

Radiodosimetric considerations on ocular brachytherapy with iodine-125 and ruthenium/rhodium-106*

Considerações radiodosimétricas da braquiterapia ocular com iodo-125 e rutênio/ródio-106

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Abstract **OBJECTIVE:** To analyze dose distribution utilizing plaques with iodine-125 and ruthenium/rhodium-106 in a computational model of the ocular region. **MATERIALS AND METHODS:** A voxel-based computational model including the different tissues of the ocular region was utilized with the plaque positioned on the sclera. The Monte Carlo code was utilized for simulating irradiation. The dose distribution is demonstrated by isodoses curves. **RESULTS:** Computational simulations demonstrate the dose distribution inside the ocular bulb as well as in adjacent outside structures. The results have allowed the authors to compare the spatial distribution of doses generated by beta particles and photons. The simulations demonstrated that the utilization of iodine-125 seeds implies a high dose to the crystalline lens, while ruthenium/rhodium-106 results in high dose on the sclera surface. **CONCLUSION:** The dose to the crystalline lens depends on the tumor position and thickness, the plaque diameter, and the radionuclide utilized. In the present study, the ruthenium/rhodium-106 source is recommended for low tumor thickness. Irradiation with iodine-125 results in higher doses to the crystalline lens than irradiation with ruthenium/rhodium-106. The maximum value for dose to the crystalline lens corresponds to 12.75% of the maximum dose with iodine-125 and only 0.005% for ruthenium/rhodium-106. **Keywords:** Brachytherapy; Eye plaque; Ocular brachytherapy; Monte Carlo code.

Resumo **OBJETIVO:** Analisar, por meio de um modelo computacional da região ocular, as características da distribuição da dose utilizando placas contendo iodo-125 e rutênio/ródio-106. **MATERIAIS E MÉTODOS:** Foi utilizado um modelo computacional de *voxels* da região ocular incluindo os diversos tecidos, com a placa posicionada sobre a esclera. O código Monte Carlo foi utilizado para simular a irradiação. A distribuição da dose é apresentada por curvas de isodoses. **RESULTADOS:** As simulações computacionais apresentam a distribuição da dose no interior do bulbo e nas estruturas externas. Os resultados permitem comparar a distribuição espacial das doses geradas por partículas beta e por fótons. As simulações mostram que a aplicação de sementes de iodo-125 implica alta dose no cristalino, enquanto o rutênio/ródio-106 produz alta dose na superfície da esclera. **CONCLUSÃO:** A dose no cristalino depende da espessura do tumor, da posição e do diâmetro da placa, e do radionuclídeo utilizado. No presente estudo, a fonte de rutênio/ródio-106 é recomendada para tumores de dimensões reduzidas. A irradiação com iodo-125 gera doses maiores no cristalino do que a irradiação com rutênio/ródio-106. O valor máximo de dose no cristalino corresponde a 12,75% do valor máximo de dose com iodo-125 e apenas 0,005% para rutênio/ródio-106. **Unitermos:** Braquiterapia; Placa ocular; Braquiterapia ocular; Monte Carlo.

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INTRODUCTION

Brachytherapy with plaques for irradiation of the ocular bulb is considered as a

good solution for the treatment and management of uveal tumors, retinoblastomas and ocular metastases, representing a feasible alternative to enucleation. This technique consists of radioactive plaques sutured onto the external scleral surface, directly above the base of the intraocular tumor. The plaque remains positioned until the minimum therapeutic dose is delivered to the tumor volume⁽¹⁻³⁾. When compared with ocular teletherapy, brachytherapy allows a better spatial dose distribution over the tumor volume with lower radiation deposition on adjacent tissues.

Plaques for ocular brachytherapy look

like a round-shaped cap whose concave surface is attached to the sclera. The radioactive material remains encapsulated within the plaque so that the patient contamination is avoided. The outer surface of the plaque has an absorbing shield that absorbs a great amount of radiation which propagates towards the opposite direction of the target volume, protecting the tissues lying posteriorly to the plaque and structures outside the ocular bulb^(4,5).

