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DISCLAIMER

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TREATMENT PLANNING FOR STEREOTACTIC HEAVY-CHARGED-PARTICLE RADIOSURGERY OF THE BRAIN [1]

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ABSTRACT

Treatment planning techniques for stereotactic charged particle (helium ion) Bragg peak radiosurgery of intracranial vascular and other disorders are described. Stereotactic neuroradiological procedures (cerebral angiography, x-ray computed tomography (CT) and magnetic resonance image (MRI) scanning) define precise intracranial treatment targets on axial, and reformatted coronal and sagittal CT slices. For a given target, beam ports are selected, and aperture size and shape, ranges, compensation, and Bragg peak spread are determined using interactive computer programs. Beam ports are selected to protect critical and sensitive brain structures, or to minimize radiation dose to adjacent normal brain, while delivering a uniform dose distribution throughout the target volume. Two-dimensional isodose treatment plans are generated by computer for each CT slice of interest on a pixel-by-pixel basis. Three-dimensional, CT-based treatment planning is developed for specialized clinical uses. In conjunction with dose-volume histograms, three-dimensional plans provide a

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method for comparing treatment plans of differing radiation modalities, i.e., photons, protons, and heavy charged particles. Treatment plans are presented for a range of intracranial target volumes.

Key Words: stereotactic radiosurgery, charged particles, treatment planning, AVM, brain, intracranial, neuroradiologic

INTRODUCTION

Stereotactic radiosurgery utilizing the Bragg peak of the helium-ion beam has been developed at the 184-inch Synchrocyclotron and the Bevatron of the Lawrence Berkeley Laboratory University of California, Berkeley, (LBL) for the treatment of intracranial vascular and pituitary disorders [2, 3, 4, 5, 6, 7]. The physical characteristics of monoenergetic heavy charged particle beams provide unique advantages for radiosurgical treatment in the brain; these include a sharp Bragg ionization peak, and minimal lateral scattering and range straggling [4, 8, 9]. We have applied these advantages to the treatment of pituitary disorders and of intracranial arteriovenous malformations (AVMs). This paper describes the treatment planning techniques used for Bragg peak stereotactic radiosurgery of AVMs with volumes from 120 mm^3 to 60,000 mm^3.

METHODS

Treatment planning begins with a series of stereotactic neuroradiologic examinations, viz., cerebral angiography, CT, and MRI, carried out with the patient immobilized in a specially constructed stereotactic frame and mask [9]. The stereotactic frame has fiducial markers that are readily observed and measured on x-ray images. The fiducials serve as reference points for image transfer from cerebral angiographic studies to CT and MR images. The fiducial markers are located on the sideplates, as seen on the lateral projection, and anteriorly and posteriorly on the frame for the AP projection. An identical but specially-designed non-metallic frame using oil-filled tubes as fiducial markers is used for stereotactic MRI imaging. Stereotactic cerebral angiography is the primary imaging modality used to determine the size, shape, and location of the AVM; stereotactic contrast CT and MRI scans are conducted to obtain additional information regarding its 3-dimensional structure, its relationship to other regions of the brain, and the physical properties of the surrounding brain tissue; all are important for treatment planning. Image correlation techniques, based on the three-dimensional information provided by the immobilization method and integrated stereotactic frame, are used (a) to transfer contours of the target volume from angiographic films to CT images for calculation of dose distributions, (b) to generate overlays of the fiducial markers, the treatment target and bone landmarks of the skull for comparison with beam-localization (port) radiographs taken at the time of treatment, and (c) to calculate the coordinates of the patient-positioner that will place the center of the target volume at the isocenter of the ISAH (Irradiation Stereotactic Apparatus for Humans) patient positioner.

Location of Intracranial Target

The target volume, reference markers, and selected midline bone landmarks, such as the inner table of the calverium, the sella turcica, the clinoids, petrous pyramids and frontal plates, are digitized. The primary physical factors of interest—the focus-film distance, focus-to-object distance, and position and angle of the central ray relative to the frame—are calculated using geometric optics. This locates the treatment target precisely within the stereotactic frame and mask.

The locations of the fiducial markers on the CT images are correlated with their positions on the digitized cerebral angiogram. The AVM volume is modelled as a series of ellipses, determined separately for each CT slice spanning the AVM. The major and minor axes of the ellipses are determined by the length and width on the angiographic projections. The target contours are reformatted on sagittal and coronal reconstructions. CT and MRI information is used to modify the shape of irregularly shaped targets, e.g., when the AVM closely follows anatomical contours of intracranial structures such as the brain stem, ventricle, or corpus callosum.

The digitized angiographic images are used to calculate the patient position and the position of the intracranial target for radiosurgery. The computer program generates isocenter coordinates for the center of the frame and the center of the target, and appropriately magnified overlays corresponding to both lateral and AP projections. The overlays show the reference points, midline bone landmarks, and the target contour in real (actual size) and magnification views. Individual beamport apertures are constructed using the overlay target image as a template. Molds conforming to the shape of the target volume are constructed out of styrofoam or lucite, and an aperture is then poured from cerrobend, a low melting point, dense metal alloy.

