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A Monte Carlo evaluation for effects of probable dimensional uncertainties of low dose rate brachytherapy seeds on dose

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ABSTRACT

The aim of this study is to determine effects of size deviations of brachytherapy seeds on two dimensional dose distributions around the seed. Although many uncertainties are well known, the uncertainties which stem from geometric features of radiation sources are weakly considered and predicted. Neither TG-43 report which is not completely in common consensus, nor individual scientific MC and experimental studies include sufficient data for geometric uncertainties. Sizes of seed and its components can vary in a manufacturing deviation. This causes geometrical uncertainties, too. In this study, three seeds which have different geometrical properties were modeled using EGSnrc-Code Packages. Seeds were designed with all their details using the geometry package. 5% deviations of seed sizes were assumed. Modified seeds were derived from original seed by changing sizes by 5%. Normalizations of doses which were calculated from three kinds of brachytherapy seed and their derivations were found to be about 3%–20%. It was shown that manufacturing differences of brachytherapy seed cause considerable changes in dose distribution.

1. Introduction

Monte Carlo (MC) simulations are popular and relatively reliable for brachytherapy. TG-43 (Task Group) report of the AAPM (the *American Association of Physicists in Medicine*) collects both experimental and MC data and evaluates them. The uncertainty of data of applied dose is momentous for medical-dosimetric studies because of human life. It is aimed that optimum dose value must be acquired in cancerous tissue to treat it in radiotherapy (brachytherapy is specialized radiotherapy). There are several uncertainties of dose and they must be determined completely to decide an optimum value in treatment planning.

Low dose rate (LDR) brachytherapy sources are commonly used for cancer treatment especially for prostate cancer. The dose distribution around a brachytherapy seed source is calculated in a formalism that is suggested in AAPM Task Group 43 Report for the treatment planning. As the TG-43 formalism the dose is calculated as follows:

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

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at a point specified by r and θ variables where Λ is dose rate constant and S_k is air kerma strength. Radial dose function $g(r)$ and anisotropy function $F(r,\theta)$ are calculated using analytical dose values. This formalism requires the usage of a number of dosimetry parameters for the calculation of dose value at a certain point around a brachytherapy source. It is also assumed that a brachytherapy source has an ideal geometry (announced manufacturer specifications). Eq. (1) was performed by partitioned functions. Uncertainties of each expression which perform main dose value have a contribution on total uncertainties. Although individual uncertainties are assumed small as they can be omitted they are effective on total uncertainties. As it is understood from the equation, dosimetric functions and main dose $D(r,\theta)$ quantity is directly dependent on geometrical variables. Components of a brachytherapy seed have specific sizes.[1] Seed models vary from one another with their general shape, material thickness, length, radius, radioactivity carrier properties, kind of radio-opaque material and radioactive material. All of these properties directly affect and change analytical dose value around the source.[1] Accurate knowledge of source geometry and details of its physical structure are especially important for Monte Carlo modeling.[1] Monte Carlo simulations are independent from detector-source geometry and detector response artifacts. Smaller estimated uncertainty can cause artifact-free dose-rate estimates at distances shorter or longer than those accessible by TLD (Thermo Luminescence Dosimeter) methods. Few Monte Carlo studies have been conducted to determine the effects of geometric uncertainties, internal component mobility, size variations of sources, and on the uncertainty of dose distributions.[1] Geometrical changes will contribute with an external uncertainty over other known uncertainties on dosimetric parameters in Eq. (1) which results in the analytical dose value. Estimation of geometric uncertainty, $\%\sigma_{\Lambda|G}$, is complex and not well understood.[1] Each source design is characterized by numerous and unique geometric parameters, most of which have unknown and potentially correlated probability distributions. However, a few studies in the literature report parametric studies in which the sensitivity of dosimetric parameters to specified sources of geometric variability is published.[1] For example, Williamson[4] has shown that the distance between the two radioactive spherical pellets of the Drax Image (Jubilant DraxImage Incorporated. 16751 Trans-Canada Highway Kirkland, Québec, Canada H9H 4J4) ^{125}I source varies from 3.50 to 3.77 mm. This leads to a source-orientation dependent variation of approximately 5% in calculated dose-rate constant. Rivard[2] published similar findings for the NASI (North American Scientific) model MED3631-A/M (Brachytherapy Services Incorporated (BSI) 7643 Fullerton Road, Springfield, VI 22153, USA) ^{125}I source.

