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Original research article

Evaluation of hypothetical ^{153}Gd source for use in brachytherapy[☆]

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ABSTRACT

Aim: The purpose of this work is to evaluate the dosimetric parameters of a hypothetical ^{153}Gd source for use in brachytherapy and comparison of the dosimetric parameters with those of ^{192}Ir and ^{125}I sources.

Materials and methods: Dose rate constant, the radial dose function and the two dimensional (2D) anisotropy function data for the hypothetical ^{153}Gd source were obtained by simulation of the source using MCNPX code and then were compared with the corresponding data reported by Enger et al. A comprehensive comparison between this hypothetical source and a ^{192}Ir source with similar geometry and a ^{125}I source was performed as well.

Results: Excellent agreement was shown between the results of the two studies. Dose rate constant values for the hypothetical ^{153}Gd, ^{192}Ir, ^{125}I sources are 1.173 cGyh^{-1} U^{-1}, 1.044 cGyh^{-1} U^{-1}, 0.925 cGyh^{-1} U^{-1}, respectively. Radial dose function for the hypothetical ^{153}Gd source has an increasing trend, while ^{192}Ir has more uniform and ^{125}I has more rapidly falling off radial dose functions. 2D anisotropy functions for these three sources indicate that, except at 0.5 cm distance, ^{192}Ir and ^{125}I have more isotropic trends as compared to the ^{153}Gd source.

Conclusion: A more uniform radial dose function, and 2D anisotropy functions with more isotropy, a much higher specific activity are advantages of ^{192}Ir source over ^{153}Gd. However, a longer half-life of ^{153}Gd source compared to the other two sources, and lower energy of the source with respect to ^{192}Ir are advantages of using ^{153}Gd in brachytherapy versus ^{192}Ir source.

1. Background

Brachytherapy is an advanced cancer treatment. In brachytherapy practice radioactive seeds or sources are placed inside or in a close vicinity of the tumor, irradiating a high radiation dose to the tumor while reducing the radiation exposure to the surrounding healthy tissues. Brachytherapy is a radiation therapy modality which is accounted as localized, precise and high-technology treatment. Photon emitting

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sources which are currently used in brachytherapy are ^{60}Co, ^{137}Cs, ^{192}Ir, ^{125}I and ^{103}Pd.[1–4] Based on the recommendation of the American Association of Physicists in Medicine (AAPM), task group No. 43 (TG-43U1[5]), dosimetric parameters of each source should be calculated before application of the source in brachytherapy. Then, these parameters can be entered to the treatment planning system using that source. Based on this report, the dosimetric parameters should be calculated by at least two independent investigators.[5] For this reason, various scientists have reported dosimetric parameters of different radioactive sources in their studies.[6–12] These fundamental parameters include: air kerma strength, dose rate constant, geometry function, radial dose function and two dimensional (2D) anisotropy function. Due to the need for use in brachytherapy practice, in last few years different scientists have introduced new hypothetical brachytherapy sources and reported their dosimetric parameters. Hypothetical sources are based on the geometry of a real source but their active materials are isotopes which are not commonly used in brachytherapy or are not available commercially. In a number of previous studies, TG-43 dosimetric parameters of new hypothetical sources were calculated, compared with commercially available sources and then introduced as brachytherapy sources.[2,13–15]

^{153}Gd is one of the hypothetical sources which were introduced by Enger et al.[14] According to the Oak Ridge National Laboratory (ORNL) study in 1960,[16] ^{153}Gd may be a favorable brachytherapy source. This radioisotope has an intermediate energy relative to other brachytherapy sources and emits photons with energies ranging between 40 and 100 keV with half-life of 242 days. In a recent study by Adams et al.[17] a novel needle, catheter and source system were presented for interstitial rotating shield brachytherapy (I-RSBT) of the prostate by ^{153}Gd sources. Their rationale for use of a shielded source and catheter system was to reduce urethra, rectum, and bladder dose. The reason for proposal of ^{153}Gd source rather than ^{125}I and ^{192}Ir sources was that the ^{125}I source has a rapid dose fall-off in tissue and the shielding thickness for ^{192}Ir would be large and, therefore, it could not be fitted inside catheters normally used in prostate brachytherapy. Treatment plans for I-RSBT and conventional brachytherapy treatments of a prostate cancer patient were obtained by Monte Carlo calculations. The platinum shield used could reduce the dose rate on the shielded side at 1.0 cm to 6.4% relative to the dose rate on the other (unshielded) side. This method also reduces the dose to the urethra, rectum and bladder. The treatment time for delivery of 20 Gy dose in I-RSBT with ten 62 GBq ^{153}Gd sources was 154 min. When it is aimed to have a reasonable dosage and treatment time, multisource approach is necessary. In the study by Enger et al.[14] the dosimetric parameters of a hypothetical source based on this radioisotope were calculated and reported in the form of plots. However, the results were not expressed numerically. Furthermore, the dosimetric parameters of the hypothetical ^{153}Gd source were not compared with commercially available sources such as ^{192}Ir. Aim is to determine the dosimetric characteristics for the hypothetical ^{153}Gd source. The results will then be compared with those reported by Enger et al. and with the dosimetric parameters of ^{192}Ir and ^{125}I brachytherapy sources.

