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Monte Carlo calculation of the dose distributions of two ^{106}Ru eye applicators

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Abstract

Background and purpose: Beta emitting ^{106}Ru applicators are widely used to treat choroidal melanoma. In view of the importance of clinical applications of this radioisotope and the relative lack of knowledge of the dose distributions, three-dimensional dose maps of two concave applicators were calculated by means of Monte Carlo simulation.

Materials and methods: Simulations of small CCA and CCB concave applicators manufactured by Bebig were performed using the Monte Carlo code PENELOPE, which allows the description of the structure (geometry and materials) of the applicator in detail. Electrons are emitted from the ^{106}Ru nuclei isotropically, with initial energy randomly sampled from the corresponding Fermi spectra and with initial positions uniformly distributed on the radioactive layer. Primary electrons, as well as the produced δ-rays, are assumed to be absorbed in the medium when they slow down to an energy of 70 keV. Bremsstrahlung photons with energies larger than 7 keV are also simulated. The simulation code has been run on a 166 MHz PENTIUM PC.

Results: Three-dimensional dose distributions produced by the CCA and CCB applicators in a water sphere, concentric with the applicator, were evaluated. To minimize the magnitude of statistical uncertainties, advantage has been taken of the cylindrical symmetry of the problem. The relative depth-dose (along the symmetry axis of the applicator) was also evaluated from the applicator surface up to distances larger than 1 cm, with statistical uncertainties of a few percent. Results compare well with data supplied by the manufacturer.

Conclusions: We have performed accurate Monte Carlo calculations of three-dimensional dose distributions from CCA and CCB ^{106}Ru applicators. The results, presented in the form of two-dimensional maps, depth-dose distributions along the symmetry axis and lateral dose profiles, provide a detailed description of the dose delivered in treatments of choroidal melanoma.

Keywords: Monte Carlo; Dosimetry; Brachytherapy; Eye melanoma; Ruthenium-106

1. Introduction

Brachytherapy using removable ophthalmic plaques is a convenient alternative to enucleation for the treatment of malignant melanoma, uvea and other tumours of the eye [2]. The choice of the most adequate plaque for each specific treatment depends mainly on the height of the tumour apex. Medium- and large-sized tumours are usually treated with ^{103}Pd or ^{125}I applicators, whereas for small-sized tumours β-ray applicators of ^{106}Ru or ^{90}Sr are preferred. In particular, choroidal melanomas can be successfully treated with applicators containing the β-emitting nuclide ^{106}Ru. Ample experience in the use of this kind of treatment has been accumulated for more than 25 years and the number of hospitals using this method is still increasing [12,13,17]. Although different types of eye applicators are available, the most commonly used are the CCA and CCB concave applicators.

An accurate delivery of the prescribed dose to a small tumour, which may not necessarily be at the surface of the applicator, is essential in the treatment of the eye to provide adequate cure with minimal irradiation of healthy tissue. Both absolute dose and isodose distributions should be accurately assessed for the evaluation of clinical results. Measurements of the absorbed dose around β-ray applicators in tissue-equivalent material can be performed using extrapolation ionization chambers (for planar sources), radiocromic film, semiconductor diodes, plastic scintillators, TLD and diamond detectors [5,6,8,11,15]. The latter have relatively small sizes and can be used to determine the dose at points close to the surface of concave applicators. In

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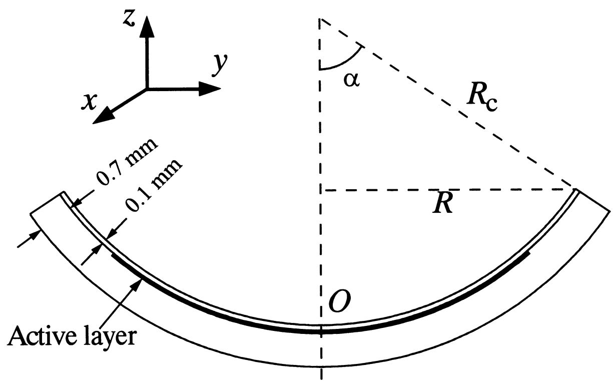

Fig. 1. Schematics of the geometry used in the simulations. The radial scale of the applicator is enlarged for clarity and the active layer, which has a negligible thickness, is indicated. Notice that the origin of the reference frame is placed at the centre of the surface *O* and the rotational symmetry of the system about the *z*-axis.

practice, however, measured isodoses and absorption rates are affected by quite sizeable errors (~5% and larger, see Ref. [11]).