Along years, certain types of radionuclides have been employed in plaques for ocular brachytherapy. Currently, iodine-125 or ruthenium/rhodium-106 seeds are

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utilized as radioactive material loaded in a metal matrix. For comparative purposes, the authors have investigated the spatial dose distribution inside the ocular bulb, vitreous body and crystalline lens, as well as external structures, bones, optic nerve and brain. An effective dosimetry is critical in the management of the dose delivered to the tumor as well as in the observation of the dose deposited in surrounding healthy tissues and, consequently, estimating the harmful effects resulting from this therapeutic process.

MATERIALS AND METHODS

Aiming at simulating the dose distribution, a computational model of the human eye was developed encompassing three different models as follows: a voxel-based model of structures adjacent to the ocular bulb, an analytical model of the ocular bulb structures, and a voxel-based discretization of the vitreous cavity to allow the observation of the dose within the bulb. A brachytherapy plate was attached to this model of the ocular region for the simulation of the dose distribution through the Monte-Carlo code (MCNP-v.5).

Computational model of the eye

The voxel-based model of the eye defines a volume including all ocular structures. The development of this first model includes the relevant structures situated externally to the ocular globe and the surrounding bone structure, and was based on images obtained from the Visible Man

Project⁽⁶⁾. A set of 43 axial images of the visible skull was selected and, from these images, only the region of interest corresponding to the left ocular bulb was extracted for the model development.

Each of the 43 sections of the ocular region was converted into a gray-scale 82×100 pixels matrix measuring $0.5 \times 0.5 \text{ mm}^2$. The overlapping of the 43 sections generated a non-isotropic volume with $82 \times 100 \times 43$ voxels, defining a volume of $41 \times 50 \times 38,7 \text{ mm}^3$ (x, y, z), corresponding to a voxel matrix whose volume elements dimensions were $0.5 \times 0.5 \times 0.9 \text{ mm}^3$. With the aid of anatomic references of the region, this gray-scale voxels-based model was colorized in a manner that each selected color corresponded to a specific tissue, allowing the differentiation among 12 types of tissues present in the region^(7,8). Figure 1a presents the image No.20 of the axial head section with delimitation of the region of interest and the image extracted from this region. This 256-tone gray-scale image of the ocular region is presented on Figure 1b in an 82×100 pixels matrix. The same image after colorization according to the tissues present in the region is shown on Figure 1c.

The analytical model of the ocular bulb was developed with basis on anatomical data which have allowed the determination of a set of geometric shapes based on mathematical equations to reproduce the bulb structures: sclera, choroid, retina, cornea, vitreous body and crystalline lens⁽⁹⁾.

The analytical model of the ocular bulb was coupled with the voxel-based model

through the Monte-Carlo code (MCNP-v.5) to allow the simulations. Figure 2 presents three sections (axial, sagittal and coronal) of the computation model of the ocular region. On each of these sections, the axis of the positioning of the other two sections is demarcated.

The third model was incorporated into the previously prepared geometrical structure, defining small voxels of $0.5 \times 0.5 \times 0.5 \text{ mm}^3$ to subdivide the vitreous body region into small cells to allow the measurement of the deposited dose and then to obtain the spatial dose distribution within the vitreous body.

Brachytherapy plaques

Two brachytherapy plaques were selected, both of them with 15 mm in diameter. The model ROPES plaque is utilized for accommodating ten iodine-125 seeds and has an insert with slots where the radioactive seeds are loaded that fits into the stainless steel shell. This shell keeps the seeds positioning and is meant to shield against radiation^(10,11). The iodine-125 seed utilized in the ocular bulb irradiation contains a cylindrical-shaped porous ceramic with 3 mm in length saturated with silver iodide containing iodine-125 enclosed by a titanium tube with 4.5 mm in length and 0.8 mm in diameter. The iodine-125 decays by electron capture in tellurium-125 (a stable nucleus), with a supplementary emission of gamma- and x-photons. The iodine-125 decay produces a 185.77 keV energy release. The half-life of an iodine-125 source corresponds to 59.408 days.