For the DraxImage (Jubilant DraxImage Inc.) seed model[3] source $\%\sigma_{\Lambda|geo} = 1.4\%$. For the Theragenics Corporation Model 200 seed, Williamson has shown that L is relatively insensitive to Pd metal layer thickness or end weld configuration.[4] Thus 2% seems to be a reasonable and conservative estimate of $\%\sigma_{\Lambda|geo}$. The reported statistical precision of Monte Carlo Λ estimates ranges from 0.5% for Williamson's recent studies to 3% for Rivard's MED3631-A/M (Brachytherapy Services Inc.) study.[5] Thus for a typical Williamson study, one obtains a $\%\sigma_{\Lambda}$ of 2.5%. Using the $\%\sigma_{\Lambda|s}$ reported by each investigator along with the standard $\%\sigma_{\Lambda|geo}$ and $\%\sigma_{\Lambda|\mu}$ values, discussed above; $\%\sigma_{\Lambda}$ varies from 2.5% to 3.7% for the eight seeds described in this report. Thus, assuming a standard or generic $\%\sigma_{\Lambda}$ of 3% for all Monte Carlo studies seems reasonable.[1]

Mobit and Badragan[6] noted geometrical specifications of Amersham (Nycomed Amersham) Model 6711 (Oncura Incorporated, 3350 North Ridge Avenue, Arlington Heights, IL 60004, USA) Seed. Their measurements (Table 1) showed that all manufactured seeds are not equal to each other and producing specifics. In that data (Table 1) dimensional uncertainties in Table 1 between 1% and 4%". Table 1 provides reference data to limit deviation amounts of components of the seeds.

Goal of this study is to examine geometrical deviations of brachytherapy seeds on dosimetric distribution. In this study, three seeds which have different geometrical properties were modeled using EGSnrc-Code Packages. Seeds were designed in all their detail with the geometry package. 5% deviations of seed sizes were assumed. Modified seeds were derived from the original seed by changing sizes by 5%.

There are several kind of geometrical uncertainty sources for brachytherapy seeds.[7] MC investigators should be free from manufacturing specifics of a seed.[7] In this study hypothetical seeds which have been derived are used to characterize some of source geometry uncertainty. Probable deviation of seed dimensions[8] was selected as some of geometrical uncertainties.

2. Materials and methods

In the present study Amersham Model 6711 (Oncura Inc.), TheraSeed 200 (Theragenics Corporation, 5203 Bristol Industrial Way, Buford, GA 30518, USA) and Imagyin Seed (Imagyn Medical Technologies, Incorporated, 1 Park Plaza Ste 1100, Irvine, CA 92614, USA) were modeled using EGSnrc[9] Monte Carlo Code.

Scenarios of geometric variations of seeds reference seed that has ideal geometrical measurements published by commercials were simulated using this code. Every geometrical combination of seed component performed hypothetic seeds which had been derived from the commercial one. Dose was calculated by mathematical process of EGS Simulation as

$$D^j = K^j_{col} = \frac{\sum_i E_i t_i (\mu_{en}/\rho)}{V_j}$$

where D^j and K^j_{col} are the dose and collision kerma in the jth voxel, E_i is the energy of the ith photon, and t_i is the track length of that photon in the voxel. The mass-energy absorption coefficient corresponding to energy E_i is (μ_{en}/ρ) and V_j is the volume of the voxel.[10] Voxels were dimensioned (Fig. 1) with optimum volume values according to Taylor et al.[10]

2.1. Seed modeling

Designed seeds and their geometrical derivative seed models were identified by identification (ID) number. Derivative seed concepts were designed by changing seed dimensions[11] with 5% ratios (Tables 2–4). This size diversity supplies large probability for practical seed properties. It must be mentioned

Table 1 – For Model 6711 seed geometrical measurements show deviations among manufactured seeds. Mobit and Badragan[6] have taken the data from Sloboda and Menon's study.[8]

