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Dose-rate constant and air-kerma strength evaluation of a new ^{125}I brachytherapy source using Monte-Carlo

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ABSTRACT

Brachytherapy is a modality of radiotherapy which treats tumors using ionizing radiation with sources located close to the tumor. The sources can be produced from several radionuclides in various formats, such as Iodine-125 seeds and Iridium-192 wires. In order to produce a new Iodine-125 seed in IPEN/CNEN and ensure its quality, it is essential to describe the seed dosimetry, so when applied in a treatment the lowest possible dose to neighboring healthy tissues can be reached. The report by the AAPM's Task Group 43 U1 is a document that indicates the dosimetry procedures in brachytherapy based on physical and geometrical parameters. In this study, dose-rate constant and air-kerma strength parameters were simulated using the Monte Carlo radiation transport code MCNP4C. The air-kerma strength is obtained from an ideal modeled seed, since its actual value should be measured for seeds individually in a specialized lab with a Wide-Angle Free-Air Chamber (WAFAC). Dose-rate constant and air-kerma strength are parameters that depends on intrinsic characteristics of the source, i.e. geometry, radionuclide, encapsulation, and together they define the dose-rate to the reference point. Radial dose function describes the dose fall-off with distance from the source. This study presents the values found for these parameters with associated statistical uncertainty, and is part of a larger project that aims the full dosimetry of this new seed model, including experimental measures.

Keywords: **brachytherapy, Iodine-125, Monte Carlo method.**

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1. INTRODUCTION

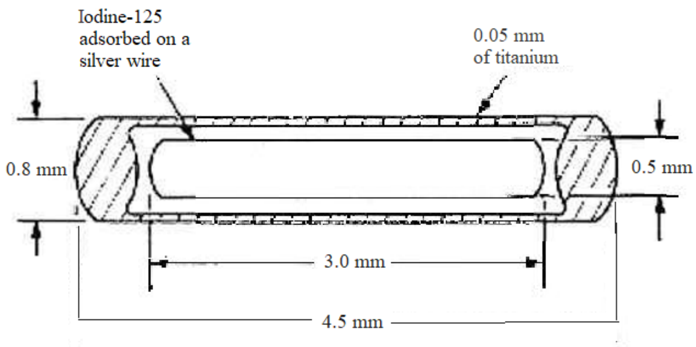
Cancer is the name of a set of diseases that affect the cells of the body resulting from an anomalous uncontrolled development with genetic mutations that were not suppressed. The treatment can be done in different combinations of surgery, radiotherapy, hormonal treatment and chemotherapy according to the specificities of each case as analyzed by the group of physicians responsible for the case.

Radiotherapy is a treatment based on ionizing radiation and is divided into teletherapy and brachytherapy. The fundamental difference is the location of the radioactive source relative to the body of the patient. In brachytherapy, the source is close to or inside the cancerous tissue and as an advantage its effects are more concentrated in the areas of interest, minimizing damage to healthy neighboring tissues. [1]

The sources used in brachytherapy can be produced from several radionuclides in different formats. In order to reduce the price for certain types of cancer treatments with brachytherapy and allow this treatment to reach more patients, IPEN/CNEN is developing a new Iodine-125 seed. The objective of this work is to carry out part of the dosimetric characterization of this Iodine-125 seed relying on Monte Carlo simulations. [2]

The seed is composed of a silver wire where Iodine-125 is laid up and encapsulated in titanium. The titanium capsule has an outer diameter of 0.8 mm, and is 0.05 mm thick and 4.5 mm long. The silver wire is 3.0 mm long and has diameter of 0.5 mm, as shown in Figure 1. [2]

Figure 1: *Schematic drawing of the Iodine-125 seed.*



Source: Rostelato, M.E.C.M. [2]

It is essential to describe the dosimetry of the seed to ensure its quality, so when applied in a treatment the lowest possible dose to neighboring healthy tissues can be achieved.