2. Materials and methods

2.1. *Geometry of hypothetical ^{153}Gd source*

The source design for the hypothetical ^{153}Gd source is similar to that of VariSource^{TM} ^{192}Ir source (Varian Medical Systems, Palo Alto, CA).[18] This design was chosen because it was proposed in the previous study on the hypothetical ^{153}Gd source[14] and to have an appropriate comparison of the results of the two studies; it was preferred to have the same geometries. There is only one difference that the active core in the ^{153}Gd hypothetical source was defined as a pure ^{153}Gd radionuclide. The design and dimensions of this source are illustrated in Fig. 1. The active core of the source is in the form of a pure ^{153}Gd cylinder (density $\rho = 7.9\,\mathrm{g\,cm^{-3}}$) with an active length of 1.0 cm and diameter of 0.84 mm. The active core was defined in a stainless steel capsule with 11.3 mm length (including the end weld). The inner diameter of the encapsulation is 0.84 mm and its outer radius is 1.0 mm. The stainless steel encapsulation is composed of Fe (67.92%), Cr (19%), Ni (10%), Mn (2%), Si (1%) and C (0.08%) with density of $8.0\,\mathrm{g\,cm^{-3}}$. The length and diameter of the simulated source's guide are 5.0 mm and 0.5 mm, respectively. The energy spectrum of photons emitted by ^{153}Gd radionuclide is tabulated in Table 1.[19]

2.2. *TG-43 dosimetric parameters*

Dosimetric parameters of a brachytherapy source can be determined using experimental or Monte Carlo simulation methods following the TG-43 report.[5,20] Based on this formalism, dose distribution around a brachytherapy source is determined using the following formula:

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

where S_K, Λ, $G(r, \theta)$, $g(r)$ and $F(r, \theta)$ are air kerma strength, dose rate constant, geometry function, radial dose function and 2D anisotropy function, respectively. These parameters are calculated from the following formulas:

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

$$\Lambda = \frac{\dot{D}(1\,\mathrm{cm}, \pi/2)}{S_K} \tag{3}$$

By using a line-source approximation, for $\theta = 0°$, the geometry function is calculated from the following equation:

$$G(r,\theta) = \left(r^2 - \frac{L^2}{4}\right)^{-1} \tag{4}$$

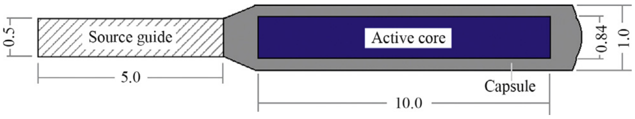

Fig. 1 – A schematic diagram showing the geometry of the hypothetical ^{153}Gd brachytherapy source (all dimensions are in millimeter).

Table 1 – The energy spectrum of ^{153}Gd radionuclide.[19]

Energy (keV)	Prevalence (%)
5.177	0.374
5.816	0.976
5.817	0.1341
5.846	8.86
6.438	0.559
6.457	5.64
6.571	0.9214
6.617	0.0845
6.844	1.8512
7.484	0.947
7.768	0.173
7.795	0.244
14.06383	0.0183
21.2	0.0224
40.467	0.00953
40.902	35.29
41.542	63.516
46.905	6.2516
47.038	12.13
47.373	0.1848
48.249	4.001
48.386	1.597
54.1934	0.00842
68.2557	0.016223
69.673	2.41923
75.42213	0.078323
83.36717	0.1964
89.48595	0.0694
96.883	0.0022
97.431	29
103.1801	21.1123
118.1123	0.000121
166.5556	0.00033
172.3043	0.00022
172.8531	0.036017

For $\theta \neq 0^\circ$ the geometry function is obtained from Eq. (5):

$$G(r,\theta) = \frac{\beta}{Lr\sin\theta} \tag{5}$$

$$g(r) = \frac{\dot{D}(r,\pi/2)G(r_0,\pi/2)}{\dot{D}(r_0,\pi/2)G(r,\pi/2)} \tag{6}$$

$$F(r,\theta) = \frac{\dot{D}(r,\theta)G(r,\pi/2)}{\dot{D}(r,\pi/2)G(r,\theta)} \tag{7}$$

