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EFFECTS OF TARGET SIZE ON THE COMPARISON OF PHOTON AND CHARGED PARTICLE DOSE DISTRIBUTIONS[1]

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INTRODUCTION

The work presented here is part of an ongoing project to quantify and evaluate the differences in the use of different radiation types and irradiation geometries in radiosurgery. In particular, we are examining dose distributions for photons using the "Gamma Knife" and the linear accelerator arc methods, as well as different species of charged particles from protons to neon ions. This work has been carried out at the Lawrence Berkeley Laboratory (LBL), with help from Dr. Michael Schell at the University of California, San Francisco (UCSF) in establishing accurate parameters for photon calculations.

A number of different factors need to be studied to accurately compare the different modalities such as target size, shape and location, the irradiation geometry (number, orientation, and shape of beamports), and biological response. Obviously much work needs to be done to characterize all of these factors. This presentation focusses on target size, which has a large effect on the dose distributions in normal tissue surrounding the lesion. An introductory paper to our methods and rationale, which also contains some preliminary results, is currently in press [1].

This work concentrates on dose distributions found in radiosurgery, as opposed to those usually found in radiotherapy, although there is much that is common between the two. This has several consequences:

1. Target size is relatively small, that is from about 0.5 cm to 8 cm in size along any one direction. This translates to target volumes from between a few tenths of a cubic centimeter to about 70 cm^3.

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2. Photon treatments are carried out using multiple converging beams. In the "Gamma Knife", this is accomplished with 203 separate Co^{60} sources; with the linear accelerator, with multiple converging arcs.
3. The lesions treated are in the brain, and the head is fixed within a stereotactic frame. Only 1 or 2 fractions are used. This implies that the repositioning errors are considered negligible.

METHOD AND MATERIALS

Dose distributions have been calculated using a 3-dimensional, CT-based treatment planning program developed at LBL; a set of dose distributions is calculated for all CT images spanning the head. The CT images are spaced 3 mm apart, and the pixel sizes for the dose calculations are 3.2 x 3.2 mm. To focus on target size, we have chosen spherical targets encompassing the range of diameters from 1 cm to 6 cm. The effects of different target shapes have not yet been fully explored. For the charged particle treatment plans, each beamport is compensated to shape the distal edge of the beam to the target shape. The widths of the spread Bragg peaks are in increments of 1 cm. The widths of the beamports (and the compensation, in the case of charged particles) are set so that the 90% isodose curve falls on the target boundary.

Irradiation geometries were defined by number of beamports, their spatial orientation, and their weighting. The charged particle geometry for each plan follows the practice at LBL: 3-5 beamports lying in the sagittal and coronal planes and angled at 20-30° from the lateral. For midline lesions, the beamports are arranged bilaterally; for lesions lying solely in one hemisphere, the beamports all lie within the affected hemisphere. The irradiation geometry for the "Gamma Knife" is described in Dahlin and Sarby [2]. The irradiation geometry chosen for the dose calculations using the linear accelerator method is that used in Heidelberg [3].

The dose distributions were evaluated using dose-volume histograms of the 3-D distributions. Peak doses of 1 Gy were used in all calculations for ease of comparison. Dose-volume histograms were calculated for the volume of the lesion and for volumes of normal tissue outside of the lesion. With such small target volumes, dose-volume histograms to the entire brain for the purpose of evaluating normal tissue exposure are not very effective. In order to improve the "resolution" of the histograms, shells of normal tissue surrounding the lesion were defined. Depending on the size of the target, shells of thickness 1 or 2 cm encompassed the entire high dose region (down to 10% of peak dose or lower), and histograms of the volumes enclosed in the shells were used to compare the different methods.