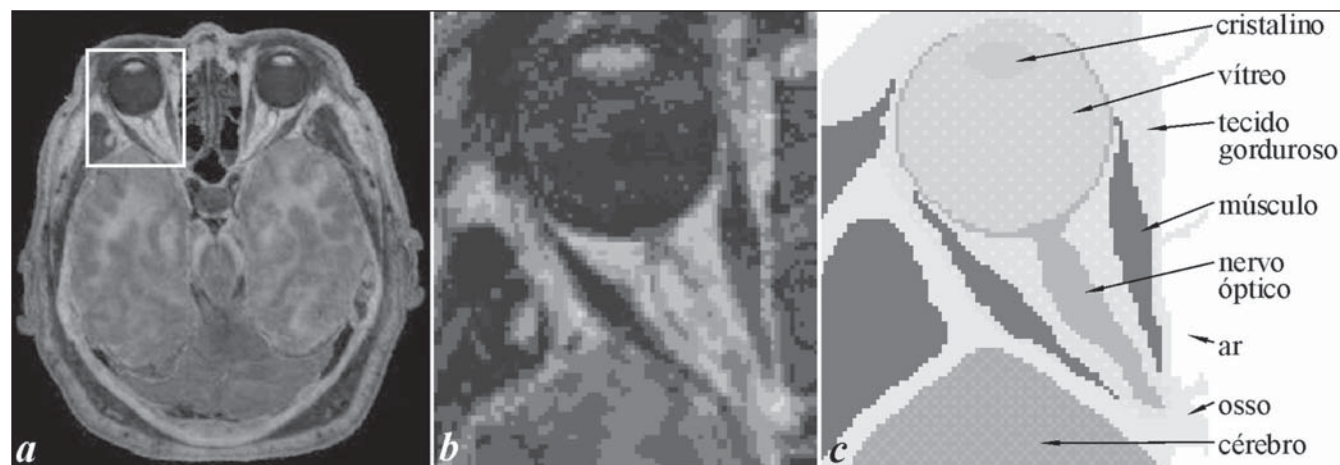


Figure 1. Axial section images. Head section (a), Gray-scale pixel matrix (b) and colorized tissues of the voxel-based model (c).

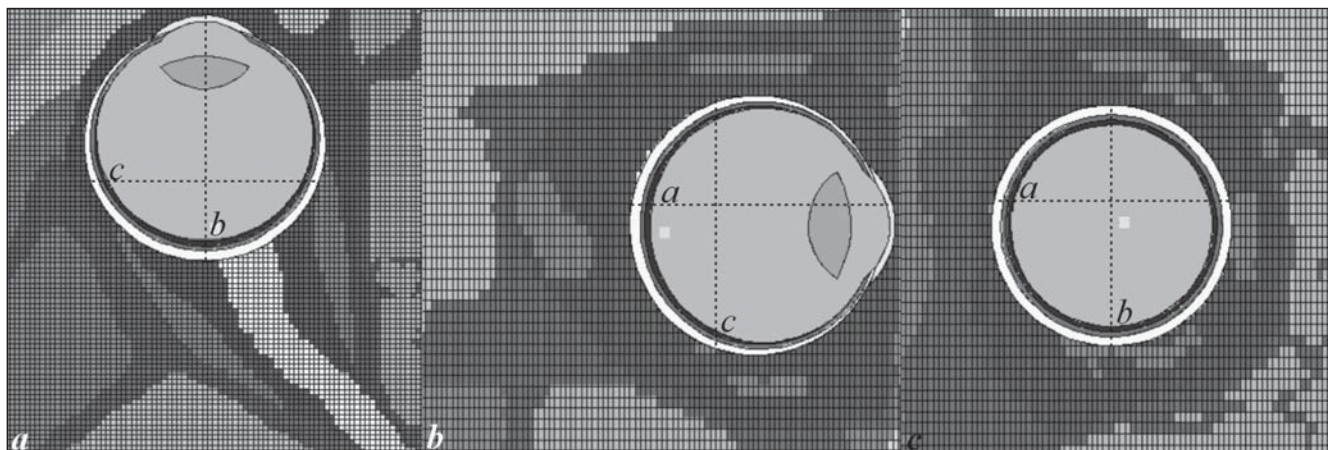


Figure 2. Section images of the computational ocular region model obtained through the graphic interface of the MCNP-v.5. Axial section (a), sagittal section (b) and coronal section (c).

