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Pooneh Saidi[1] , Mahdi Sadeghi[2]

Dosimetry of two new interstitial brachytherapy sources

[1] Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2] Agricultural, Medical & Industrial Research School, Nuclear Science and Technology Research Institute,
P.O. Box 31485/498, Karaj, Tehran, Iran
E-mail: msadeghi@nrcam.org

With increased demand for low ^{103}Pd (palladium) seed sources, to treat prostate and eye cancers, new sources have been designed and introduced. This article presents the two new palladium brachytherapy sources, IR03-^{103}Pd and IR04-^{103}Pd that have been developed at *Nuclear Science and Technology Research Institute*. The dosimetry parameters such as the dose rate constant Λ, the radial dose function $g(r)$, and the anisotropy function $F(r,\theta)$, around the sources have been characterized using Version 5 Monte Carlo radiation transport code in accordance with the update AAPM Task Group No. 43 report (TG-43U1). The results indicated the dose rate constant of 0.689±0.02 and 0.667±0.02 cGy h^{-1} U^{-1} for the IR03-^{103}Pd and IR04-^{103}Pd sources respectively, which are in acceptable agreement with other commercial seeds. The calculated results were compared with published results for those of other source manufacturers. However, they show an acceptable dose distribution, using for clinical applications is pending experimental dosimetry.

Key Words: Monte Carlo calculation; brachytherapy; TG-43U1; MCNP5; ^{103}Pd.

Introduction

Brachytherapy became available as early as 1911 using radium needles. After discovering of new radio-nuclides, brachytherapy sources containing ^{103}Pd and ^{125}I are most commonly used in the treatment of eye and prostate cancer. Patients often suffer fewer side effects compared to when the employment of external radiation therapy or surgery is used and on the other hand the simplicity of the implementation causes the increasing the use of brachytherapy technique and providing new sources. For permanent implant brachytherapy, low energy photon emitting sources should be used which are encapsulated in brachytherapy seeds and embedded in tumour tissue [10-14]. Because low energy photon emitting sources are sensitive to design specifications and fabricating references, American Association of Physicists in Medicine (AAPM) TG-43U1 recommends that dosimetric parameters of a new brachytherapy source, should be accurately determined at least one experimental and one Monte Carlo determination before using each new source clinically [15].

This study presents the results of Monte Carlo calculations of the dosimetric parameters as TG-43U1 guidelines for IR03-^{103}Pd and IR04-^{103}Pd sources. Subsequently the results were compared with dosimetric parameters of other commercial sources model [5-7].

Materials and Methods

^{103}Pd source description

The IR03-^{103}Pd is depicted in Figure 1(a). The seed contains five resin beads, each in diameter of 0.6 mm with the compositions of (by weight percent): H- 8%; C- 90%; N- 0.3%; Cl- 0.7%; and Pd- 1%; and the density equal to 1.14 g/cm^3, which are packed inside a titanium cylinder of 4.5 mm length, 0.7 and 0.8 mm internal and external diameter respectively, and with an effective length of 3 mm. ^{103}Pd radioactive material is absorbed uniformly in the resin bead volume.

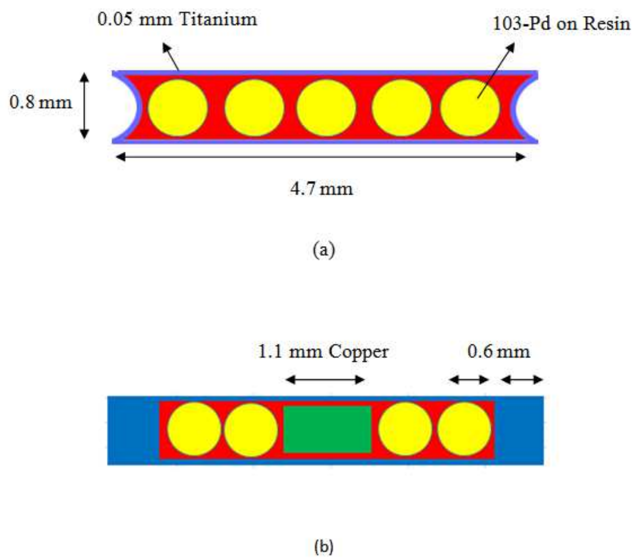

Figure 1. Schematic diagram of the (a) IR03-^{103}Pd seed, (b) IR04-^{103}Pd seed

Figure 1(b), shows a schematic diagram of the IR04-^{103}Pd seed. The seed contains four resin beads, each in diameter of 0.6 mm with the compositions of (by weight percent): H- 8%; C-90%; N- 0.3%; Cl- 0.7%; and Pd- 1%; and the density equal to 1.14 g/cm^3, and also contains a cylindrical copper marker with 1.1 mm length and 0.6 mm diameter which are packed inside a titanium cylinder of 4.7 mm length, 0.7 and 0.8 mm internal and external diameter respectively, and with an effective length of 2.4 mm. ^{103}Pd radioactive material is absorbed uniformly in the resin bead volume.

