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MONTE CARLO SIMULATION-BASED DOSIMETRIC EVALUATION OF A NOVEL ^{125}I BRACHYTHERAPY SOURCE
Comparative Assessment of Dosimetry Parameters and Shadowing Effects

by

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This study investigates a novel ^{125}I radiotherapy source. It evaluates its dosimetric parameters using Monte Carlo simulation around the source, following the updated American Association of Physicists in Medicine Task Group recommendations. For this new source configuration, the dose rate constant Λ, geometry function $G(r, \theta)$, radial dose function $g_L(r)$, and anisotropy function $F(r, \theta)$, were determined using Geant4 Monte Carlo simulations. Additionally, a comparison of the obtained dosimetric parameters with those of an earlier ^{125}I source model was conducted to analyze the shadowing effect between the two designs during multi-source brachytherapy implants.

Key words: brachytherapy, Geant4, Monte Carlo simulation, capsule structure

INTRODUCTION

Nowadays, brachytherapy is widely used to treat various types of cancers, including oral, prostate, cervix, breast, skin, neck, and other cancers. Brachytherapy sources are primarily classified into two categories: high-dose-rate (HDR) and low-dose-rate (LDR) sources. Radioactive isotopes such as ^{125}I, ^{103}Pd, and ^{131}Cs are commonly preferred for LDR brachytherapy due to their low energy levels, short half-lives, and material versatility [1-4].

Before starting radiotherapy treatment, it is essential to enhance and validate dosimetric parameters such as the dose rate constant, geometry function, radial dose function, and anisotropy function around the brachytherapy seed. This can be achieved experimentally or through simulation [5, 6]. Monte Carlo (MC) simulation codes are especially valuable for modeling brachytherapy sources. They effectively simulate the geometry of these sources, the physics of radiation interacting with matter, and the process of dose absorption. A significant advantage of these simulations is their ability to provide dose data at locations where experimental measurements are difficult or impractical to obtain [7, 8].

There are many MC simulation codes capable of modeling source geometry, radiation interaction, and dose absorption in cells [9-11]. Among these, Geant4 stands out due to its exceptional capability in constructing and handling various designs of radioactive sources. Geant4, developed by CERN (the European Organization for Nuclear Research), is one of the most powerful simulation codes available. It provides a comprehensive description of experiments and supports the extraction of data necessary for simulations [12, 13].

This study aims to characterize the dosimetric parameters of a novel ^{125}I brachytherapy source using Geant4 MC simulations, adhering to the updated American Association of Physicists (AAPM) Task Group recommendations. The specific objectives are to determine the dose rate constant, geometry function, radial dose function, and anisotropy function, and to compare these parameters with a previous ^{125}I source model to evaluate the shadowing effect in multi-source brachytherapy implants.

MATERIAL AND METHODS

Geant4 MC simulations

Geant4 is a simulation toolkit built on C++ class libraries, widely used in high-energy physics, space radiation modeling, and medical physics. Developed

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in 1998 by CERN, it employs object-oriented programming and MC methods to simulate particle interactions with matter. The toolkit enables users to define complex geometries and materials, track particles using robust physical models, visualize interactions, and generate simulated data. By integrating experimental and theoretical models, Geant4 provides a comprehensive understanding of particle-material interactions across a wide energy range, making it a preferred choice for complex simulations over traditional MC codes [12, 13].

The geometry and source arrangements are coded in the mandatory Geant4 class *DetectorConstruction.cc*. Physics processes are defined in *PhysListEmLowEnergy.cc*, where the following interactions are implemented: For gamma rays: Compton scattering, photoelectric absorption, pair production, and Rayleigh (coherent) scattering. For electrons and positrons: multiple scattering, ionization, and bremsstrahlung. All classes are designed with object-oriented programming principles in C++ and include comprehensive routines for handling complex tasks. The *G4RunManager* class acts as the maestro, controlling all actions and initializing the simulation setup by coordinating the execution of all arrangements.