Table 1 presents the values of gamma- and x-photons energy released by the iodine-125 decay, as well as each photon emission frequency. Figure 3 presents the spatial distribution of the iodine-125 seeds on the insert of the ROPES plaque.

The other brachytherapy plaque utilized in the computational simulation is made of silver, with 1 mm thickness, containing a ruthenium/rhodium-106 film at 0.1 mm from the concave surface⁽¹²⁾. Ruthenium-106 decays to rhodium-106 by the emission of beta particle to palladium-106 which is a stable nucleus. The ruthenium-106 decay releases a 39.4 keV energy corresponding to the maximum value of energy emitted by the single beta particle in the decay. The half-life of a ruthenium-106 source corresponds to 373.59 days. The rhodium-106 decay releases a 3,542 keV energy. This energy is distributed between the beta-particle and the antineutrino emitted in the decay, so the beta spectrum becomes continuous. The energy of the rhodium-106 beta particle is utilized in the therapeutic process, considering that the ruthenium-106 beta particle presents a poor penetration and does not contribute to the dose deposition on the tumor tissue. The half-life of a rhodium-106 source corresponds to 29.8 s, so the assumed ruthenium/rhodium-106 source half-life is 373.9 days⁽¹³⁾.

Monte Carlo code simulation

The Monte Carlo code is a method utilized for simulating the transport of particles such as neutrons, photons and electrons and their interactions with the envi-

Table 1 Photons emitted by 125-iodine.

Energy (keV)	Frequency (%)	Energy (keV)	Frequency (%)	Energy (keV)	Frequency (%)
3.335	0.2300	4.173	0.0430	27.472	75.7000
3.606	0.1120	4.302	1.0100	30.944	6.8300
3.759	0.6300	4.572	0.4500	30.995	13.2000
3.769	5.6000	4.829	0.1030	31.237	0.1210
4.030	3.5000	4.829	0.1600	31.704	3.8110
4.069	0.4200	26.875	0.0032	31.774	0.5800
4.121	0.7000	27.202	40.6000	35.492	6.6800

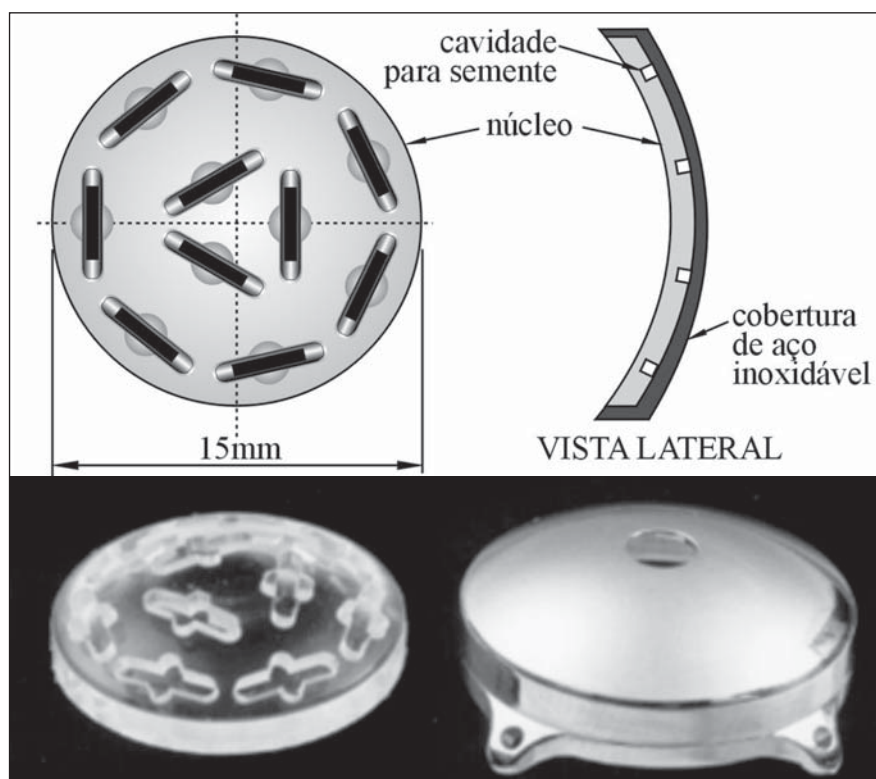


Figure 3. Iodine-125 seeds distribution on the 15 mm ROPES plaque.