RESULTS AND DISCUSSION

When calculating dose distributions to such small volumes (less than or equal to several cubic centimeters), care must be exercised to ensure accurate representations of the dose deposition characteristics of the different radiation types. Single beam treatment plans were calculated for each of the radiation types and depth dose characteristics were compared with measured dose distributions. Data from UCSF were obtained to model the single beam dose distributions characteristic of linear accelerator single beam radiosurgical dose distributions. Comparisons were also made between calculations and measured dose distributions resulting from irradiation with all of the beamports. "Gamma Knife" and linear accelerator results were compared to 2-dimensional dose profiles in the literature [4,5]. Dose-volume histograms for linear accelerator geometries used at UCSF were compared to histograms calculated using the LBL program in order to ensure complete, 3-dimensional accuracy. Such comparisons have proven valuable, and modifications in the computer-calculated single beam dose distributions and in the parameters for defining the irradiation parameters have been made as a result. Currently, our calculations are in good agreement with the measurements and calculations cited above. Differences, when they exist, are usually approximately 5% and occur in the tails of the distributions, where the overall contribution to the dose is relatively small.

Once the accuracy of the method was established, dose distributions were calculated for spherical, midplane lesions of diameters from 1 to 6 cm. All methods provided good coverage of the target volume. Figures 1 and 2 demonstrate the results of the different radiation types for lesions 1 and 6 cm in diameter, respectively. Little difference was seen between the "Gamma Knife" and linear accelerator results, so only the latter results (LINAC) are plotted. A comparison of histograms calculated for protons and photons for five target sizes between 1 and 5 cm diameters demonstrated a result that is also illustrated in Figures 1 and 2. Namely, that as target size increased, the ability of charged particle single beam dose distributions to be tailored to the target (using compensation and spreading of the Bragg peak) resulted in little change in the shape of the charged particle dose distributions. For photons, on the other hand, as the target size increased, the shape of the histogram for the shell changed from being favorable (the high dose region encompasses only a small volume) to being unfavorable (the histograms approach the shape of the histogram for the target volume). It must be noted that when viewing the histograms attention must be paid to the fact that the absolute volume of normal tissue included within the shell increases rapidly with increasing target diameter. It should also be noted that spherical targets result in the most favorable comparisons between charged particles and photons since, in practice, photon beams are not shaped to correspond to irregular target volumes and are either elliptical or circular in cross-section.

Figures 1 and 2 also illustrate differences between species of charged particles. Carbon ions are expected to give the best dose distributions as a result of their decreased range straggling and multiple scattering when compared to lighter ions, and this is borne out in the results. Similarly, helium ions have an advantage over protons. The relatively large differences between protons, helium ions and carbon ions for the 1 cm target decrease markedly when the target size increases to 6 cm. For large targets, all three species of charged particles result in similar dose distributions. This is a result of the amount of multiple scattering relative to the target size. For protons penetrating to a depth of 10 cm in water, the width of the multiple scattering distribution is on the order of 1 cm, whereas for helium ions and carbon ions it is 0.5 cm and smaller. As target size increases, the size of this penumbra region stays constant and it has less of an effect relative to the increasing size of the central area of the beam.

SUMMARY

Much work needs to be done to accurately quantify the differences in radiosurgical dose distributions obtained using different species of charged particles and photons. One important factor is the size of the target. Present results indicate that for small targets (on the order of 1 cm diameter), protons and photon techniques yield similar results. As target size increases, proton dose distributions become more similar to heavier charged particle distributions (helium and carbon ions), and photon dose distributions result in relatively larger volumes of normal tissue being irradiated. Clinical results with the "Gamma Knife" in particular have shown that photons provide clinically useful dose distributions for target sizes less than or equal to 2 cm. In the future, we hope to utilize such clinical results to determine the biological importance of differences in dose-volume histograms, and to provide a basis for the optimal application of the appropriate radiosurgical method.