Monte Carlo evaluation

Brachytherapy dose distributions were simulated with the MCNP5 Monte Carlo (MC) radiation transport code written by Los Alamos National Laboratory [9][8]. The MCPLIB04 photon cross--section library was applied using data from ENDF/B-VI [1]. The results from the MCNP5 calculations contained numerous flexible tallies: surface current and flux, volume flux (track length), point or ring detectors, particle heating, fission heating, pulse height tally for energy or charge deposition, mesh tallies, and radiography tallies [3]. Particle fluence and cell-heating tallies (F4 and F6) were employed to calculate kerma and absorbed dose in this study. The ^{103}Pd photon spectrum used in these simulations was obtained from TG-43U1 Table XIII [15]. All sources have been simulated in the center of a spherical phantom of water with 15 cm radius, large enough to consider all the scattering effects of the surrounding medium with an array of 1 mm thick detector rings. According to TG-43U1 recommendation, detectors should be tabulated at radial distances, r = 0.5, 1, 2, 3, and 5 cm for ^{103}Pd, and from θ=0° to 90° with 10° increments for all sources that are symmetric about the transverse plane, so the rings were bounded with two cones (10°) bisecting the sphere corresponding to points [11, 15]. Detectors were defined at distances of r= 0.25, 0.5, 0.75, 1, 2, 3, 4, 5 and 7 cm, away from the source and at polar angles relative to the seed longitudinal axis from 0° to 90° with 10° increment.

Dose distributions around the sources

According to TG43-U1 formalism, the proposed formula for two-dimensional dose rate is:

$$\dot{D}(r,\theta) = S_K \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r) F(r,\theta) \tag{1}$$

where $\dot{D}(r,\theta)$ is the dose rate in water at the distance r in cm from a line source and θ denotes the polar angle specifying the point of interest, S_K is the air -kermastrength has unit of $U = cGy\ cm^2\ h^{-1}$, Λ is the dose rate constant expressed in $cGy\ h^{-1}\ U^{-1}$ and depends on radionuclide and source model;
$\frac{G(r,\theta)}{G(r_0,\theta_0)}$ is the geometry factor; r_0, θ_0 are the reference position, $r_0 = 1$ cm and $\theta_0 = 90^0$, $g(r)$ is the radial dose function; and $F(r,\theta)$ is the anisotropy function.

The dose rate constant is calculated using the following equation:

$$\Lambda = \frac{\dot{d}(r_0,\theta_0)}{S_K} \qquad (2)$$

The parameter $\dot{d}$ $(r_0\theta_0)$, is the dose rate per history estimated using Monte Carlo methods at the reference position. Air-kerma strength is the product of air-kerma rate in free space at the measured distance from the source centre along the perpendicular bisector, r, multiplied by the square of this distance, r^2:

$$S_K = \dot{K}_\delta(r)r^2 \qquad (3)$$

Generally, to relate the calculated collision kerma rate ($\dot{K}_\delta$) with the source strength (air-kerma-U) the following equations are used:

$$\dot{K}_\delta\left[\frac{MeV}{(g.dis)}\right] = K'\left[\frac{MeV}{g.\gamma}\right].f.\left[\frac{\gamma}{dis}\right] \qquad (4)$$

Where K' is kerma per photon, γ is the unit of MeV/(g. γ) and f is the ratio of photon/disintegration [22].

Due to the low energy of the photons from ^{103}Pd, it was assumed in the Monte Carlo calculations that all electrons generated by the photon collisions are absorbed locally, so dose is equal to kerma at all points of interest [17, 18]. The air-kerma rates, $\dot{k}_\delta(r)$, of the IR03-^{103}Pd and IR04-^{103}Pd seeds were estimated by calculating the dose in 1 mm-thick air-filled rings in a vacuum. The rings were bounded by 86° and 94° conics and defined with a radial increment of 5 cm to 150 cm along the transverse axis of the source [8, 19]. In these calculations, the titanium characteristic x-ray production was suppressed with δ=5 keV (δ is the energy cutoff) [13]. The MCNP F6 tally was used in order to calculate the dose distribution around the seeds.