Recently, a simple theoretical calculation of the dose distribution around a curved radiation source with the shape of a spherical cap has been published by Hokkanen et al. [9]. In practice, analytical methods are approximate and applicable only to homogeneous media of uniform density. More reliable solutions to the present dosimetric problem can be obtained by using Monte Carlo simulation techniques, which play an important role in radiation dosimetry and radiotherapy [1]. In principle, Monte Carlo methods are nominally exact and are able to accurately describe the geometry of the system. The major limitation of Monte Carlo techniques is the large calculation times that may be needed for the simulation of realistic radiation sources and geometries. To date, the majority of Monte Carlo simulations of coupled electron-photon transport in dosimetry have been performed by using two well-tested computer code systems, namely the EGS4 system developed by Nelson et al. [14] and the ITS system of Halbleib et al. [7], which is based on the ETRAN code of Berger and Seltzer [4].

In this paper, we present dose distributions for CCA and CCB eye applicators calculated by means of the Monte Carlo code system PENELOPE [3,16], which provides a reliable description of electron transport in arbitrary materials for a wide energy range. Our results are in fairly good agreement with depth-dose data provided by the manufacturer, but differ appreciably from previously published studies.

2. Materials and methods

The Monte Carlo code PENELOPE (an acronym for penetration and energy loss of positrons and electrons) [3,16] is a general-purpose code system for the simulation of coupled electron-photon transport which has been developed at the University of Barcelona. Its differentiating feature is that electrons (and positrons) are simulated by means of a mixed algorithm. Thus, regarding charged particle transport, PENELOPE can be considered as a class II code [16]. Individual interaction events are classified according to the magnitude of the scattering angle θ and energy loss W by introducing certain cut-off values θ_c and W_c, respectively. Events with $\theta > \theta_c$ or $W > W_c$, which will be referred to as hard events, are simulated in detail from the corresponding differential cross sections. The rest of the interactions are considered as soft events. Suitably small values of the cut-offs are selected according to well-defined prescriptions in such a way that soft events between two consecutive hard events have only a mild effect on the electron tracks, which are accurately simulated by means of simple multiple scattering approximations. For electrons and positrons with energies less than some hundred keV, this mixed scheme is more accurate than the condensed schemes adopted in other simulation codes. In particular, the code provides an accurate description of electron transport in the vicinity of interfaces and, hence, the effect of inhomogeneities on the dose distributions is properly accounted for. Photons are followed by using conventional detailed simulation. PENELOPE is applicable in the energy range from 1 keV up to 1 GeV. The code system also includes a geometry subroutine package which allows the simulation of geometric structures consisting of homogeneous bodies limited by quadric surfaces.

2.1. Simulated radiation source

The radioactive nucleus ^{106}Ru disintegrates to the stable nuclide ^{106}Pd via ^{106}Rh. The half-live of ^{106}Ru is 368 days and for the state of ^{106}Rh, which mainly contributes to the β-particle emission, the half-live is 30 s. The electron spectrum of ^{106}Ru has a maximum energy of 39 keV, whereas in the later disintegration of ^{106}Rh the mean energies of the continuous β-particle spectra for the three transitions with the highest yields are 1.51 MeV (79%), 0.97 MeV (9.7%) and 1.27 MeV (8.4%), with a maximum energy of 3.5 MeV [10]. In the calculations, we have considered only the three β-transitions of the ^{106}Rh nuclear decay and, therefore, the initial energies of the simulated electrons are randomly selected from the ^{106}Rh β-spectrum.

In the present study we consider the CCA and CCB concave applicators, with a radius of curvature of 12 mm and external diameters of 15.5 and 20 mm, respectively. They consist of two sealed concentric spherical foils of silver with the radioactive substance placed between them (see Fig. 1). These applicators are produced by Bebig Isotopentechnik und Umweltdiagnostik (Germany). With each delivered applicator, the manufacturer provides a dosimetric calibration, with a stated accuracy of ±30%, determined with 2-mm-diameter plastic scintillators.

