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Original Article

Determination of dosimetric dependence for effective atomic number of LDR brachytherapy seed capsule by Monte Carlo simulation

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ABSTRACT

Brachytherapy is a special case of radiotherapy. It should be arranged according to some principles in medical radiation applications and radiation physics. The primary principle is to use as low as reasonably achievable dose in all ionizing radiation applications for diagnostic and therapeutic treatments. Dosimetric distributions are dependent on radioactive source properties and radiation-matter interactions in an absorber medium such as phantom or tissue. In this consideration, the geometrical structure and material of the seed capsule, which surrounds a radioactive material, are directly responsible for isodose profiles and dosimetric functions. In this study, the radiometric properties of capsule material were investigated on dose distribution in a water phantom by changing its nuclear properties using the EGSnrc Monte Carlo (MC) simulation code. Effective atomic numbers of hypothetic mixtures were calculated by using different elements with several fractions for capsule material. Model 6711 brachytherapy seed was modeled by EGSnrc/Dosrcnrc Code and dosimetric functions were calculated. As a result, dosimetric parameters of hypothetic sources have been acquired in large-scale atomic number. Dosimetric deviations between the data of hypothetic seeds and the original one were analyzed. Unit dose (Gy/Particle) distributions belonging to different types of material in seed capsule have remarkably differed from the original capsule's data. Capsule type is major variable to manage the expected dose profile and isodose distribution around a seed. This study shows us systematically varied scale of material type (cross section or effective atomic number dependent) offers selective material usage in production of seed capsules for the expected isodose profile of a specific source.

1. Introduction

Brachytherapy is a therapeutic cancer treatment that has common clinical practice. Although it has been studied by scientists and researchers for almost fifty years [1], brachytherapy has kept its importance and currency in the scientific and clinical fields. The factor that makes brachytherapy an efficient technique is the well-targeted delivery of the expected radiation dose into small volumes (clinically) or voxels (theoretically) [2]. Brachytherapy is preferred for several types of cancer in clinical treatments; also, prostate cancer treatment is the largest application area [2,3]. Brachytherapy seed sources are classified into two types: high-dose rate (HDR) and low-dose rate (LDR) seeds. While HDR seeds contain radioactive material with activity around 10 Ci, it is between 0.3 and 0.8 Ci for LDR seeds. LDR seeds commonly include iodine-125 and palladium-103 radioisotopes. Commercially, Amersham 6702 (I-125), Amersham 6711 (I-125), Best Industries 2301 (I-125), Bebig/Theragenics I25 (I-125), and Theragenics 200 (P-103) are common seeds in clinical treatments [4]. LDR seeds, which have a short radioactive material lifetime, are generally implanted permanently, but HDR seeds are only implanted temporarily during treatment. Therefore, HDR seeds are widespread. LDR seeds have greater geometrical and material diversity.

The American Association of Physicists in Medicine (AAPM) published the TG-43 report in 1995. The report that has been updated suggests criteria, formalizations, and calculation methods for scientists (both experimental and simulation) and clinic experts. Dose calculation and expected or required formalism has been reported in TG-43. Although the report is not a common standard for academic and clinic staff, it offers proper techniques. There are partial functions, which are g(r), F(r, θ) of dose rate expression in the suggested formalism [4]. While g(r) represents spatial dose

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distribution, F(r, θ) represents spatial and angular dose deviations around the seed source in tissue or phantom. These functions are calculated for the analytical P(r,θ) point (Fig. 1) in the absorbing media (tissue or phantom material) included in the unit volume (voxel).

Common formalism of dosimetric parameters is given as;

$\dot{D}(r,\theta) = S_k \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r) F(r,\theta)$ gives dose rate in a voxel where P(r, θ) is set.

While S_k is air kerma strength, Λ is dose rate constant G(r, θ) is geometry factor that is acquired by completely geometrical calculation. Other parameters are:

$$g(r) = \frac{\dot{D}(r,\pi/2).G(1,\pi/2)}{\dot{D}(1,\pi/2).G(r,\pi/2)} \qquad F(r,\theta) = \frac{\dot{D}(r,\theta).G(r,\pi/2)}{\dot{D}(r,\pi/2).G(r,\theta)}$$

(*Radial dose function*) (*Radial and angular dose function*)

$\dot{D}$ (r, θ) is dose rate at any P(r, θ) point on analytical system, $\dot{D}$ (r, π/2) is dose rate at point on vertical axe and $\dot{D}$ (1,π/2) is dose rate at 1 cm distance from seed center on vertical axe. 1 cm distance is reference point as suggested by AAPM. It is not scientific fact; it is just optimum reference point. Some scientific data can cause to discuss or disagree the reference point such as mobile part of seeds or geometrical uncertainties [5]. Except the report formalism; dose data can be directly measured, calculated or simulated to produce isodose profiles around a seed without mathematical formulations. But Tg-43 formalism commonly is preferred in brachytherapy researches as it can be seen in literature. There is no self-geometric definition of radiation dose; it is defined by radiation-matter interactions, which also define the dose and cause attenuation and energy absorption. Absorption of energy by material is dependent on initial radiation energy and atomic number of the absorber. Dose is function of energy and material type in real. If dose rate is defined as s the energy absorbed per unit volume per unit time, it is given as D' = μI(E,r) where $I(E, r)$ is the flux density of energy E at a distance r from a point source and μ is absorbing coefficient [6]. In equation, dose rate which is calculated by simulation is depended on photon energy for all stage of radiation-matter interactions. Raw data include this dependence before calculations. It is important that energy dependence of dosimetric parameters should be investigated for seed sources as another study suggestion.