Radiation dosimetry is the measurement and calculation of absorbed dose due to exposition to ionizing radiation. In the case of brachytherapy, dosimetry is used to establish dose parameters at a given distance from the source. To do so, it is necessary to follow a protocol that grants reliability to the data. The formalism currently adopted is the update of the report by Task Group 43 of the AAPM (American Association of Physicists in Medicine), which was originally published in 1995 to normalize the dosimetric practices of brachytherapy through a dose-calculation formalism. This protocol is also known as TG-43, or TG-43 U1 since its update in 2004. [3,4]

The equation for the dose rate, suggested for 2D dosimetry in the TG-43 U1, is the following:

$$\dot{D}(r,\theta) = S_K.\Lambda.\frac{G_L(r,\theta)}{G_L(r_0,\theta_0)}.g_L(r).F(r,\theta) \quad (1)$$

The coordinate system used by the TG-43 is polar, where r and θ represent the polar coordinates of the point of interest in relation to the origin. The point of interest $P(r;\theta)$ can be evaluated anywhere in the plane, and shall present cylindrical symmetry in relation to the longitudinal axis of the seed. The reference point $P(r_0,\theta_0)$, is defined as r_0=1 cm and θ_0=π/2, where r is the distance from the geometric center of the source and θ is the angle related to the longitudinal axis of the source.

The S_K parameter (air-kerma strength) refers to the intensity of the source, calculated as the kerma rate due to photons of the source transported *in vacuo* and absorbed in air at a given distance from the source, multiplied by this distance squared. In this way, this parameter displays an intensity value for different sources for reference. [4]

The Λ parameter is the dose-rate constant and it aims to describe the dose rate at the reference point and relate it to the air-kerma strength. The $G_L(r,\theta)$ refers to the geometry factor, which represents the variation of the dose due to the geometric conformation of the propagation of photons. [4]

The radial dose function $g_L(r)$ describes the fall-off of the dose rate by the radial component in the transverse axis of the source due to absorption and scattering in the medium. $F(r,\theta)$ is the 2D anisotropy function, which represents the variation of the dose as a function of the polar angle θ at a given distance r. [4]

The TG-43 U1 protocol proposes that Monte Carlo simulations shall be used to benchmark experimental dosimetric data. Monte Carlo simulations follow statistical methods of estimating the value of an unknown quantity using principles of inferential statistics. This method assumes that the averaged sum of reiterated simple events can delineate a complex process. [5]

The MCNP (Monte Carlo N-Particle Transport Code) is one of the most recognized Monte Carlo codes for radiation transport. The code has several methodologies, simply known as tallies, to estimate a set of parameters. There are tallies that represent absorbed dose or collisional kerma that can be used for dosimetry. [5]

The MCNP code is a standard method for brachytherapy recommended by TG-43 U1 and it is widely used to estimate its parameters. [4,6,7] In this work, the dose-rate constant, air-kerma strength and radial dose function were evaluated with Monte Carlo simulations for this new Iodine-125 brachytherapy source developed in Brazil, as a part of a larger project that will include experimental measurements in the future for data comparison.

2. MATERIALS AND METHODS

Since this work relies only on Monte Carlo simulations, no experimental material was needed. For the simulation, a personal computer with a 7th gen Intel® core i5 processor and 8GB RAM was used to run MCNP4C. The Iodine-125 seed was modeled following Figure 1 dimensions. The composition used for materials is presented in Table 1. Iodine itself was not used as a material in the simulation. In the seed model that was adopted, iodine is laid up on the silver wire and it is considered a regular deposition in which its volume is so small that the presence of iodine as a material does not impact the dose distribution. It was rather considered that the surface of the silver wire emitted photons with the Iodine-125 energy spectrum, which was obtained from National Nuclear Data Center, Brookhaven National Laboratory based on

ENSDF and the Nuclear Wallet Cards. [8,9]

Table 1: Compositions of materials used in simulation.

Material	Density	Composition
Titanium encapsulation	4.54 g/cm³	Ti: 100%
Silver wire	10.5 g/cm³	Ag: 100%
Air [10] (both for free-space within the seed and S_K detector)	1.20479 x 10-03 g/cm³	C: 0.0124% N: 75.5268% O: 23.1781% Ar: 1.2827%
Water Medium	1.00 g/cm³	H_2O: 100%

Another Monte Carlo run was executed to evaluate S_K. In this simulation, the seed was located in vacuum, except for an air ring with radius of 1 meter and transverse section of 1 cm radius placed concentrically to the seed. Dose to this ring was calculated using tally F6 (kerma) and 10^8 particle-stories, only photons being considered. Resulting S_K was converted to units of U (cGy cm^2 h^{-1}).