There are two calculation methods for geometry function:

a) Analytical method, where geometry function is calculated according to the following equation:

$$G_P(r,\theta) = r^{-2} \quad \text{For the point-source}$$

$$G_L(r,\theta) = \begin{cases} \frac{\beta}{Lr\sin\theta} & if\ \theta \neq 0^\circ \\ (r^2 - \frac{L^2}{4})^{-1} & if\ \theta = 0^\circ \end{cases} \quad \text{For the line-source} \qquad (5)$$

$$\beta = \tan^{-1}\left(\frac{r\sin\theta}{r\cos\theta - L/2}\right) - \left(\frac{r\sin\theta}{r\cos\theta + L/2}\right)$$

b) MCNP computer code;

According to the TG-43 report, the role of the geometry factor, G(r,θ), is to suppress the influence of the inverse square law on the radial dose function and the anisotropy function and it provides a definition of the geometry factor in two simple forms, one for point sources and one for line sources [4, 11, 16].

In this study, for each source, the geometry function was calculated for line source.

According to the methodology described in TG-43U1; radial dose function, *g(r)*, was calculated by using line and point-source geometry for IR03-^{103}Pd and IR04-^{103}Pd seeds with an effective length of 2.4 and 3 mm respectively. The radial dose function is defined as:

$$g_X(r) = \frac{\dot{D}(r,\theta_0)}{\dot{D}(r_0,\theta_0)} \frac{G_X(r_0,\theta_0)}{G_X(r,\theta_0)}, \quad X = P\ or\ L\ (Point\ or\ line\ source) \qquad (6)$$

The anisotropy function values were calculated for each seed at radial distances from r = 0.25, to 7 cm, away from the sources and at polar angles relative to the seed longitudinal axis from 0° to 90° with 10° increment by the following equation:

$$F(r,\theta) = \frac{\dot{D}(r,\theta)}{\dot{D}(r,\theta_0)} \frac{G_X(r,\theta_0)}{G_X(r,\theta)} \qquad (7)$$

The simulations were performed up to 1×10^9 histories in water with statistical uncertainties of 0.05% to 0.1% at 1 and 5 cm on the transverse plane and 1.1% and 2.3% at

1 cm and 5 cm along the long axis. In air with 7×10^7 histories, statistical uncertainty was 1%. The MCNP simulation method in this work was benchmarked with the Teragenics model 200 [21].

Results

The comparison of MCNP-calculated value of Λ, with the previously published data for the Teragenics model 200 source, [21] demonstrated the accuracy of our simulation method (see Table 1). The dose rate constant values for the IR03-^{103}Pd and IR04-^{103}Pd seeds are 0.689±0.02 and 0.667±0.02 cGy h^{-1} U^{-1}, respectively. Table 1 presents a comparison between the calculated dose rate constant for these sources and dose rate values for other commercial sources [5, 7, 11]. According to the Table 1, the dose rate constant values of two new ^{103}Pd sources are in range with the dose rate constant values for three other commercial sources.

Table 1. Monte Carlo calculated dose rate constant, Λ, of the IR03-^{103}Pd, IR04-^{103}Pd and Theragenics200 sources and comparison with the measured and calculated values of model MED3633, Theragenics model 200 and Best® double-wall ^{103}Pd sources

Source type	Method	Medium	Λ (cGy h^{-1} U^{-1})	Reference
IR03-^{103}Pd	Monte Carlo simulation (MCNP5)	Liquid water	0.692±0.02	This study
IR04-^{103}Pd	Monte Carlo simulation (MCNP5)	Liquid water	0.689±0.02	This study
Theragenics200	TLD dosimetry	Solid water	0.650±0.08	Ref. [11]
	Monte Carlo simulation	Liquid water	0.686±0.03	Ref. [21}
	Monte Carlo simulation (MCNP5)	Liquid water	0.685±0.01	This study
MED3633	TLD dosimetry	Solid water	0.688±0.05	Ref. [20]
	Monte Carlo simulation	Liquid water	0.677±0.02	Ref. [5]
Best ^{103}Pd	TLD dosimetry	Solid water	0.69±0.08	Ref. [7]
	Monte Carlo simulation	Liquid water	0.67±0.02	Ref. [7]

The Monte Carlo simulated line and point-radial dose function of the IR03-^{103}Pd and IR04-^{103}Pd sources has been determined in water, over the range of 0.25 to 7 cm. The results are shown in Table 2. The *g(r)*, of the two new ^{103}Pd seeds was calculated at 0.25 cm increments from 0.25 to 1 cm, 0.5 cm increments from 1 to 2 cm and 1 cm increments from for distances between 2 and 7 cm.