Seed number	Ti capsule		Silver rod	
	Length (mm)	Diameter (mm)	Length (mm)	Diameter (mm)
1	4.75 ± 0.01	0.80 ± 0.01	2.88 ± 0.04	0.57 ± 0.04
2	4.57 ± 0.01	0.80 ± 0.01	2.82 ± 0.04	0.56 ± 0.04
3	4.62 ± 0.01	0.79 ± 0.01	2.84 ± 0.04	0.55 ± 0.04
4	4.54 ± 0.01	0.80 ± 0.01	2.84 ± 0.04	0.55 ± 0.04
5	4.66 ± 0.01	0.80 ± 0.01	2.90 ± 0.04	0.55 ± 0.04
6	4.58 ± 0.01	0.80 ± 0.01	2.84 ± 0.04	0.55 ± 0.04
7	4.52 ± 0.01	0.80 ± 0.01	2.90 ± 0.04	0.55 ± 0.04
8	4.59 ± 0.01	0.80 ± 0.01	2.90 ± 0.04	0.55 ± 0.04
Average	4.60 ± 0.01	0.80 ± 0.01	2.87 ± 0.04	0.55 ± 0.04

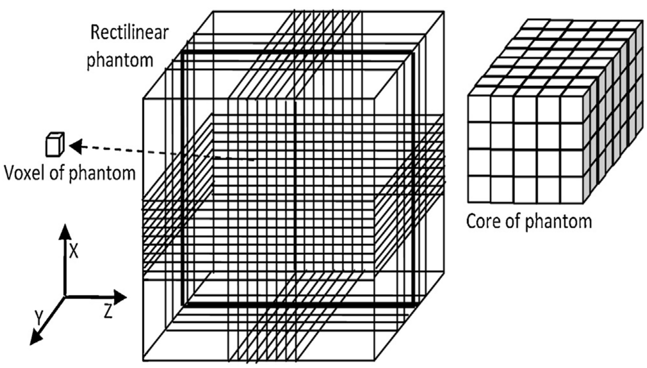

Fig. 1 – Voxels were generated by cutting rectilinear phantom into intersected slabs. Voxel is a term that was derived from pixel for three dimensions. Voxel is a volume element.

that, although three seeds are previously studied by several scientists, these seeds were used to represent different kinds of seed geometries in recent study instead of studying their dosimetric characteristics. Novel approximation of this study is related to seed component designed separately. Separately designed elements were given sub-ID numbers which are bound to the main seed ID number. This technique enabled to easily change sizes of components separately to produce probable seed situations. ID systematics of modeling was inspired by the logic of 3D drawing software such as 3DsMax. ID numbers were not chosen systematically. They were a completely personal decision.

2.2. *Amersham Model 6711 I-125 (Oncura Inc.)*

Original seed was identified by 2090 ID number as shown in Table 2. The seed consists of the main titanium cylinder capsule that is sealed by titanium semi spheres on its both sides. It contains ^{125}I adsorbed argent core. This seed has general and simple brachytherapy seed geometry (Fig. 2).

2.3. *Theragenics 200 Pd-103 (Theragenics Corporation)*

Original seed was identified by 2200 ID number as seen in Table 3. The seed consists of the main titanium cylinder capsule that is sealed by titanium semi spherical concave shells. There are two graphite pellets that contain ^{103}Pd placed at both sides of the lead marker (Fig. 3)

2.4. *Imagyn Seed I-125 (Imagyn Medical Technologies Inc.)*

Original seed was identified by 2110 ID number as seen in Table 4. The seed consists of the main titanium cylinder capsule that is sealed by titanium semi spheres likely Model 6711. Inside the capsule there are five argent spheres (Fig. 4) which contain ^{125}I.

Fig. 2 – Cross sections of Model 6711 seed: (a) longitudinal cross section and (b) transverse cross section (ID: 2090).

Fig. 3 – Cross sections of TheraSeed 200: (a) longitudinal cross section and (b) transverse cross section (ID: 2200).

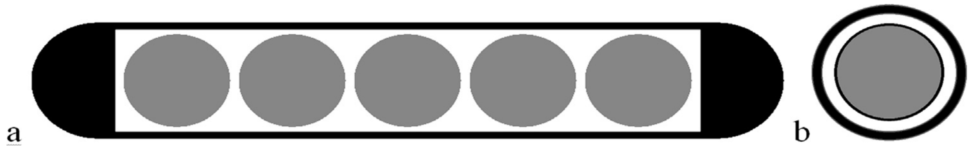

Fig. 4 – Cross sections of ImagynSeed: (a) longitudinal cross section and (b) transverse cross section (ID: 2090).

Table 2 – Geometrical variation data of derived seeds from Model 6711 source were obtained by changing 5% ratios of original dimensions. Each designed model was identified by an ID number. ID numbers will be standard in database of MG Package Code. Original seed ID is 2090.