Experimental studies can cause unavoidable measurement uncertainties in brachytherapy research (for 1 σ standard deviation, uncertainty assessment is about 8,7% [4]). For instance, TLDs (thermoluminescence dosimeters) have a shadowing effect, and dose is calculated in LiF dosimeter material instead of tissue, among other factors. Dose uncertainty is important for health risk in medical treatments. Although a single uncertainty source may be ignored, the sum of uncertainty sources becomes notable. Simulation calculations can give raw results with ignorable uncertainties (<1%) because of MC nature [7]. Additionally, hypothetical approaches on geometry and material properties of seed and phantom can be easily run by MC method while it is hard to study in real. EGSnrc/Dosrznrc simulation code was used in this study. Furthermore, producing several capsules physically in the expected effective atomic number value is difficult, if not impossible, so MC simulation appears to be the best way to achieve the goal of the study. All types of seeds have a capsule with two missions: first, to isolate the radioactive material from the tissue physically and chemically, and second, to form the dosimetric distribution around the seed to achieve the maximum dose into the target volume. Commercial seeds have fixed capsule material and routinely it is produced by suppliers. However, scientific expectations need flexible zone where almost all parameters can be changed or altered to examine all possibilities to find out optimum conditions. For this study, hypothetical seed capsule materials with different mixtures have been mathematically arranged for MC Simulation in an effective atomic number scale. Also, the energy dependence of radial dose deviation was examined in limited features in this study.

2. Material and method

Model 6711 [4] brachytherapy seed was selected as seed model which represents general form of a seed as illustrated in AAPM TG-43 Report. This is well known seed; its dosimetric characteristics and common geometry is not needed validation. Many previous experimental and simulation studies have agreed on its dosimetric data. Model 6711 seed was used as general brachytherapy seed concept. Original seed capsule is manufactured by titanium. In this study, the capsule material has changed with hypothetical mixtures which have systematically changed in effective atomic numbers scale. MC calculations were focused on g(r) function. F(r,θ) can be calculated but radial dose function is special form of F(r,θ) and angular situation is relative geometrical case of radial property (Fig. 2.).

2.1. Effective atomic number calculation

Effective atomic number concept has been used by Nevil Vincent

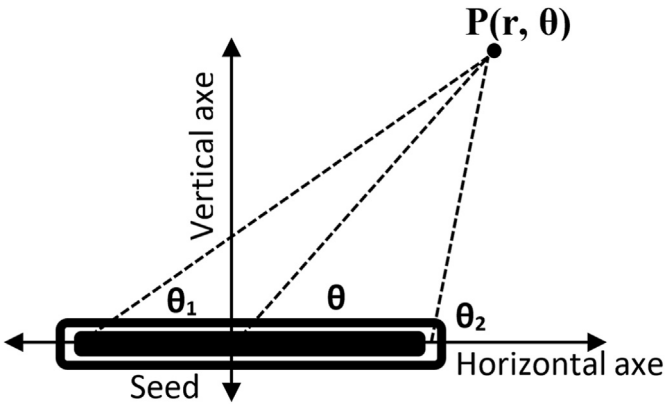

Fig. 1. Two-Dimensional generalized dose calculation formalism which is suggested by AAPM. Although there are many commercial/experimental seeds in different geometrical type which are different than the generalized geometry (such as Thera 200 model – Pd-103 seed [4] but suggested formalism is common.

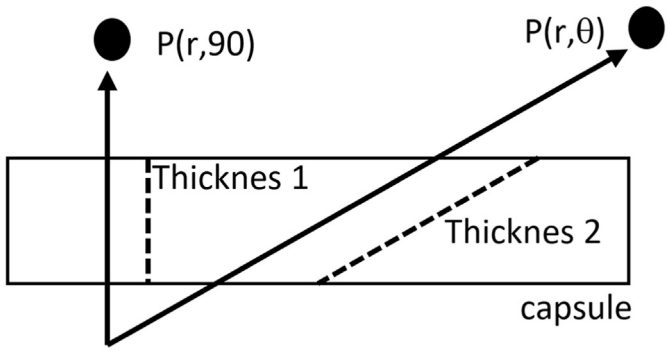

Fig. 2. Angular case of a P point is different thickness/radial situation for radiation absorption.

Table 1
For same effective atomic number different mixture elements with different weights (w1, w2, w3, w4).

Mixture elements	w1	w2	w3	w4	Zeff
Cr, Co, Ge, Au	0.18	0.08	0.51	0.23	40
Cr, Ni, Ge, Au	0.13	0.09	0.56	0.22	40
Cr, Fe, Ge, Au	0.11	0.22	0.43	0.24	40
(single element) Zr	–	–	–	–	40

Sidgwick around 1920 [8]. There are several calculation methods of effective atomic analytically and empirically.

$$Z_{eff} = \sum_i \frac{wi}{Ai} Zi2 \Big/ \sum_i \frac{wi}{Ai} Zi$$

Equation was preferred for the brute force algorithm to get element mixture fractions (weights), where Z_i is the atomic number of elements, A_i is the mass number of elements, and W_i is the element percent (weight) in the total mixture. If the element fractions are calculated for a known effective atomic number, analytical calculations became complicated. There is one known value against multi-variables. A simple Brute Force (Fig. 3) method [9,10] was improved to calculate or determine fractions of different atoms in a desired mixture.