Table 2. Monte Carlo calculations for radial dose function, $g_L(r)$ and $g_P(r)$ for line and point source geometry for IR03-^{103}Pd and IR04-^{103}Pd seeds in comparison with other available sources in water

Distance, r (cm)	$g_L(r)$ in water					$g_P(r)$ in water	
	IR03-^{103}Pd	IR04-^{103}Pd	Teragenics200	MED3633	Best ^{103}Pd	IR03-^{103}Pd	IR04-^{103}Pd
	Present work (MCNP5)	Present work (MCNP5)	Ref. [15]	Ref. [15]	Ref. [7]	Present work (MCNP5)	Present work (MCNP5)
0.25	1.404	1.280	1.370	1.331	1.212	1.389	1.129
0.5	1.291	1.300	1.300	1.243	1.224	1.273	1.124
0.75	1.154	1.190	1.150	1.125	1.127	1.134	1.068
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.5	0.777	0.735	0.749	0.770	0.769	0.762	0.790
2	0.583	0.575	0.555	0.583	0.583	0.572	0.600
3	0.320	0.350	0.302	0.325	0.325	0.314	0.360
4	0.173	0.200	0.163	0.177	0.179	0.170	0.200
5	0.093	0.120	0.089	0.098	0.097	0.092	0.120
7	0.027	0.050	0.026	0.028	0.031	0.027	0.030

Discussion

Figure 2 shows a comparison of the radial dose function of the seeds with the MED3633, Teragenic model 200 and Best® double-wall ^{103}Pd sources [7, 15]. The differences between these data sets are probably due to the use of two different version of MCNP code with different cross-section libraries, and also since the seed geometries differ; but as shown in the figure, acceptable agreement appears between the curves.

Radial dose functions for both seeds were fit to a fifth order polynomial function yielded the following relationship. (Distance r is expressed in cm and $r \geq 0.5$ cm):

$$g_L(r) = a_0 + a_1r + a_2r^2 + a_3r^3 + a_4r^4 + a_5r^5 \quad (8)$$

where:

for IR03-^{103}Pd: a_0 = 1.534, $a_1 = 5.933\times10^{-1}$, $a_2 = 2.731\times10^{-2}$, $a_3 = 2.362\times10^{-2}$, $a_4 = 4.778\times10^{-3}$, and $a_5 = 2.783\times10^{-4}$ define $R^2 = 9.998\times10^{-1}$,

for IR04-^{103}Pd: a_0 = 1.702, $a_1 = 8.333\times10^{-1}$, $a_2 = 1.302\times10^{-1}$, $a_3 = 1.022\times10^{-2}$, $a_4 = 4.996\times10^{-3}$ and $a_5 = 3.742\times10^{-4}$ define $R^2 = 9.985\times10^{-1}$,

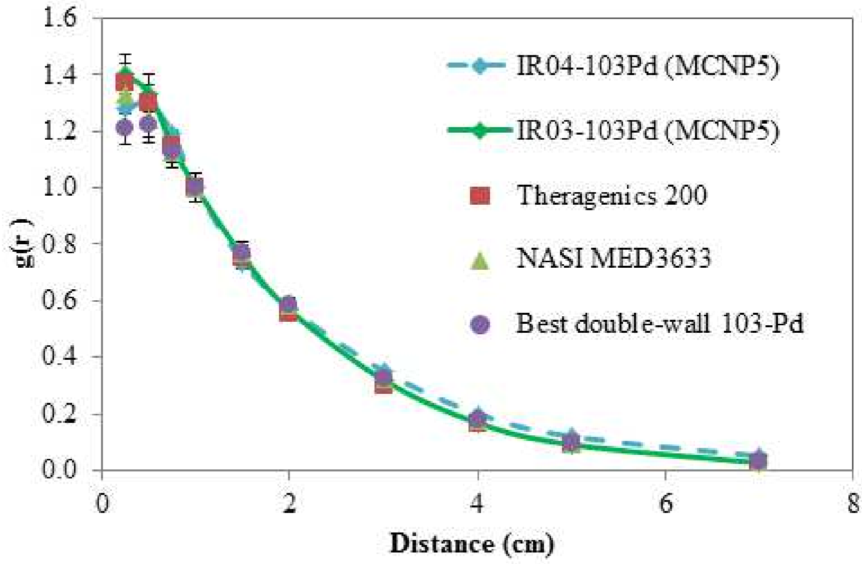

Figure 2. Comparison of calculated radial dose function of IR03-^{103}Pd and IR04-^{103}Pd seeds in water versus other available sources

