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Determination of dosimetry parameters of ADVANTAGE™ ^{103}Pd brachytherapy seed using MCNP4C computer code

Vahideh Ataeinia, Gholamreza Raisali, Mahdi Sadeghi

Abstract. The IsoAid LLC Inc. has been introduced ADVANTAGE™ ^{103}Pd brachytherapy seed in 2006. The aim of this work is to determine the dosimetric characteristics of this seed according to AAPM's recommendation in TG43-U1 using MCNP4C computer code. The dose rate constant has been determined to be 0.694 ± 0.001 cGy·h^{-1}·U^{-1}. The radial dose function has been calculated at distances from 0.25 to 7 cm. Two-dimensional anisotropy function have been calculated at distances from 0.25 to 7 cm and at angles from 0 to 90° at 10° increments. The one-dimensional anisotropy function and anisotropy constant have been also calculated. The anisotropy constant in water has been calculated as 0.872 ± 0.001. The results of this investigation are compared with the results of Meigooni *et al*. obtained by PTRAN code in 2006 and Sowards results obtained by PTRAN code in 2007. The comparison of the dose rate constant and the one-dimensional anisotropy function obtained from the two codes shows good agreement; also the radial dose function at distances lower than 3 cm and the two-dimensional anisotropy function at angles greater than 20° are in good agreement. But, for the calculated radial dose function at distances beyond 3 cm, we observed differences between our values and Meigooni *et al*. and Sowards results. Also, differences between the calculated two-dimensional anisotropy function using the two codes for angles smaller than 20° are considerable. The differences between the results of MCNP4C and PTRAN codes could be related to the different cross-section data libraries used in these two codes.

Key words: brachytherapy • ^{103}Pd source • dosimetry parameters • MCNP4C • ADVANTAGE™ ^{103}Pd

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Introduction

Recently, the use of radionuclides such as ^{125}I and ^{103}Pd for interstitial brachytherapy treatments, especially for prostate cancer, has been widely increased. The advantages of brachytherapy to surgery is treatment simplicity, minimum damage to the surrounding normal tissues [4, 10], and the reduction of side effects for patient after treatment [10]. The advantages of brachytherapy to teletherapy is its ability in radiation localization on tumor tissue, minimizing radiation to the surrounding normal tissues [4, 10, 15], and rapid dose reduction in normal tissues surrounding the tumor [7]. Having a shorter half-life (17 days) than that of ^{125}I (59.4 days), ^{103}Pd may provide a biologic advantage in permanent implants, because the dose is delivered at a much faster rate [7]. Palladium-103 shows a fast decrease in depth dose in comparison with other radioisotopes due to its lower energy photons, thus reduces the delivered dose to the surrounding normal tissues [1, 18].

Before clinical application of brachytherapy sources, it is necessary to accurately measure and calculate the dosimetric parameters of the ^{103}Pd source seed and specify the required data for treatment planning [14].

In 2006, IsoAid LLC Co. has manufactured ADVANTAGE™ ^{103}Pd seed [11] for brachytherapy. The aim of this investigation is the determination of the dosimetric parameters of ADVANTAGE™ ^{103}Pd seed by Monte Carlo calculation using MCNP4C code. The results of this work have been compared with the results of Meigooni *et al.* obtained by PTRAN code in 2006 [11], and with Sowards results obtained from the same code in 2007 [23].

Materials and methods

Source description

Figure 1 shows the schematic diagram of ADVANTAGE™ ^{103}Pd seed [11, 23]. A cylindrical shape capsule of the seed is made of titanium, 4.5 mm in length and 0.8 mm in external diameter. Inside the seed there are a central silver cylindrical marker, 1.25 mm in length and 0.5 mm in diameter and two polystyrene spherical resins, 0.5 mm in diameter, at each side of the marker. Paladium-103 is absorbed in resins. The thickness of the capsule wall is 0.05 mm and the thickness of the laser welded caps is 0.35 mm [11, 23]. The resin compositions (percentage by mass) is: H, 8%; C, 90%; N, 0.3%; Cl, 0.7%; and Pd, 1%; and its density is 1.2 g/cm^3. The space between any of the two resins is considered as 0.091 mm air [11, 23] with a density of 1.1965×10^{-3} g/cm^3, and with the following composition (by weight): 75.520% – nitrogen, 23.176% – oxygen, 1.288% – argon and 0.016% – carbon.