An effective atomic number with acceptable uncertainty can be calculated using different W_i fraction sets for different atoms. The question is: which W_i set should be used? When validation calculations have been realized, the same effective atomic numbers, which have been calculated using different W_i sets (Table 1), should give the same dose profile in a fixed phantom voxel. Dose values at 3, 4, and 5 cm distances were normalized for different mixture fractions at a given distance.

Validation: A selected effective atomic number in different fractions that equals the atomic number of an element was tested. This validation is important because different element groups were used to get fixed effective atomic number values. Table 1 has been acquired for validation.

The elements that supply the targeted effective atomic numbers have been given in Results and Discussion section with dosimetric calculations: Since element types were determined by brute force method for expected/input effective atomic numbers, different element groups were acquired instead of single element group with variable fractions. Samples of element groups for the effective atomic number scale (from 15 to 70) are also classified in the Results and Discussion. The brute force method gives multiple element groups for the same effective atomic number. In the tables, single group of elements was picked up as a sample. All groups were tested for dosimetric parameters. Also, real Brachytherapy seed (model 671) capsule material Titanium (with a 22 atomic number) was studied comparatively.

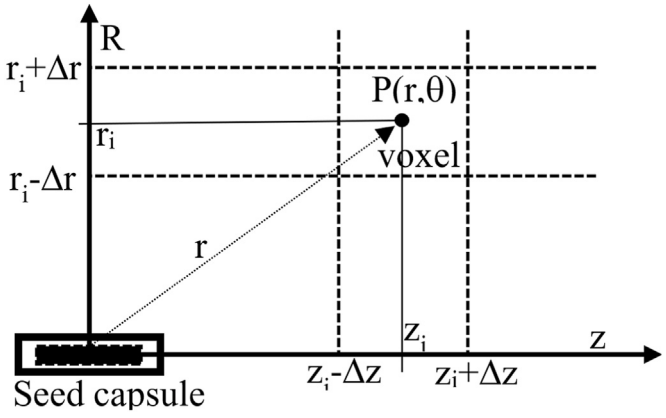

Fig. 4. Simulation geometry. "P" is analytical point defined by dosimetric functions. Optimized voxels were designed in 2D (R-Z cylindrical analytic system) that represents cubic volume unit.

2.2. EGSNRC code and study design

The brachytherapy seed was designed in Model 6711 geometry. Seed and surrounded water phantom were designed by cylindrical geometry. Water phantom was divided into optimized [11] voxel volumes (Fig. 4).

Nuclear data (cross section tables) was calculated by using acquired W_i sets using EGS-GUI Code of EGSNRC simulation Code system. Capsule geometry was defined by different effective atomic number at each independent run. Main simulation was run using DOSRZNRC sub-code of EGSNRC. For I-125 radionuclide the

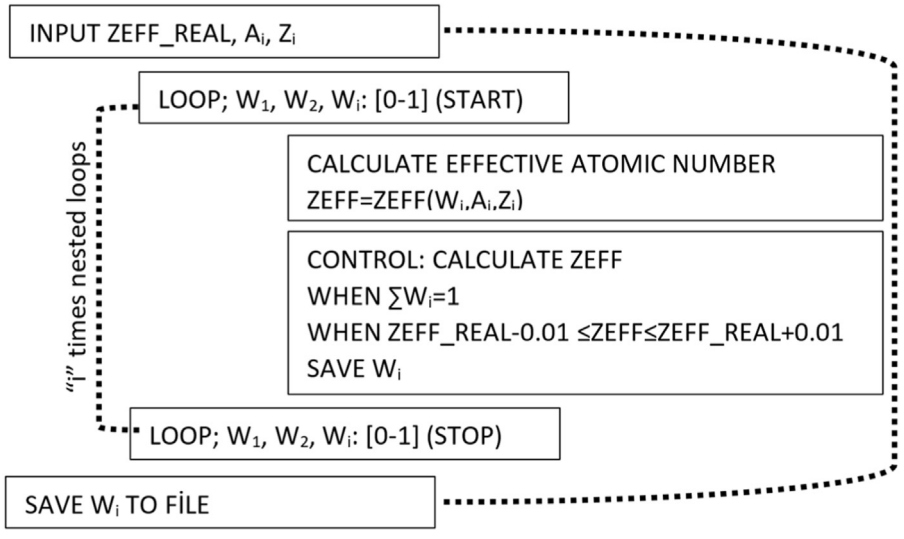

Fig. 3. Calculation algorithm of element fractions W_i for entered effective atomic number, If sensitivity (±0.0 … 01) of Z_{eff} is wanted to be better, This affects run time.

Table 2
Characteristic properties of I-125 radionuclide [12].

