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Dosimetric parameters of the new design ^{103}Pd brachytherapy source based on Monte Carlo study

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Abstract In this study version 5 of the MCNP photon transport simulation was used to calculate the dosimetric parameters for new palladium brachytherapy source design following AAPM Task Group No. 43U1 report. The internal source components include four resin beads of 0.6 mm diameters with ^{103}Pd uniformly absorbed inside and one cylindrical copper marker with 1.5 mm length. The resin beads and marker are then encapsulated within 0.8 mm in diameter and 4.5 mm long cylindrical capsule of titanium. The dose rate constant, Λ , line and point-source radial dose function, $g_L(r)$ and $g_P(r)$, and the anisotropy function, $F(r, \theta)$ of the IR01- ^{103}Pd seed have been calculated at distances from 0.25 to 5 cm. All the results are in good agreement with previously published thermoluminescence-dosimeter measured values [3] for the source. The dosimetric parameters calculated in this work showed that in dosimetry point of view, the IR01- ^{103}Pd seed is suitable for use in brachytherapy of prostate cancer.

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Introduction

Brachytherapy sources of low energy photons (such as those emitted by ^{125}I and ^{103}Pd) commonly are used for radiotherapy of eye and prostate cancers. 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. The short half-life (~ 17 days) and low energy photon emissions of ^{103}Pd (20 keV) are advantages in permanent implants in comparison with ^{125}I [1–3]. Since low energy photon-emitting sources are sensitive to design specifications and fabrication practices, American Association of Physicists in Medicine (AAPM) TG-43U1 recommends that before using each new source clinically, the dosimetric characteristics of the source must be

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Figure 1 Schematic diagram of the IR01-¹⁰³Pd seed.

determined to provide reliable data for use in treatment planning calculations and dose prescription. The AAPM has recommended that dosimetry characteristics of low energy photon-emitting sources should be established by two independent investigators, theoretical calculations and experimental measurements [4].

This work is dedicated to the Monte Carlo method to calculate the dosimetric parameters by MCNP5 code, as TG-43U1 guidelines for the new palladium brachytherapy source, IR01-¹⁰³Pd, which was developed at *Nuclear Science and Technology Research Institute*, and through comparison with measured values from another published report for the same source [3]. All data compared favorably with the Theragenics, Inc. (Buford, GA) model 200 and Brachytherapy Service, Inc. (Chatsworth, CA) model MED3633 sources.

Methods

IR01-¹⁰³Pd seed description

Figure 1, shows a schematic diagram of the IR01-¹⁰³Pd brachytherapy 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/cm³, which are packed inside a titanium cylinder of 4.5 mm length, 0.7 and 0.8 mm internal and external diameter respectively. ¹⁰³Pd radioactive material is absorbed uniformly in the resin bead volume. The source also contains a cylindrical copper marker with 1.5 mm length and 0.6 mm diameter which is located at the center of the seed. According to TG-43U1,

the effective length is considered as the distance between proximal and distal aspects of the activity distribution which is 3.9 mm.

Monte Carlo evaluation

Brachytherapy dose distributions were simulated with the MCNP5 Monte Carlo (MC) radiation transport code written by Los Alamos National Laboratory [5]. The MCPLIB04 photon cross-section library was applied using data from ENDF/B-VI [6]. The results from the MCNP5 calculations contains 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. Particle fluence and cell-heating tallies, F4 and F6 respectively were employed to calculate kerma and absorbed dose in this study. The ¹⁰³Pd photon spectrum used in these simulations was obtained from TG-43U1 Table XIII from Reference [4]. For the calculations, the titanium characteristic X-ray production were suppressed with $\delta = 5$ keV (δ is the energy cutoff) [7]. The spherical water phantom was modeled with a 30 cm diameter, large enough to consider effects of the surrounding medium, with an atomic ratio of 2:1 for H:O and $\rho = 0.998$ g/cm³. The seed was positioned at the center of the phantom and an array of detector rings were defined in this phantom for Monte Carlo simulation at polar angles from 0° to 90° in 15° increments and at radial distances of $r = 0.25, 0.5, 1, 1.5, 2, 3, 4$ and 5 cm. To compare the experimental values [3] and calculated data the spherical Perspex phantom was modeled. The composition of the Perspex was taken to be H, 8%; C, 60%; O, 32% with a density of 1.19 g/cm³ [8].