Monte Carlo calculations

In this work, we have applied the MCNP4C computer code [3] to simulate the transport of radiation inside the seed and the surrounding medium. MCNP4C simulates photoelectric absorption and *K* and *L*-shell characteristic X-ray emission and coherent and incoherent scattering [3]. The cross-section data and the form factors for coherent and incoherent scattering are taken from Storm and Israel [24] or from ENDF (Hubbell *et al.* [6]), the fluorescence data are taken from Everett and Cashwell report [5].

The ADVANTAGE™ ^{103}Pd seed has been simulated by MCNP4C code in the center of a spherical phantom of water with a 15 cm radius, large enough to consider all the scattering effects of the surrounding medium. For dose scoring purposes, the phantom has been divided into several spherical and conical shells [19, 20]. The dosimetry cells assumed to be as volumes bounded by two spherical surfaces with small differences between their radii and two conical surfaces with small differences between their apex angles. The volume dose averaged over these small volume cells has been regarded as the dose value at the center of the cell. This assumption is eligible because the variations of dose inside the cell are negligible in comparison with statistical errors of MCNP [19, 20]. Due to the source photon low energies and a small range of secondary electrons produced by photons emitted from the source, which results in electron equilibrium, kerma and dose in these cells is assumed to be equal [16, 21]. The energy spectra of photons emitted from a ^{103}Pd source have been considered as the values reported in TG43-U1 protocol [21]. Dose distribution in water has been calculated using F6 tally and then dosimetric parameters of Pd-103 seed were calculated, according to recommendations suggested in TG43-U1 protocol. The dose distribution calculations in water were performed up to 2×10^9 source particle histories. With this number of histories, statistical errors along the longitudinal axis at distances from 0.25 to 7 cm are lower than 5% and at other angles less than 0.7%. The run time of the program by an Intel(R)-Celeron(R) computer (2.4 GHz), was about 220 h. The higher statistical error along the longitudinal axis of the seed is due to the attenuation of the source photons by the caps resulting in the emission of lower energy X-rays on that direction. This error is higher at far distances [17].

In order to calculate S_K for unit activity using MCNP4C code, the seed is assumed in vacuum to suppress the effects of attenuation and scattering [10, 22]. Air kerma rate was calculated using F6 tally at 1 m distance along the transversal axis of the seed. In a simulation program, photons with energies less than 5 keV have been suppressed because these photons, which are produced in a titanium tube, have no considerable effect on the absorbed dose in water [10, 19, 21]. Then, using the inverse square law and Eq. (1), the air kerma rate at 1 m distance was corrected to an air kerma rate at 1 cm [8, 13].

$$S_K = \dot{K}_\delta(d)d^2 \quad (1)$$

where $\dot{K}_\delta(d)$ is the air-kerma rate at distance d in vacuum due to the photons of energy greater than δ and δ is considered as 5 keV.

TG43-U1 dosimetry formalism

Dose distribution around a symmetric cylindrical brachytherapy seed is determined by TG43-U1 formalism as Eq. (2). Dosimetric parameters used in two-dimensional dose calculation formula were described in TG43-U1 protocol [21]. These parameters have been determined for ADVANTAGE™ ^{103}Pd seed using MCNP4C code [3].

$$\dot{D}(r,\theta) = S_K \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r) F(r,\theta) \quad (2)$$

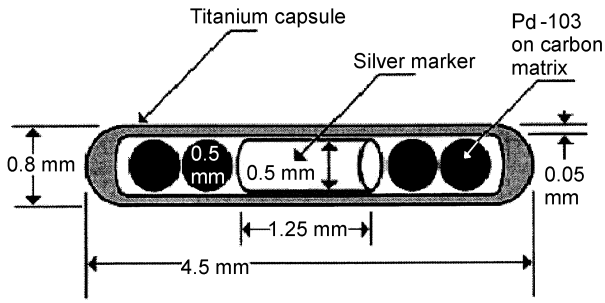

Fig. 1. Schematic diagram of ADVANTAGE™ ^{103}Pd source [11, 23].

