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A dosimetric evaluation using the Monte Carlo method considering geometric variations of the Iodine-125 seed for brachytherapy

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Abstract: The Institute for Energy and Nuclear Research – IPEN-CNEN/SP is uniquely positioned to develop a new source of Iodine-125 for brachytherapy treatment. Therefore, research into the dosimetric process and source design is widely studied. Task Group 43 – TG 43 cites methodologies for dosimetry of sources for brachytherapy, the most used method is Monte Carlo. However, the dosimetric protocol does not mention possible variations in the source geometry after its conception. The investigative focus of the work was to obtain measurements of the Iodine-125 seed during the production stages until completion, quantify them and simulate them using the Monte Carlo method with the MCNP – 4C code, the formalism was in water and a 101x101 matrix was used to calculate the dose point by point. Two variations were chosen: a) seed length; b) nucleus length, using a batch of 100 seeds for each case. 100 simulations were carried out for each variation and one simulation using the reference seed geometry. The following calculations were applied: relative difference to compare variations to the reference; average among the 100 seeds of each batch to calculate the standard deviation. In both cases there was no point that exceeded 4.48% relative difference, and for standard deviation the largest point was 1.6%, while the Type A uncertainty was 0.018% at the largest point.

Keywords: Radiotherapy, Brachytherapy, Dosimetry, Radiation.

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Avaliação dosimétrica pelo método de Monte Carlo considerando variações geométricas da semente de iodo-125 para braquiterapia

Resumo: O Instituto de Pesquisas Energéticas e Nucleares – IPEN-CNEN/SP está em um ponto único para desenvolver uma nova fonte de iodo-125 para tratamento de braquiterapia. Desse modo, a investigação quanto ao processo dosimétrico e concepção da fonte é amplamente estudado. O Task Group 43 – TG 43 cita metodologias para a dosimetria das fontes para braquiterapia, o método mais utilizado é o Monte Carlo. Entretanto, o protocolo dosimétrico não cita possíveis variações na geometria da fonte após a sua concepção. O foco investigativo do trabalho foi obter medidas da semente de iodo-125 durante as etapas de produção até a finalização, quantificá-las e simular usando o método de Monte Carlo com o código MCNP – 4C, o formalismo foi na água e uma matriz de 101x101 foi utilizada para calcular a dose ponto a ponto. Duas variações foram escolhidas: a) comprimento da semente; b) comprimento do núcleo, usando um lote com 100 sementes para cada caso. Foram realizadas 100 simulações para cada variação e uma simulação usando a geometria de referência. Foram aplicados os seguintes cálculos: diferença relativa para comparar as variações à referência; média entre as 100 sementes de cada lote para calcular o desvio padrão. Nos dois casos não houve nenhum ponto que passou 4.48% de diferença relativa e desvio padrão o maior ponto ficou em 1.6%, enquanto a incerteza Tipo A foi de 0.018% no maior ponto.

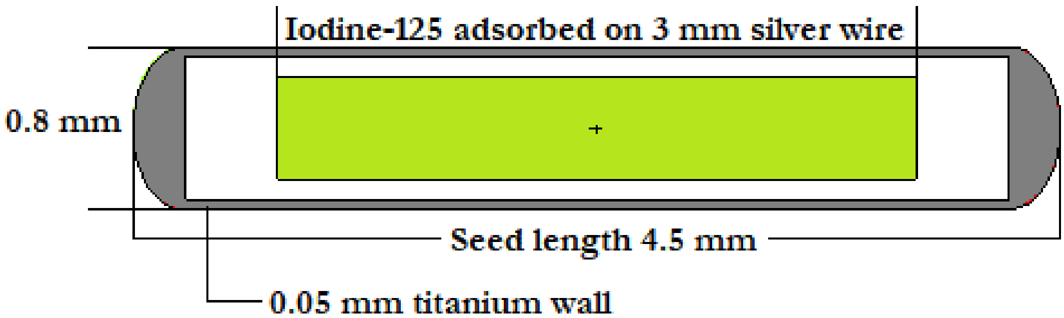
Palavras-chave: Radioterapia, Braquiterapia, Dosimetria, Radiação.