Photon energy (keV)	Photon emission rate
27.202	0.406
27.472	0.757
30.98	0.202
31.71	0.0439
35.492	0.0668
Average energy = 28.37 (keV)	**Total photon = 1.476**

characteristics given in Table 2, were used in MC simulation.

Validation: Normalization = $D_i(r_i, Zeff_i)/D_i(r_i, Zeff_j)$, where $Zeff_i = Zeff_j$ by different element weights (Fig. 4) and i = 1,2, 3 (Table 1). Deviations of dose fractions are greater comparatively with smaller distances around 100% at 5 cm (Fig. 5). The reason is statistical uncertainty that stems from Monte Carlo calculations. Dose rapidly decreases, so the initial photon number should be greater for distant voxels for small deviations at the farther distance from the radiation source. The number of initial photons was not increased to show the nature of the dosimetric uncertainty in the MC simulation.

g(r) radial dose function was calculated for real seed with Titanium capsule by compared TG-43 Report data (Fig. 6).

In this study effective atomic number scale was determined by several W_i set and different atom sets. Fixed W_i and atom set cause calculation limitation on effective number in brute force algorithm (Fig. 3.) for expected Zeff scale. Elements of groups were tried to select as solid almost because someone can produce them physically.

2.3. Energy dependence

Intensity and dose attenuation is function of initial photon energy. Although it is not distinguished directly in dosimetry of the seed, energy dependence should be considered. Photons of I^{125} spectrum and hypothetical energies of photons have been separately simulated using EGSnrc MC Code for original Titanium capsule of Model 6711 seed. Individual spectrum energies and hypothetic energies were simulated to investigate their contributions in regular scale.

3. Results an discussion

Result data is given in table form instead of graphical illustration because multiple curves are overlapping in scale of 0–7 cm; it is impossible to distinguish them. Element groups were selected as input data to get element weights in mixtures in effective atomic number calculation (Fig. 3.) groups selected as it includes small, middle, and high atomic numbers of elements to supply expected Z_{eff} value. If small Z_{eff} is calculated, wight of element with small atomic number is higher (Table 3:9, A) (see Table 4).

High Z materials in the capsule may provide internal shielding/absorbing for low energetic photons such as the I-125 spectrum [13,14]. Thomadsen and colleagues [13] showed that dependence on direction has attenuated primary radiation in almost 99%. However, this approach seems effective seed orientation that stems from tissue movements, which causes remarkable uncertainties for target in clinical implants [15]. Titanium (atomic number is 22) is commonly used as a seed capsule. If Titanium is assumed to have an average atomic number, a Z > 30 scale can be assumed to be high Z, and Z = 50, 60, and 70 is extremely high Z. But dose rate cannot be affected in great deviations by increasing or decreasing the atomic number of capsules, as it seems in the tables, although the attenuation of primary radiation is expected to dramatically decrease.

Z_{eff} = 40 is also validation value of this study (Table 6) (see Table 5). It should be mentioned in this scale point; alternative element group of 40 numbers results different g(r) dataset. Source of his differences are not clear but first probable reason is statistical deviations in simulation. Because of MC simulation nature, every single re-run of simulation is independent. Separated nuclear interactions cause different (in logical scale) results in both real radiometric techniques and well-designed simulation codes (see Table 7).

As seen on Table 9–B; g(r) function of Z_{eff} = 70 is remarkable greater than the real (assumed) data. g(r) function of Z_{eff} = 15 is relatively smaller (less notable) than real dosimetric data (see Table 8). Z = 15 and Z = 70 atomic numbers may be extreme values

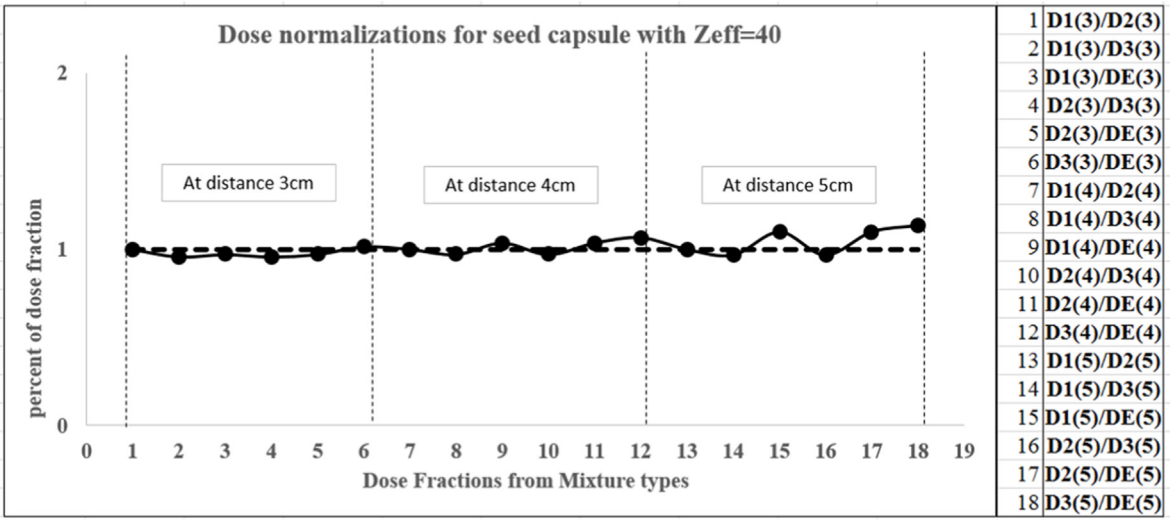

Fig. 5. Dose normalizations for different mixture types of capsule material at distance 3, 4 and 5 cm. Di: i = 1, 2, 3 (Table x.) Chosen of 40 number is not systematic, it is nearly middle of used effective atomic number scale.