where: $\dot{D}(r,\theta)$ is the two-dimensional dose distribution around the seed, S_k is the air kerma strength per source particle estimated using the Monte Carlo method, Λ is the dose rate constant which is calculated using Eq. (3), $G(r,\theta)$ is known as the geometry function which takes into account the effect of the physical shape of the radioactive material inside the seed on the dose distribution at point (r,θ) and $G(r_0,\theta_0)$ is the geometry function at point (r_0,θ_0) where the point (r_0,θ_0) refers to the reference point (r_0 = 1 cm, $\theta_0 = \pi/2$), $g(r)$ is the radial dose function and $F(r,\theta)$ is the two-dimensional anisotropy function which are calculated using Eqs. (4) and (5), respectively.

The dose rate constant for ADVANTAGE™ ^{103}Pd has been calculated using the calculated value of S_K for unit activity (per source particle) and dose rate in reference point for unit activity (per source particle), $\dot{D}(r_0,\theta_0)$, according to Eq. (3) [21]. The results of the calculations are given in Table 1 and compared with the results of Meigooni *et al.* [11] and with Sowards [23] results for ADVANTAGE™ ^{103}Pd seed.

(3) $$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_K}$$

for calculation of the geometry function, the seed was simulated in the center of a sphere with a 30 cm diameter [10]. The geometry function has been calculated using fluence calculation by F4 tally at various distances and angles, excluding all materials used in the seed and the surrounding, in order to just considering the effect of activity distribution inside the seed [21].

Radial dose function has been calculated for several distances from 0.2 to 8 cm using Eq. (4). The dose rates and geometry functions are also calculated at the same distances.

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

Two-dimensional anisotropy function has been calculated at radial distances ranging from 0.25 to 7 cm and at angles from 0 to 90° at 10° increments using Eq. (5). The dose rates and the geometry functions are also calculated at the same distances and angles [21].

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

One-dimensional anisotropy function and anisotropy constant have been calculated according to Eqs. (6) and (7), respectively [21].

(6) $$\phi_{an}(r) = \frac{\int_0^{\pi} \dot{D}(r,\theta)\sin(\theta)d\theta}{2\dot{D}(r,\theta_0)}$$

(7) $$\overline{\phi} = \frac{\sum_{r\geq 1\mathrm{cm}}^{r_{max}} \phi_{an}(r)r^{-2}}{\sum_{r\geq 1\mathrm{cm}}^{r_{max}} r^{-2}}$$

Results and discussion

The calculated dose rate constant using MCNP4C code has been obtained to be 0.694±0.001 cGy·h^{-1}·U^{-1} nearly the same as the values reported of 0.69±0.02 cGy·h^{-1}·U^{-1} from PTRAN code calculated by Meigooni *et al.* [11] and 0.709±0.014 cGy·h^{-1}·U^{-1} from PTRAN code calculated by Sowards [23].

The geometry function was determined by fluence calculation at different distances and angles. The results have been shown in Fig. 2.

The radial dose function obtained by Eq. (4) at various distances has been presented in Table 1 and drawn in Fig. 3, respectively and has been compared with the results of Meigooni *et al.* [11] and with those by Sowards [23]. The calculated radial dose function by MCNP4C code at distances less than 3 cm has acceptable differences less than 7% with the calculated radial dose function obtained by Meigooni *et al.* [11] and differences of less than 9% with the radial dose function calculated by

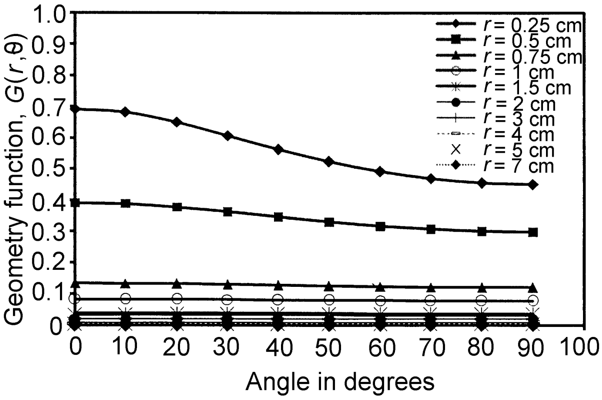

Fig. 2. The variation of the calculated geometry functions of ADVANTAGE™ ^{103}Pd seed at various distances vs. angle.