ronment, allowing inclusive the observation of the dose distribution in determined structures. This code has been initially developed to the observation of neutrons transport and later was extended to include other particles such as photons and electrons^(14,15). The Monte Carlo code runs with a three-dimensional configuration utilizing a Table with the characteristics of every tissue and material defined through geometric cells and has been extensively utilized for validating the utilization of brachytherapy with beta particles and photon-emitter radioisotopes⁽¹⁶⁾.

The plates were coupled with the computational model of the ocular region on the sclera surface, with its center aligned with the ocular bulb equator on its medial region. This positioning was selected for being considered to be closest to the crystalline lens. The simulations have taken the dose distribution into consideration because of the photons emitted by the iodine-125 and of beta particles emitted by rhodium-106.

RESULTS

The plaques simulations were performed through the nuclear code MCNP-v.5, obtaining the dose distribution in the ocular region. The simulations for the ruthenium/rhodium-106 plaque, were aimed only at the rhodium-106 beta emissions, since the contribution of the ruthenium-106 decay to the dose is non-significant because of the low energy release and consequent low beta particles penetration⁽¹⁷⁾.

Therefore, two different simulations were performed for ocular brachytherapy with rhodium-106 in relation to beta particles emission, as follows: one for the external and another for the internal region of the ocular bulb. The simulations for observing the dose distribution due to beta particles were performed with a continuous spectrum of the rhodium-106 beta emissions. For the effects of simulation, occurrence probabilities were considered for each 1 keV variation. As the maximum energy of the rhodium-106 beta particle is 3,541 keV, 3,541 indices of beta decay occurrence probability were generated in this simulation.

Two different simulations were performed for ROPES plaque with iodine-125 seeds: one for the internal region of the ocular bulb and another for the external region, for observing the dose generated by the complementary gamma photons and x-photons emitted in the iodine-125 decay by electron capture. Data regarding energy and iodine-125 photons occurrence rates included on Table 1 were utilized for this simulation.

The doses results in each voxel of the vitreous body, bone structure, brain and optic nerve obtained by simulation on the MCNP-v.5, were utilized as input for the software SISCODES to be transformed into a dose distribution color matrix, allowing the observation of the isodoses curves in the ocular region⁽¹⁸⁾. Internal and external simulations were separately performed and later overlapped. Figure 4 presents two images of a same axial section passing on

the center of the ocular bulb and, consequently, on the center of the brachytherapy plaque.

The image on Figure 4a presents the perceptual dose distribution due to beta particles emitted by rhodium-106. Based on the legend, both the external and internal dose distribution can be understood, the maximum external dose corresponding to 32.4% of the maximum internal dose. This condition must be taken into consideration in the observation of the dose distribution.

The image on Figure 4b presents the perceptual dose distribution due to photons emitted by iodine-125. Based on the legend, both the internal and external dose distribution can be understood, the maximum external dose corresponding to 5.77% of the maximum internal dose.

The dose distribution for irradiation with rhodium-106 beta particles is spatially restricted and for this reason the isodose curves are very close in shape and end up mixing with each other. If a dose of 50 Gy is to be obtained on the region corresponding to 10% (at a 7 mm depth), the maximum dose delivered near the sclera surface is of 500 Gy. The mean dose deposited on the crystalline lens for this irradiation condition is only 2.62 Gy (0.005%). The maximum dose in the external region of the ocular bulb is of 162 Gy, but it is observed in a punctual manner.