According to TG-43U1 recommendation, the proposed formula for two-dimensional dose rate is:

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

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-kerma strength has unit of $U = \text{cGy cm}^2 \text{ h}^{-1}$, Λ is the dose rate constant expressed in $\text{cGy h}^{-2-1} U^{-1}$; $\frac{G(r, \theta)}{G(r_0, \theta_0)}$ is the geometry factor; r_0, θ_0 are the reference position, $r_0 = 1 \text{ cm}$ and $\theta_0 = 90^\circ$, $g(r)$

Table 1 Monte Carlo calculated dose rate constant, Λ , of the IR01-¹⁰³Pd seed and comparison with the measured and calculated values of model MED3633, Theragenics 200 and Best[®] double-wall sources.

Source type	Method	Medium	Λ (cGy h ⁻¹ U ⁻¹)
IR01- ¹⁰³ Pd	Monte Carlo simulation (MCNP5) (Present work)	Liquid water	0.677 ± 0.02
	Monte Carlo simulation (Ref. [3])	Liquid water	0.69 ± 0.05
	Monte Carlo simulation (MCNP5) (Present work)	Perspex	0.679 ± 0.02
	TLD dosimetry (Ref. [3])	Perspex	0.83 ± 0.05
Theragenics 200	Monte Carlo simulation (MCNP5) (Present work)	Liquid water	0.685 ± 0.02
	Monte Carlo simulation (Ref. [13])	Liquid water	0.686 ± 0.03
	TLD dosimetry (Ref. [16])	Solid water	0.650 ± 0.08
MED3633	Monte Carlo simulation (Ref. [17])	Liquid water	0.677 ± 0.02
	TLD dosimetry (Ref. [18])	Liquid water	0.680 ± 0.05
Best [®] double-wall	TLD dosimetry (Ref. [15])	Solid water	0.69 ± 0.08
	Monte Carlo simulation (Ref. [15])	Liquid water	0.67 ± 0.02

Table 2 Monte Carlo calculated normalized geometry function for the IR01- ^{103}Pd seed.

$r(\text{cm})$	$\theta = 0^\circ$		$\theta = 15^\circ$		$\theta = 30^\circ$		$\theta = 45^\circ$		$\theta = 60^\circ$		$\theta = 90^\circ$	
	(MCNP5) (Present work)	(MCNP4C) (Ref. [3])	(MCNP5) (Present work)	(MCNP4C) (Ref. [3])	(MCNP5) (Present work)	(MCNP4C) (Ref. [3])	(MCNP5) (Present work)	(MCNP4C) (Ref. [3])	(MCNP5) (Present work)	(MCNP4C) (Ref. [3])	(MCNP5) (Present work)	(MCNP4C) (Ref. [3])
0.25	3.205	3.245	2.532	2.574	1.682	1.691	1.200	1.202	0.949	0.952	0.790	0.793
0.5	1.256	1.293	1.253	1.233	1.179	1.183	1.089	1.089	1.013	1.011	0.948	0.946
1	1.036	1.072	1.065	1.078	1.055	1.062	1.037	1.040	1.019	1.019	1.000	1.000
1.5	1.006	1.060	1.033	1.047	1.032	1.037	1.026	1.030	1.019	1.022	1.011	1.013
2	0.994	1.042	1.023	1.036	1.025	1.030	1.023	1.025	1.019	1.021	1.014	1.018
3	0.989	1.025	1.015	1.027	1.019	1.026	1.020	1.022	1.019	1.020	1.017	1.021
4	0.987	1.032	1.013	1.027	1.017	1.024	1.019	1.021	1.019	1.021	1.018	1.022
5	0.985	1.024	1.012	1.024	1.016	1.022	1.019	1.021	1.019	1.020	1.019	1.022

is the radial dose function; and $F(r, \theta)$ is the anisotropy function.