1. INTRODUCTION

One of the modalities of using ionizing radiation for cancer therapy is brachytherapy, which utilizes sealed sources (seeds) placed close to or in contact with the target (tumor). The dose to be used is carefully studied through prior treatment planning to understand the distribution of radiation in the target and adjacent healthy tissues. Computational simulation methods are widely employed in this process, taking into account the chosen source, type of radiation, and treatment duration, to ensure that the estimated dose for delivery meets the treatment requirements [1], [2], [3].

As therapeutic methodologies become more refined and computer systems improve, it is essential to investigate the dosimetry of radionuclides in detail. The seed investigated in this study, developed by the Instituto de Pesquisas Energéticas e Nucleares IPEN-CNEN/SP, follows a geometry similar to the OncoSeed 1251 6711 model from Amersham/GE. This seed consists of a titanium tube with a silver core containing radioactive material, with soldered ends. Its physical dimensions are as follows: 0.8 mm in width, 4.5 mm in total length, 3 mm in core length, and 0.05 mm in wall thickness, as illustrated in Figure 1 [3], [4], [5], [6].

Figure 1. Geometry of the Iodine-125 seed.



Source : Adapted from Feher, 2014 [4].

During the decay process, photons are emitted with the following energies: 27 keV, 31 keV, and 35 keV, resulting in an average energy of 29 keV. The new seed model emits additional photons of 22.1 keV and 25.2 keV, generated by the interaction of the Iodine-125 photons with the silver rod, with a half-life of 59.4 days [5].

The production of the seed is carried out through a rigorous flowchart, starting with the cutting of the titanium tube, followed by finishing the ends through sanding to minimize excess material. A visual inspection of the ends is conducted to verify compliance. If the tube is approved at this stage, it is forwarded to the first laser welding. Subsequently, the tube is repositioned for the insertion of the silver core, which already contains adsorbed Iodine-125. The sealing of the source is performed through a second laser welding, using the surplus material from the tube itself to ensure the integrity of the joint. After the conception of the seed, an approval or rejection criterion is applied based on visual inspection and leak tests. The production process takes into account the possibility of geometric variations of $\pm$ 5% in the seeds from the same batch. In this study, micrographs of the seeds were presented after approval by visual inspection, aiming to verify possible internal geometric variations. Irregular geometry was observed in the welds at one of the ends, even in seeds that passed leak tests [4].

Additionally, the group conducted a comparative study investigating geometric variations in another source produced in the same laboratory, using the same methodology. It was concluded that variations in the welds could cause uncertainty of up to 2% within the same batch. Another relevant aspect was the analysis of random positions the core could assume inside the seed due to internal geometric irregularities and empty space, leading to an 18% relative difference compared to the reference seed [3]. Therefore, an investigative study regarding the final dose is necessary, considering that geometric variations may impact radiation distribution.

The earliest investigations into the dosimetry of Iodine-125 date back to 1960, presenting an initial seed model that already incorporated titanium encapsulation, similar to current models.The analysis of the build-up region was conducted by Beger (1968) [7] in a study that utilized water as a reference medium, whose results showed that the dose reached its maximum peak within 1 cm around the source, with an average energy of Iodine-125 of 28.5 keV. Between 1982 and 1986, the introduction of the Monte Carlo method in dosimetry brought a significant advancement in the characterization of this source. Dale (1982) [8] compared dose distribution in water and human tissue, concluding that the radial dose function varied according to the type of tissue analyzed, and observed that the dose decreased rapidly as the penetration distance increased. Williamson (1988) [9] determined the specific dose constant in water using a large homogeneous phantom through the Monte Carlo methodology [10].

Cygler et al. (1990) [11] highlighted the importance of titanium and the radiopaque marker in dosimetry, emphasizing that the emission of low-energy photons by Iodine-125 resulted in limited penetration in clinical practice. Thus, the Monte Carlo method stood out for its ability to accurately model the complex dose distributions associated with Iodine-125 [7].