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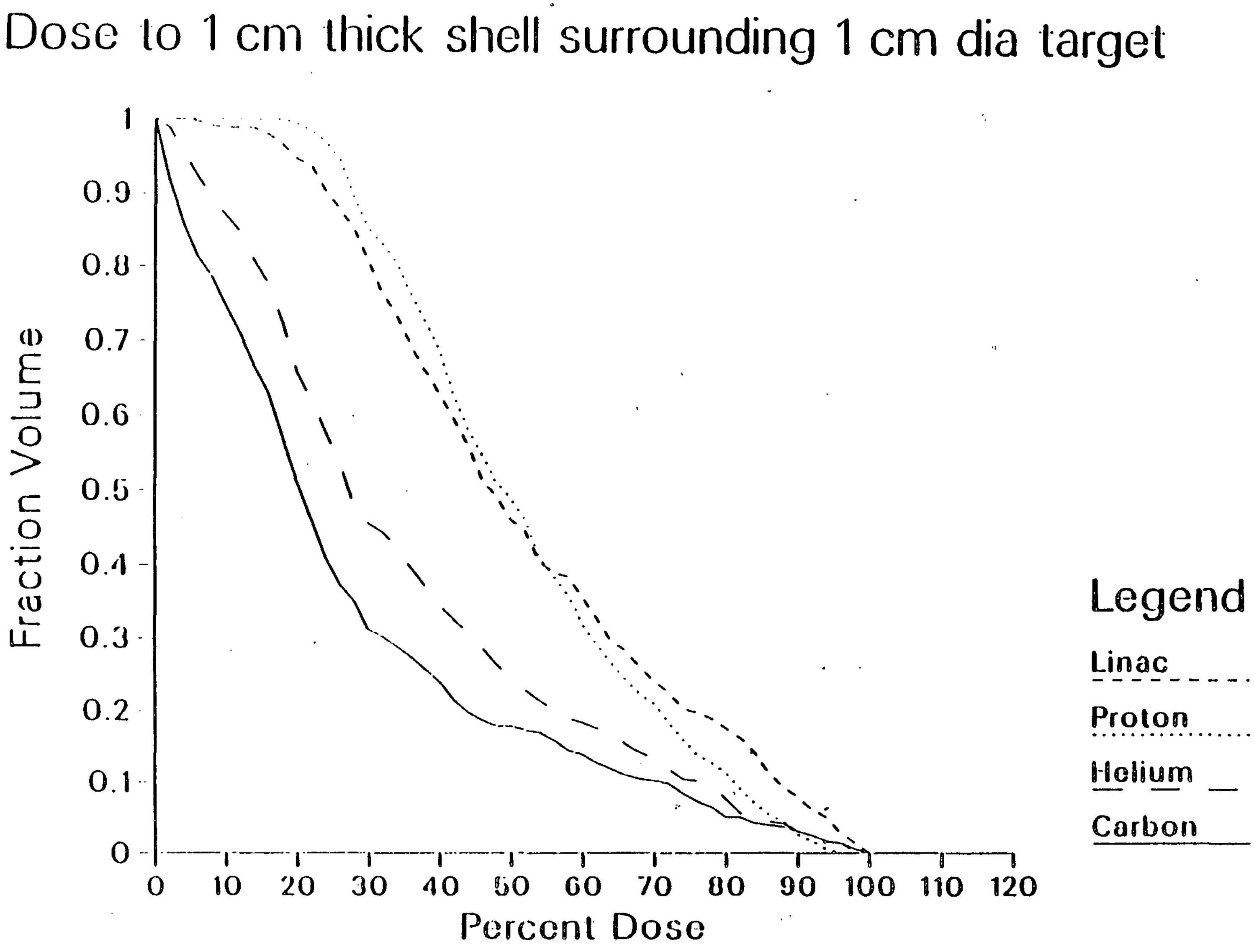

Figure 1: Dose-volume histogram calculated for the volume of tissue enclosed within a 1 cm-thick shell surrounding a 1 cm diameter target. Histograms are calculated from the dose distributions resulting from linear accelerator photons (Linac), protons, helium ions and carbon ions. Peak target doses for each case were 1 Gy. Photon and proton results are seen to be very similar.