The dose rate constant, Λ , for the IR01- ^{103}Pd seed was calculated as the ratio of the dose to water at 1 cm from the seed along the transverse axis, to the source's air-kerma strength, S_K , at distance r from the source center. The air-kerma strength was calculated using the recommended equation below [4],

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

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 it was assumed that dose is equal to kerma at all points of interest [8]. The air-kerma rate, $\dot{K}_\delta(r)$, of the IR01- ^{103}Pd seed was estimated by calculating the dose in 1 mm-thick air-filled rings in vacuum. The rings were bounded by 86° and 94° conics and defined with a radial increment of 5 cm–150 cm along the transverse axis of the source to find the S_K that is independent to distance [9]. The dose distributions were calculated from the energy deposition averaged over a cell tally F6 in MeV/g/source photon. To evaluate the simulation accuracy in this study, the Λ value was calculated for Theragenics model 200 source.

The geometry function takes into account the effect of the distribution of radioactive material inside the capsule on the dose distribution [10]. $G(r, \theta)$ is a function of r which is equal to distance from the source center, polar angle θ and L_{eff} , effective length of source [11]. Geometry function is calculated according to the following equation:

$$G_L(r, \theta) = \begin{cases} G_p(r, \theta) = r^{-2} & \text{For the point – source} \\ \left\{ \begin{array}{l} \frac{\beta}{L r \sin \theta} \\ \left(r^2 - \frac{L^2}{4} \right)^{-1} \end{array} \right\} & \begin{array}{l} \text{if } \theta \neq 0^\circ \\ \text{if } \theta = 0^\circ \end{array} \end{cases} \quad \text{For the line – source} \quad (3)$$

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

In this study the geometry function was calculated for a line source using the MCNP F4 tally, particle fluence ($1/\text{cm}^2$) with the mass densities of all materials within the entire computational geometry set equal to zero so there were no interaction through the seed and phantom geometry [11,12].

The radial dose function describes the effect of tissue attenuation on photons emitted from a brachytherapy source and accounts for the dose fall-off along the source transverse axis due to the photon scattering and attenuation. According to the TG-43U1 Monte Carlo methodology; $g(r)$ was calculated by using line (with an effective length of 3.5 mm) and point-source geometry for IR01- ^{103}Pd seed [4]:

$$g_X(r) = \frac{\dot{D}(r, \theta_0)}{\dot{D}(r_0, \theta_0)} \frac{G_L(r_0, \theta_0)}{G_L(r, \theta_0)} \quad (4)$$

Dose variations due to the distribution of radioactivity within the seed, self-absorption and oblique filtration of the radiation in the encapsulating material, are described by the 2D anisotropy function.

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

Table 3 Monte Carlo calculations for radial dose function for line and point-source geometry, $g_L(r)$ and $g_P(r)$, for IR01- ^{103}Pd seed with an effective length of 3.9 mm, in comparison with TLD measurements of (Ref. [3]) in Perspex and also calculated in water.

r (cm)	$g_L(r)$ (Perspex)			$g_L(r)$ (Water)		$g_P(r)$ (Water)
	MCNP5 (Present work)	TLD measurement (Ref. [3])	MCNP4C (Ref. [3])	MCNP5 (Present work)	MCNP4C (Ref. [3])	MCNP5 (Present work)
0.25	1.230	—	1.09	1.39	1.24	1.088
0.5	1.224	1.07	1.12	1.242	1.22	1.173
1	1.000	1.00	1.00	1.000	1.00	1.000
1.5	0.793	0.83	0.85	0.767	0.78	0.774
2	0.640	0.66	0.71	0.576	0.60	0.580
3	0.392	0.41	0.47	0.338	0.35	0.341
4	0.254	0.28	0.30	0.165	0.20	0.166
5	0.171	0.19	0.19	0.089	0.11	0.092

The simulations in water and Perspex were performed up to 2.3×10^9 histories. With this number of histories, statistical uncertainty for the source along the longitudinal axis from 0.25 to 5 cm is lower than 0.1%, and at other angles it is between 0.04% and 2%. In air, with 1.3×10^8 histories, statistical uncertainty is 0.1%.