In the simulations, the geometry specifications given by

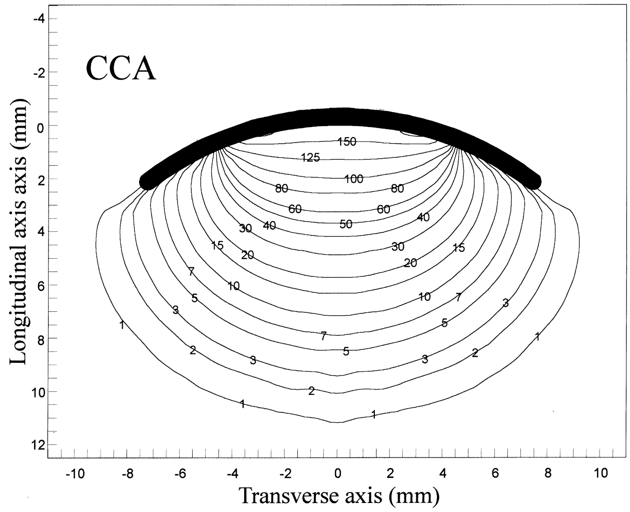

Fig. 2. Relative dose distribution of the CCA applicator. The dose in the central axis at 2 mm from the applicator surface has been normalized to the value 100.

the manufacturer have been strictly followed (Fig. 1). The volume of each silver foil is limited by two concentric spherical sectors and a cone of aperture $\alpha = \arccos(R/R_c)$, where R and R_c are the external radius of the applicator and the curvature radius of the inner surface, respectively. The laboratory reference frame used in the simulations has its origin at the centre of the applicator inner surface, with the symmetry axis as the z-axis. The centre of curvature of the applicator is 1.2 cm from the inner surface. We have assumed that the active radionuclide ^{106}Ru is uniformly distributed on the spherical interface between the backing and window silver foils. The outer radius of the active area is smaller than the applicator radius, i.e. 0.5 cm for the CCA and 1.0 cm for the CCB, according to the manufacturer's specifications. To compute 3D dose distributions we have considered that the applicator is immersed in a 6-cm-radius water sphere concentric with the applicator.

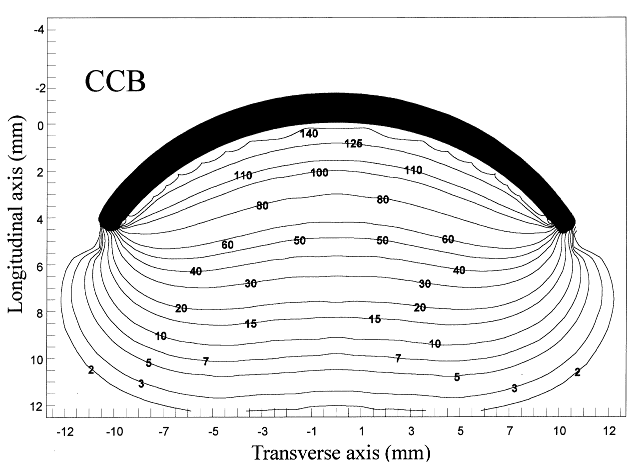

Fig. 3. Relative dose distribution of the CCB applicator. The dose in the central axis at 2 mm from the applicator surface has been normalized to the value 100.

2.2. Computer simulation

Primary electrons (β-rays) in the course of their slowing down generate bremsstrahlung photons and secondary electrons (δ-rays). In the simulations, we have followed primary electrons and the generated secondary radiations down to the corresponding absorption energies, which have been set equal to 70 and 7 keV for electrons and photons, respectively.