Source description

The specifications of the currently investigated ^{125}I seed are shown in fig. 1. The ^{125}I source features rounded ends. The seed encapsulation has a total length of 4.8 mm (0.3 mm longer than the previous design) and is constructed from titanium with a 0.05 mm wall thickness (0.05 mm thinner). The total length of seed encapsulation is equal to 4.6 mm and is made of titanium ($\rho = 4.54$ gcm^{-3}) with 0.05 mm thickness that contains a palladium core having a 3.5 mm active length, with 0.6 mm thick end. In contrast, our previous brachytherapy source design contained four polystyrene ion-exchange resin beads and two centrally positioned radiographic markers composed of an 80 % gold and 20 % copper alloy.

Simulations assumed 40 % relative humidity and an air density of 0.00120 gcm^{-3}. The dry air composition (by mass percentage) was defined as H: 0.0732 %, C: 0.0123 %, N: 75.0325 %, O: 23.6077 %, and Ar: 1.2743 %. The atomic number and density of elements used in the ^{125}I brachytherapy sources are provided in tab. 1.

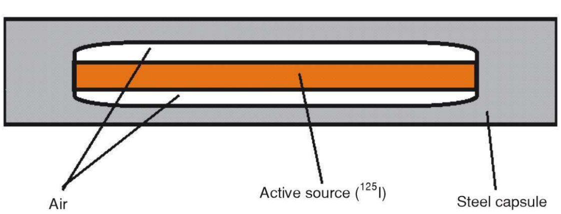

Figure 1. Simulated model of ^{125}I brachytherapy source

Table 1. Atomic number and density of elements used in the ^{125}I seeds

Element	Proton number (Z)	Density [gcm^{-1}]
Iodine (I)	53	4.93
Titanium (Ti)	22	4.51
Palladium (Pd)	46	12.02
Copper (Cu)	29	8.92
Gold (Au)	79	19.32

Dose rate constant Λ

Dose rate constant Λ is the ratio of dose rate $\dot{D}(r_0, \theta_0)$[cGyh^1] in water at $r_0 = 1$ cm, from the source center on the transverse plane and $\theta_0 = 90°$ to the air kerma strength S_K

$$\Lambda = \frac{\dot{D}(r_0, \theta_0)}{S_K} \tag{1}$$

The air-kerma strength S_K is the product of the air kerma rate K_d [μGyh^{-1}] and the square of the distance d to the point of specification

$$S_K = K_d d^2 \tag{2}$$

It is expressed in Gys^{-1} but in a more convenient way especially for low-dose rate brachytherapy, in μGyh^{-1}, at 1 m. For convenience, μGym^{2}h^{-1} is denoted by the symbol U where 1U = cGycm^{2}h^{-1} = μGym^{2}h^{-1}. So, the dose rate constant Λ has the unit of cGyh$^1U^{-1}$. To calculate the air kerma strength of the ^{125}I capsule, an air sphere ring with a thickness 0.01 cm was used to detect the absorbed dose as shown in fig. 2.

Radial dose function calculation

Radial dose function considers dose reduction due to photon attenuation and scattering in the medium. According to AAPM [14], the radial dose function $g(r)$ is defined as

$$g_L(r) = \frac{\dot{D}(r, \theta_0)\, G_\mathrm{L}(r_0, \theta_0)}{\dot{D}(r_0, \theta_0)\, G_\mathrm{L}(r, \theta_0)} \tag{3}$$