Results and discussions

We had performed MCNP simulation for Theragenics model 200 source for benchmark and validate our MCNP simulation method. Comparison of MCNP-calculated value of Δ for Theragenics model 200 source in this study and the previous published data for the source demonstrated the accuracy of our simulation method. The calculated dose rate constant for the seed was found to be $0.677 \pm 0.02 \text{ cGy U}^{-1} \text{ h}^{-1}$ compared to the value, $0.69 \pm 0.05 \text{ cGy U}^{-1} \text{ h}^{-1}$, obtained by Raisali et al. [3]. The difference between these two data derives from the use of different methods to calculate the air-kerma strength, S_K . Raisali et al. calculated S_K only in one air-filled detector placed at a distance of 1 m in the transverse plane of the seed, use of two different versions of MCNP code (MCNP4C & MCNP5) and two different simulation geometries. In our study, S_K was calculated in several

air-filled detectors at distances ranging from 5 to 150 cm in the transverse plane, and was found to be independent of distance. The result is comparable with Δ values obtained for other ^{103}Pd sources which are presented in TG-43U1. Table 1 shows the calculated dose rate constant for the IR01- ^{103}Pd seed and the calculated and measured values of Δ , for NASI model MED3633, Theragenics model 200 and Best® double-wall sources.

Geometry function values for the IR01- ^{103}Pd seed have been calculated by MCNP5 at $r = 0.25, 0.5, 0.75, 1, 2, 3, 4$ and 5 cm distances from the source and for angles $\theta = 0^\circ\text{--}90^\circ$. The form, $r^2 G(r, \theta)$, is used instead of $G(r, \theta)$, for easier calculations and then normalized to $G(1 \text{ cm}, \pi/2)$ for convenience to compare with other published data [14]. The calculated values by Raisali et al. are shown in Table 2 to compare with the calculated data in this study. The differences between these two data sets vary by less than 4.5% probably due to the use of two different version of MCNP code, MCNP5 and MCNP4C with different cross-section libraries, DLC-200 and MCPLIB04 respectively.

The calculated line and point-source radial dose function, $g_L(r)$ and $g_P(r)$, for the IR01- ^{103}Pd seed in Perspex and water in this work and those determined from calculated and measurement by Raisali et al. are presented in Table 3.

Figure 2 Comparison of the measured and the Monte Carlo calculated radial dose function of the IR01- ^{103}Pd seed in Perspex phantom using the line source approximation.

Figure 3 Comparison of the Monte Carlo calculated radial dose function of the IR01- ^{103}Pd seed in water vs. three available sources.

Table 4 Monte Carlo calculated anisotropy function, $F(r, \theta)$, for IR01- ^{103}Pd seed in Perspex in compare with measured values.

r (cm)	MCNP5 (Present work)							Measurement (Ref. [3])		
	0°	15°	30°	45°	60°	75°	90°	0°	30°	60°
0.25	1.100	0.732	0.944	0.968	0.975	0.992	1.000			
0.5	0.836	0.609	0.701	0.853	0.924	0.975	1.000			
1	0.598	0.531	0.556	0.590	0.793	0.957	1.000	0.650	0.600	0.900
1.5	0.697	0.598	0.678	0.813	0.916	0.978	1.000			
2	0.690	0.604	0.685	0.813	0.916	0.977	1.000	0.700	0.720	0.950
3	0.672	0.615	0.698	0.819	0.918	0.980	1.000	0.670	0.720	0.900
4	0.635	0.622	0.708	0.823	0.921	0.979	1.000			
5	0.673	0.629	0.711	0.823	0.919	0.979	1.000

Figure 4 Comparison between measured and calculated results for IR01- ^{103}Pd seed anisotropy functions in Perspex phantom at (a) 1 cm, (b) 2 cm and (c) 3 cm.