For irradiation with iodine-125, the dose distribution generates well-defined isodose curves, which allows an improvement in the identification of the dose with depth. If a dose of 50 Gy is to be obtained

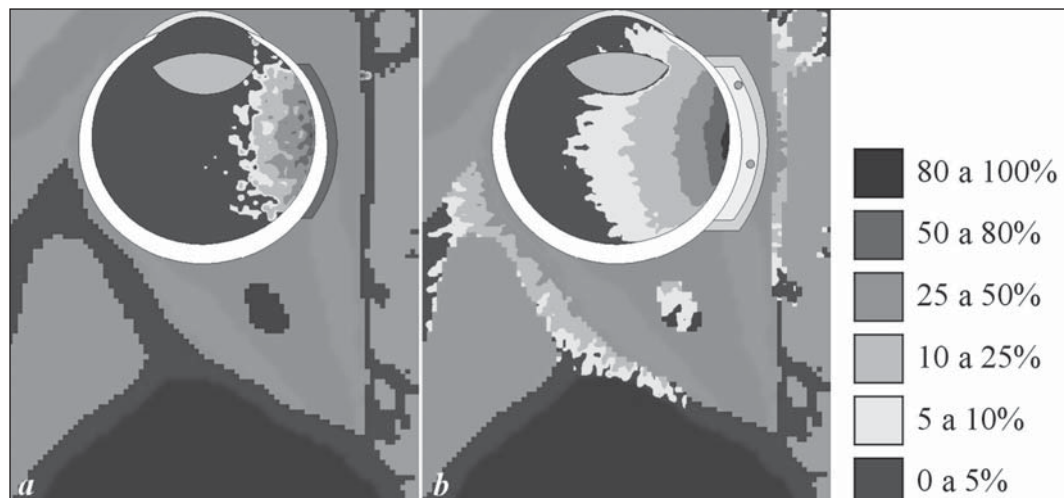


Figure 4. Percentual dose distribution in ocular brachytherapy. Ruthenium/rhodium-106 plaque (a) and ROPES plaque with iodine-125 seeds (b).

on the region corresponding to 50%, the maximum dose delivered near the sclera surface is of 100 Gy. For this condition of ocular bulb irradiation, the maximum dose deposited in the crystalline lens is 12.74 Gy on the nearest border of the plaque. The maximum dose observed in the external region of the ocular bulb is 7.84 Gy.

One of the factors which defines the maximum dose to be delivered is the desired dose to the apex of the tumor; for this reason, the thicker the ocular tumor, the higher should be the maximum dose delivered to the sclera, and the increase in maximum dose implies in increase in the dose to external tissues and crystalline lens.

Figure 5 presents two graphs with perceptual variation of the dose with depth obtained through simulation on the MCNP-v.5, based on an axis originating in the center of the plaque concave surface towards the center of the ocular bulb. These graphs depict the variation of dose with depth for the rhodium-106 plaque, and for the ROPES plaque with iodine-125 seeds.

The variation of dose with depth for the rhodium-106 plaque is represented by a typical curve of beta particles penetration which, following a slight decrease, presents a fast decay with depth, achieving null values at about 10 mm. Because of this characteristic, beta emitting radioisotopes with high energies are utilized to achieve a penetration deep enough to irradiate the tumor tissue. In case of irradiation of the ocular bulb with ruthenium/rhodium-106 plaque, 20% of the value for maximum dose is

achieved at a 5.16 mm depth and 10% at 7.19 mm. From this point on, the dose presents a fast decrease, limiting the application of irradiation with rhodium-106.

The variation of dose with depth with iodine-125 is represented by a typical curve of photon beam penetration which presents an exponential decay with depth. Considering the high reentrance of photons, the employment of gamma emitting radionuclides with energy photons in the range of tenths of keV, such as iodine-125, is recommended in brachytherapy so as to circumscribe the dose deposition to the source surroundings. In case of irradiation of the ocular bulb with the ROPES plaque, 50% of the value for the maximum dose is achieved at a 3.16 mm depth, and 30% at 5.25 mm.

DISCUSSION

The results from the simulation of ocular bulb irradiation with the plaque with iodine-125 seeds demonstrate the spatial dose distribution, particularly with the depth in the vitreous body. However, an appropriate tumor dose deposition implies a considerable dose to the crystalline lens. The dose deposited on the crystalline lens primarily depends on the plaque positioning, its distance from the crystalline lens, the desired dose for tumor apex and, therefore, the tumor thickness.