2.3. *Calculation of the dosimetric parameters*

MCNPX code (version 2.6.0)[21] was employed for stimulation of the hypothetical ^{153}Gd source, phantom, etc. The source geometry was defined in this code and used for calculation of dosimetric parameters which were recommended by the updated task group No. 43 (TG-43U1) report of AAPM. These parameters are air kerma strength, dose rate constant, radial dose function and 2D anisotropy function. Based on Table 1, energy spectrum of the photons emitted by ^{153}Gd was defined in source definitions in the Monte Carlo simulations of the source.

For calculation of the air kerma strength, the source was stimulated in a vacuum environment in the form of a spherical volume with 100 cm radius. In this environment, air-filled toroid tally cells in the form of rings located at 1.0–50.0 cm transverse distance from the source center were defined. These cells had 1.0 cm increments at this distance range. The thicknesses of the cylindrical rings were 0.5 cm. Energy cut off was the only variance reduction method which has been used in all input files. The energy cut off of 1 keV was defined for both electrons and photons. F6 tally was used for calculation of air kerma rate in the torus cells. This tally in MCNPX scores energy deposition averaged over a cell in terms of MeV/g. The input file for calculation of air kerma strength was run for 4.7×10^6 particles and the maximum type A Monte Carlo statistical uncertainty in the outputs was 1.2%. Finally, calculation of air kerma strength was based on Eq. (2). The input files were run on a high processing capability computer which had a central processing unit (CPU) with 12 processing cores. The characteristics of this computer are:

- model of the processing core: Intel(R) Xeon(R) CPU X5675@3.07 GHz,
- 32 GB random access memory,
- 32-bit Microsoft Windows 7 operating system.

Each input file was run on a single core. On this system, the time needed for running the input file used for calculation of air kerma strength was 41 min (for scoring 4.7×10^6 particles).

To obtain dose rate constant, computation was performed by division of dose rate in water at 1.0 cm by air kerma strength. The formula of this calculation is written in Eq. (3). To obtain dose rate in water, a water phantom with 40.0 cm radius was defined and *F4 tally and related mass energy absorption coefficients of water were used. In MCNP for calculation of energy deposition, it is possible to use *F8 tally, however, to have an acceptable level of the Monte Carlo statistical uncertainty, calculation with this tally type is time consuming. Therefore, to have higher calculation performance, *F4 tally was a more suitable choice. *F4 tally in MCNPX scores energy flux averaged over a cell in terms of MeV/cm^2. In the next step, when the energy flux is multiplied by the mass energy absorption coefficient, collision kerma is obtained. The latter variable can be an approximation of absorbed dose. Since the mass energy absorption coefficient depends on energy and the source is not monoenergetic, the energy spectrum emitted by the source was divided by different energy intervals. Then, *F4 tally in each energy interval was multiplied by the mass energy absorption coefficient of water in the energy interval. The mass energy absorption coefficients of water were extracted from the website of the National Institute of Standards and Technology (NIST).[22] The multiplication results of energy flux by the mass energy absorption coefficient in various energy intervals were summed up.

Calculation of the radial dose function was in the same condition of dose rate constant, while the toroid tally cells, which were cylindrical rings ranging 1.0–15.0 cm distance along the transverse bisector of the source, were defined. The thickness of the toroid rings was defined as 1.0 mm for 1.0 mm to 7.0 cm distances. In the other distances (10.0–14.0 cm), the thickness was specified as 2.0 mm. *F4 tally, DE and DF cards were used for scoring dose at various radial distances. The energy cut off used was equal to 1 keV. The input file was run for 6.47×10^7 particles and the maximum type A Monte

Carlo statistical uncertainty in the output results was equal to 0.5%. The calculation time for the running of the radial dose function input file on the aforementioned computer was 1408 min (to score 6.47×10^7 particle histories). Calculation of radial dose function was based on Eq. (6), using a linear-source approximation for the source with an active length of 1.0 cm.

2D anisotropy functions were calculated at distances of 0.5, 1.0, 5.0, 7.0, 10.0, 12.0 and 15.0 cm at 24 polar angles (ranging from 0° to 180°). Those data points overlapping with source or source cable were excluded in these calculations. Other details of the calculation, such as tally and energy cut off in scoring the 2D anisotropy function, was the same as that in the radial dose function. However, the thickness of the toroid rings was different for various distances (ranging from 0.04 cm for $r = 0.5$ and 1.0 cm; and 0.1 for other distances up to 15.0 cm). The number of photon histories in the scoring of the 2D anisotropy function was 2.5×10^8, having a maximum type A Monte Carlo statistical uncertainty of 3.6%. The processing time for the running of the 2D anisotropy function program on the described computer was 13,726 min (for scoring 2.5×10^8 particles). 2D anisotropy function was calculated from Eq. (7), as assigned by the TG-43 formalism.