ID	Capsule length, L_c (cm)	Capsule thickness, T_c (cm)	Core length, L (cm)	Core radius, R_c (cm)
2090	0.45	0.005	0.3	0.025
2060	0.45	0.007	0.3	0.025
2064	0.45	0.005	0.3	0.02625
2065	0.45	0.007	0.3	0.02625
2066	0.4725	0.005	0.3	0.025
2069	0.45	0.005	0.315	0.025
2071	0.4275	0.005	0.3	0.025
2074	0.45	0.005	0.285	0.025
2076	0.4275	0.005	0.285	0.025
2077	0.4725	0.005	0.315	0.025

Table 3 – Geometrical variation data of derived seeds from TheraSeed 200 source were obtained by changing 5% ratios of original dimensions. Each designed model was identified by an ID number. ID numbers will be standard in database of MG Package Code. Original seed ID is 2200.

ID	Capsule length, L_c (cm)	Capsule thickness, T_c (cm)	Marker length, L_m (cm)	Marker radius, R_m (cm)	Core length, L (cm)	Core radius, R_c (cm)
2200	0.45	0.005	0.0545	0.0225	0.0445	0.028
2250	0.45	0.0072	0.0545	0.0225	0.0445	0.028
2253	0.45	0.005	0.0545	0.0225	0.0445	0.0294
2257	0.45	0.0072	0.0545	0.0225	0.0445	0.0294
2258	0.4725	0.005	0.0545	0.0225	0.0445	0.028
2261	0.45	0.005	0.0545	0.0225	0.04672	0.028
2265	0.4275	0.005	0.0545	0.0225	0.0445	0.028
2268	0.45	0.005	0.0545	0.0225	0.04227	0.028
2272	0.4275	0.005	0.0545	0.0225	0.04227	0.028
2273	0.4725	0.005	0.0545	0.0225	0.04672	0.028
2274	0.45	0.00293	0.0545	0.0225	0.0445	0.028
2277	0.45	0.005	0.0545	0.0225	0.0445	0.0266
2281	0.45	0.00293	0.0545	0.0225	0.0445	0.0266

After identification of seed size situations by several modified or derived seed models, seed combinations were acquired as seen in Tables 2–4. Combinations of seed size deviations were performed using Table 1 data reference. Situation types and ID numbers were expressed as.

2.5. *Dose calculation method*

Dosimetric parameters are analytical functions dependent on radial and angular variables on a defined $P(r,\theta)$ point however the dose cannot be described in a dimensionless point. A small

Table 4 – Geometrical variation data of derived seeds from Imagyn Seed source were obtained by changing 5% ratios of original dimensions. Each designed model was identified by an ID number. ID numbers will be standard in database of MG Package Code. Original seed ID is 2110.

ID	Capsule length, L_c (cm)	Capsule thickness, T_c (cm)	Core radius, R_c (cm)
2110	0.37	0.05	0.032
2310	0.37	0.07	0.032
2311	0.37	0.03	0.032
2312	0.37	0.05	0.0336
2320	0.37	0.05	0.0304
2328	0.37	0.07	0.0336
2329	0.37	0.03	0.0304
2330	0.3885	0.05	0.032
2331	0.3515	0.05	0.032
2332	0.3515	0.05	0.0304
2333	0.3885	0.05	0.0366