For the main simulation, a total number of 10^8 particle-stories (photons only) were tracked. Since Iodine-125 has low emission energy for photons which results in low secondary electrons mean-range and that the medium is homogeneous water, collisional kerma (tally F6) was considered numerically equal to absorbed dose. The tallying regions were taken as 1 x 1 x 1 mm³ cubes of water, placed at different distances from the source, aligned to its transversal plane. The distances used were from 0.5 cm to 5.0 cm, with a 0.5 cm step, and a last point at 7.0 cm. The greater spacing between the last two points was inserted to better fit the curve. As far as distance increases uncertainty gets worse and due to the low energy of photons involved the code would require an exponentially increasing run time to further improve the certainty, with no significant benefit. Since brachytherapy seeds are meant specially to attend cases in which the target tumoral tissue is near the radioactive source, dose to closer distances was given attention: as we can see in TG-43 U1, radial dose function for Iodine-125 seeds was measured with smaller intervals at small distances along transverse axis. [4]

Results were obtained in units of MeV/g per photon, and converted to J/kg, thus Gy. To assess dose rate absolute values, one need to consider the average number of photons per disintegration of the Iodine-125, taken here as 1.5767, and the activity of the source. Since estimated activity for this source during production is approximately 1.85 x 10^8 Bq, this value was used to estimate dose rate to the reference point.

MATLAB® was used to analyze data corresponding to $g_L(r)$ as well to calculate the polynomial parameters suggested by the TG-43 U1. According to the protocol, data obtained for $g_L(r)$ may be presented as a 5th-order polynomial that fits the data within ±2%, as represented in Equation 2:

$$g_L(r) = a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + a_5 r^5 \tag{2}$$

3. RESULTS AND DISCUSSION

After performing the Monte Carlo simulations, S_K=8.808 ± 0.038 U was obtained for air-kerma strength. This value, however, can only be considered as theoretical for the nominal seed, since it was calculated for an ideal seed that not takes into account real defects in its manufacturing. Possible defects include uncertainties in the source manufacturing parameters as length, welding thickness, capsule thickness and iodine deposition on the silver wire. As mentioned before, the deposition was considered regular and due to low impact of the presence of iodine on dose distribution, it was not considered as a material in the simulation. Future works will evaluate how these parameters impact the dose. The value for a real seed should be measured experimentally (and not taken from simulation) under TG-43 U1 recommendations, i.e., in a reference laboratory using a Wide-Angle Free-Air Chamber (WAFAC) detector. [4]

The value obtained for dose-rate constant, with its uncertainty related to MCNP4C simulation, was Λ = 0.788±0.004cm^{-2}. This value is lower than Λ for most commercial Iodine-125 sources.

The values for $g_L(r)$ were calculated for points at every 0.5 cm up to 5.0 cm, and for 7.0

cm, in the transverse plane (Table 2). For this, values of $G_L(r,\theta)$ also have to be evaluated, following TG-43 U1 given formula.

MATLAB® was used to analyze all data as well to find the parameters of the fitting curve proposed by the protocol as a 5th-order polynomial fit (represented in Equation 2, parameters shown in Table 3). The fitting is satisfactory, as TG-43 U1 recommends a difference of no more than 2% between points calculated with Monte Carlo and fitted with the polynomial, and the higher difference achieved amongst those points was 0.7% in this work. Figure 2 shows the fitting curve over the Monte Carlo results.

The decrease of $g_L(r)$ with increasing r is expected. This fall-off is not related to the inverse-square law, as the value of $g_L(r)$ is corrected by the geometry factor. It is rather the component to dose fall-off due to attenuation and scattering over the medium. Considering only the contribution from this factor, dose rate is halved in relation to reference point before 5.0 cm and halved again before 7.0 cm, and so this seed presents a steep dose gradient. If geometry factor is also taken into account, its influence would be rather large, as dose rate falls to 51% from the reference point at 4.0 cm, but $G_L(r,\theta)$ calculated at this point yields a decrease to 6.25%. Considering both components, dose rate at this point is approximately 3.2% of reference point, decreasing to less than 0.5% at 7.0 cm, the farthest point considered in this work.