Calculations performed using the Monte Carlo method were enhanced with the inclusion of more precise data on the interaction of photons with matter. As a result, the dosimetry of Iodine-125 was solidly established, with the Monte Carlo method consolidating as the standard tool for planning clinical treatments. The dosimetric guidelines were published by the American Association of Physics in Medicine (AAPM) in Task Group 43 (TG-43) in 1995, taking into account aspects such as scattering, attenuation, and anisotropy of doses and the source. Therefore, the dosimetry of Iodine-125 was widely recognized. In 2004, an update of TG-43 to TG-43-U1 occurred, which mentioned significant advancements in the dosimetry of Iodine-125, highlighting the recommendation for the use of the Monte Carlo method for this purpose. Furthermore, the analysis of seeds using computational methods indicated that dosimetry showed high concordance when performed at distances of up to 1 cm from the source. Additionally, it was not mentioned that potential geometric variations arising from the production of the sources should be considered in simulations performed by the Monte Carlo method [7], [12].

1.1. Purpose

The main objective of the work was to investigate two geometric variations that may occur during the conception of the Iodine-125 seed for brachytherapy, which are normally not considered in dosimetry. To this end, two different batches were investigated, each consisting of 100 units for: 1) seed length and 2) core length. The purpose was to compare these variations through the relative difference to the reference geometry presented in Fig. 1 and to calculate the standard deviation for each of the two batches. Additionally, the aim was to avoid future inconsistencies when this protocol is applied to both experimental dosimetry and dosimetry using the Monte Carlo method.

2. MATERIALS AND METHODS

The Monte Carlo N-Particle Transport Code (MCNP-4C) was utilized, leveraging its comprehensive database, which includes detailed cross-section data and the underlying physics of stochastic events. The input development process strictly followed the specifications outlined in the MCNP™ – A General Monte Carlo N-Particle Transport Code Version 4C Manual [13]. The description of the input data was carried out according to the guidelines proposed for MCNP work published by TG-268 of the AAPM and showed in Tab. 4 [14].

One of the main features of MCNP 4C is its ability to simulate photons, making it ideal for studies involving dose distribution around radioactive sources, such as the Iodine-125 seed. To assess the dose distribution around the simulated object, MCNP 4C allows the use of cards that quantify photon interactions surrounding the simulated geometry. This technique enables a detailed calculation of the radiation dose around an object, providing an accurate representation of radiation interactions with water (the medium referenced in the TG-43 formalism) [13].

The input data for MCNP is organized into three blocks: the first two define the geometry of the problem. The first block (cells) performs the intersection and union of the geometric shapes to create the simulated object, while the second block (surfaces) describes these shapes and their sizes. The third block uses cards to specify the physical parameters of the simulation, including the position and energy spectrum of the source, types of particles, cutoff energy, requested calculations (tally), number of particle histories, and types of materials, among various other control options [15].

2.1. Iodine-125 core and seed measurements

Measurements were taken at different stages of the production of the Iodine-125 seed, using a Digimess® digital caliper, model 100.176BL, with a precision of ± 0.03 mm, as per the manufacturer's catalog, and this was not considered when transcribing the values for the input data writing. As seen in Fig. 2 [16].

A total of 100 measurements were performed for each case, from 2 different batches. The choice of 100 units was based on the fact that some brachytherapy treatments typically use an average of 100 units in clinical applications. Therefore, even though seeds and cores of the same size were found within the same batch, they were included in the modeling. The values obtained during the measurements for the variation in the length of the seed and the length of the core are presented in Tab. 1 and 2, respectively.

Figure 2. (a) Measurement of the length of the Iodine-125 seed ; (b) Measurement of the core.

Source : The authors.

Table 1. Iodine-125 seed length measurements in millimeters (mm).