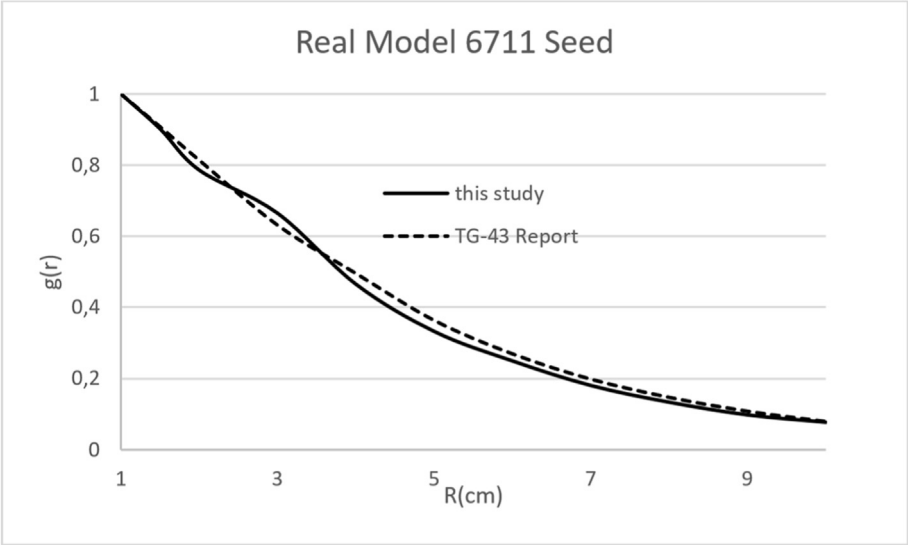

Fig. 6. Real seed validation for g(r) function. This data (TG-43 data) was named as "real" for comparisons in results section.

Table 3
A- Alternative Element groups for fixed Effective atomic number 15, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 15.

A						
Mixtures $Ze_{ff} = 15$		w1	w2	w3	w4	w5
1	C, Si, Fe, Cr, Ni	0.17	0.63	0.05	0.05	0.1
2	B, Si, Ti, Pt	0.43	0.38	0.12	0.07	
3	B, Zr, Ta, Pt	0.81	0.07	0.06	0.06	
4	C, Si, V, Pt	0.47	0.37	0.08	0.08	

B					
R (cm)	$g(r)_1$	$g(r)_2$	$g(r)_3$	$g(r)_4$	Real
1	1	1	1	1	1
2	0.76	0.76	0.75	0.76	0.79
3	0.58	0.58	0.57	0.58	0.67
4	0.45	0.45	0.44	0.45	0.47
5	0.31	0.31	0.32	0.32	0.33
6	0.23	0.23	0.23	0.24	0.25
7	0.17	0.17	0.17	0.17	0.18

Table 4
A- Alternative Element groups for fixed Effective atomic number 20, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 20.

A						
Mixture $Z_{eff} = 20$		w_1	w_2	w_3	w_4	w_5
1	C, Si, Fe, Cr, Ni	0.04	0.35	0.46	0.08	0.7
2	B, Si, Ti, Pt	0.16	0.43	0.32	0.09	–
3	B, V, Mo, W	0.69	0.04	0.1	0.17	–
4	C, Si, V, Pt	0.45	0.2	0.2	0.15	–
5	Si, Ti, Nb, Ta	0.75	0.11	0.07	0.07	–
6	Si, Ti, Ni, Au	0.75	0.1	0.07	0.08	–
7	Si, Ti, Ni, Ge	0.4	0.42	0.09	0.09	–

B								
R (cm)	$g(r)_1$	$g(r)_2$	$g(r)_3$	$g(r)_4$	$g(r)_5$	$g(r)_6$	$g(r)_7$	Real
1	1	1	1	1	1	1	1	1
2	0.77	0.77	0.76	0.77	0.76	0.76	0.76	0.79
3	0.59	0.59	0.58	0.59	0.58	0.58	0.58	0.67
4	0.45	0.45	0.44	0.46	0.44	0.45	0.44	0.47
5	0.32	0.32	0.31	0.32	0.31	0.32	0.31	0.33
6	0.24	0.24	0.24	0.24	0.23	0.24	0.23	0.25
7	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.18

Table 5
A- Alternative Element groups for fixed Effective atomic number 30, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 30.