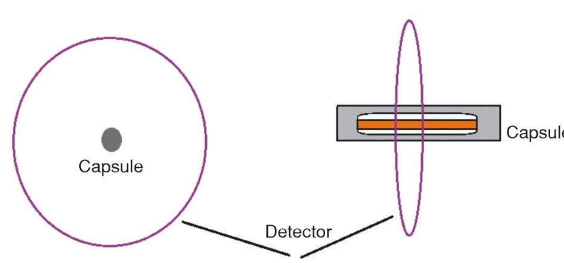

Figure 2. Dose rate calculation geometry at 1 cm from the source's center

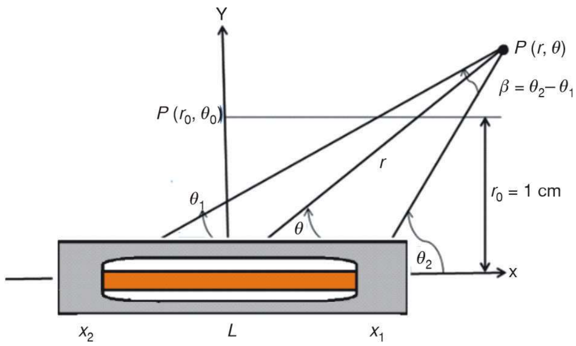

Figure 3. Co-ordinate system used for brachytherapy dosimetry calculations

where L represents the length of the active source, θ is the polar angle as shown in fig. 3. The $\dot{D}(r_0, \theta_0)$ and $\dot{D}(r, \theta_0)$ are dose rates measured away from the source center; the $G_L(r_0, \theta_0)$ and $G_L(r, \theta_0)$ are the geometry functions on the transverse plane at 1 cm and r in cm, respectively.

Geometry function

The geometry function $G(r, \theta)$ [cm^{-2}] is calculated by the following formulas

$$G(r,\theta) = \begin{pmatrix} \dfrac{\theta_2 - \theta_1}{Lr\sin(\theta)}, & \text{if } \theta \neq 0 \\ \left(r^2 - \dfrac{L^2}{4}\right)^{-1}, & \text{if } \theta \neq 0 \end{pmatrix}$$

$$\beta = \theta_2 - \theta_1 = \left(\frac{r\sin(\theta)}{r\cos(\theta) - \frac{1}{2}L}\right) - \tan^{-1}\left(\frac{r\sin(\theta)}{r\cos(\theta) + \frac{1}{2}L}\right) \tag{4}$$

Anisotropy function

According to the AAPM [14], the anisotropy function describes the anisotropy of dose distribution around the seed. It is defined as the angular dependence of photon scattering and attenuation in encapsulating layers and media

$$F(r,\theta) = \frac{\dot{D}(r,\theta) G_L(r_0,\theta_0)}{\dot{D}(r_0,\theta_0) G_L(r,\theta)} \tag{5}$$

Absorbed dose

The general, 2-D equation of the absorbed dose $D(r, \theta)$ at a point from a brachytherapy source is [14]

$$D(r,\theta) = S_k \Lambda G(r,\theta) F(r,\theta) t \tag{6}$$

where r – the distance from the center of the active source to the point of interest, θ – the polar angle specifying the point of interest, relative to the source longitudinal axis, and t – the time of exposure. In multi-source brachytherapy implant scenarios, the intensity of photons emitted from each seed into the treatment volume may be reduced due to the shadowing effect from neighboring seeds. This inter-seed effect (ISE), dimensionless quantity, between brachytherapy sources can be quantified using the following equation [14]

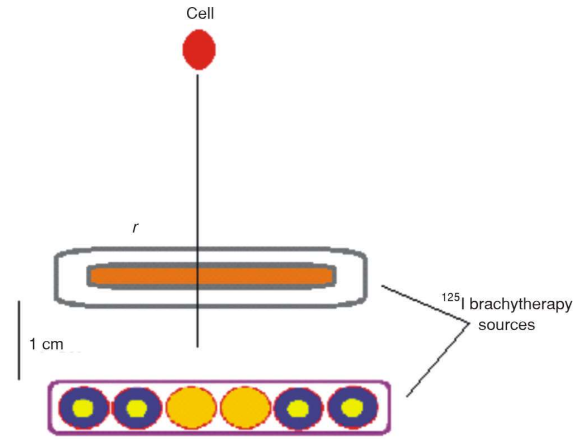

Figure 4. Simple method for calculating ISE for current and earlier ^{125}I brachytherapy sources

$$\text{ISE} = \frac{D_{12}}{D_1 + D_2} \tag{7}$$

where D_{12} is the absorbed dose at a given point inside the dosimetry medium caused by the two seeds implants, D_1 and D_2 – the absorbed dose at the same point due to the separate presence of source 1 and source 2. The geometrical arrangement for ISE evaluation is shown in fig. 4.