SEED	mm	SEED	mm	SEED	mm	SEED	mm
1	4.63 mm	26	4.49 mm	51	4.51 mm	76	4.63 mm
2	4.53 mm	27	4.56 mm	52	4.53 mm	77	4.64 mm
3	4.57 mm	28	4.57 mm	53	4.58 mm	78	4.66 mm
4	4.57 mm	29	4.49 mm	54	4.60 mm	79	4.66 mm
5	4.53 mm	30	4.45 mm	55	4.64 mm	80	4.62 mm
6	4.52 mm	31	4.54 mm	56	4.64 mm	81	4.65 mm
7	4.55 mm	32	4.51 mm	57	4.66 mm	82	4.62 mm
8	4.51 mm	33	4.50 mm	58	4.53 mm	83	4.61 mm
9	4.50 mm	34	4.57 mm	59	4.69 mm	84	4.60 mm
10	4.50 mm	35	4.57 mm	60	4.65 mm	85	4.60 mm
11	4.52 mm	36	4.50 mm	61	4.63 mm	86	4.63 mm
12	4.54 mm	37	4.56 mm	62	4.62 mm	87	4.59 mm
13	4.52 mm	38	4.56 mm	63	4.65 mm	88	4.67 mm
14	4.50 mm	39	4.52 mm	64	4.60 mm	89	4.67 mm
15	4.52 mm	40	4.56 mm	65	4.69 mm	90	4.60 mm
16	4.50 mm	41	4.56 mm	66	4.68 mm	91	4.63 mm
17	4.50 mm	42	4.50 mm	67	4.61 mm	92	4.60 mm
18	4.48 mm	43	4.57 mm	68	4.63 mm	93	4.63 mm
19	4.54 mm	44	4.54 mm	69	4.64 mm	94	4.65 mm
20	4.59 mm	45	4.50 mm	70	4.66 mm	95	4.58 mm
21	4.57 mm	46	4.51 mm	71	4.61 mm	96	4.59 mm
22	4.50 mm	47	4.57 mm	72	4.60 mm	97	4.67 mm
23	4.56 mm	48	4.57 mm	73	4.66 mm	98	4.62 mm
24	4.56 mm	49	4.57 mm	74	4.66 mm	99	4.69 mm
25	4.53 mm	50	4.51 mm	75	4.69 mm	100	4.64 mm

Source : The authors.

Table 2. Silver core length measurements in milímeters (mm).

SEED	mm	SEED	mm	SEED	mm	SEED	mm
1	2.95 mm	26	2.97 mm	51	2.97 mm	76	3.01 mm
2	2.93 mm	27	2.97 mm	52	3.00 mm	77	2.99 mm
3	2.98 mm	28	3.01 mm	53	2.93 mm	78	2.96 mm
4	2.97 mm	29	2.98 mm	54	2.96 mm	79	2.95 mm
5	2.96 mm	30	2.93 mm	55	2.89 mm	80	2.98 mm
6	2.99 mm	31	2.98 mm	56	2.96 mm	81	2.94 mm
7	2.97 mm	32	2.96 mm	57	2.98 mm	82	3.00 mm
8	2.91 mm	33	2.95 mm	58	2.96 mm	83	2.95 mm
9	2.94 mm	34	2.98 mm	59	2.91 mm	84	3.02 mm
10	2.95 mm	35	2.92 mm	60	2.97 mm	85	3.00 mm
11	3.00 mm	36	2.99 mm	61	2.98 mm	86	2.94 mm
12	2.92 mm	37	2.94 mm	62	3.01 mm	87	2.97 mm
13	2.93 mm	38	2.96 mm	63	2.94 mm	88	2.96 mm
14	2.96 mm	39	2.93 mm	64	3.00 mm	89	2.97 mm
15	2.98 mm	40	2.97 mm	65	2.91 mm	90	2.97 mm
16	3.00 mm	41	2.94 mm	66	2.97 mm	91	2.97 mm
17	2.97 mm	42	2.98 mm	67	2.99 mm	92	2.98 mm
18	2.96 mm	43	2.99 mm	68	3.03 mm	93	2.94 mm
19	2.99 mm	44	2.99 mm	69	2.94 mm	94	2.94 mm
20	2.95 mm	45	2.99 mm	70	2.88 mm	95	2.97 mm
21	2.98 mm	46	2.98 mm	71	2.97 mm	96	2.95 mm
22	2.95 mm	47	2.96 mm	72	2.96 mm	97	2.97 mm
23	2.94 mm	48	2.95 mm	73	2.92 mm	98	2.98 mm
24	2.95 mm	49	2.95 mm	74	2.97 mm	99	2.95 mm
25	2.93 mm	50	2.95 mm	75	2.99 mm	100	2.98 mm

Source : The authors.

2.2. Input data for the simulation

The first two blocks of input data were developed based on the reference geometry shown in Fig. 1, serving as the foundation for creating 200 additional inputs—100 for the seed length and 100 for the core length. Furthermore, these blocks define the materials used, which are presented in Tab. 3.

Table 3. Materials used in the simulation.