A				
Mixtures $Z_{eff} = 30$		w_1	w_2	w_3	w_4
1	B, Si, Ti, Pt	0.04	0.56	0.12	0.28
2	B, V, Mo, W	0.43	0.13	0.2	0.24
3	B, Zr, Ta, Pt	0.51	0.23	0.11	0.15
4	Cr, Fe, Ge, Au	0.51	0.12	0.3	0.07
5	C, Si, V, Pt	0.35	0.14	0.2	0.31
6	Si, Ti, Nb, Ta	0.16	0.46	0.29	0.09
7	Si, Ti, Ni, Au	0.28	0.44	0.08	0.2
8	Mn, Ga, Se, Au	0.69	0.17	0.07	0.07

B									
R (cm)	$g(r)_1$	$g(r)_2$	$g(r)_3$	$g(r)_4$	$g(r)_5$	$g(r)_6$	$g(r)_7$	$g(r)_8$	Real
1	1	1	1	1	1	1	1	1	1
2	0.78	0.75	0.77	0.79	0.79	0.77	0.69	0.8	0.79
3	0.6	0.57	0.6	0.62	0.61	0.58	0.53	0.62	0.67
4	0.47	0.44	0.46	0.49	0.47	0.45	0.41	0.49	0.47
5	0.33	0.32	0.34	0.35	0.34	0.31	0.29	0.35	0.33
6	0.25	0.24	0.26	0.27	0.25	0.24	0.22	0.26	0.25
7	0.18	0.18	0.19	0.2	0.18	0.18	0.16	0.19	0.18

Table 6
A- Alternative Element groups for fixed Effective atomic number 40, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 40.

A				
Mixtures $Z_{eff} = 40$		w_1	w_2	w_3	w_4
1	B, Si, Ti, Pt	0.09	0.29	0.18	0.44
2	B, V, Mo, W	0.09	0.42	0.16	0.33
3	B, Zr, Ta, Pt	0.43	0.09	0.24	0.24
4	Cr, Fe, Ge, Au	0.11	0.22	0.43	0.24
5	C, Si, V, Pt	0.17	0.28	0.08	0.47
6	Si, Ti, Nb, Ta	0.23	0.08	0.43	0.26
7	Si, Ti, Ni, Au	0.12	0.1	0.46	0.32
8	Mn, Ga, Se, Au	0.31	0.34	0.11	0.24

B									
R (cm)	$g(r)_1$	$g(r)_2$	$g(r)_3$	$g(r)_4$	$g(r)_5$	$g(r)_6$	$g(r)_7$	$g(r)_8$	Real
1	1	1	1	1	1	1	1	1	1
2	0.78	0.8	0.8	0.8	0.79	0.79	0.8	0.81	0.79
3	0.61	0.61	0.63	0.64	0.61	0.59	0.62	0.64	0.67
4	0.47	0.48	0.5	0.51	0.48	0.45	0.48	0.5	0.47
5	0.34	0.35	0.36	0.38	0.34	0.33	0.35	0.36	0.33
6	0.26	0.26	0.27	0.28	0.26	0.25	0.27	0.27	0.25
7	0.19	0.19	0.2	0.21	0.19	0.19	0.2	0.2	0.18

Table 7
A- Alternative Element groups for fixed Effective atomic number 50, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 50.

A				
Mixtures $Z_{eff} = 50$		w_1	w_2	w_3	w_4
1	B, Si, Ti, Pt	0.21	0.09	0.08	0.62
2	B, V, Mo, W	0.11	0.14	0.25	0.5
3	B, Zr, Ta, Pt	0.17	0.32	0.43	0.08
4	Cr, Fe, Ge, Au	0.13	0.17	0.24	0.46
5	C, Si, V, Pt	0.2	0.1	0.07	0.63
6	Si, Ti, Nb, Ta	0.11	0.11	0.29	0.49
7	Si, Ti, Ni, Au	0.27	0.04	0.12	0.57
8	Mn, Ga, Se, Au	0.22	0.18	0.16	0.44

B									
R (cm)	$g(r)_1$	$g(r)_2$	$g(r)_3$	$g(r)_4$	$g(r)_5$	$g(r)_6$	$g(r)_7$	$g(r)_8$	Real
1	1	1	1	1	1	1	1	1	1
2	0.79	0.78	0.79	0.82	0.78	0.83	0.81	0.84	0.79
3	0.62	0.61	0.63	0.65	0.61	0.64	0.63	0.66	0.67
4	0.48	0.5	0.51	0.53	0.48	0.5	0.49	0.52	0.47
5	0.35	0.35	0.38	0.38	0.35	0.37	0.36	0.39	0.33
6	0.26	0.27	0.28	0.3	0.26	0.27	0.27	0.29	0.25
7	0.19	0.2	0.21	0.22	0.2	0.2	0.2	0.21	0.18

Table 8
A- Alternative Element groups for fixed Effective atomic number 60, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 60.

A					
Mixtures $Z_{eff} = 60$		w_1	w_2	w_3	w_4
1	B, V, Mo, W	0.08	0.1	0.07	0.75
2	B, Zr, Ta, Pt	0.09	0.22	0.4	0.29
3	Cr, Fe, Ge, Au	0.24	0.06	0.02	0.68
4	Mn, Ga, Se, Au	0.09	0.14	0.14	0.63
B					
R (cm)	$g(r)_1$	$g(r)_2$	$g(r)_3$	$g(r)_4$	Real
1	1	1	1	1	1
2	0.82	0.81	0.79	0.84	0.79
3	0.64	0.66	0.64	0.67	0.67
4	0.53	0.52	0.51	0.53	0.47
5	0.37	0.38	0.39	0.39	0.33
6	0.29	0.3	0.3	0.29	0.25
7	0.22	0.22	0.22	0.22	0.18

Table 9
A- Alternative Element groups for fixed Effective atomic number 70, where w_i is element weight in hypothetical mixture. **B**- For a capsule defined as material with Z_{eff} is 70. Only one group can be founded/selected to acquire 70.