Finally, the dosimetric parameters of the hypothetical ^{153}Gd source were compared with those of this source by Enger et al. The data of Enger et al. on this source were obtained based on a personal communication (Ryan Flynn, 2014, personal communication). Furthermore, the dosimetric parameters of this source were compared with those of ^{192}Ir and ^{125}I sources which are two important and commercially available sources for use in brachytherapy. The dosimetric data of the VariSource ^{192}Ir source (model classic) and BEBIG IsoSeed ^{125}I source (model I25.S17) were extracted from the Carleton university database for brachytherapy sources for these two source models.[23,24]

3. Results

Air kerma strength per GBq activity for the hypothetical ^{153}Gd source was obtained as equal to 6.77 cGy cm^2 h^{-1} GBq^{-1}. Dose rate constant for this source was obtained as equal to 1.17 cGy h^{-1} U^{-1}. Dose rate constant values for the VariSource ^{192}Ir and ^{125}I BEBIG IsoSeed sources as reported by Wang and Sloboda[18] and Pantelis et al.[25] studies are 1.044 cGy h^{-1} U^{-1} and 0.925 cGy h^{-1} U^{-1}, respectively. It could be useful to compare the dose rate constant for the hypothetical ^{153}Gd source obtained in this study and that in the study by Enger et al., but the value was not reported in that study. Based on our calculations, the dose rate at 1.0 cm radial distance for the ^{153}Gd source was obtained as 7.95 cGy h^{-1} GBq^{-1}. In the study by Enger et al.[14] the dose rate at 1.0 cm for the hypothetical ^{153}Gd source with 242 GBq activities having the same geometry is 13.12 Gy/h. This equals to 5.42 cGy h^{-1} GBq^{-1} dose rate at 1.0 cm.

Radial dose function values for the hypothetical ^{153}Gd source obtained in the current study are tabulated in Table 2. Radial dose function values from the present study and the study of Enger et al., as well as the percentage differences between the values in these two studies are illustrated in Fig. 2.

Table 2 – Radial dose function for the hypothetical ^{153}Gd source.

r (cm)	$g(r)$
0.1	0.681
0.2	0.745
0.3	0.809
0.4	0.857
0.5	0.894
0.75	0.958
1.0	1.000
1.5	1.062
2.0	1.107
2.5	1.134
3.0	1.155
3.5	1.162
4.0	1.168
4.5	1.166
5.0	1.159
6.0	1.130
7.0	1.083
10.0	0.926
12.0	0.810
15.0	0.642

The maximum difference between these two data series is 2.69%. In the supplement report to the TG-43 formalism, difference within 2–5% in 2D anisotropy function was interpreted as an excellent agreement.[26] For the purpose of comparison of

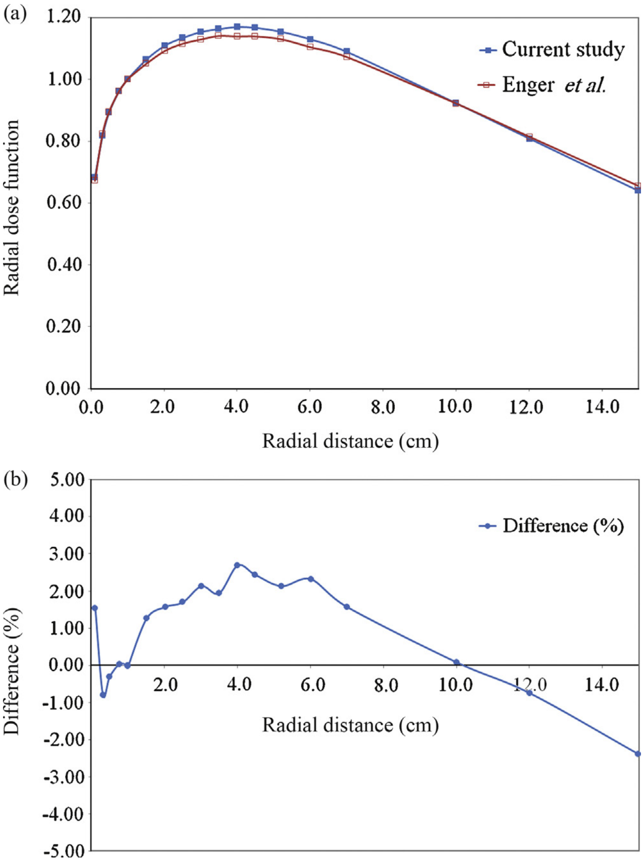

Fig. 2 – (a) Radial dose function for the hypothetical ^{153}Gd brachytherapy source obtained in the present study and by Enger et al.[14] and (b) the percentage differences between two studies.