In the evaluation of the 3D dose distributions, advantage has been taken of the cylindrical symmetry of the system about the z-axis, which implies that the local dose is a function of only the vertical coordinate z and the radial distance to the z-axis, $\rho = \sqrt{(x^2 + y^2)}$. The dose distributions of CCA and CCB applicators have been calculated by scoring the energy deposited within annular volume bins perpendicular to the z-axis of height $\Delta z = 0.5$ mm and radial thickness $\Delta\rho = 0.5$ mm (i.e. each volume bin is limited by two planes $z = z_j$ and $z = z_j + \Delta z$ and by two cylinders $\rho = \rho_k$ and $\rho = \rho_k + \Delta\rho$). Thus, the simulated dose distribution is obtained as a bi-dimensional histogram, although the result does represent the true 3D distribution. This reduction to

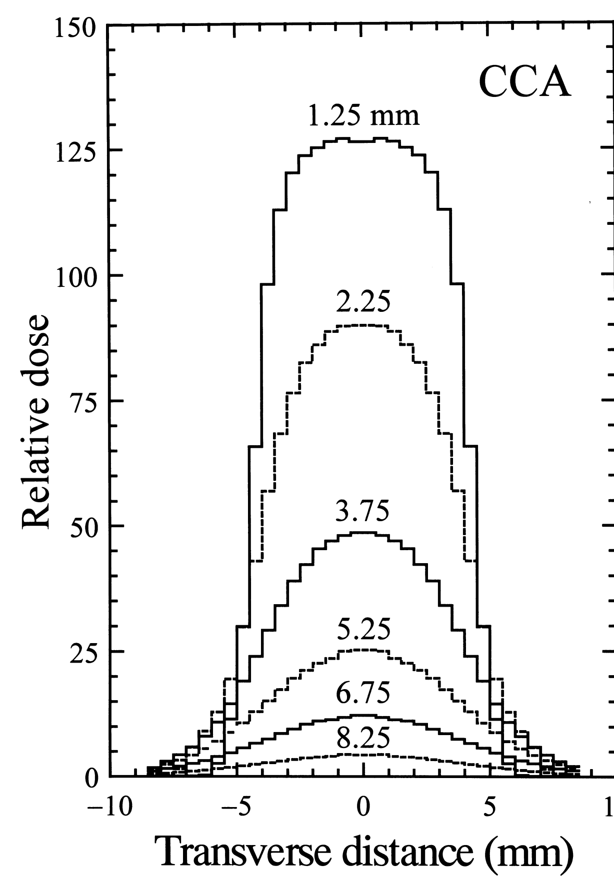

Fig. 4. Lateral dose profiles for the indicated longitudinal distances for the CCA applicator. Normalization is the same as in Fig. 2.

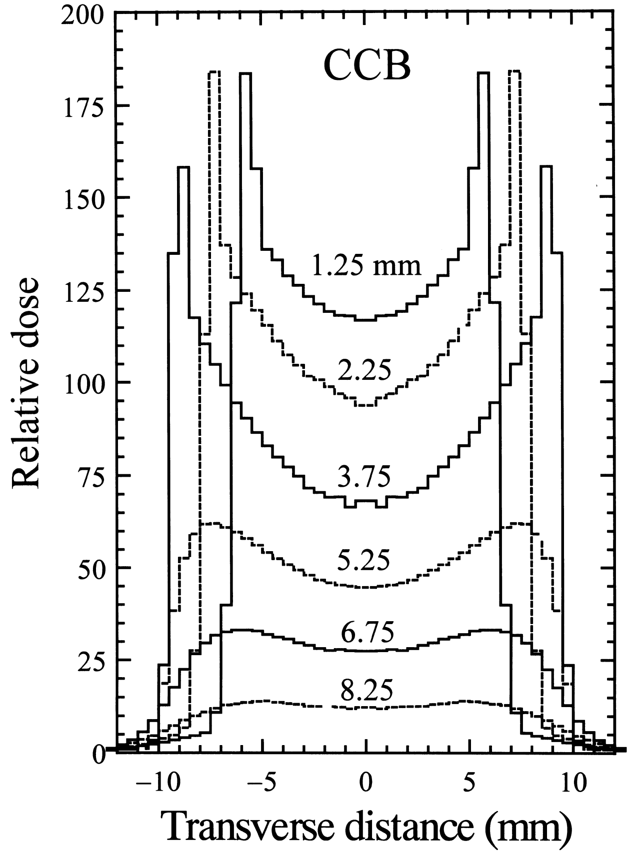

Fig. 5. Lateral dose profiles for the indicated longitudinal distances for the CCB applicator. Normalization is the same as in Fig. 3.