A				
Mixtures $Z_{eff} = 70$	w_1	w_2	w_3	w_4
B, Zr, Ta, Pt	0.06	0.05	0.21	0.68
B				
R (cm)		g(r)		Real
1		1.00		1
2		0.83		0.79
3		0.68		0.67
4		0.54		0.47
5		0.40		0.33
6		0.31		0.25
7		0.23		0.18

for a seed capsule material, but these numbers are at the edges of the study scale. This study has put forward the material spectrum of a seed capsule as dosimetric area. In general view of the results, there is a characteristic situation, which is dependence on the atomic number. On the other hand, data has small deviations as they are close to each other.

During literature searches, similar or comparable studies could not be found (in access conditions or possibilities) for external discussion since research on nuclear properties of materials and brachytherapy are separate study areas, even if they are not actually. Brachytherapy is more clinically focused than pure scientific efforts due to its nature; it is based on scientific research in principle, but theoretical and clinical research are splitting. Such as, it is almost impossible to realize this study as clinical/experimental. Additionally, dosimetric parameters of a brachytherapy seed are apparently dependent on geometrical properties (radial and angular), but energy dependence cannot be seen directly in the calculation formalism. Nuclear cross-section database of MC simulations has a large energy scale. In this study, the I-125 energy region is used for those effective atomic numbers of hypothetical mixtures. But the effective atomic numbers are dependent on the initial radiation energy in dosimetric studies. This derived data has a hidden energy dependence.

Even though there is not a certain consensus on the TG-43 Report of AAPM, the study construction has been based on the report, and the report has potentially common elements. In this simulation fiction, g(r) functions were acquired for different effective atomic numbers of hypothetical capsule material, and calculation data was compared with common literature data and the single atomic number of the capsule. Real titanium has an atomic number of 22, and when its g(r) function is compared with data for atomic numbers 15–70, it seems that the calculated g(r) values are smaller than the real ones until atomic number 40. After the 40, it turns into reverse. Acquired dependence characteristics of the dosimetric parameter to the atomic number can be fixed for new seeds. Titanium (A = 22) is near No = 20, and it is between 20 and 30; in comparison, for that scale, MC data is still smaller in narrow deviations. Although there is a dependence profile in the study dataset differences between real and hypothetical values of g(r), it can be ignored because g(r) is just one parameter of dose rate expression. F(r,θ) function has also similar small differences (g(r) is a special case of F(r,θ)). F(r,θ)xg(r) expression in the dose rate formula will have a bigger deviation. As a result, this study offers capsule material scale as a dosimetric function. Furthermore, there are no significant differences in the 15–70 scale.

Although it is not directly relevant to the study focus, the energy dependence of radiation absorption is obvious. Capsule material absorbs initial radiation, and dose (dependent on absorbed energy) begins with this value in tissue radially. Even if it cannot be noticed, the energy absorption property of the capsule is a major factor in the dose values of radial isodose form propagation. So, the energy dependence of capsule absorption was calculated by the MC code in this study. Fig. 7 is partially showing the energy dependence of the capsule.

There are some mono-energetic studies for brachytherapy seed sources [16, 17]. Julio [4] has studied photons ranging between

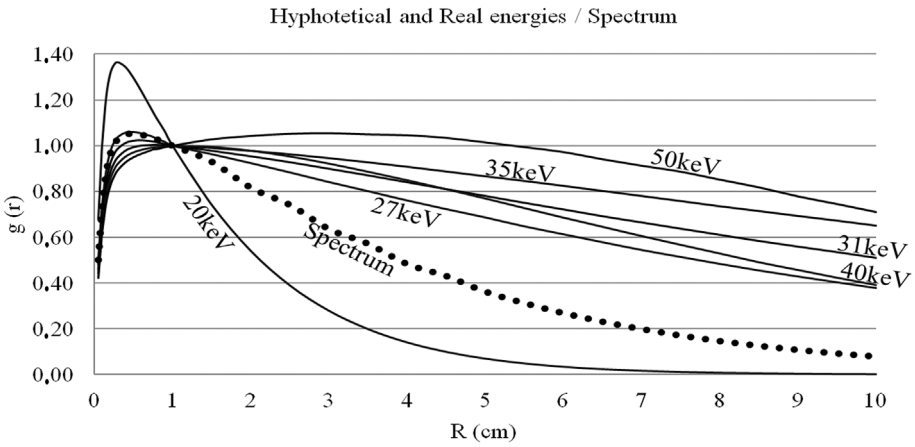

Fig. 7. Comparison of radial dose functions for separate hypothetical and real energies with 20, 27, 31, 35, 40, and 50 keV versus combined spectrum energies in [0–10 cm].

10 keV and 2 eV by the Monte Carlo method. He compared radial dose distributions. Julio has reported that, at distances from the source closer than 1 cm, the deviations are larger [16]. Luxton and Jozsef [17] have studied monoenergetic photons to determine dose distribution in water phantoms using EGS4 MC simulation. They obtained dosimetric data on water over the photon energy range of 15 keV–2 keV. The dose changing by distance is expected in the case of water for those energy scales.