Alignment is accomplished by comparing lateral and AP localization x-ray radiographs at the Bevatron and comparing them with the computer-generated overlay images. One of these films is exposed to a very low intensity charged particle beam so that an image of the aperture is superimposed on the radiograph of the skull. Comparisons of the radiographic and overlay images are used to adjust the patient position until the bone landmarks, target contours and beam image are correctly positioned.

Treatment Planning Procedure

Stereotactic radiosurgery treatment plans are generated using a computer program developed at LBL for heavy charged particle radiotherapy [1] and radiosurgery. The physical properties of the helium-ion beam (i.e., Bragg peak, sharp penumbra, and small fragmentation) are incorporated in the treatment planning program. A calibration curve relating the measured X-ray attenuation coefficient to charged particle stopping power is used to convert the CT data to water equivalent path length for each charged particle beamport [1].

Treatment planning is initially carried out using a two-dimensional treatment planning system of multiple CT slices through the desired target volume. For spherical or ellipsoidal targets treatment planning usually considers only the central slices, in the axial, coronal, and sagittal planes, with isodose contours taking into account only those beamports in the plane. For AVMs with complex anatomical shapes, or for those with diameters greater than 5 cm, treatment planning is performed on several slices to assure well-confined, uniform dose distributions that spare normal adjacent brain tissue. Most treatment plans are comprised of 3 to 5 noncoplanar beamports. For irregularly-shaped lesions we use three-dimensional treatment planning programs to optimize compensation and range selection, and to generate isodose distributions, taking into account noncoplanar beamports.

The contours of the target volume to be irradiated are determined from angiography (or from the sagittal and coronal views of the lesion on either MRI or CT scans in the case of angiographically occult AVMs), and transferred to the noncontrast CT scan. A two-dimensional isodose treatment plan is generated and beamport parameters calculated. The computer program generates isodose curves on the CT slice of interest and is used to determine beam range, the width of the spread-out Bragg peak, and compensation. The dimensions of the beamport aperture and range are usually set to place the 90% isodose contour at the edge of the target volume, and achieve a uniform dose distribution throughout the target volume. The 50% or 70% isodose contour is sometimes placed at the edge of the lesion, depending on such factors as dose, volume, and location.

Representative Treatment Plans

Figure 1 demonstrates the treatment plan for a centrally located AVM in the midbrain. Four coplanar ports were used to treat an 1800 mm^3 lesion with 15 GyE helium in 2 d. The Bragg peak was spread 1 cm, and a 19 mm x 17 mm elliptical aperture was used. Beamports chosen were at 20° anteriorly and posteriorly from the lateral directions. Isodose curves at 10, 30, 50, 70, 90, and 99% levels are displayed on the CT scan. For this plan, the dose to the surrounding adjacent brain tissue is distributed evenly about the surrounding normal midbrain, with rapid dose fall-off in all directions. The 50% isodose line falls within 8 mm of the target along the beam direction, and within 4 mm in the perpendicular direction. The 10% isodose line extends to the skin along the directions of the beamports.

For thalamic lesions smaller than 15,000 mm^3, four treatment beams from one side are commonly used (from 3 to 5 beams), and treatment is carried out from one side only—usually 2 in the axial plane and 2 in the coronal plane. For larger lesions anterior and posterior beams in the sagittal plane are often added; when possible, all beamports are chosen to lie solely within the affected hemisphere, thereby completely sparing the contralateral hemispheric structures.

A large thalamic AVM (18,000 mm^3) is shown in Figure 2. The patient received 15 GyE in 2 d. There are two beams displayed in the coronal plane (upper left) at 30° superior and inferior from the axis, and two in the sagittal plane (upper right), the anterior beamport at 5° superior, and the posterior at 15° superior. The two coronal ports were collimated with a 44 mm x 28 mm aperture. The Bragg peak was spread 2 cm. The anterior and posterior ports were collimated with a 32 mm x 28 mm aperture and a 4 cm spread peak was used. Two ports, the inferior in the coronal plane, and the anterior on the sagittal plane, required lucite compensators. A comparison coronal view without compensation is shown (lower left). The treatment plan with compensation adjusts the location of the distal peak (which otherwise would extend far beyond the edge of the AVM), and provides more uniform dose distribution throughout the AVM. A useful approximation of the dose distribution can be obtained in the axial plane by generating a treatment plan using three beams: left lateral, posterior, and anterior (lower right). Two-dimensional analysis can approximate the dose distribution well, but 3-dimensional treatment planning is needed for the most accurate isodose information.

Three Dimensional Treatment Planning

Three-dimensional treatment planning allows the visualization of dose distributions that take into account all coplanar and noncoplanar beams. The program currently used at our laboratory is a modification of the two-dimensional treatment planning program. The calculations are performed using a 3 x 3.2 x 3.2 mm matrix. The program automatically matches the shape of the beamport collimator to the projection of the target volume in the direction of the beamport. The dimensions of the apertures are set to place the 90% isodose contour at the edge of the target volume. Charged-particle compensation and ranges are automatically calculated to place the distal edge of the Bragg peak on the distal edge of the target contour. Values of the spread-out Bragg peak are chosen by the computer in 1 cm increments to conform to the dimension of the target along the beamport direction.