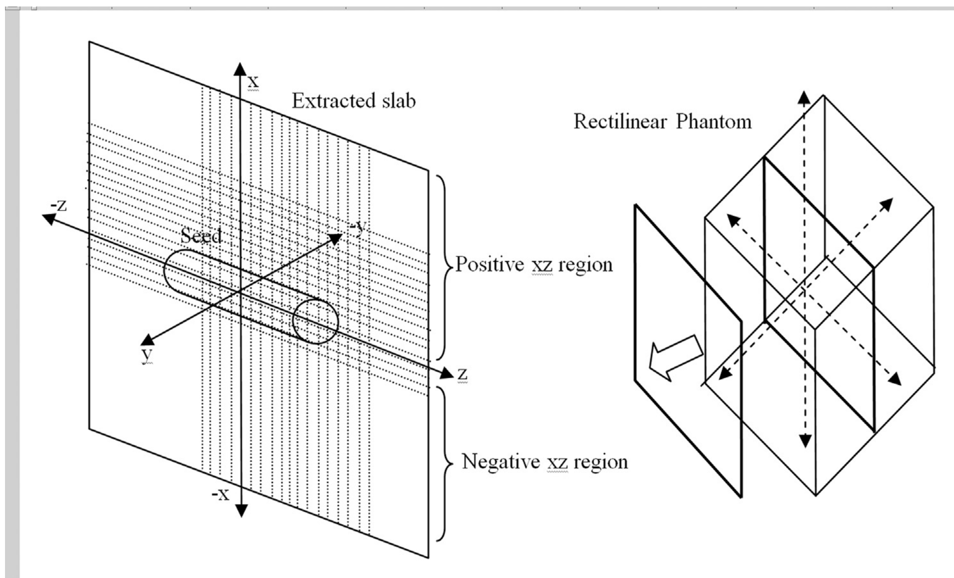

Fig. 5 – Analytic system of Monte Carlo calculation for phantom design. Dose values of modified seeds were acquired in the XZ slab that was extracted from the 3D dose data matrix obtained using the *xyz* rectilinear phantom (it is referred to in Fig. 1).

volume that includes *P* point was assumed to calculate analytical dose data. These volumes which are named as voxels were constructed in an optimum size.[10] Dose distribution in water was calculated based on a cubic water phantom. 1D dose values were extracted from 3D dose data in the phantom (Fig. 5). Radial distributions of modified and original seed models were calculated on single axis of Cartesian system using two different phantoms with dimensions of 0.1 mm × 0.1 mm × 0.1 mm voxels and dimensions of 0.5 mm × 0.5 mm × 0.5 mm voxel to normalize dose distribution data of modified seeds in the [0 cm, 1 cm] and [0 cm, 5 cm] scale.

3. Results and discussion

EGSnrc Monte Carlo simulation and the AAPM-TG43 dosimetry protocol is generally within 10% for radial distances smaller than 2.5 cm but increases to 20% for radial distances greater than 3.0 cm. As the polar angle decreases and the radius increases, the difference between Monte Carlo simulation and the AAPM-TG43 dosimetry protocol increases. In the longitudinal direction of the source, there are differences greater than 20% between EGSnrc Monte Carlo simulations and the AAPM-TG43 dosimetry protocol for radial distances between 0.5 cm and 2.0 cm. The differences increase to more than 40% for radial distances greater than 2.5 cm in the longitudinal direction of the[6] source. Obviously, these considerations do not include geometrical effects. Dose deviations were processed by the following normalization equation:

$$N = \frac{D_{\text{modified}}}{D_{\text{original}}}$$

If normalization (*N*) is 1 then two doses were calculated as the same else doses are different from each other. *N* graphics

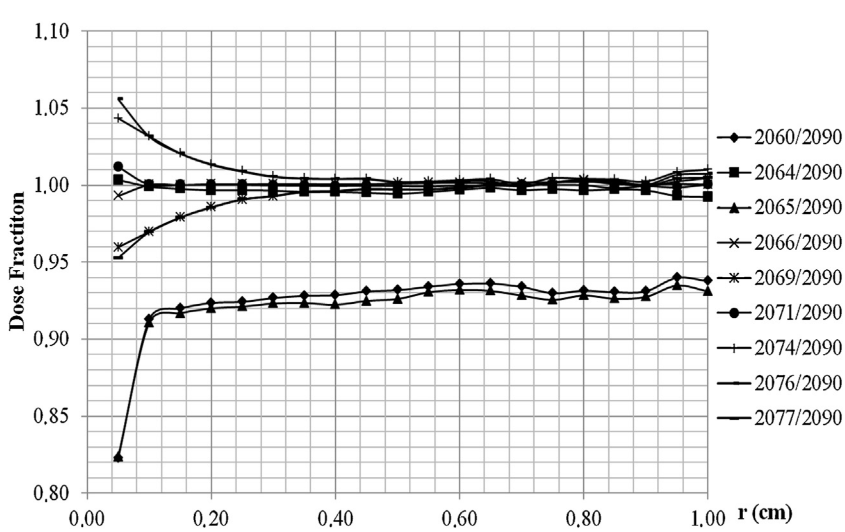

Fig. 6 – Dose normalizations for Model 6711 up to 1 cm distance.