According to Nag et al.⁽¹⁹⁾, the prescribed dose for irradiation with plaques with iodine-125 seeds is 85 Gy to the apex

for tumors > 5 mm, and to the base of the tumor in case of lower thickness. Considering a dose of 85 Gy to the apex of a 5 mm tumor, the dose to the crystalline lens ranges from 33.4 to 10.3 Gy, according to the simulation. Considering that recommended dose limit for the crystalline lens is 5 Gy, this high dose to the crystalline lens is directly associated with late development of cataract and, consequently, referral for surgery, in this population of patients^(19,20).

In simulations with the ruthenium/rhodium-106 plaque, the adequation of the spatial dose profile, especially in relation to the tumor depth, is not so easily achieved because of the smaller penetration of the beta particles beam. This characteristic allows the therapeutic dose concentration on the tumor tissue, generating lower doses to the crystalline lens than those found for the plaque with iodine-125. In spite of this characteristic, the utilization of ruthenium/rhodium-106 should be recommended for tumors with < 5 mm in thickness and base diameter < 15 mm. Tumors with higher thickness may require higher doses to the sclera surface, generating subsequent complications and a low dose to the tumor apex^(19,21).

The dose to the scleral surface should be limited to 160 Gy, which means a dose of 50 Gy for 4.06 mm depth for a ruthenium/rhodium-106 plaque⁽¹⁹⁾. If a therapeutic dose of 55 Gy to the tumor apex is considered for this irradiation, the occurrence depth is 3.79 mm. So, the selection of an irradiation method, plaque type and

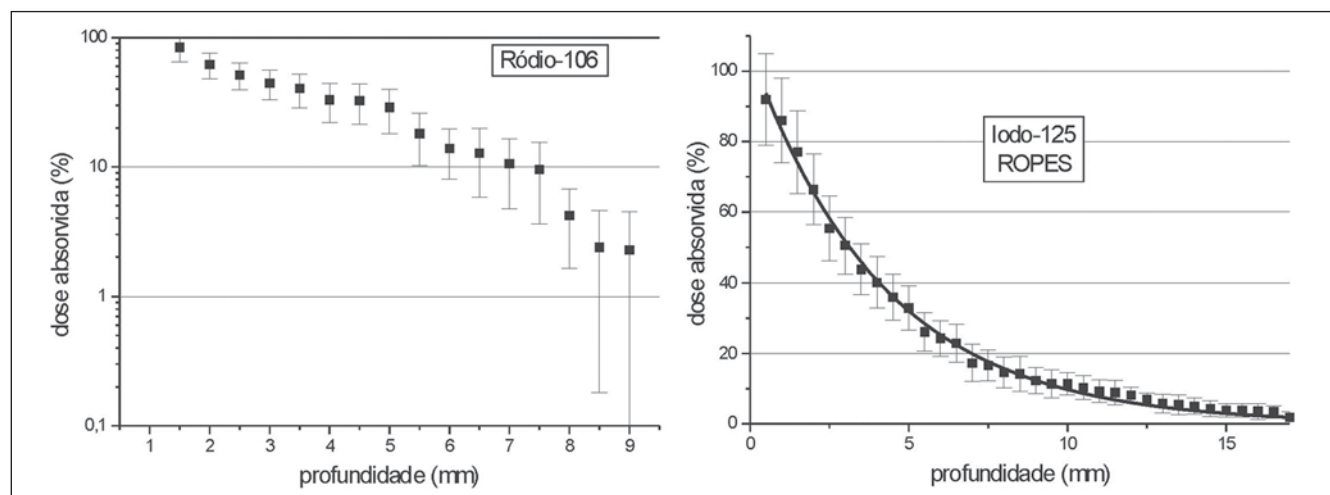


Figure 5. Percentual variation of dose with depth.

radionuclide depends on the tumor dimensions.

For the simulation evaluated in the present study, the irradiation with iodine-125 generates doses to the crystalline lens higher than those of ruthenium/rhodium-106. The dose to the crystalline lens corresponds to 12.75% of the maximum dose generated with iodine-125, and only 0.005% for ruthenium/rhodium-106.

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