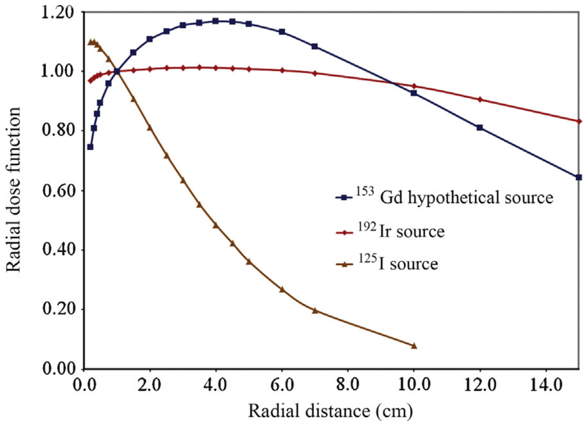

Fig. 3 – Radial dose function for the hypothetical ^{153}Gd, ^{192}Ir and ^{125}I brachytherapy sources.

the radial dose functions for the hypothetical ^{153}Gd, ^{129}Ir and ^{125}I sources, the values were illustrated in Fig. 3.

2D anisotropy function data for the hypothetical ^{153}Gd source are listed in Table 3. To compare the 2D anisotropy function, values from the current study and those reported by Enger et al., the corresponding diagrams are plotted in Fig. 4(a). The percentage differences between these two studies are plotted in Fig. 4(b). The maximum difference between these two data sets is 10.87%. It should be noted that this level of difference exists only in one data point and in most of points the difference is much lower than this value. Plots of the 2D anisotropy functions for the hypothetical ^{153}Gd, ^{129}Ir and ^{125}I sources are shown in Fig. 5.

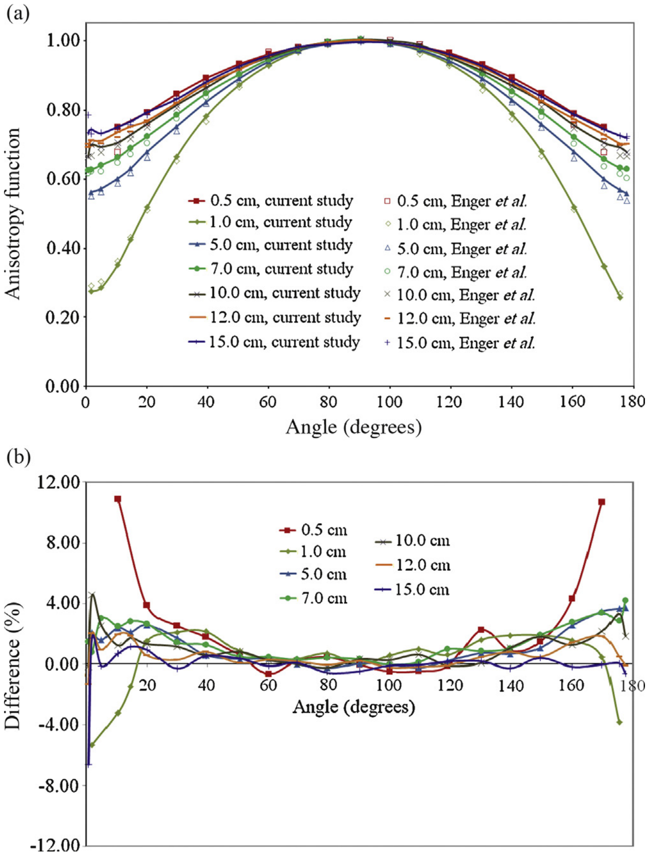

Fig. 4 – (a) 2D anisotropy function for the hypothetical ^{153}Gd brachytherapy source obtained in the present study and by Enger et al.[14] and (b) the percentage differences between two studies.