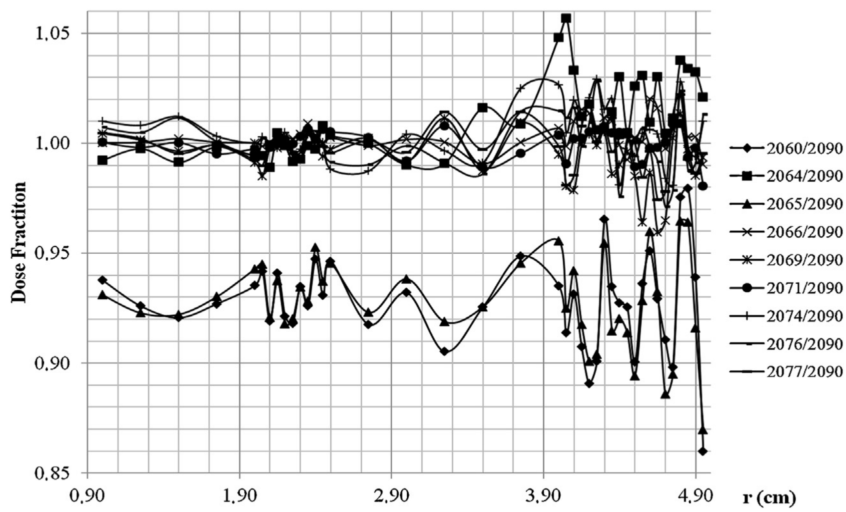

Fig. 7 – Dose normalizations for Model 6711 up to 5 cm distance.

of modified seeds were plotted individually as cited ID number of seeds. In the Cartesian analytic system, the calculated doses were shown on the *x*-axis that is the transverse axis of seed. Three kinds of seed are symmetric for all axes so data were taken on $[0 - +X_i]$. In *N* graphics, there are some oscillations which disturb uniformity of plot curves since they are plotted in a small scale of the radial axis and data were not interpolated. Statistical errors of MC calculations increase as spatial. Plots of normalized doses are shown in Fig. 6.

Dose normalization of seeds identified by 2060, 2065, 2074, 2076 and 2077 include considerable deviation of about 10%, especialy at a small distance (Fig. 6) for [0,1]. Uncertainties are about 4%–8% while MC dose calculation uncertainties are 0.1% (histories-initial photon numbers in simulation were selected as great to acquire maximum 0.1% uncertainties).

Seeds with 2060 and 2065 ID have also remarkable deviations from 1 in *N* plots of 5 cm length. Deviations are about 3%–7%. Others do not have serious deviations. General characteristic of *N* plots is defined by decreasing uncertainties versus increasing distance (Fig. 7). Seed radius has a spatial line on the x axis where dose was calculated and the radius is about 0.04 cm N deviations are very big within a comparatively short distance in a material space aroun the seed. Dose has the most effective values to destroy cancerous cell at a small distance in tissue for LDR (^{125}I and ^{103}Pd) sources. Uncertainty can exceed 10% in those ragions. At [0,1] distances, it seems clear that there are great deviations around the seed. Environs of the seed is an effective area for LDR therapy.

Looking at Theragenic 200 (Theragenics Corporation) seed (Fig. 8), normalization values diverge considerably from 1 at [0,1] distance around the seed capsule. 2281, 2250 and 2274 (Table 3.) seeds show remarkable dose differences from the original one.

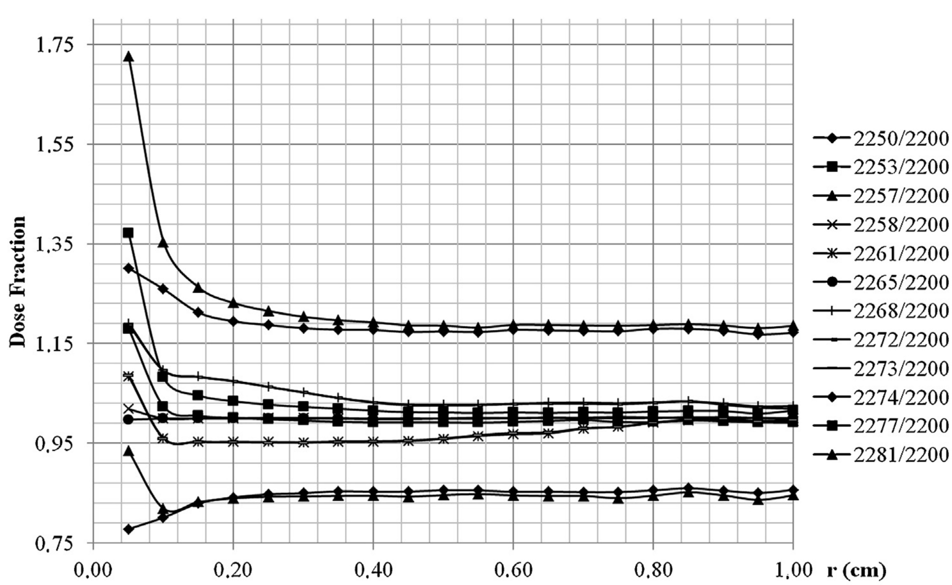

Fig. 8 – Dose normalizations for Theragenic 200 Seed up to 1 cm distance.