4. Conclusion

The material dependence of seed capsules as a function of dose is quite noticeable. When it is assumed as one another parameter of dose rate, it is important. This study offers a dependence scale for capsule only. It should be considered for new modeling and productions of seeds. On the other hand, when deviations are omitted (it can be ignorable for aimed uncertainties), scientific MC studies can be constructed for a suitable atomic number of capsule materials. Even if results are remarkable or not, the truth is that there is a systematically dosimetric dependence on the effective atomic number of the capsule. For new concepts, it is possible that radioactive material can be inserted into a capsule (the full seed body), so it is needed to calculate the total atomic number with the radioelement and capsule elements mixture. Also, the energy dependence of the capsule as a radiation absorber should not be underestimated when considering dose profile parameters. Studied parameters and their deviation scale can guide seed production and design. The current manufactured seed properties or dose calculation formalism are not discussed in this study. Instead, the study offers a parameter dependence spectrum for probable new seed productions.

Author contributions

* Berkay Camgöz designed the study, wrote main manuscript, prepared all figures and tables.

* Diala Tarım realized calculations and some of design of the study, got numerical results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M.J. Rivard, J.L.M. Venselaar, L. Beaulieu, The evolution of brachytherapy treatment planning, Jun, Med. Phys. 36 (6) (2009) 2136–2153.
[2] J.M. Hannoun-Lévi, Brachytherapy for prostate cancer: Present and future Cancer/Radiothérapie, 21, 2017, pp. 469–472.
[3] C. Boukarama, J.M. Hannoun-Levi, Management of prostate cancer recurrence after definitive radiation therapy, Cancer Treat Rev. 36 (2010) 91–100.
[4] J.M. Rivard, B.M. Coursey, L.A. DeWerd, W.F. Hanson, M.S. Huq, G.S. Ibbott, M.G. Mitch, R. Nath, J.F. Williamson, American Association of Physicists in Medicine (AAPM) Task Group No.43 Report, 2004, p. 42p.
[5] B. Camgöz, M.N. Kumru, A Monte Carlo evaluation for effects of probable dimensional uncertainties of low dose rate brachytherapy seeds on dose, RPOR (1 9) (2014) 301–309.
[6] S Radiation Gad, Dosimetry Department of Nuclear and Biomedical Engineering Ben Gurion University Beer Sheva. Israel Instrumentation and Methods Second Edition, Boca Raton, London New York Washington. D.C, 2001.
[7] N.D. Mukhopadhyay, A.J. Sampson, D. Deniz, G.A. Carlsson, J. Williamson, A. Malusek, Estimating statistical uncertainty of Monte Carlo efficiency-gain in the context of a correlated sampling Monte Carlo code for brachytherapy treatment planning with non-normal dose distribution, Appl. Radiat. Isot. 70 (2012) 315–323.
[8] J.A. Davies, C.M. Hockensmith, V.Y. Kukushkin, Y.N. Kukushkin, Synthetic Coordination Chemistry: Principles and Practice, World Scientific, 1996, p. 423p.
[9] D.J. Bernstein, Understanding Brute Force, Department of Mathe-matics, Statistics, and Computer Science, 2005, 2010, http://cr.yp.to/snue/bruteforce-20050425.pdf.
[10] C.P.J. Pelzl, Understanding Cryptography, A Textbook for Students and Practitioners, Springer Heidelberg, Dordrecht London New York, 2010.
[11] R.E.P. Taylor, G. Yegin, D.W.O. Rogers, Benchmarking BrachyDose: voxel based EGSnrc Monte Carlo calculations of TG-43 dosimetry parameters, Med. Phys. 34 (2007) 445p.
[12] L.P. Reis, A. Facure, S.C. Cardoso, A.X. Silva, Characterization of some dosimetric parameters of ^{125}I seeds used for prostate implants using Monte Carlo simulations, in: International Nuclear Atlantic Conference (INAC), Brazil, 2009, p. 10p.
[13] L. Lin, R.R. Patel, B.R. Thomadsen, D.L. Henderson, The use of directional interstitial sources to improve dosimetry in breast brachytherapy, Med. Phys. 35 (2008) 240–247.
[14] V. Chaswal, B.R. Thomadsen, D.L. Henderson, Development of an adjoint sensitivity field-based treatment-planning technique for the use of newly designed directional LDR sources in brachytherapy, Phys. Med. Biol. 57 (2012) 963–982.
[15] Y.S. William, K. Tanderup, B. Pieters, Emerging Technologies in Brachytherapy, CRC Press, 2017.
[16] F. Julio, R.G. Almansaa, M.O. Feras, et al., Dose distribution in water for monoenergetic photon point sources in the energy range of interest in brachytherapy: Monte Carlo simulations with PENELOPE and GEANT4, Radiat. Phys. Chem. 76 (2007) 766–773.
[17] G. Luxton, G. Jozsef, Radial dose distribution, dose to water and dose rate constant for monoenergetic photon point sources from 10 keV to 2MeV: EGS4 Monte Carlo model calculation, Med. Phys. 26 (1999) 2531–2538.