RESULTS AND DISCUSSION

In this study, the dosimetric properties of the ^{125}I brachytherapy source were analyzed using Geant4-based MC simulations. The simulation results were compared with previously published data from our earlier paper [9] and other studies, including the ^{125}I-6711 [15], ^{125}I-BT [16], ^{125}I-IRA [17], and ^{125}I-MED3631A/M [18] sources. In this experiment, a dose-rate constant of (0.925 ±0.019) cGyh$^{-1}U^{-1}$ was calculated for the encapsulated source design using MC simulations. When compared to published data for other commercial ^{125}I brachytherapy sources tab. 2, the results demonstrate minimal discrepancies between the values obtained in this study and established reference data.

Table 2. Comparison of dose rate constant Λ, with other ^{125}I seeds

Source (^{125}I seeds)	Dose-rate constant [cGyh^{-1}U^{-1}]
^{125}I-MED3631A/M [18].	1.067
125I-6711 [15]	0.942 ±1.76
^{125}I-BT [16]	0.928 ±0.01
^{125}I-IRA [17]	1.068
Our previous paper [9]	0.925 ±0.019
Current work	

Table 3. Comparison of radial dose function, with other ^{125}I seeds

Distance r [cm]	$g_L(r)$					
	^{125}I-MED3631A/M [18]	^{125}I-6711 [15]	^{125}I-BT [16]	^{125}I-IRA[17]	Previous paper [9]	Current work
	MCNP	MCNP	MCNP	MCNP	Geant4	Geant4
0.25	0.992	–	–	1.102	1.007	0.998
0.30	1.002	–	–	–	1.005	1.004
0.35	1.008	–	–	–	1.010	1.007
0.40	1.012	–	–	–	1.018	1.016
0.50	1.015	1.07	1.074	1.075	1.017	1.015
0.60	1.016	–	–	–	1.021	1.018
0.75	1.014	1.025	1.025	1.042	1.019	1.016
1.00	1.000	1.000	1.000	1.000	1.013	1.013
1.25	0.977	–	–	–	1.002	0.973
1.50	0.948	0.908	0.914	0.914	0.968	0.943
1.75	0.917	–	–	–	0.936	0.917
2.00	0.883	0.814	0.822	0.819	0.84	0.883
2.50	0.810	–	–	–	0.768	0.814
3.00	0.733	0.633	0.645	0.643	0.697	0.735
4.00	0.590	0.482	0.496	0.492	0.565	0.594
5.00	0.466	0.361	0.379	0.37	0.432	0.436
7.00	0.277	0.199	0.212	0.205	0.256	0.267
10.00	0.121	–	–	–	0.112	0.115

The radial dose function, $g_L(r)$, was calculated over a distance range of 0.25 cm to 10 cm from the source center using the Geant4 MC toolkit. The results showed a notably strong agreement with published data for other commercial ^{125}I brachytherapy sources, tab. 3. Additionally, the simulated radial dose function, $g(r)$, for the ^{125}I source was compared to both prior ^{125}I seed designs and our earlier work, as illustrated in fig. 4.

As shown in fig. 5, the radial dose function values of the model closely match those of the reference data in the regions $0 < r < 1$ cm and $6 < r < 10.0$ cm. Nevertheless, moderate deviations are observed within the intermediate range ($1 < r < 6$ cm). Compared to published data for commercial ^{125}I seeds, the differences between the model's results and the reference data are negligible, indicating good agreement across most radial distances.