Table 1. Comparison of the calculated radial dose function in water and dose rate constant of ADVANTAGE™ ^{103}Pd source in this work and Meigooni *et al.* [11] and Sowards [23] results

Distance (cm)	Meigooni *et al.*	Sowards	This work
0.2	1.212	1.234	1.306
0.25	–	–	1.322
0.4	1.293	1.290	1.280
0.5	1.263	1.260	1.241
0.6	1.216	1.213	1.190
0.75	–	1.134	1.126
0.8	1.111	1.106	1.103
1.0	1.000	1.000	1.000
1.5	0.761	0.768	0.784
2.0	0.579	0.576	0.599
2.5	0.431	0.429	0.462
3.0	0.323	0.318	0.347
3.5	0.235	0.233	0.261
4.0	0.177	0.173	0.198
4.5	0.127	0.127	0.150
5.0	0.092	0.092	0.112
6.0	0.050	0.050	0.063
7.0	0.029	0.028	0.035
8.0	0.018	0.015	0.021
(cGy·h^{-1}·U^{-1})Λ	0.69 ± 0.02	0.709 ± 0.014	0.694 ± 0.001

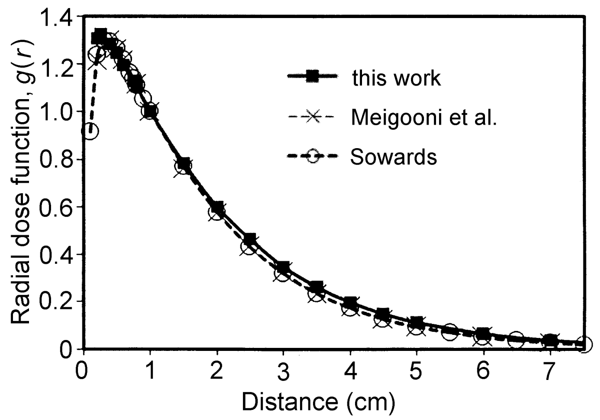

Fig. 3. Comparison of the calculated radial dose function of ADVANTAGE™ ^{103}Pd source in water with calculated radial dose function by Meigooni *et al.* [11] and Sowards [23].

Sowards [23]. For distances beyond 3 cm, the differences between our values and Meigooni *et al.* [11] and Sowards [23] calculated results are about 20%, while the differences between the results of this work and Meigooni *et al.* [11] measured values are about 16%.

Two-dimensional anisotropy function calculated in this work at various distances and angles are given in Table 2 and the results obtained by Meigooni *et al.* [11] and Sowards [23] are given in Tables 3 and 4, respectively. These results are also compared in Fig. 4. Differences between the calculated two-dimensional anisotropy function in this work and the results by Meigooni *et al.* at angles larger than 20° is less than 6%, while it is about 13% at angles less than 20°. Differences between the calculated two-dimensional anisotropy function in this work and those by Sowards [23] at angles greater than 20° are less than 9% and at angles between 0 to 20° is about 15%.

From the two-dimensional anisotropy function using Eq. (6), one-dimensional anisotropy function has been calculated. The calculated one-dimensional anisotropy function is given in Table 2. We have also calculated the anisotropy constant using Eq. (7) as 0.872±0.001, while the anisotropy constants obtained from Meigooni *et al.* (Table 3) and Sowards (Table 4) using the same equation gave values 0.874 and 0.880, respectively. All the three results are in acceptable agreement.