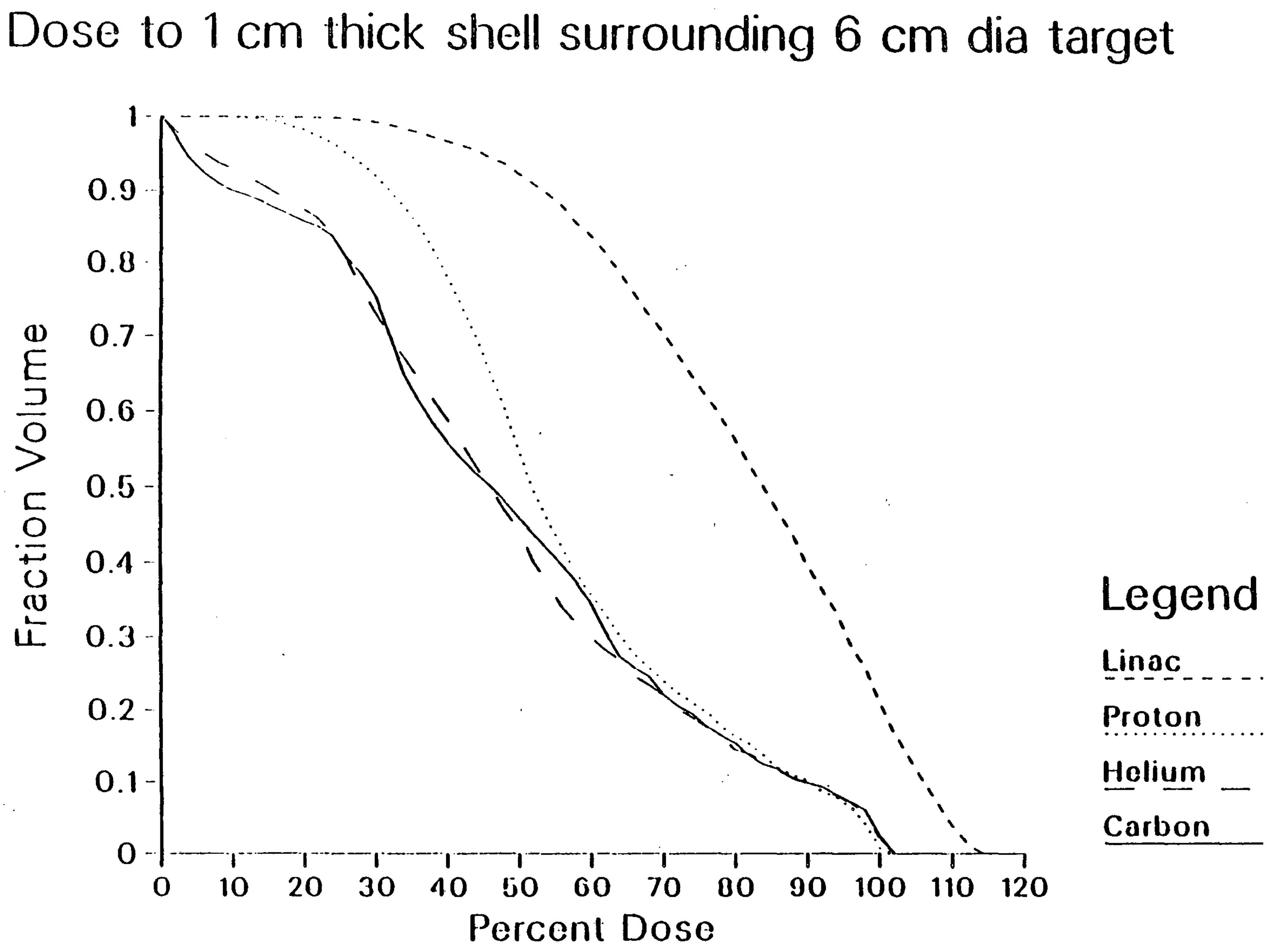

Figure 2: Dose-volume histogram calculated for the volume of tissue enclosed within a 1 cm-thick shell surrounding a 6 cm diameter target. Histograms are calculated from the dose distributions resulting from linear accelerator photons (Linac), protons, helium ions and carbon ions. Peak target doses for each case were 1 Gy. The differences between the different species of charged particles are much less when compared to the 1 cm target distributions.

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