Material	Composition	Density	Simulated objetc
Liquid Water	100% H_2O	1.0 g/cm³	Water Sphere
Pure Silver	100% Ag	10.49 g/cm³	Core
Pure Titanium	100% Ti	4.506 g/cm³	Encapsulation

Source : Adapted from NIST, 2024.

The third block, which includes the physical data of the source, remained unchanged for the 2 investigated batches and the reference seed. For this block, photon simulations were conducted using the same spectrum and 10^9particle histories for each simulation, as detailed in Tab. 4.

Table 4. Input data for the simulation with Monte Carlo following the TG-268 protocol.

Item	Description and References
Software	MCNP™ – A General Monte Carlo N-Particle Transport Code Version 4C [13].
Hardware	12th gen Intel® Core™ i9 processor (16 cores, 24 threads), 64 GB RAM (clock speed 3.2 GHz). Each simulation took an average of 60 minutes.
Geometry	The water formalism was used as the medium for the Monte Carlo simulations, following the recommendations of TG-43. The Iodine-125 seed was simulated within a sphere of water, which is the medium referenced by TG-43 [12].
Materials	See Tab. 2.
Source	It is shown in Fig. 1, based on the manufacturer's original description, and discussed in the text [4]. And 200 varied geometries that are presented in the text as they were obtained, with 100 for the seed length and 100 for the core length.
Physic and Transport	Cross-section data were obtained from MCPLIB04, referred to in the code as 04p or 84p for the updated versions [17]. The spectrum of Iodine-125 was obtained from the International Atomic Energy Agency and is shown in Tab. 1 [18]. Default particle weight and energy cutoffs from MCNP4C were used, along with the default transport settings for secondary particles (where secondary electrons were transported). The F4 tally was used with subdivisions to create points of interest around the simulated object in a two-dimensional format, measuring 101x101 pixels of 0.1 cm. This allowed for the

Item	Description and References
Physic and Transport	application of point-to-point relative difference calculations and standard deviation. The DE/DF cards were utilized to convert the values obtained from the tally, based on a table with defined energy ranges. For photon transport, a table with values of the mass energy absorption coefficient $^{\mu en}/_{\rho}$ can be used in combination with the F4 tally, automatically providing the dose results in MeV. The mass energy attenuation coefficient (DF) corresponding to liquid water was obtained from the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory [19]. A total of 10^9 particle histories were simulated for each of the simulations, resulting in a Type A uncertainty calculated by MCNP4C of less than 0.3% for any given point.
Analysis	The scored quantities were not filtered or cleaned. Since the data were analyzed as relative differences to the reference case or standard deviation within the same batch, the pixels coinciding with the seed core were excluded, and no further conversion was necessary.

The source was defined using the SDEF card with parameters (ERG, PAR, POS, AXS, RAD, EXT, SUR). This configuration established the characteristics and properties of the particle source. The SI and SP cards were used together to define distributions of variables associated with the source, such as position, energy, and direction. The SI command created a histogram over a range of -0.15 cm to 0.15 cm, corresponding to a pixel shift of 0.1 cm in the simulation. The SP command specified a discrete probability distribution between values of 0 and 1. Both SI and SP commands incorporated the values from the IAEA's Iodine-125 spectrum, as shown in Tab. 5.

The simulation geometry was subdivided into smaller cells to perform point-by-point dose calculations, allowing for a detailed mapping of dose rates. Initially done manually, this subdivision was automated using MATLAB to optimize time and reduce input errors. Each cell measures 0.1 cm along each axis, covering 10.1 cm along the x and z axes, resulting in a 101x101 matrix of interest points, with the y axis having a single pixel of 0.1 cm to create a two-dimensional matrix. Dose calculations were performed for each cell individually, and the results were used to calculate the mean, standard deviation, relative difference, and associated type A uncertainty.

The dose was determined using tally F4 in combination with DE/DF cards, which provide information on the mass-energy absorption coefficient for water. This procedure enabled the quantification of the average energy deposited in the medium (collisional kerma), taking into account electronic equilibrium to establish that its value is numerically equivalent to the received dose.

Table 5. Iodine-125 spectrum.