Anisotropy functions were calculated at radial distances ranging from 0.25 cm to 10 cm and at angles spanning 0° to 180° around the source. The resulting anisotropy function values are summarized in tab. 4, and their graphical representation for the ^{125}I source is provided in fig. 6. Smooth variations in anisotropy function values were observed across all evaluated angles around the brachytherapy source.

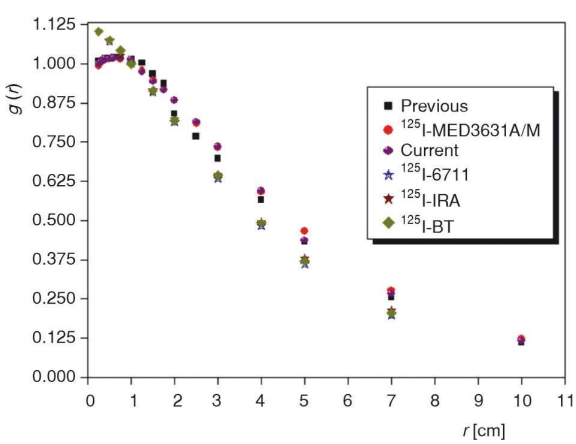

Figure 5. Simulation of radial dose function compared to other studies

Finally, we evaluated ISE of the current ^{125}I brachytherapy source and our previous source at distances from 1 cm to 7 cm, in increments of 0.5 cm. As illustrated in fig. 7, ISE values at distances greater than 3.5 cm converge, resulting in a flattened trend of ISE variations at far distances from the multi-seed implant. This phenomenon likely arises from the increased contribution of scattered radiation to the absorbed dose at larger distances, which counterbalances attenuation effects. The interplay between scattering and attenuation ultimately leads to the observed plateau in ISE trends at far distances.

CONCLUSION

In this study, the updated ^{125}I brachytherapy source was validated using a Geant4 MC simulation code. The source geometry was modeled, and key AAPM-recommended dosimetric parameters-including the dose rate constant, geometry function, radial dose function, and anisotropy function-were calculated for the source. These results were compared with data from our earlier design and published values for commercial ^{125}I sources. The computed parameters were within clinically acceptable tolerances, confirming that the updated source provides a dosimetric distribution that meets clinical standards. Additionally, the ISE between the current and earlier source designs was evaluated to quantify the shadowing effect in

Table 4. Simulation for anisotropy function of the designed ^{125}I source from 0° to 180°

Polar angle (θ°)	Simulated $F(r, \theta)$					
	r [cm]					
	0.25	0.50	1.00	2.00	5.00	10.00
0°	0.813	0.625	0.624	0.650	0.699	0.689
10°	0.833	0.780	0.761	0.790	0.744	0.756
20°	0.863	0.866	0.789	0.799	0.823	0.843
30°	0.888	0.846	0.886	0.851	0.886	0.881
40°	0.886	0.891	0.922	0.907	0.918	0.933
50°	0.943	0.931	0.915	0.914	0.942	0.941
60°	0.961	0.950	0.970	0.973	0.978	0.988
70°	1.001	0.985	0.955	0.957	0.957	0.953
80°	1.010	0.980	1.008	0.998	1.001	0.999
90°	1.000	1.000	1.000	1.000	1.000	1.000
100°	1.007	0.990	0.991	1.000	1.004	0.978
110°	0.979	0.967	0.967	0.978	0.987	0.989
120°	0.956	0.933	0.945	0.967	0.956	0.977
130°	0.931	0.901	0.926	0.967	0.966	0.933
140°	0.888	0.895	0.889	0.904	0.901	0.883
150°	0.840	0.801	0.810	0.833	0.852	0.861
160°	0.733	0.691	0.701	0.712	0.767	0.789
170°	0.715	0.620	0.676	0.666	0.701	0.723
180°	0.644	0.623	0.677	0.667	0.700	0.715