The differences between the results of MCNP4C and PTRAN codes could be related to the use of different data libraries. This is in agreement with the results obtained by Bohm *et al.* [2] and Reniers *et al.* [18]. Bohm *et al.* [2] calculated dosimetric parameters of 6711 ^{125}I seed and TheraSeed 200 ^{103}Pd seed using MCNP code and compared their results with the calculated results by Williamson [25] using PTRAN code and the calculated results by Mainegra *et al.* [9] using EGS4 code. In their work, the obtained dose rate constant using MCNP and PTRAN or EGS4 codes have differences lower than 5%, while differences between the calculated radial dose functions using MCNP and PTRAN or EGS4 codes at far distances were about 18–20% [2]. Also, Reniers *et al.* [17] simulated InterSource103 seed using MCNP4B code. Differences between their calculated radial dose function using MCNP code and the calculated radial dose function by Meigooni *et al.* [12] using PTRAN code and the measured radial dose function by Meigooni *et al.* [11] was about 15% at distances more than 3 cm from the source [18].

Using the dose distribution obtained from MCNP4C calculations, isodose curves of ADVANTAGE™ ^{103}Pd seed have also been drawn in Fig. 5. The values on the

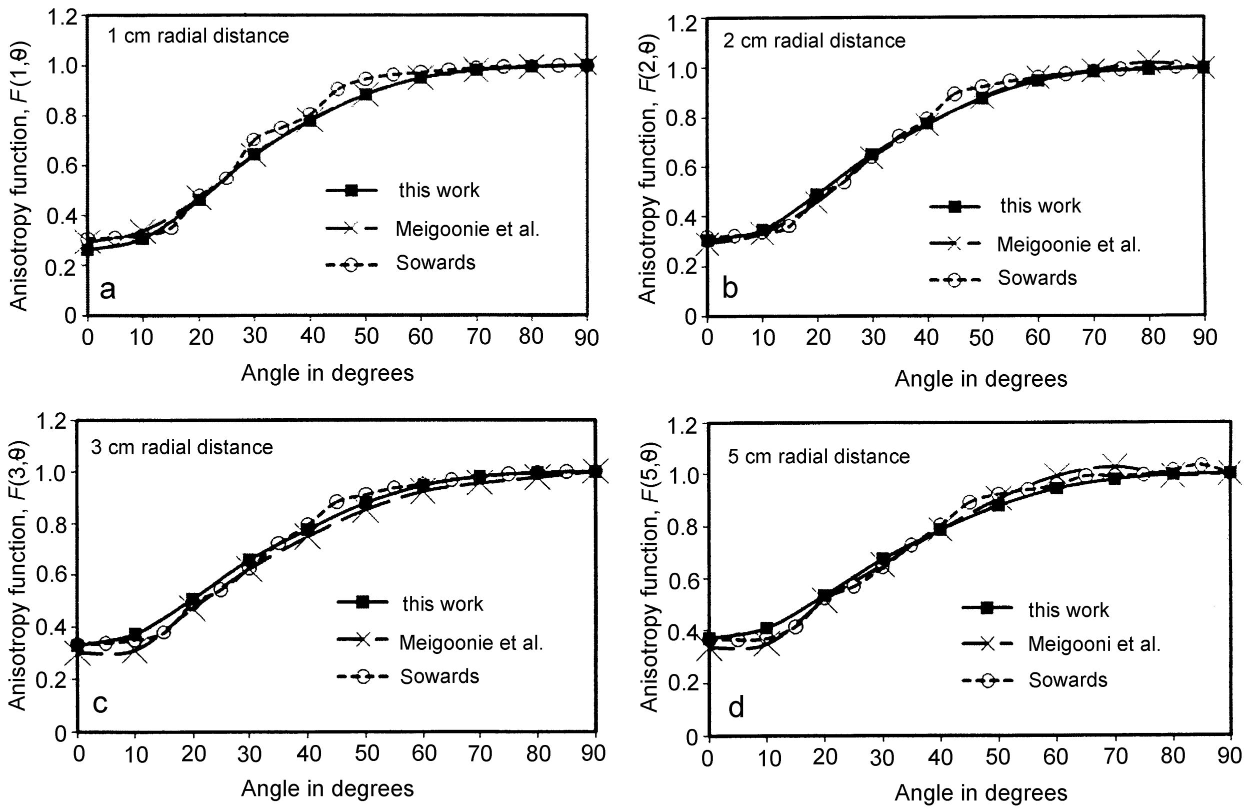

Fig. 4. Comparison of the calculated two-dimensional anisotropy function in water in this work and the results of Meigooni *et al.* [11] and Sowards [23] for radial distances of: a – 1 cm; b – 2 cm; c – 3 cm; d – 5 cm.

Table 2. The calculated two-dimensional anisotropy function and one-dimensional anisotropy function of ADVANTAGE™ ^{103}Pd source

Radial distance (cm)	Angle (deg.)										$\Phi_{an}(r)$
	0	10	20	30	40	50	60	70	80	90	
0.25	0.203	0.287	0.511	0.724	0.865	0.928	0.964	0.988	0.999	1.000	0.993
