A NEW HUMAN EYE MODEL FOR OPHTHALMIC BRACHYTHERAPY DOSIMETRY

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The present work proposes a new mathematical eye model for ophthalmic brachytherapy dosimetry. This new model includes detailed description of internal structures that were not treated in previous works, allowing dose determination in different regions of the eye for a more adequate clinical analysis. Dose calculations were determined with the MCNP-4C Monte Carlo particle transport code running n parallel environment using PVM. The Amersham CKA4 ophthalmic applicator has been chosen and the depth dose distribution has been determined and compared to those provide by the manufacturer. The results have shown excellent agreement. Besides, absorbed dose values due to both 125I seeds and 60Co plaques were obtained for each one of the different structures which compose the eye model and can give relevant information in eventual clinical analyses.

INTRODUCTION

Brachytherapy using ophthalmic plaques has shown to be a good alternative to enucleation for the treatment of eye tumour. Several radioactive materials, such as 60Co, 125I, 103Pd, 106Ru and 106Rh, with different shapes and structures have been the object of clinical studies, with a focus towards providing minimum irradiation to healthy tissues while delivering maximum doses to the tumour(1). Cross et al. (2) have compared the dose results of various codes with experimental values for different kinds of applicators, investigating the accuracy and reliability of the calculated results. Usually, the eye anatomy is represented by a simple sphere with the presence of few distinct structures(2,3). However, sometimes distinct dose determination in different regions of the eye is needed for a more adequate clinical analysis. Taking into account this fact, a detailed geometric model of the human eye, including the choroid, retina, sclera, lens, cornea, anterior chamber, vitreous humour and optic nerve has been developed. Dose calculations have been performed utilising the Monte Carlo code MCNP-4C(4) using 125I seeds and 60Co CKA4-plaques.

MATERIALS AND METHODS

The eye anatomy

The eye anatomy is composed of three layers enclosing the eye body, namely the retina (inner), choroid (middle) and the sclera (outer). According to the ICRP 23(5) the total weight of both eyes is 15 g. Both sclera and choroid are 1 mm thick on average. The critical parts for vision are the retina, optic nerve and disc, macula and lens. The cornea is a transparent structure formed by a segment of spherical shell and permits the passage of light. The lens is a transparent biconvex body with no blood supply and particularly vulnerable to radiation. Its germinative zone has a high mitotic activity, being considered as the origin of the radiation-induced cataracts(6). The sclera is important to protect the intra-ocular contents and optic integrity and to avoid deformation of the eyeball.

The tumour volumes assume different sizes and shapes and can be classified into three categories: small tumours, whose sizes are <400 mm3, medium-sized tumours, ranging from sizes of 400 to 1000 mm3 and large tumours, with sizes over 1000 mm3. Basically, for simulation purpose the tumour volumes are represented by a semi-ellipsoid located in some part of the eyeball.

The eye and tumour geometry model

The mathematical model of the eye and its components are described by the following equations:

Sclera, choroid and retina. The sclera, choroid and retina have been defined as three concentric spherical shells, which are ~1 mm thick, according to the expression:

\[(R_i - 0.1)^2 \leq (x^2 + (y + 1.6)^2 + (z)^2),\]

where \(i = 1, 2, 3; R_1 = 1.22\) cm for sclera; \(R_2 = 1.13\) cm for choroid; and \(R_3 = 1.03\) cm for retina.

Tumour. The tumour has been defined as an ellipsoid cut by the spherical surface of the sclera forming a semi-ellipsoid which is situated inside the inner...
most part of the eye:
\[
0.444(x^2 + 0.04(y + 3.6)^2 + 0.444(z)^2 \leq 1; \\
(x^2 + (y + 1.6)^2 + (z)^2 \leq 1.22^2.
\]

**Cornea.** The cornea is an elliptical shell limited by two concentric ellipses and the outer spherical surface of the sclera:
\[
1.56(x)^2 + 1.62(y + 1.6)^2 + 1.66(z - 0.73)^2 \geq 1; \\
1.29(x)^2 + 1.39(y + 1.6)^2 + 1.52(z - 0.73)^2 \leq 1; \\
(x^2 + (y + 1.6)^2 + (z)^2 \geq 1.22^2.
\]

**Optic nerve and wall.** The optic nerve and wall are represented, respectively, by a cylinder and a cylindrical shell, concentrically placed, which extend from the outer sclera surface to plane \( y = 3 \).
\[
(x)^2 + (z)^2 \leq 0.35^2; \\
(x)^2 + (z)^2 \leq 0.4^2; \\
(x)^2 + (y + 1.6)^2 + (z)^2 \geq 1.22^2; \\
y \leq 3.
\]

The cylinders are rotated by 30° in relation to the coordinate system.

