2000)	- - -	0.990	- - -	0.988	0.970

Discussion

IrSeed-125 source is one of the ^{125}I sources that have been recently introduced for interstitial brachytherapy. In this study, the dosimetric parameters of this new source were theoretically determined according to the recommendations of TG-43 (U1) protocol and AAPM recommendations on calibration of photon sources. Calculations were performed inside a water phantom, using Monte Carlo MCNPX code.

The findings of this study confirmed that the dosimetric characteristics of this new source are comparable to those of other commercially available sources, which are practically being used in clinical radiation oncology applications. Based on this fact, it can be concluded that this new source has the potential as a clinical brachytherapy source.

Furthermore, there was a good agreement between the results of Monte Carlo simulation and our previous TLD measurements.[12] This fact demonstrates that the simulated dosimetric parameters can be employed to obtain the dose distribution around this new brachytherapy source.

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References

1. Russell KJ, Blasko JC. Recent advances in interstitial brachytherapy for localized prostate cancer. *Probl Urol.* 1993; 7: 260 – 278.
2. Brachman DG, Thomas T, Hilbe J, Beyer DC. Failure-free survival following brachytherapy alone or external beam irradiation alone for T1-2 prostate tumors in 2222 patients: results from a single practice. *Int J Radiat Oncol Biol Phys.* 2000; 48: 111 – 117.
3. Ragde H, Blasko JC, Grimm PD, Kenny GM, Sylvester J, Hoak DC, et al. Brachytherapy for clinically localized prostate cancer: results at 7-and 8-year follow-up. *Semin Surg Oncol.* 1997; 13: 438 – 443.
4. Yu Y, Anderson LL, Li Z, Mellenberg DE, Nath R, Schell MC, et al. Permanent prostate seed implant brachytherapy: Report of the American Association of Physicists in Medicine Task Group No. 64. *Med Phys.* 1999; 26: 2054 – 2076.
5. Meigooni AS, Hayes JL, Zhang H, Sowards K. Experimental and theoretical determination of dosimetric characteristics of IsoAid ADVANTAGE™ ^{125}I brachytherapy source. *Med Phys.* 2002; 29: 2152 – 2158.
6. Zelefsky MJ, Hollister T, Raben A, Matthews S, Wallner KE. Five-year biochemical outcome and toxicity with transperineal CT-planned permanent I-125 prostate implantation for patients with localized prostate cancer. *Int J Radiat Oncol Biol Phys.* 2000; 47: 1261 – 1266.
7. Stock RG, Stone NN, Tabert A, Iammuzzi C, DeWyngaert JK. A dose-response study for I-125 prostate implants. *Int J Radiat Oncol Biol Phys.* 1998; 41: 101 – 108.
8. Heints BH, Wallace RE, Hevezi JM. Comparison of I-125 sources used for permanent interstitial implants. *Med Phys.* 2001; 28: 671 – 682.
9. Rivard MJ, Butler WM, DeWerd LA, Huq MS, Ibbott GS, Meigooni AS, et al. Supplement to the 2004 update of the AAPM Task Group No. 43 Report. *Med Phys.* 2007; 34: 2187 – 2205.
10. Solberg TD, DeMarco JJ, Hugo G, Wallace RE. Dosimetric parameters of three new solid core I-125 brachytherapy source. *J Appl Clin Med Phys.* 2002; 3: 119 – 134.
11. Wallace RE. Dosimetric characterization of a new 125Iodine brachytherapy source, model I125-SL. *Conf Proc IEEE Eng Med Biol Soc.* 2001; 1: 376 – 379.
12. Lohrabian V, Sheibani S, Aghamiri MR, Ghozati B, Pourbeigi H, Baghani HR. Determination of Dosimetric Characteristics of IrSeed 125I Brachytherapy Source. *Iran J Med Phys.* 2013; 10: 109 – 117.
13. Nath R, Meigooni AS, Muench P, Melillo A. Anisotropy functions for Pd-103, I-125 and Ir-192 interstitial brachytherapy sources. *Med Phys.* 1993; 20: 1465 – 1473.
14. Meigooni AS, Gearheart DM, Soward K. Experimental determination of dosimetric characteristics of Best ^{125}I brachytherapy sources. *Med Phy.* 2000; 27: 2168 – 2173.
15. Meigooni AS, Yoe-Sein MM, Al-Otoom AY, Sowards KT. Determination of the dosimetric characteristics of InterSource[125] Iodine brachytherapy source. *Appl Radiat Isot.* 2002; 56: 589 – 599.
16. Sowards KT, Meigooni AS. A Monte Carlo evaluation of the dosimetric characteristics of the Best[a] Model 2301 ^{125}I brachytherapy source. *Appl Radiat Isot.* 2002; 57: 327 – 333.
17. Williamson JF. Comparison of measured and calculated dose rates in water near I-125 and Ir-192 seeds. *Med Phys.* 1991; 18: 776 – 786.
18. Nath R, Anderson LL, Luxton G, Weaver KA, Williamson JF, Meigooni AS. Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group No. 43. *Med Phys.* 1995; 22: 209 – 234.
19. Rivard MJ, Coursey BM, DeWerd LA, Hanson WF, Huq MS, Ibbott GS, et al. Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations. *Med Phys.* 2004; 31: 633 – 674.
20. Williamson JF, Coursey BM, DeWerd LA, Hanson WF, Nath R, Ibbott GS. Dosimetric prerequisites for routine clinical use of new low energy photon interstitial brachytherapy sources. *Med Phys.* 1998; 25: 2269 – 2278.
21. Pelowitzs DB. MCNPX User's Manual, Vresion 2.6.0. Los Alamos: Los Alamos National Laboratory; 2008
22. Bohm TD, DeLuca PMJr, DeWerd LA. Brachytherapy dosimetry of ^{125}I and ^{103}Pd sources using an updated cross section library for the MCNP Monte Carlo transport code. *Med Phys.* 2003; 30: 701 – 711.
23. T-2 Nuclear Information Service, 2007. Available from: URL: "http://t2.lanl.gov/data/atomic.html", Los Alamos National Laboratory.
24. NCRP. A handbook of radioactivity measurements procedures; NCRP Report No. 58. Bethesda: National Council on Radiation Protection and Measurements, 1985.