The anisotropy functions, *F(r,θ),* in this study were calculated using MCNP5 in water phantom at radial distances of r = 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5and 7 cm relative to the seed center and polar angle, θ ranging from 0° to 90° in 10° increment with respect to the seeds long axis. A complete set of anisotropy data determined by Monte Carlo calculations is tabulated in Table 3.

Dosimetric parameters, including dose rate constant, *Λ*, geometry function, *G(r,θ),* radial dose function, *g(r),* and anisotropy function, *F(r,θ)* of the IR03-^{103}Pd and IR04-^{103}Pd brachytherapy seeds have been calculated by using the MCNP5 Monte Carlo code. These results indicate an acceptable agreement between the two new ^{103}Pd sources and other commercial available sources. It shows in distances greater than 0.5 cm, the effect of absorption and scatter in water along the source transverse axis, are the same for all ^{103}Pd sources considered in this study

Table 3. Monte Carlo calculated anisotropy function, *F(r;θ)*, of a) IR03-^{103}Pd and b) IR04-^{103}Pd source in water

r (cm)	a) Calculated *F(r;θ)* of IR03-^{103}Pd, (MCNP5)									
	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
0.25	0.999	0.619	0.787	0.888	0.937	0.965	0.982	0.993	0.998	1
0.5	0.597	0.666	0.64	0.79	0.885	0.936	0.969	0.987	0.998	1
0.75	1.07	0.653	0.647	0.768	0.871	0.927	0.963	0.984	0.996	1
1	0.545	0.664	0.668	0.781	0.883	0.943	0.98	1.002	1.014	1
1.5	0.557	0.655	0.668	0.771	0.861	0.924	0.96	0.984	0.995	1
2	0.591	0.663	0.679	0.776	0.862	0.923	0.96	0.984	0.995	1
3	0.66	0.675	0.694	0.785	0.863	0.925	0.961	0.984	0.996	1
4	0.715	0.684	0.706	0.79	0.868	0.924	0.962	0.984	0.997	1
5	0.621	0.61	0.713	0.796	0.864	0.924	0.962	0.983	0.996	1
7	0.88	0.714	0.736	0.803	0.878	0.928	0.963	0.984	0.997	1
r (cm)	b) Calculated *F(r;θ)* of IR04-^{103}Pd, (MCNP5)									
	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
0.25	0.048	0.058	0.552	0.807	0.899	0.931	0.951	0.971	0.992	1
0.5	0.115	0.126	0.329	0.568	0.738	0.848	0.919	0.962	0.99	1
0.75	0.157	0.166	0.327	0.548	0.708	0.823	0.905	0.959	0.989	1
1	0.179	0.194	0.343	0.551	0.703	0.817	0.901	0.958	0.99	1
1.5	0.236	0.236	0.371	0.562	0.707	0.815	0.899	0.957	0.99	1
2	0.262	0.264	0.392	0.572	0.711	0.816	0.9	0.957	0.989	1
3	0.306	0.302	0.422	0.589	0.719	0.82	0.9	0.956	0.989	1
4	0.324	0.325	0.441	0.602	0.726	0.824	0.903	0.956	0.99	1
5	0.342	0.347	0.455	0.608	0.728	0.827	0.901	0.955	0.989	1
7	0.367	0.374	0.476	0.619	0.736	0.829	0.905	0.956	0.989	1

Figure 3 shows a comparison between the Monte Carlo calculated anisotropy function of the IR03-^{103}Pd and IR04-^{103}Pd seeds at distances of 1, 2 and 5 cm from the source centre in water with the published data. The values of calculated anisotropy function for two new ^{103}Pd sources agreed with those for the model MED3633, Teragenic model 200 and Best® double-wall ^{103}Pd sources, within 4% in angles greater than 20º. The differences in smaller angles can be as large as 17%, due to the thicker end caps of IR03-^{103}Pd and IR04-^{103}Pd sources in comparison with three other sources.