4. Discussion and conclusion

In the present study TG-43 dosimetric parameters for a hypothetical ^{153}Gd source were calculated and compared with previously published data and those of ^{192}Ir and ^{125}I brachytherapy sources. The dosimetric parameters including air kerma strength per activity, dose rate constant, radial dose function and the 2D anisotropy function obtained for the hypothetical ^{153}Gd source can be used for this source if it would be commercially available for use in brachytherapy with the geometry which was designed in this study. The dosimetric parameters calculated herein are in agreement with the corresponding data reported by Enger et al. Therefore, with comparing the dosimetric parameters of the hypothetical ^{153}Gd sources obtained in this study with those reported by Enger et al.,[14] the simulation of the ^{153}Gd source is validated.

A comparison of the dose rate at 1.0 cm radial distance for the ^{153}Gd source in this study (7.95 cGy h^{-1} GBq^{-1}) and the study by Enger et al.[14] (5.42 cGy h^{-1} GBq^{-1}) may be useful. These data have some difference. While relatively the same geometries, photon yields and energy spectra have been used in these two studies, the difference is due to the method used for dose calculation. Since in the present study the dose rate was calculated by Monte Carlo simulation, while in the study by Enger et al. an analytical method was utilized. Since the value of dose rate at 1.0 cm reported by Enger et al. is lower than the value obtained in this study and the Monte Carlo method is more precise than the analytical method, it is evident that the value reported by Enger et al., is not an overestimation of dose rate at 1.0 cm.

The results of the comparison of the radial dose function of the ^{153}Gd source with those of ^{192}Ir and ^{125}I sources (Fig. 3) indicates that ^{192}Ir has a more uniform radial dose function as compared to ^{153}Gd source. This may be an advantage for the ^{192}Ir source over ^{153}Gd. Furthermore, the fall-off in the radial dose function for the ^{125}I source is higher compared to the ^{153}Gd and ^{192}Ir sources. It should be noted that while the hypothetical ^{153}Gd and VariSource ^{192}Ir sources have the same geometries, the hypothetical ^{153}Gd source and IsoSeed ^{125}I source have different geometries. The differences in radial dose functions for these sources can be related to the types of the radioisotopes, photon energies of the sources, and self-absorption in the active parts. Furthermore, the difference in the geometries can also be a source of differences in the radial dose functions.

When one compares the 2D anisotropy function for various distances in Fig. 4(a), a general trend is observed with increase in distance, with an exception of 0.5 cm distance. In other words, with this general trend it is expected that the 2D anisotropy function for 0.5 cm distance should be downward to that of 1.0 cm, but a reverse effect is observed. The reason for this effect could be found by considering the definition of the 2D anisotropy function. In the definitions of the 2D anisotropy

Table 3 – 2D anisotropy function for the hypothetical ^{153}Gd source.

θ (°)	r (cm)						
	0.5	1.0	5.0	7.0	10.0	12.0	15.0
0	–	0.2693	0.5498	0.6356	0.6456	0.7554	0.7178
2	–	–	0.5667	0.6346	0.6960	0.7077	0.7369
5	–	0.2856	0.5744	0.6341	0.6900	0.7226	0.7337
10	0.7416	0.3472	0.6013	0.6596	0.7080	0.7327	0.7559
15	–	0.4319	0.6358	0.6891	0.7352	0.7519	0.7702
20	0.7916	0.5186	0.6794	0.7196	0.7654	0.7707	0.7969
30	0.8470	0.6693	0.7532	0.7861	0.8093	0.8262	0.8360
40	0.8948	0.7879	0.8281	0.8494	0.8685	0.8742	0.8832
50	0.9319	0.8702	0.8892	0.9036	0.9163	0.9165	0.9211
60	0.9605	0.9292	0.9384	0.9464	0.9504	0.9538	0.9533
70	0.9813	0.9702	0.9719	0.9740	0.9817	0.9813	0.9771
80	0.9957	0.9956	0.9933	0.9964	0.9981	0.9952	0.9913
90	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
100	0.9951	0.9944	0.9913	0.9953	0.9988	0.9934	0.9962
110	0.9816	0.9690	0.9717	0.9778	0.9830	0.9796	0.9857
120	0.9618	0.9288	0.9388	0.9468	0.9430	0.9520	0.9571
130	0.9313	0.8699	0.8902	0.9041	0.9125	0.9212	0.9264
140	0.8935	0.7865	0.8263	0.8500	0.8714	0.8767	0.8836
150	0.8455	0.6738	0.7563	0.7878	0.8166	0.8280	0.8388
160	0.7919	0.5240	0.6794	0.7226	0.7593	0.7744	0.7816
170	0.7497	0.3410	0.6036	0.6579	0.7090	0.7371	0.7559
175	–	0.2679	0.5714	0.6296	0.6812	0.7100	0.7340
178	–	–	0.5603	0.62881	0.6702	0.7074	0.7255
180	–	–	0.5595	0.6606	0.6722	0.6851	0.8143