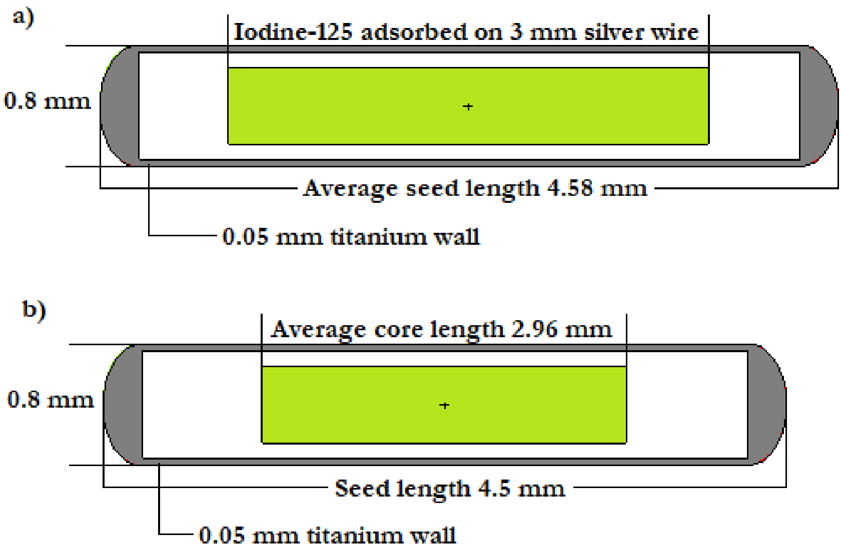
X-rays			Gamma		
#	E [keV]	I(abs) [%]	#	E [keV]	I(abs) [%]
1	3.335	14.8 6	1	35.4925 5	6.68 13
2	27.202	39.4 5			
3	27.473	73.4 10			
4	30.944	21.0 4			
5	30.944	25.6 4			
6	31.693	4.56 13			

Source : Adapted from IAEA, 2024 [18].

2.3. Iodine-125 seed modeling

To visualize the graphical interface of the simulated object, the Visual Editor for Data (VISED) software was used for this purpose [20]. It is applied in nuclear simulation and particle physics. It is designed to assist in real-time visualization and editing of parts of the input codes for MCNP. Fig. 3a shows an example of geometry modeling for the seed length parameter using the average value (4.58 mm) obtained during measurements with the caliper, as shown in Tab. 1. In Fig. 3b, the same example was followed, and the average value was obtained from Tab. 2, being 2.96 mm.

Figure 3. Example of modeling using the average value of measurements in practice, being: a) seed length; b) core length.



Source : The authors.

2.4. MATLAB

The output data were interpreted using MATLAB software, which allows data management using a matrix system. The outputs are delivered by MCNP in .txt format, with a size of 101x101 points forming a matrix for each of the 201 simulations, consisting of 100 for each investigated parameter and 1 for the reference geometry from Fig. 1. The outputs was analyzed point-by-point, and the following calculations will be is applied: point-by-point standard deviation within the matrices of the same variation, relative difference between the reference seed output and the mean value of the matrices of the same variation, and MCNP provides type A uncertainty for all points. Furthermore, MATLAB allows matrix illustration to visualize the dose rate map and visually understand in which points the dose is more significant. The mean dose rate map was omitted, as it was only used to calculate the standard deviation. The points considered are up to 10.1 cm on the x and y axes around the simulated object [2], [21].