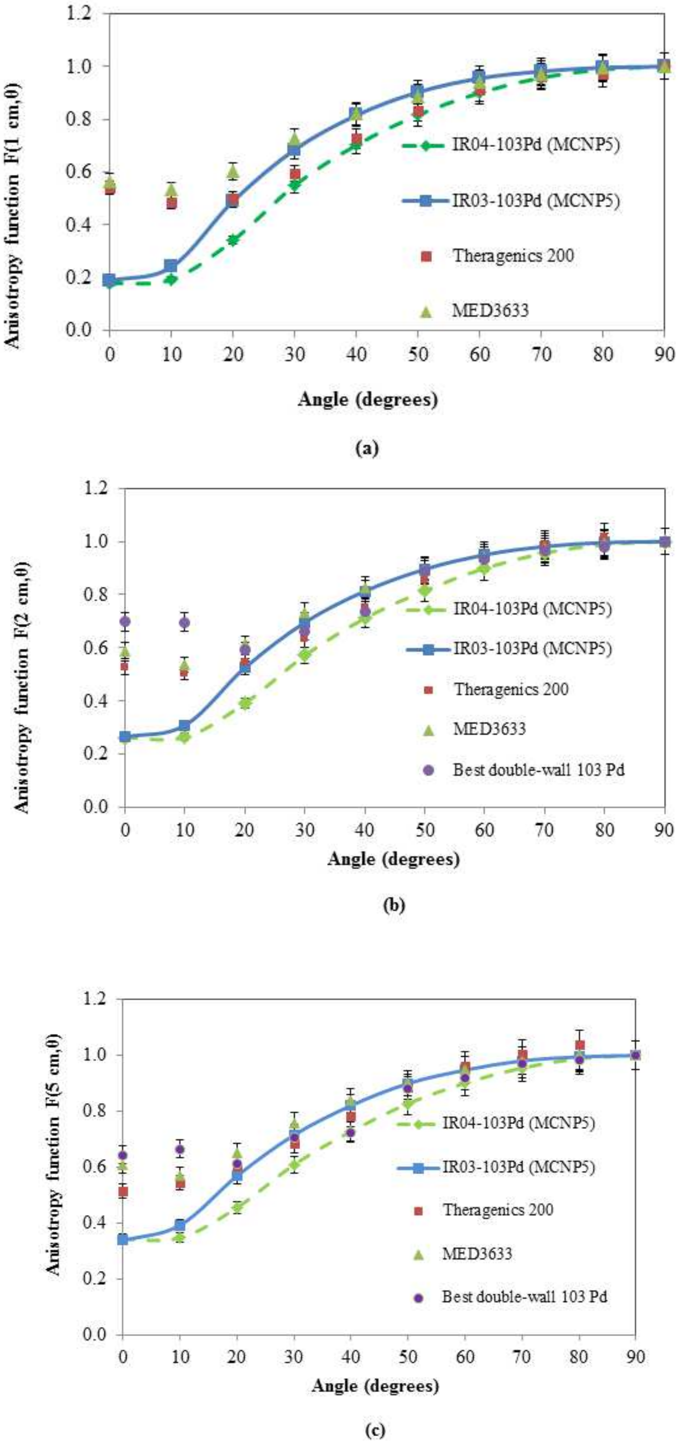

Figure 3. Comparison of the calculated anisotropy function of the IR03-103Pd and IR04-103Pd seeds versus other available sources at the distances (a) 1 cm, (b) 2 cm and (c) 5 cm from the source

Conclusions

Three brachytherapy seeds - the model IR03-^{103}Pd, IR04-^{103}Pd and Theragenics model 200 - were simulated using MCNP5. Dosimetric parameters, including dose rate constant, Λ, radial dose function, $g(r)$, and anisotropy function, $F(r,\theta)$ of the three seeds, have been calculated, based on TG-43U1 recommendations. Calculation results of the Theragenics model 200 were in good agreement with previously published values. The results were compared with other published data in tabulated and graphical format. The dose rate constant, Λ, values for IR03-^{103}Pd and IR04-^{103}Pd seeds in water were calculated to be 0.692 ± 0.02 and 0.689 ± 0.02 cGy h^{-1} U^{-1}. Acceptable agreement between dosimetric parameters of these two new designed sources and other sources models indicates that IR03-^{103}Pd and IR04-^{103}Pd seeds have an acceptable dose distribution and implementation of these seeds for brachytherapy, is pending experimental dosimetry.

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