**Lens.** The lens is formed by the region surrounded by two surfaces: the spherical surface of the sclera and the elliptical surface given by:
\[
2.98(x)^2 + 2.98(y + 1.6)^2 + 9.15(z - 0.73)^2 \leq 1; \\
(x)^2 + (y + 1.6)^2 + (z)^2 \leq 1.22^2.
\]

**Anterior chamber.** The anterior chamber is the geometric region between the surface that defines the inner wall of the cornea and the outer surface of the sclera:
\[
1.56(x)^2 + 1.62(y + 1.6)^2 + 1.66(z - 0.73)^2 \leq 1; \\
(x)^2 + (y + 1.6)^2 + (z)^2 \geq 1.22^2.
\]

**Vitreous body.** The vitreous body is the spherical region limited by the inner surface of the retina. Most part of the tumour is modelled as being located inside this region:
\[
(x)^2 + (y + 1.6)^2 + (z)^2 \leq 0.935^2.
\]

The complete geometric model of the eye including the tumour region is shown in Figure 1.

**Ophthalmic applicators**

Two types of applicators have been modelled in the present work: the Amersham 60Co CKA4 type and the plaque containing 24 model 6711 125I seeds manufactured by Oncoseed. Both applicators are located such that they cover the region where the tumour base is settled, as shown in Figure 1.

The 60Co disc is covered by a 2 mm platinum sheath to absorb the beta radiation, and it is arranged in a ring pattern to improve the dose uniformity, assuming that the source is uniformly distributed in the ring. The seeds are composed of 0.5 mm diameter silver rods, covered by a thin layer of 125I and they are encapsulated by titanium, which is 0.8 mm in diameter and 0.05 mm thick. The plaque configuration considered in the present work is composed of 24 seeds, placed in a 20 mm diameter silastic insert that has a gold backing glued to it. Table 1 shows the main characteristics of some of the radioisotopes utilised in ophthalmic brachytherapy.
RESULTS

The $^{60}$Co applicator and the $^{125}$I seeds geometry and plaque configuration were incorporated into the MCNP geometry model to perform the radiation transport simulation. The material composition of the silastic insert was considered to be the same as the eye phantom and tumour composition, which is soft tissue with density of 1.04 g cm$^{-3}$.

Table 2 shows the masses of each eye phantom component, which have been defined in the previous section. Owing to the lack of information, some of the mass values presented in this table were estimated only by visual inspection of some eye anatomy images taken from the literature. Figure 2 shows the depth–dose profile calculated for the $^{60}$Co source applicator along its central axis compared with the result provided by the manufacturer. Doses have been obtained by scoring the energy deposited in small cubic cells having a side of length 0.4 mm distributed along the central axis of the applicator. The absorbed energy in each internal eye structure was scored. One hundred million histories were run to achieve a SD of 0.6% without using variance reduction techniques. The values show very good agreement with the results provided by the manufacturer, with maximum discrepancies of the order of 2%.

Figure 3 shows the depth–dose curve for both the $^{125}$I seeds plaque and $^{60}$Co. One hundred and fifty million histories were run for this case achieving a SD of 1.5%. It can be observed that the dose per accumulated activity due to the plaque of $^{125}$I seeds obtained is about one order of magnitude lower than the one due to the $^{60}$Co source. Table 3 shows the average dose in the same eye structures as listed in Table 2.

Notwithstanding the fact that the doses presented in this paper are only a preliminary estimate, due to the incomplete data employed, the general behaviour of the eye internal structure doses can be easily derived. A deeper study would require more accurate data and the subdivision of the studied structures into smaller scoring regions. With more accurate information about the masses of each eye component, further dose levels can be easily obtained from the eye phantom model presently developed. According to these results, one can observe that the eye structures that receive higher doses are the sclera, choroid and retina. For the tumour and applicator, the investigated configuration ($^{60}$Co source) dose levels are 68% for the sclera, 57% for the choroid and 50% for the retina compared with the dose to the tumour. For the $^{125}$I seeds plaque, the percentage doses to the previously mentioned tissue structures are within 8 and 9% of the dose to the tumour, which represents a very significant improvement in the dose saving to healthy tissues. However, distributions within the treated eye are strongly dependent on a series of parameters, i.e. applicator shape and dimensions, seeds distributions, type of radionuclide employed and tumour size and position inside the eye volume. Therefore, a series of studies are underway to implement an
CONCLUSION

The proposed mathematical eye phantom model includes a detailed description of internal structures that have never been treated in previous works. The new model allows estimating doses to the tumour and to the healthy tissues for a conventional brachytherapy treatment with $^{60}$Co or $^{125}$I. This preliminary model could be improved employing more accurate anatomical data from CT scans, for example. The development of a software coupled to the MCNP Monte Carlo code can automatically generate different eye phantom, tumour and radiation source applicator configurations, which can be a valuable tool in the field of ophthalmic brachytherapy.

REFERENCES