The $g(r)$, of the new ^{103}Pd seed was calculated at 0.5 cm increments from 0.25 to 5 cm. The data for line source are shown graphically in Fig. 2. The differences between calculated and measured values are a function of phantom size and depending on the distance: 2 cm (3%), 3 cm (4%) and 5 cm (11%). The characteristic X-rays generated from the copper ($K_{ab} = 8.98$ keV, $K_{\beta 2} = 8.97$ keV, $K_{\beta 1} = 8.90$ keV, $K_{\alpha 1} = 8.047$ keV, $K_{\alpha 2} = 8.047$ keV) are substantially attenuated in the titanium capsule and so have no significant effect on the photon spectrum and the source emits an essentially pure ^{103}Pd decay scheme spectrum [7].

The radial dose function, $g(r)$, for IR01- ^{103}Pd seed and three other commercial sources is presented in Fig. 3. $g_L(r)$ for the seed was fit to a fifth order polynomial function yielded the following relationship:

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

Where $a_0 = 1.5137\text{E}+00$, $a_1 = -4.9472\text{E}-01$, $a_2 = -9.7157\text{E}-02$, $a_3 = 8.8355\text{E}-02$, $a_4 = -1.9072\text{E}-02$ and $a_5 = 1.3950\text{E}-03$, define $R = 0.999$.

The 2D anisotropy function, $F(r, \theta)$, of the IR01- ^{103}Pd seed was calculated in Perspex and water phantom at radial distances of $r = 0.25, 0.5, 1, 1.5, 2, 3, 4$ and 5 cm relative to the seed center and polar angle, θ ranging from 0° to 90° in 15° increment with respect to the seed long axis. The results are presented in Table 4 in comparison with the

Figure 5 Comparison of the Monte Carlo calculated anisotropy function of IR01- ^{103}Pd seed with MED3633, Theragenics 200 and Best double-wall sources in water at distance of 5 cm from the source center.

measured data and shown graphically at distances of $r = 1$, 2 and 3 cm in Fig. 4.

Figure 4(c), shows a good agreement between the measured and calculated 2D anisotropy function of the IR01- ^{103}Pd source in Perspex at 3 cm distance from the source center at all angles. A slight difference between Monte Carlo calculated anisotropy function and measured values at shorter distances and small angles, has been attributed to the large gradient of radiation in this angular range due to oblique filtration of the photons through the capsule and marker [15]. Figure 5 shows a comparison of the anisotropy function in water at $r = 5$ cm of the IR01- ^{103}Pd with Theragenics 200, MED3633 and Best double-wall sources.

Conclusion

The new brachytherapy source, IR01- ^{103}Pd model, was simulated in water and Perspex phantom using MCNP5. Dosimetric parameters including dose rate constant, A , geometry function, $G(r, \theta)$, radial dose function, $g(r)$, and anisotropy function, $F(r, \theta)$ of the seed were calculated according to the AAPM TG-43U1 recommendations. The results compared with measured values for the same seed and also compared with three other commercial sources. The information is presented in tabulated and graphical format. Based on the calculations, the dose rate constant for the IR01- ^{103}Pd source estimated to be 0.677 ± 0.020 cGy $\text{U}^{-1} \text{h}^{-1}$ which is comparable with the published data of 0.686 ± 0.003 for Theragenics 200 and 0.677 ± 0.003 for MED3633 [13,18]. The radial dose function values calculated in this study differ from those measured using TLD technique up to 11% at 5 cm away from the source. Measurement may be in error due to the inaccuracy in positioning and the unsuitable size of TLDs as Raisali et al. noted in their manuscript [3]. The comparison of the calculated and measured parameters showed good agreement. Also the dosimetric parameter values of IR01- ^{103}Pd are in acceptable agreement with three other commercial source models, Theragenics 200, MED3633 and Best double-wall. So it shows this new brachytherapy source has an acceptable dose distribution.

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