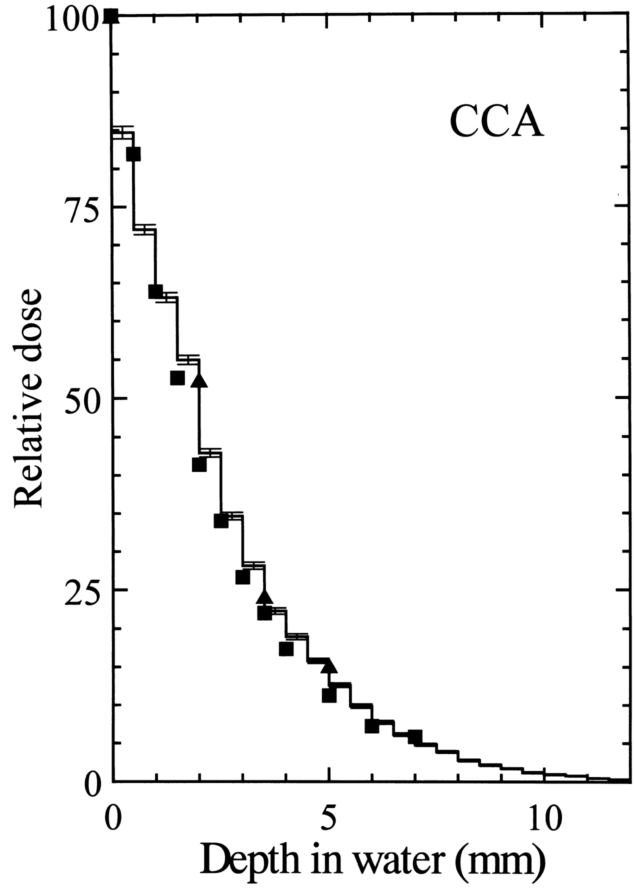

Fig. 6. Depth-dose (along the central axis) of the CCA applicator. Data from the manufacturer (triangles) and from Ref. [6] (squares) are also shown. Error bars indicate statistical uncertainties of simulation results.

two dimensions largely reduces the magnitude of the statistical uncertainties (for a given number of simulated nuclear decays) and allows great savings in computer time. Simulations have been performed on a 166 MHz PENTIUM PC. Typical running times were of the order of 4 days and involved the generation of about 10^7 primary electron histories. The statistical uncertainties (3σ) of the calculated dose distributions are of the order of 2% near the applicator. Far from the applicator surface, at distances of about 0.5 cm, the statistical uncertainty is less than 6%. As the number of simulated histories was similar for both applicators, uncertainties are larger for the CCB applicator (roughly by a factor of 2).

3. Results and discussion

Figs. 2 and 3 display the simulated dose maps for the CCA and CCB Bebig applicators. In order to avoid strong discontinuities, only the dose in water is displayed (i.e. energy deposited per unit volume); within the applicator, where the medium is silver, doses are much larger. The plotted isodoses have been generated by means of a commercial plotting program which determines continuous isodose curves by linear interpolation of the calculated 2D histogram. This interpolation procedure introduces slight distortions of the data in regions where the dose gradient is large, namely in the vicinity of the applicator. Notice that relative doses in Figs. 2–5 have been normalized to 100 at $z = 2$ mm.

Figs. 4 and 5 show simulated lateral-dose profiles (i.e. the dose along a line perpendicular to the z-axis as a function of the transverse distance, $\rho = \sqrt{(x^2 + y^2)}$) for the indicated longitudinal distances to the applicator surface. There are striking differences between the dose profiles of the two applicators. For the CCB applicator, the lateral dose has a clear maximum at the symmetry axis, whereas the dose for the CCA decreases monotonously with transverse distance. This difference is due to the different extensions of the active regions. The sharp maxima for the CCB applicator for longitudinal distances up to about 3.75 mm correspond to the silver region, with a higher atomic number and density than water. For larger longitudinal distances, the smooth maxima are due to the proximity of the active layer of the applicator. The same effects are predicted by the analytical calculation of Hokkanen et al. [9].