0.50	0.216	0.286	0.480	0.680	0.825	0.917	0.960	0.986	0.998	1.000	0.940
0.75	0.233	0.290	0.450	0.629	0.765	0.871	0.929	0.958	0.971	1.000	0.867
1.0	0.263	0.309	0.465	0.643	0.779	0.887	0.953	0.985	0.996	1.000	0.877
1.5	0.282	0.331	0.478	0.646	0.774	0.880	0.949	0.983	0.996	1.000	0.867
2.0	0.305	0.349	0.490	0.653	0.775	0.877	0.947	0.983	0.995	1.000	0.866
3.0	0.329	0.375	0.508	0.660	0.778	0.878	0.946	0.982	0.995	1.000	0.866
4.0	0.348	0.393	0.521	0.668	0.780	0.876	0.943	0.980	0.997	1.000	0.867
5.0	0.370	0.409	0.535	0.674	0.784	0.878	0.945	0.981	0.996	1.000	0.870
7.0	0.413	0.441	0.560	0.686	0.795	0.883	0.941	0.977	0.997	1.000	0.874

Table 3. The two-dimensional anisotropy function and one-dimensional anisotropy function of ADVANTAGE™ ^{103}Pd source calculated by Meigooni *et al.* [11]

Angle (deg.)	Radial distance (cm)					
	0.5	1.0	2.0	3.0	4.0	5.0
0	0.2618	0.2961	0.2917	0.3011	0.3081	0.3349
5	0.2754	0.3049	0.2962	0.3122	0.3218	0.3493
10	0.3199	0.3369	0.3313	0.3437	0.3533	0.3798
15	0.3964	0.3921	0.3800	0.4000	0.4024	0.4459
20	0.5025	0.4705	0.4567	0.4710	0.4725	0.5143
25	0.6125	0.5592	0.5585	0.5495	0.5726	0.6007
30	0.7118	0.6418	0.6380	0.6233	0.6341	0.6519
35	0.7944	0.7148	0.7079	0.6918	0.7068	0.7156
40	0.8593	0.7814	0.7740	0.7477	0.7599	0.7871
45	0.9082	0.8387	0.8359	0.8080	0.8105	0.8491
50	0.9416	0.8853	0.8842	0.8520	0.8515	0.9055
55	0.9622	0.9215	0.9278	0.9062	0.8918	0.9551
60	0.9765	0.9506	0.9601	0.9224	0.9360	0.9940
65	0.9862	0.9700	0.9791	0.9391	0.9406	0.9803
70	0.9927	0.9828	0.9914	0.9561	0.9462	1.0265
75	0.9973	0.9911	0.9961	0.9670	0.9605	1.0201
80	0.9989	0.9964	1.0216	0.9760	0.9669	0.9935
85	0.9995	0.9992	1.0103	0.9955	0.9907	0.9996
90	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
$\phi_{an}(r)$	0.94	0.88	0.88	0.84	0.85	0.85