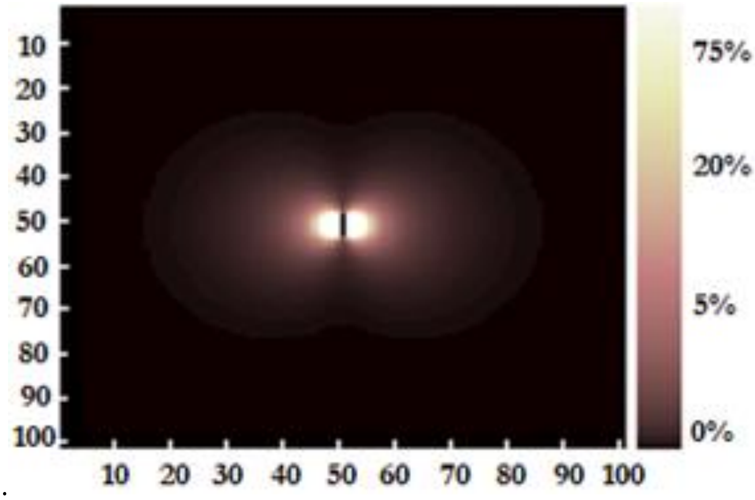
3. RESULTS AND DISCUSSIONS

The Type A uncertainty for the reference case at distant points, close to 10 cm, did not exceed 0.005%, while near the seed, up to 1 cm, it remained below 0.001%. For the batch with 100 seeds of varying lengths, the errors did not exceed 0.018% at any point on the seed. For the batch with 100 cores of different lengths, the highest point was near 10 cm away from the seed, reaching up to 0.018%, and the most significant uncertainties were within 1 cm around the source, with an absolute error of 0.002%.

3.1. Reference seed

The dose rate profile response for the reference case is shown in Fig. 4. Dose points up to 10.1 cm along the x and y axes were considered. The seed is positioned along the y-axis, longitudinally, and centered at the origin. The dose is radial, with the highest dose rate observed along the x-axis and near the seed, representing 75% of the dose within 1 cm around the source. This behavior aligns with the expected dose distribution pattern, as the reference seed geometry from IPEN-CNEN/SP, illustrated in Fig. 1, was used. Starting from the center, the dose pattern is symmetrical along the transverse axis, and there is a lower concentration of dose at the seed extremities, where the welds are located on the longitudinal axis. This likely occurs because the welds contain more titanium compared to the seed walls, resulting in greater radiation attenuation. However, it is important to note that changes in the amount of material in the welds could modify the dose rate map, leading to greater or lesser attenuation than observed in the reference.

Figure 4. Reference seed dose rate map.

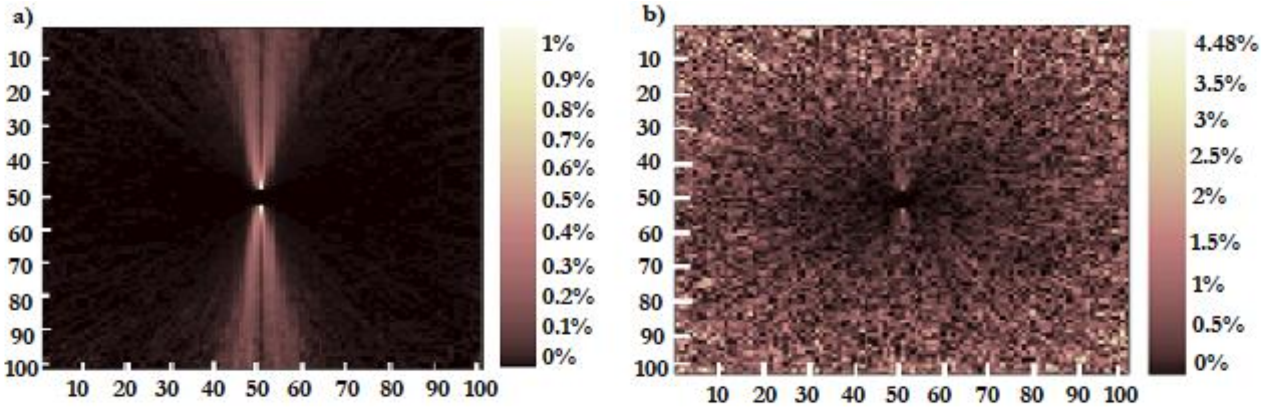


Source : The authors.

3.2. Variation in Iodine-125 seed length

For this variation, the calculated standard deviation did not show significantly relevant values, as shown in Figure 5a. Along the seed's long axis, near the ends of the welds, between 4 cm and 6 cm, the highest percentage obtained did not exceed 0.5%. This value is likely due to the fact that the first and second welds were considered symmetrical, with no material excess or shortage variations to seal the titanium tube for the simulations, since the practical measurement was performed with the seed sealed, thus assuming that the welds are the same size. Furthermore, at no point up to 10.1 cm on the x and y axes did the standard deviation exceed 1%. The results obtained show that the standard deviation within the same batch from Tab. 1 is not significant.

Figure 5. a) Standard deviation between 100 Iodine-125 seeds; b) Relative difference between 100 Iodine-125 seeds and the reference.