Simulated depth-dose curves along the symmetry axes of the two plaques are shown in Figs. 6 and 7. These curves were obtained by scoring the energy deposited on right

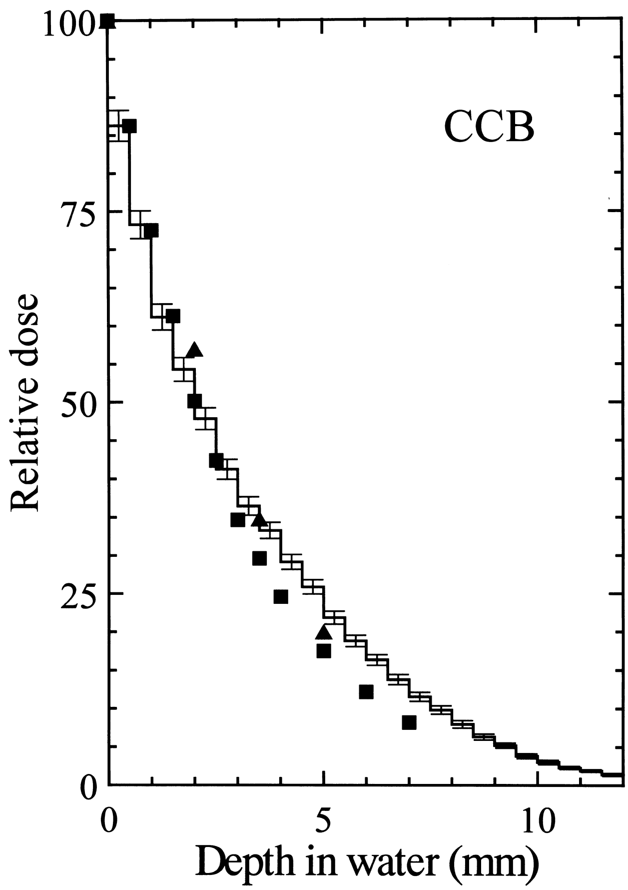

Fig. 7. Depth-dose (along the central axis) of the CCB applicator. Data from the manufacturer (triangles) and from Ref. [6] (squares) are also shown. Error bars indicate statistical uncertainties of simulation results.

cylinders perpendicular to the z-axis of 2 mm in diameter and 0.5 mm in height. The depth-dose values supplied by the manufacturer, which were measured with a plastic scintillator of 3 mm in diameter, are also displayed. For comparison purposes, data computed by Davelaar et al. [6], using a simplified Monte Carlo simulation of electron transport based on the continuous slowing down approximation, are also shown. For the sake of consistency with data from the other authors, depth-doses have been normalized to the value 100 at the surface of the applicator (zero depth). To normalize our Monte Carlo results, we have used a smooth curve that approximates the histogram to determine the dose at the surface.

Our results agree reasonably with the manufacturer's data. Differences with the calculation of Davelaar et al. [6], although systematic in the case of the CCB applicator, may still be less than the uncertainties indicated by these authors. The calculated central-axis dose at 5 mm from the applicator is approximately 12% (CCA) and 20% (CCB) of the maximum dose, whereas at 12 mm the dose reduces to about 1% of its maximum value for both the CCA and the CCB applicators. Thus, if we prescribe a dose of 800 Gy for the sclera of the eye, which is approximately at the applicator surface, at 5 mm we obtain about 160 Gy, whereas at 1.2 cm from the applicator the dose will be less than 8 Gy (for the CCB).

In conclusion, we have used the Monte Carlo code system PENELOPE to compute 3D dose distributions for Bebig CCA and CCB ^{106}Ru applicators. Our results agree closely with the manufacturer's depth-dose data and provide a detailed description of local doses delivered in treatments of choroidal melanoma. It is important to note, however, that in the calculations we have assumed a homogenous distribution of the nuclide over the active surface of the applicator. Although this is a plausible assumption, in practice fluctuations of the specific activity (or surface dose) up to 20% may be found between different points of the same applicator. To obtain reliable dose distributions, the Monte Carlo code should be run using the actual distribution of radioactive material in the applicator, which can be approximately inferred from measurements made with a small diode detector near the applicator surface.

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