An Interactive Treatment Planning System For Ophthalmic Plaque Radiotherapy

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ABSTRACT

Brachytherapy using removable episcleral plaques containing sealed radioisotope sources is being studied as an alternative to enucleation in the treatment of choroidal melanoma and other tumors of the eye. Encouraging early results have been reported, but late complications which lead to loss of vision continue to be a problem. A randomized national study, the Collaborative Ocular Melanoma Study (COMS) is currently in progress to evaluate the procedure. The COMS specified isotope is I-125. Precise dosimetric calculations near the plaque may correlate strongly with complications and could also be used to optimize isotope loading patterns in the plaques. A microcomputer based treatment planning system has been developed for ophthalmic plaque brachytherapy. The program incorporates an interactive, 3-dimensional, solid-surface, color-graphic interface. The program currently supports I-125 and Ir-192 seeds which are treated as anisotropic line sources. Collimation effects related to plaque structure are accounted for, permitting detailed study of shielding effectiveness near the lip of a plaque. A dose distribution matrix may be calculated in any subregion of a transverse, sagittal, or coronal planar cross section of the eye, in any plane transecting the plaque and crossing the eye diametrically, or on a spherical surface within or surrounding the eye. Spherical surfaces may be displayed as 3-dimensional perspective projections or as funduscopic diagrams. Isodose contours are interpolated from the dose matrix. A pointer is also available to explicitly calculate and display dose at any location on the dosimetry surface. An interactive editing capability allows new plaque designs to be rapidly added to the system.

Key words: I-125, Plaque, Choroidal melanoma, Radiation dosimetry.
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DISCUSSION

This program can potentially be applied to optimize plaque design, seed placement, and treatment planning. For example, in the geometry depicted in Figure 10, if the dose at the 6 mm normalization point were 100 Gy, then the estimated dose to the center of the optic disc would be about 80 Gy without accounting for lip collimation, and about half that when lip collimation is included. If a 40 Gy variation in dose to a critical structure were associated with a significant difference in complication rate, the ability to account for lip collimation will be important. In addition to plaque orientation, the effects of using mixed isotopes, and/or seeds of unequal activity can be modelled. This may be of value in reusing sources and tailoring the dose distribution to an irregular tumor volume. The ability to immediately display point dose values without necessarily calculating a complete dose matrix provides rapid feedback for plaque design, and permits detailed study of dose gradients within structures such as the lens, optic disc or macula.

Absolute dosimetry for plaques containing Ir-192 seeds, and relative dosimetry for I-125 seeds, were compared to TLD measurements in an acrylic phantom for the calculational model used in this program by Luxton et al. (17). The dosimetry for I-125 seeds, however, should be considered only approximate at this time. Recent Monte Carlo evaluations by Williamson (24) suggest that characteristic X rays from the titanium seed capsule may lead to a 7% overestimate of the specific dose constant when calibration is performed in air. These low energy photons are rapidly absorbed in water-like media and therefore have negligible contribution to tissue dose at distances greater than 0.5 mm. Williamson (24) suggests a specific dose constant (the ratio of absolute dose rate at 1 cm on the transverse bisector of a seed in a specific medium to the source strength) of 0.909 for the model 6711 seed. This is about 14% lower than the 1.035 value recommended by Ling et al. (15) for the same model seed. In light of the present uncertainties concerning the absolute dosimetry of I-125 seeds, all dose distributions reported here were normalized to a point on the central axis of the plaque, 6.0 mm from the plaque surface, and near the apex of a hypothetical 5 mm tumor. This represents a typical dose specification point at this institution and by the COMS.

The multi-window, 3-dimensional graphics interface provides an intuitive environment for both the physicist and physician to work within. Goitein and Miller (9) used a similar approach for planning proton therapy of the eye. This earlier work was implemented in FORTRAN on a computer (VAX 11/780) and required about 1.3 full-time-equivalent (FTE) man-years to implement. The program described here was developed in about 0.4 FTE man-years with the aid of the ROM "toolbox" functions built into the Macintosh computer. Since the program adheres to the recommended user interface guidelines, it is simple to learn and use, and is an example of how this new hardware and software technology can be rapidly and successfully applied to clinical dosimetry tasks.

There are several aspects of the current dosimetry system which require refinement prior to clinical implementation. The generalized approximation of intraocular anatomy within a spherical globe may be too imprecise for many variants of human ocular anatomy. Digitization of the tumor perimeter from fundus photography, estimation of the 3-dimensional tumor volume from sequential CT or MRI images,
and display of the 3-dimensional tumor volume within a translucent eye would be desirable additions. These would provide visual aids during plaque positioning and permit correlation of isodose surfaces with actual tumor and normal tissue contours. Surgical reproduction of the preplanned plaque orientation and location could be difficult to achieve. If the source locations are fixed relative to the suture eyelets on the plaque, however, and the spatial location of the suture eyelets relative to real anatomical landmarks, such as the limbus, can be specified, precise surgical placement may be facilitated. Three-dimensional isodose surface displays and loading optimization based on available isotope resources would also be desirable. The lip collimation algorithm currently assumes a circular lip. This could be refined to handle lips of arbitrarily shaped perimeters. The COMS plaques use a silicone rubber carrier to offset the sources by 1 mm from the sclera. Our model presently considers this intervening medium to be tissue equivalent. For the low energy photons from I-125 seeds, photoelectric attenuation and scatter characteristics in silicone rubber could vary significantly from tissue and probably need to be accounted for. Dose resulting from scatter into the penumbral region close to the plaque perimeter is not modelled and may be of significance as well. We are presently adding these capabilities to the dosimetry system reported here.