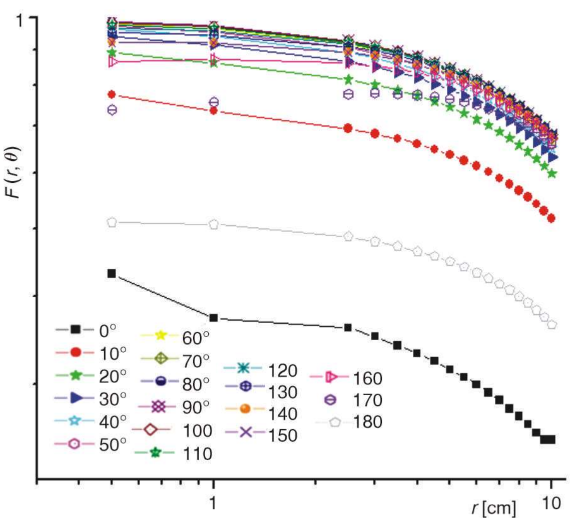

Figure 6. Geant 4 MC simulations for $F(r, \theta)$

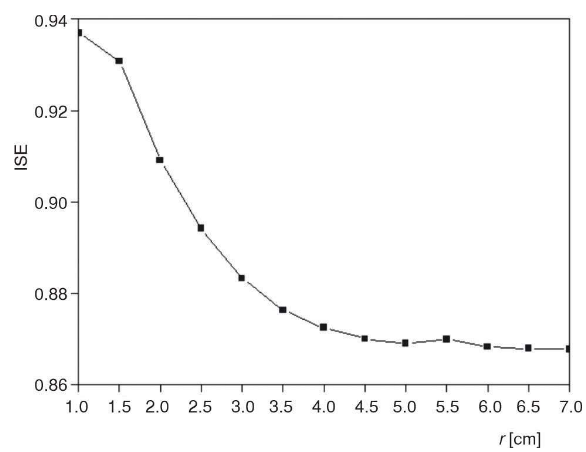

Figure 7. The values of inter-seed effect at different distances from the current ^{125}I brachytherapy source and our previous source

multi-source implant configurations. The ISE values converge at distances beyond 3.5 cm, resulting in a flattened dose trend at larger radial distances. This behavior is attributed to the interplay between scattered radiation (which increases with distance) and attenuation effects, ultimately stabilizing dose variations in multi-source implants.

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AUTHORS' CONTRIBUTIONS

W. Duo: building simulation configuration, writing the original manuscript, and project administration. W. Shuahua: literature review, running simulations, data analysis, correcting manuscript, and project administration. O. M. Mostafa: literature review, conducting simulations, and data analysis. M. E. Medhat: proposing the research idea and developing the theoretical framework.

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REFERENCES

[1] Swain, M., *et al*., Challenges in the Sustainability of Brachytherapy Service in Contemporary Radiotherapy, *Clinical Oncology, 35* (2023), 8, pp. 489-496

[2] Colson-Fearon, D., *et al*., Updated Trends in Brachytherapy Utilization and Disparities in the United States from 2004 to 2020, *Int J Radiat Oncol Biol Phys, 1* (2024), 119, pp. 154-162

[3] Schiefer, H., *et al*., A Precise and Simple Isodose-Volume-Based Verification Method for HDR and LDR Brachytherapy Plans, *Brachytherapy, 22* (2023), 3, pp. 400-406

[4] Azahari, A. N., *et al*., Variation of Optimization Techniques for High Dose Rate Brachytherapy in Cervical Cancer Treatment, *Nuclear Engineering and Technology, 54* (2022), 4, pp. 1414-1420

[5] Alshreef, A., *et al*., Validation of GAMOS Monte Carlo Simulation for ^{131}Cs Brachytherapy Source in Water and Dosimetric Characterization of Solid Water, Bone, and Brain Tissues, *Radiation Physics and Chemistry, 226* (2025), 112268