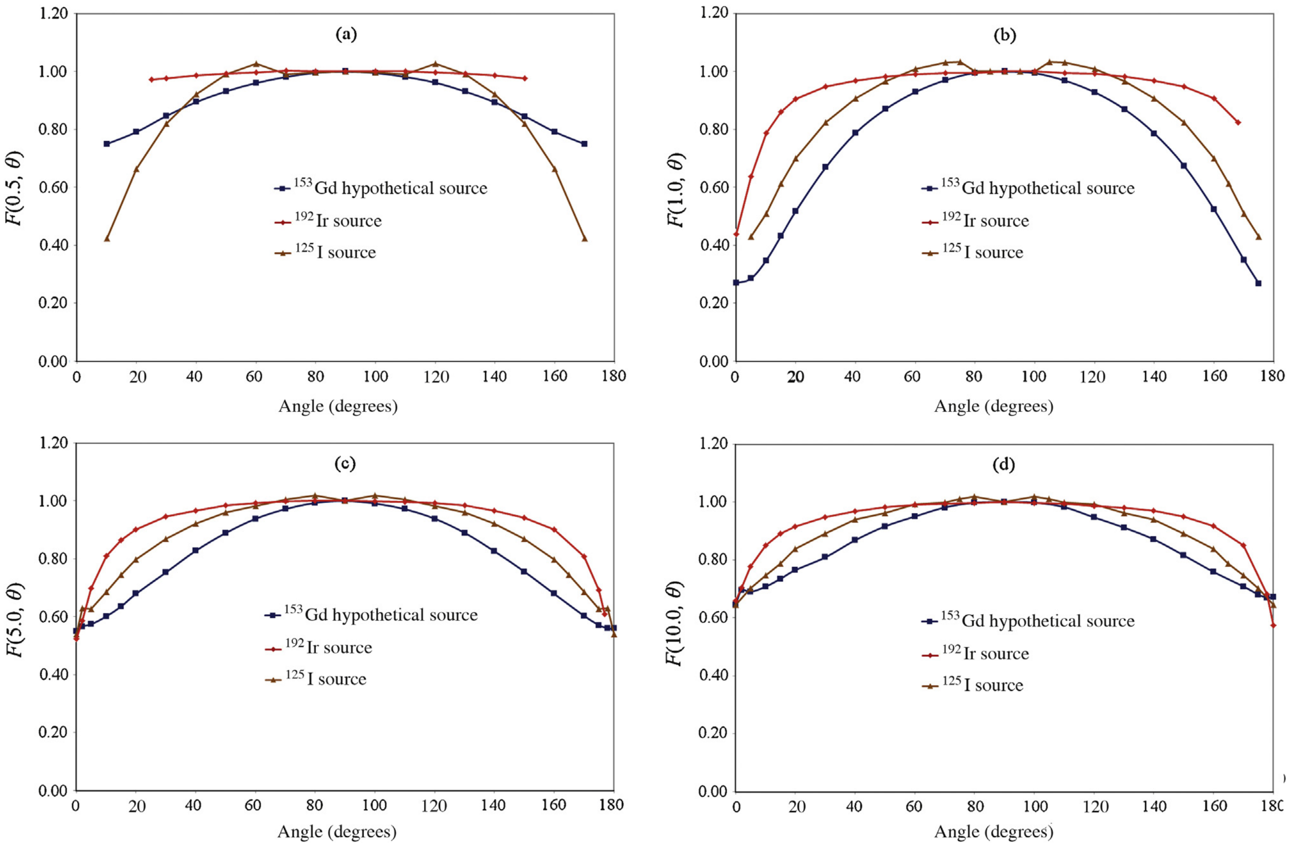

Fig. 5 – 2D anisotropy function for the hypothetical ^{153}Gd, ^{192}Ir and ^{125}I brachytherapy sources. Parts (a), (b), (c), and (d) are related to 0.5 cm, 1.0 cm, 5.0 cm and 10.0 cm distances, respectively.

function, the dose rate for each angle at a distance is divided by the dose rate at that distance and 90°. As the point of calculations gets closer to the linear source, along the 90° angle, the dose rate decreases as it becomes dominant dose rate from the nearest point and loses the contribution from other parts of the source. Actually it can be seen from Fig. 2(a) that the radial dose functions at distances lower than 1.0 cm are higher than those at distances beyond 1 cm. Therefore, when the 2D anisotropy function of 0.5 cm is compared to 1.0 cm, there is a smaller denominator for the 0.5 cm than 1.0 cm, thus a larger 2D anisotropy function for 0.5 cm is justified.