Table 2: Radial dose function calculated values

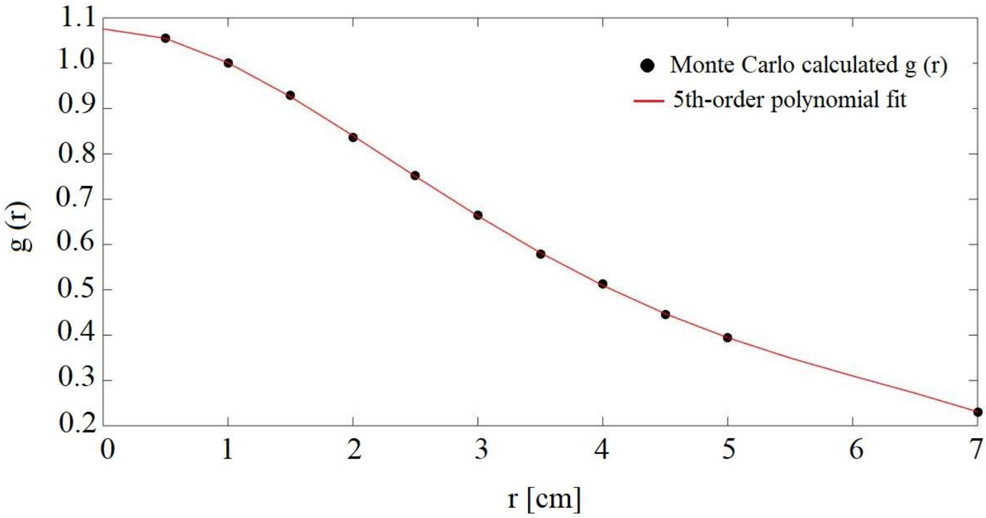
r (cm)	**g(r)**
0.5	1.055 ± 0.40%
1.0	1.000 ± 0.51%
1.5	0.929 ± 0.67%
2.0	0.837 ± 0.88%
2.5	0.752 ± 1.11%
3.0	0.664 ± 1.39%
3.5	0.579 ± 1.72%
4.0	0.513 ± 2.08%
4.5	0.445 ± 2.50%
5.0	0.395± 2.95%
7.0	0.231 ± 5.30%

Table 3: Values of fitting parameters for $g_L(r)$ polynomial

Parameter	Parameter value
a_0	1.0761
a_1	-1.0092 *x* 10^{-3}
a_2	-9.2392 *x* 10^{-2}
a_3	1.9819 *x* 10^{-2}
a_4	-1.4902 *x* 10^{-3}
a_5	2.7912 *x* 10^{-5}

The 7.0 cm point was chosen so the data for $g_L(r)$ could be interpolated beyond 5.0 cm. Farther points, however, need more computational time to present an improved uncertainty, as it is already unsatisfactory for this point ($\sigma_{7.0cm} = 5.30\%$, in contrast to $\sigma < 3\%$ for all other points) and uncertainty decreases with computational time squared. Besides this, a good uncertainty was achieved for all other points and are presented in this work. It is also worth noting that uncertainty presented for $g_L(r)$ is obtained through propagation of uncertainty at each individual point and that of the reference point, since $g_L(r)$ is obtained as a ratio. Also, $G_L(r, \theta)$ do not contribute to uncertainty due to being a geometrical factor obtained theoretically.

Figure 2: *Radial dose function per distance.*



Source: Author

4. CONCLUSION

This work proposed to carry out the first step of the dosimetry of a Brazilian Iodine-125 brachytherapy source. This national source could be produced with lesser costs than imported seeds, reducing the costs for treatment and allowing more patients to benefit from it. Air-kerma strength, dose-rate constant and radial dose function were calculated using Monte Carlo simulation code MCNP4C.

Air-kerma strength and dose-rate constant are parameters that depend on unique characteristics of the seed, and together they indicate the dose at the reference point. Dose-rate constant found was below typical values from literature, which can indicate this seed presents a steep dose gradient. This also can be noted from the radial dose function.

Radial dose function was calculated for several points up to 5.0 cm and to 7.0 cm away from the source at its transversal plane. Values were found to decrease with the distance~~,~~ as expected. The contribution to final dose from this component was analyzed and compared to dose fall-off due to the geometric conformation of the emission of photons.

Radial dose function was also presented as a polynomial according to the TG-43 U1 report. The protocol suggests that data for the radial dose function must fit the polynomial with no more than ±2% of relative difference. The actual value achieved was 0.7%, which shows that this parameter can be safely interpolated within the analyzed range with this polynomial.

This work is the first step on a project that aims to perform the full dosimetry of this seed. These values were analyzed first because they depend on a simpler geometry with no reference to points beyond the transverse plane. Future work shall consider the full 2D dosimetry, allowing to calculate the anisotropy function. Experimental work will also be carried out to compare values found in practice with calculated with Monte Carlo simulations. With this, all parameters demanded by the TG-43 U1 shall be calculated for the dose rate profile of this seed to be completely described in terms of it, thus allowing it to be used under clinical practice, impacting costs and reach of its application.

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