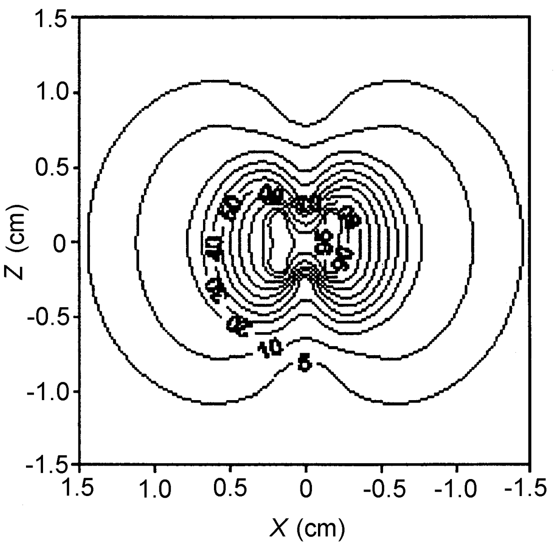

Fig. 5. Isodose curves of ADVANTAGE™ ^{103}Pd seed, obtained by Monte Carlo simulation using MCNP4C; Z axis is along the longitudinal axis of the seed.

curves are the dose values that are normalized to the maximum dose.

Conclusion

The results obtained in this work using MCNP4C code for ADVANTAGE™ ^{103}Pd seed are in good agreement with the results obtained by PTRAN code for the calculated dose rate constant and the calculated anisotropy constant. Also the radial dose function at distances less than 3 cm from the source center, and the two-dimensional anisotropy function at angles greater than 20° obtained from the two codes are in good agreement. The main discrepancies between the results obtained using the two mentioned codes are in the calculated radial dose functions for distances farther than 3 cm from the source center and in the two-dimensional anisotropy function for angles between 0 and 20°.

The differences between the results of MCNP4C and PTRAN codes could be related to the use of different data libraries.

Table 4. The two-dimensional anisotropy function, one-dimensional anisotropy function, and anisotropy constant of ADVANTAGE™ ^{103}Pd source calculated by Sowards [23]

Angle θ (deg.)	$F(r,\theta)$							
	0.5 cm	1.0 cm	2.0 cm	3.0 cm	4.0 cm	5.0 cm	6.0 cm	7.0 cm
0	0.319	0.307	0.320	0.337	0.349	0.365	0.392	0.379
5	0.333	0.310	0.324	0.340	0.356	0.365	0.384	0.397
10	0.349	0.321	0.335	0.352	0.367	0.371	0.390	0.399
15	0.436	0.350	0.362	0.381	0.395	0.413	0.425	0.430
20	0.520	0.482	0.482	0.490	0.500	0.522	0.521	0.518
25	0.807	0.549	0.539	0.544	0.553	0.568	0.579	0.577
30	0.852	0.705	0.641	0.627	0.626	0.641	0.647	0.650
35	0.880	0.752	0.724	0.724	0.716	0.727	0.741	0.740
40	0.902	0.807	0.796	0.794	0.792	0.802	0.805	0.782
45	0.941	0.906	0.895	0.882	0.873	0.890	0.882	0.858
50	1.021	0.948	0.926	0.912	0.903	0.921	0.918	0.887
55	1.020	0.964	0.946	0.936	0.930	0.940	0.937	0.888
60	1.016	0.976	0.963	0.951	0.946	0.957	0.936	0.956
65	1.009	0.984	0.975	0.967	0.966	0.992	0.990	0.975
70	1.003	0.990	0.986	0.979	0.976	0.992	1.018	0.953
75	0.997	0.994	0.994	0.988	0.986	0.997	1.019	0.961
80	0.992	0.997	0.999	0.993	0.975	1.013	1.009	0.985
85	0.990	0.999	1.000	0.999	0.989	1.033	1.005	0.973
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$\phi_{an}(r)$	0.940	0.890	0.860	0.860	0.870	0.860	0.880	0.870
Φ_{an}	0.880 ± 0.040							

According to our results and other investigations in this field, it seems that using photon and electron cross-section data libraries with more suitability for low energies will reduce these discrepancies and enhance the accuracy of the results.

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