[6] Faj, D., *et al*., Monte Carlo Simulation of Photon Breast Radiotherapy of the Pregnant Patient Beam Characteristics, *Nucl Technol Radiat, 39* (2024), 2, pp. 154-159

[7] Díaz-Comeche, A., *et al*., Methodology for Integrating MCNP6 Monte Carlo Simulation into PLUNC for Prostate Brachytherapy Planning, *Radiation Physics and Chemistry, 223* (2024), 111955

[8] Camg, B., Tarim, D., Determination of Dosimetric Dependence for Effective Atomic Number of LDR Brachytherapy Seed Capsule by Monte Carlo Simulation, *Nuclear Engineering and Technology, 55* (2023), 8, pp. 2734-2741

[9] Jie Liu, *et al*., Geant 4 Monte Carlo Simulation for I-125 Brachytherapy, *Nuclear Engineering and Technology, 56* (2024), 7, pp. 2516-2523

[10] Sahmaran, T., Tugrul, T., Investigation of Radiological Properties of Imaging Agents Used in Nuclear Medicine with Different Methods and GATE/Geant4 Simulation Program, *Nucl Technol Radiat, 38* (2023), 2, pp. 116-124

[11] Albqoor, A., *et al*., Validation of Electromagnetic Physics Models and Electron Range in Geant4 Brachytherapy Application, *Nuclear Engineering and Technology, 55* (2023), 1, pp. 229-237

[12] ***, Geant4 – a Toolkit for the Simulation of the Passage of Particles Through Matter, Version 4.9.3.p01, CERN, http://geant4.cern.ch.

[13] Agostinelli, S., *et al*., Geant4-A Simulation Toolkit. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, *Detectors and Associated Equipment, 506* (2003), pp. 250-303

[14] Rivard, J. M., *et al*., Update of AAPM Task Group No. 43 Report: *A Revised AAPM Protocol for Brachytherapy Dose Calculations, 31* (2004), 3, pp. 633-674

[15] Dolan, J., Li, Z., Williamson, J., Monte Carlo and Experimental Dosimetry of an ^{125}I Brachytherapy Seed, *Med Phys., 33* (2006), 12, pp. 4675-4684

[16] Solberg, T. D., *et al*., Dosimetric Parameters of Three New Solid Core ^{125}I Brachytherapy Sources, *Med Phys., 3* (2002), 2, pp. 119-134

[17] Sadeghi, M., Khanmohammadi, Z., Dosimetric Characteristic of a New ^{125}I Brachytherapy Source, *Radiat Prot Dosimetry, 147* (2011), 3, pp. 451-456

[18] Hadadi, A., *et al*., Monte Carlo Characterization of Biocompatible Beta-Emitting ^{90}Y Glass Seed Incorporated with the Radionuclide ^{153}Sm as a SPECT marker for Brachytherapy Applications, *Journal of Applied Clinical Medical Physics, 14* (2013), 5, pp. 90-103

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ДОЗИМЕТРИЈСКА ПРОЦЕНА НОВОГ ^{125}I БРАХИТЕРАПИЈСКОГ ИЗВОРА ЗАСНОВАНА НА МОНТЕ КАРЛО СИМУЛАЦИЈИ

Компаративна процена дозиметријских параметара и ефеката заклањања

Користећи Монте Карло симулацију око извора и пратећи ажуриране препоруке радне групе Америчког удружења физичара у медицини, истраживан је нови извор за радиотерапију ^{125}I. За ову нову конфигурацију извора, константа брзине дозе Λ, геометријска функција $G(r, \theta)$, функција радијалне дозе $g_L(r)$ и функција анизотропије $F(r, \theta)$, одређене су коришћењем Geant4 Монте Карло симулације. Поред тога, спроведено је поређење добијених дозиметријских параметара са онима из ранијег модела извора ^{125}I, да би се анализирао ефекат заклањања између два дизајна током имплантата брахитерапије са више извора.

Кључне речи: брахитерапија, Geant4 Монте Карло симулација, капсуларна структура