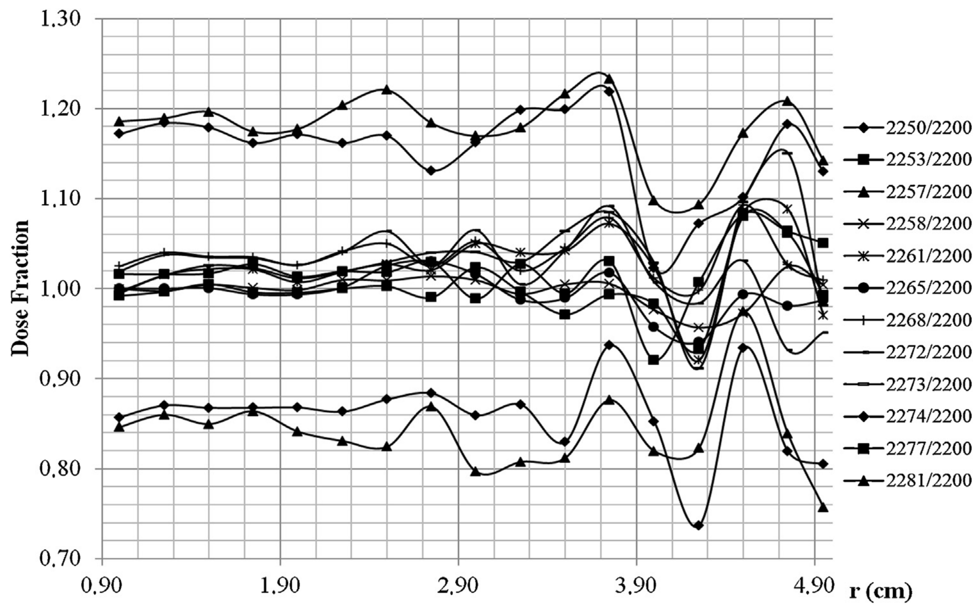

Fig. 9 – Dose normalizations for Theragenic 200 Seed up to 5 cm distance.

In the [0,5] scale distance: 2250, 2257, 2274 and 2281 seeds (Table 3) have clear deviations from 1 cm. Deviation is around 20%. Statistical uncertainties of dose values increase by distance. This causes uniformity losses on curves for relative distant points (Fig. 9).

There are two modified seeds of ImagySeed (Imagyn Medical Technologies, Inc.) model which have important normalization deviations (Fig. 10). 2311 ID numbered seed has deviations over 30% and 2329 seed has deviations of about 10%.

2311 and 2329 seeds conserve their deviations on the [0,5] scale distance. Additionaly, 2328 and 2333 seeds have about 8% deviations (Fig. 11).

In the present study, primary dose data were processed instead of calculating dosimetric functions in Eq. (1). Brachytherapy has been used for over 100 years,[12,13] and the brachytherapy dose calculation formalism recommended by the American Association of Physicists in Medicine AAPM Task Group No. 43 TG-43 report has been in clinical use for over 15 years.[14] Suggestions of the TG-43 formalism have been challenged by many studies.[15] Dose distributions of modified seeds were normalized by data belonging to the seeds assumed as original to make results independent from TG-43 referenced data. This detailed study that is supported by literature data proves an optimization for geometrical properties–dimensions of brachytherapy seeds in MC calculations for their size effects on dose. Normalization values show remarkable deviations which have a serious contribution on total statistical uncertainties.