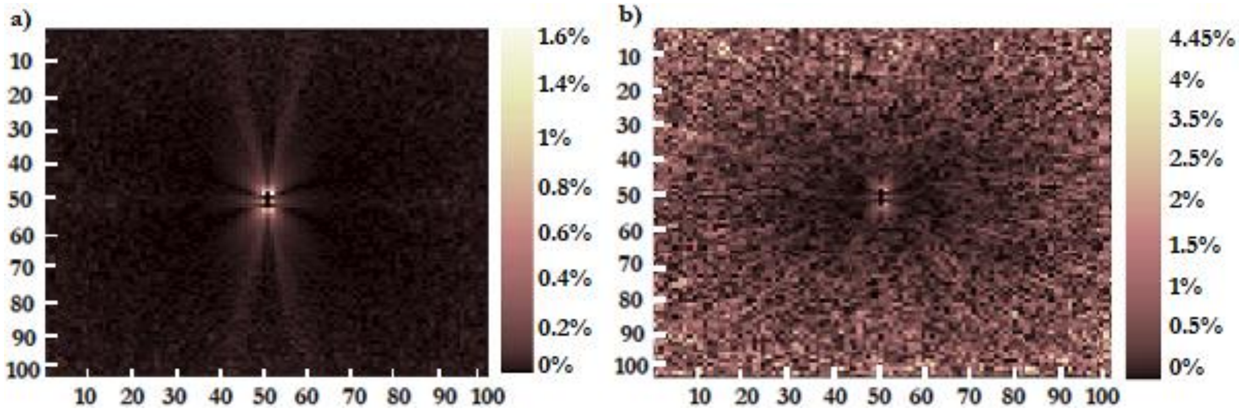
Source : The authors.

The relative difference was significant at some points to be discussed, illustrated in Fig. 5b. Near the seed, along the y-axis, the percentage remained below 1.5% between 4 cm and 6 cm; however, at more distant points, close to 10 cm, values of up to 4.48% were observed on both axes. Thus, the regions between the seed and the more distant points along the x-axis, between 3 cm and 7 cm, were below 2%, and along the y-axis, below 1.5%. Since the manufacturer assumes a ± 5% geometric variation in the seeds within the same batch, the difference found could be related to the production flowchart of the source during the cutting or welding stage of the titanium tube. The reference geometry (Fig. 1) has a length of 4.5 mm, while in the batch investigated for this case (Table 1), the average size was 4.58 mm, the smallest being 4.48 mm, and the largest 4.69 mm.

3.3. Core length variation

The standard deviation showed irrelevant values at any point on the dose rate map. The highest point is near the ends of the seed, along the x-axis, at 1.6%, between 4.5 cm and 5.5 cm. On the y-axis, the most significant points do not exceed 0.6% at any distance, as illustrated in Figure 6a.

Figure 6. a) Standard deviation between 100 cores; b) Relative difference between 100 cores and the reference



Source : The authors.

The relative difference is shown in Figure 6b and followed values similar to those of the variation in the length of the seed. The most important points are farther from the seed, close to 1 cm and 9 cm, with up to 4.45%. Meanwhile, around the seed, along the x and y axes, no points within 1 cm around the source were above 3.5%.

The percentages obtained for the relative difference are significant. The reference geometry has a core length of 3 mm (Fig. 1), and the measured silver wires show some variation from this measurement. As highlighted in Table 2, the practical measurements of the core vary between 2.91 mm and 3.01 mm, with an average of 2.96 mm. These length variations may be related to the process of cutting the silver wire during the preparation of the source core.

4. CONCLUSIONS

The geometric variation in the length of the Iodine-125 seed and the core significantly contributed to variations in the final dose rate. It is essential that the evaluated geometric variations be incorporated into considerations for future dosimetries. This is because the requested dose (reference) may have points with significant differences compared to the dose actually delivered (batches). To ensure accuracy in measurements and consistency in delivered doses, future analyses should include these variable factors, adopting methods that consider these geometric variations. The most significant difference for the variations investigated is at points further away from the seed, with values above 4%, while for points close to the seed, it ranged from 1% to 1.4%. Therefore, in addition to dosimetry in future works, the geometric variations should be considered during the manufacture of the seed to attempt to reduce the variations so that the final dose is closer to the requested dose.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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