The 2D anisotropy functions of the ^{153}Gd, ^{192}Ir and ^{125}I sources (Fig. 5) imply that ^{153}Gd has a less isotropic dose distribution in the longitudinal plane as compared to ^{192}Ir and ^{125}I sources. The effect can be due to the differences in photon energies, self-absorptions as well as sources' geometries. This effect will be an advantage for the ^{192}Ir and ^{125}I sources over ^{153}Gd.

^{153}Gd emits photons with an average energy of 53.70 keV if self-shielding and encapsulation are not accounted for. The average photon energies for ^{192}Ir and ^{125}I sources are 360 keV and 28.37 keV, respectively. Having lower photon energy emitted by the ^{153}Gd source as compared to ^{192}Ir result to lower shielding requirement for the ^{153}Gd. This will result in lower costs in room shielding constructions for the brachytherapy treatment room. On the other hand, the cost of construction of a ^{153}Gd source is much higher than that of a ^{192}Ir source. The half-life of ^{153}Gd radionuclide is 242 days. The half-lives for ^{192}Ir and ^{125}I sources are 74 days and 59.40 days. Longer half-life of the ^{153}Gd source minimizes the source exchange requirements. This will also reduce the times of source calibrations and commissioning costs. A comparison of the specific activities will also be useful. The specific activity of ^{153}Gd is 5.55 TBq/g.[14] The specific activity for ^{192}Ir is 341 TBq/g. It is clear that ^{153}Gd has a much lower specific activity than ^{192}Ir. In summary, a more uniform radial dose function, and the 2D anisotropy function with more isotropy, having a higher specific activity are advantages of ^{192}Ir source over ^{153}Gd. However, lower energy of the ^{153}Gd source with respect to ^{192}Ir and longer half-life of ^{153}Gd source compared to the other two sources are advantages of using ^{153}Gd in brachytherapy versus ^{192}Ir source.

Since it was aimed that the obtained dosimetric parameters for the ^{153}Gd source be compared with those reported by Enger et al., the energy spectrum referenced by Enger et al. was used in the present study. However, according to a report by AAPM and European Society for Radiotherapy and Oncology (ESTRO),[27] the energy spectrum which is announced by the National Nuclear Data Center (NNDC)[28] is recommended to be used. For ^{153}Gd source NNDC listed two different data sets. Rivard et al.[29] have studied the influence of various photon energy spectra for three brachytherapy sources on kerma rate, dose rate and TG-43 dosimetric parameters via Monte Carlo simulations. While the differences reported for various spectra were not significant, the use of NNDC energy spectrum database was recommended in brachytherapy simulations.

As it was presented in Section 1, the rationale for the use of a shielded ^{153}Gd source and catheter system is to reduce the dose to normal organs. However, in the study by Enger et al.,[14] to have a reasonable dose rate, a relatively large (10.0 mm length and 0.84 mm diameter of active length) ^{153}Gd source was designed; therefore, this size of source is too large to be partially shielded effectively interstitially, and inefficient due to self-attenuation. The source that is much more likely to be used clinically is that described in the study by Adams et al.[17] In that study, an active diameter of 0.44 mm and active length of 10.0 mm was used for each source, while 10 such shielded sources were evaluated. Taking into account the specific activity, self-absorption, construction costs, the needed dosage and duration of an effective treatment by ^{153}Gd source, there should be a trade-off between dosimetric effectiveness and treatment time. Reviewing the literature on ^{153}Gd source, reveals that there are some issues with ^{153}Gd brachytherapy that have not yet been addressed adequately. For example, no study exists on the importance of self-attenuation for ^{153}Gd sources, and that is a very important consideration for these sources due to the relatively low photon energies emitted. The reason why this is important is that ^{153}Gd is very expensive. As an example, the cost of a 0.9 mm diameter source relative to a 0.44 mm diameter source is much higher, then the cost to the user becomes prohibitive and, therefore, the only way to achieve a reasonable treatment time at an affordable cost is to use multiple small sources. Performing a Monte Carlo study on source dimensions with roughly the same as the commercially available sources such as GammaMed Plus, Flexisource, and VariSource and calculation of absolute dose rate at 1.0 cm distance assuming a realistic specific activity, will deliver novel results that are clinically and economically relevant. With the assumption that the overall treatment time for a typical prostate brachytherapy treatment is proportional to the dose rate at 1.0 cm for a given ^{153}Gd source model, the number of sources and, therefore, total activity for each different design can be calculated. These issues call for further research on brachytherapy with ^{153}Gd sources in clinical setting.

Conflict of interest

None declared.

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