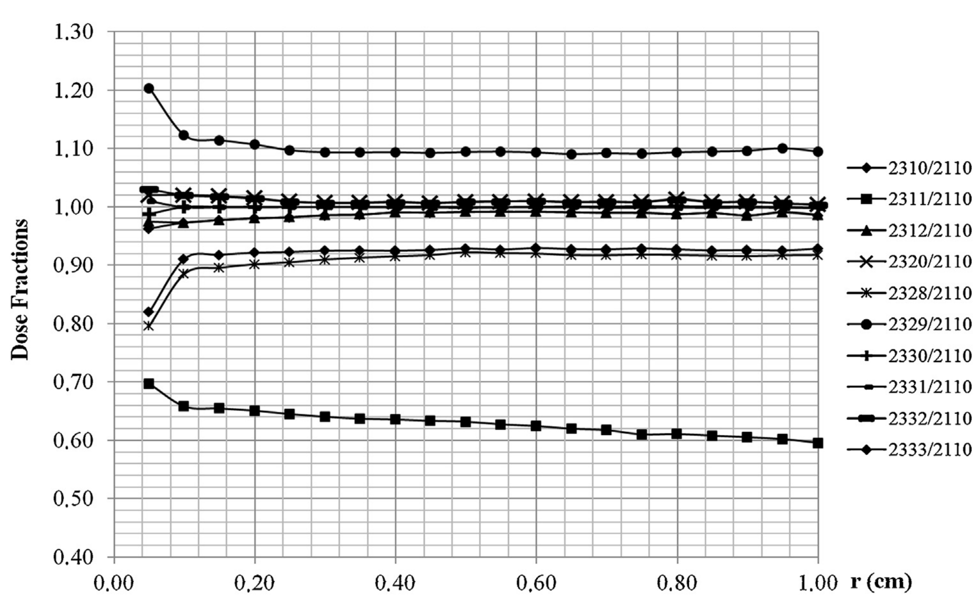

Fig. 10 – Dose normalizations for Imagyn Seed up to 1 cm distance.

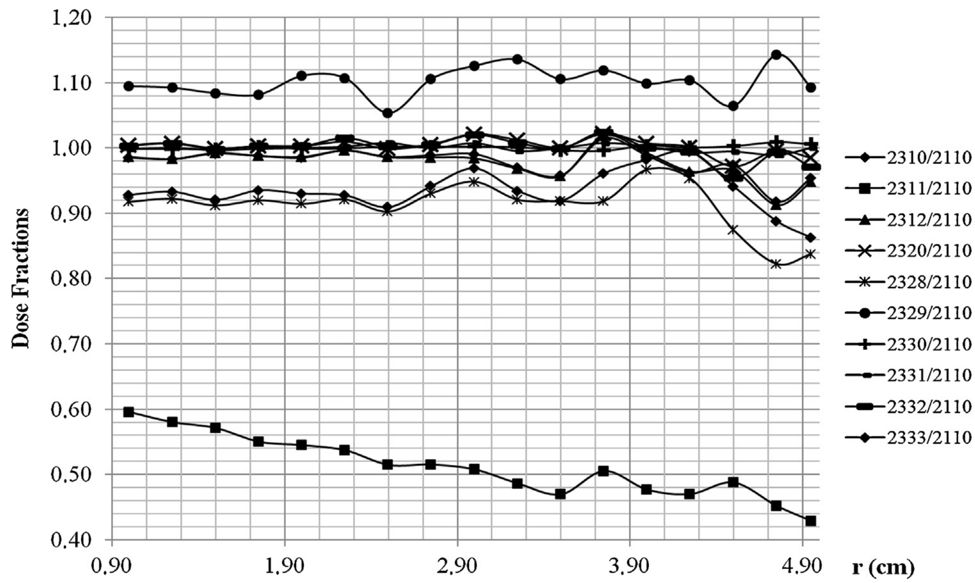

Fig. 11 – Dose normalizations for Imagyn Seed up to 1 cm distance.

4. Conclusion

Experimental results do not directly require optimized conditions for the seeds since particular and user selective seeds which have unchanged manufacturing specifications are used in the experiment. In MC studies all effects should be considered with detail to determine specific uncertainties. Most of uncertainties come from geometrical differences, although ideal conditions were assumed in simulation designs. Consequently, TG-43 data may be revised using optimized MC values according to geometrical uncertainties. It can be understood from comparison between seed specifications (Tables 2–4) and ratios of normalization deviations that capsule geometry is a dominant factor for dose amount. In addition, it can be said that MC studies on geometrical uncertainties can be useful to investigate a secondary subject.[16] Clinical applications should be optimized for dimensional deviations of the brachytherapy seeds since small changes in dimensions cause remarkable dose deviation as understood from this study. Also dosimetric parameters as suggested in TG-43 report should include dimension uncertainties.

Conflict of interest

The authors declare that they have no conflict of interest.

Financial disclosure statement

All authors are disclose any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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