REFERENCES


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RESULTS

The Macintosh implementation (16MHz 68020 processor) requires approximately 3 secs per seed to calculate a 40 X 40 dose matrix with lip detection activated, and is about 20% faster when lip detection is disabled. Interpolating the dose matrix and generating the screen display requires from 3 to 30 secs, depending only on the size of the display window and the type of display surface requested (planar or 3D perspective projection). The time required to generate a screen display is independent of the dose matrix resolution. Although matrices up to 160 X 160 points are available at the cost of proportionately longer computation time, no visual improvement in isodoses within the hypothetical tumor volume was apparent between the 40 X 40 and 80 X 80 modes. The higher resolution modes which generated the figures in this report are primarily intended to reduce aliasing in the penumbral region near the lip. A typical plaque with 10 seeds normally requires < 60 sec to calculate and display a dosimetry matrix adequate for clinical purposes, and about 1 sec to generate a dose table for the central axis and critical structures.

Fig. 7. Test of the partial visibility algorithm using a single I-125 source: (a) in a slot near the center of the plaque, (b) in a slot near the lip, (c) in a modified version of the plaque with a radially oriented slot near the lip. The plane of dose calculation is the plane z = 0.
The partial visibility algorithm was tested using a 16 mm diameter COMS plaque. A single 4 mCi seed of I-125 was assigned to a slot near the center of the plaque (Fig. 7a), near the lip (Fig. 7b), and to a radially oriented slot near the lip of a modified plaque (Fig. 7c). The displayed isodose distributions are consistent with the expected shielding effects. Shielding of the sclera adjacent to the plaque is greatest for the seed near the lip and nonexistent for the centrally located seed. Some aliasing in the penumbral region is evident for the radially oriented seed, but is of little practical concern. This aliasing results from the limit of five iterations imposed (to improve speed) on the pvr calculation.

Fig. 8. Comparison of a peripheral loading pattern versus a uniform loading pattern for the COMS 16 mm diameter plaque. The dose distribution is calculated for the plane \( z = 0 \). The display has been normalized to a value of 1.0 at 6 mm from the plaque surface on the central axis of the plaque, near the apex of a hypothetical tumor. The nominal position of the retina is indicated by the inner white semi-circle, inset 1 mm from the scleral surface. The tumor is roughly conical in shape, and is indicated by the darkened region within the eye. Dose volume is calculated in \( \text{mm}^3 \). (a) 13 equal sources filling all available slots. (b) 7 equal sources in the peripheral ring.
Alternative loading patterns for the plaque were studied to model pre-treatment planning capability, again using the 16 mm COMS plaque loaded with I-125 seeds. The plaque was centered on the y-axis at the intersection of the equator and lateral (90°) meridian (Fig. 4). Dose matrices were calculated in the plane z = 0 which transects both the plaque and eye. In the first case, 13 sources of equal activity filled all of the available slots in the plaque (Fig. 8a). This was compared to seven sources of equal activity in the peripheral ring of slots (Fig. 8b). The dose distributions of Figure 8 have been normalized to a value of 1.0 at 6 mm above the surface of the plaque near the apex of a hypothetical 5 mm tumor. While dose to the tumor volume appears to be similar, retinal dose appears to be more homogenous for the peripheral loading pattern. A dose-volume histogram for 1 mm³ voxels within the eye was calculated for each case. The results indicate that the peripheral loading pattern increased the volume of eye tissue receiving a dose >= 4X the normalization dose by only 1 mm³ while decreasing the volume >= 2X by 52 mm³. For this particular geometry, the improved homogeneity of the peripheral loading pattern was achieved at the cost of a slight increase in dose to the lens and to the sclera near the peripheral edge of the plaque.
Fig. 9. Dose distributions on the scleral and retinal surfaces for the COMS 16 mm plaque with 7 equal I-125 sources in the peripheral ring. The display has been normalized to a value of 1.0 at 6 mm from the plaque surface on the central axis of the plaque. (a) 3-dimensional perspective projection view of the scleral dose distribution. (b) Funduscopic diagram of dose to the retina.

The dose distribution on the scleral surface and the retina (assumed to be 1 mm inset from the scleral surface) are modeled in Figures 9 & 10 for the plaque depicted in Figure 8b. All dosimetry is normalized as in Figure 8. The scleral dose distribution is plotted as a 3D perspective projection in Figure 9a. The retinal dose distribution is plotted in the manner of a funduscopic diagram in 9b. Localized areas of high dose on the sclera adjacent to each seed, which were not readily apparent in Fig. 8b are now clearly seen in Fig. 9a. Outside the lip perimeter indicated by the yellow wire-frame in
Figure 9a, a distinctive lobular pattern is observed in the 0.1 to 0.7 relative dose range. This pattern apparently results from partial visibility of alternating sources. Figures 10a & 10b display views of the retinal dose from anterior and posterior vantage points. Figure 10c is identical to 10b except that lip collimation is ignored. The dose distribution in Figure 10c suggests that the lip, rather than anisotropy is the source of the lobular pattern. For this particular geometry and orientation, in which the plaque is adjacent to the optic nerve, the calculated dose to the center of the optic disc in Figure 10c is roughly twice that of 10b.

Fig. 10. Retinal dose distributions for the COMS 16 mra plaque with 7 equal I-125 sources in the peripheral ring. The display has been normalized to a value of 1.0 at 6 mm from the plaque surface on the central axis of the plaque. (a) and (b) are 3dimensional perspective projection views from anterior and posterior vantage points. (c) is identical to (b) except that lip collimation effects have been ignored.