The 3-dimensional program is also used to generate treatment plans for comparison of different radiation modalities. Dose-volume histograms are calculated for each CT slice. Histograms are calculated for any volume of interest, such as the target, the entire brain, or specific sites, such as an adjacent brain structure or the region surrounding a lesion.

Figure 3 illustrates a three-dimensional treatment plan for a large, left thalamic lesion treated with four beams—one lateral, two posterior, (one at 20° superior, one at 25° inferior), and one anterior at 20° superior. The three-dimensional treatment plan is shown on four representative axial slices. The inferior beam 10% isodose level lies at the edge of the midbrain. Without accurate dose distributions incorporating all of the non-coplanar beams, it would be difficult to assess the dose to this critical brain structure.

Dose Volume Histograms

Through the use of dose-volume histograms, differences in dose distributions of different radiation types and geometries can be compared. Dose-volume histograms of the brain, using actual treatment targets, were calculated for targets of volumes 0.8, 5, 14, and 56 cm^3; this corresponds to diameters of approximately 1, 2, 3, and 5 cm, for corresponding spherical targets. Current photon and charged particle irradiation geometries were used in the calculations. All radiation modalities cover the target volume adequately. For the smallest target dose distributions for different radiation types were approximately the same, but as target size increased, the photons delivered significantly greater dose to normal tissue than charged particles.

The volume of normal tissue directly adjacent to the AVM may be at risk for radiation injury. The region of normal tissue surrounding the target that receives 80% or more of the maximal target dose was calculated for each radiation type, for spherical targets. The volume irradiated by photons is always greater than that by charged particles for all target volumes by a factor of approximately 2-2.5, and increases with target volume.

SUMMARY AND CONCLUSION

The present system of treatment planning for heavy charged particle Bragg peak stereotactic radiosurgery generates isodose distributions on selected CT scan slices and overlays for patient localization, and determines beamport range values and aperture shape. While two-dimensional based treatment planning is usually adequate for stereotactic radiosurgery, three-dimensional techniques provide more accurate dose distributions for optimizing treatment strategies, and this is applied in all special cases. Conformal therapy, using multiple coplanar and noncoplanar beamports with suitable compensation and spreading of the Bragg peak, will enable more precise deposition of radiation dose with less dose to surrounding brain tissues. Three-dimensional treatment planning techniques are useful for comparing effectiveness of different radiation modalities. Tissues directly adjacent to irradiated intracranial targets receive greater dose from photon irradiation schemes than from charged particles. The results for different charged particle species (protons, helium, carbon) appear to be similar; this may be due to the resolution of the present calculations. Work is in progress to develop high-resolution 3-d treatment planning to refine the dose-comparison calculations.

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Figure Legends

Figure 1: Stereotactic heavy-charged-particle Bragg peak radiosurgery treatment plan for a midbrain AVM (defined by the inner ring of white dots). Isodose curves for 10, 30, 50, 70, 90, and 99% of the maximum are shown. There is a rapid drop-off in dose outside the AVM target, and very little brain tissue receives as much as 10% of the dose to the AVM. The helium-ion beam was collimated by a 19 x 17 mm elliptical brass aperture. The treatment was performed using 4 ports in 2 d to a volume of 1800 mm^3 (dose, 15 GyE).

Figure 2: Stereotactic radiosurgery treatment plan for a thalamic AVM Isodose curves of 10, 30, 50, 70, 90, and 99% of the maximum dose are shown. Two coronal **(upper left)** and two sagittal beams **(upper right)** were used. The inferior beam in the coronal beam projection traversed a lucite compensator to adjust the distal edge of the Bragg peak to the edge of the AVM. A treatment plan without compensation **(lower left)** demonstrates less coverage of the target (dark solid line) with some extent of radiation beyond the AVM. A pseudo-projection of the axial plane **(lower right)**, weighted with two beams from the left—one anterior, and one posterior—allows demonstration of the dose adjacent to the AVM in the axial plane. Two apertures were used: a 44 x 28 mm aperture (coronal plane ports), and a 32 x 28 mm aperture (sagittal plane ports). The patient was treated treated in 2 d to a volume of 18,000 mm^3 (dose, 15 GyE).

Figure 3: Three dimensional treatment plan on four representative axial slices. The patient was treated with one left lateral beam, and three sagittal plane beams (posterior beams 20° superior and 25° inferior to the axial plane, and an anterior beam 25° superior to the axial plane). Isodose curves of 10, 30, 50, 70, and 90% of the maximum dose are shown, and indicate that the 10% isodose curve lies on

the edge of the midbrain **(upper left)**; this structure receives only minimal radiation dose. The patient received a dose of 15 GyE of helium-ion radiation in 2 d to a volume of 17,000 mm^3. The left lateral beam was delivered through a 46 x 42 mm aperture, and the sagittal plane beams were delivered through a 42 x 33 mm aperture.

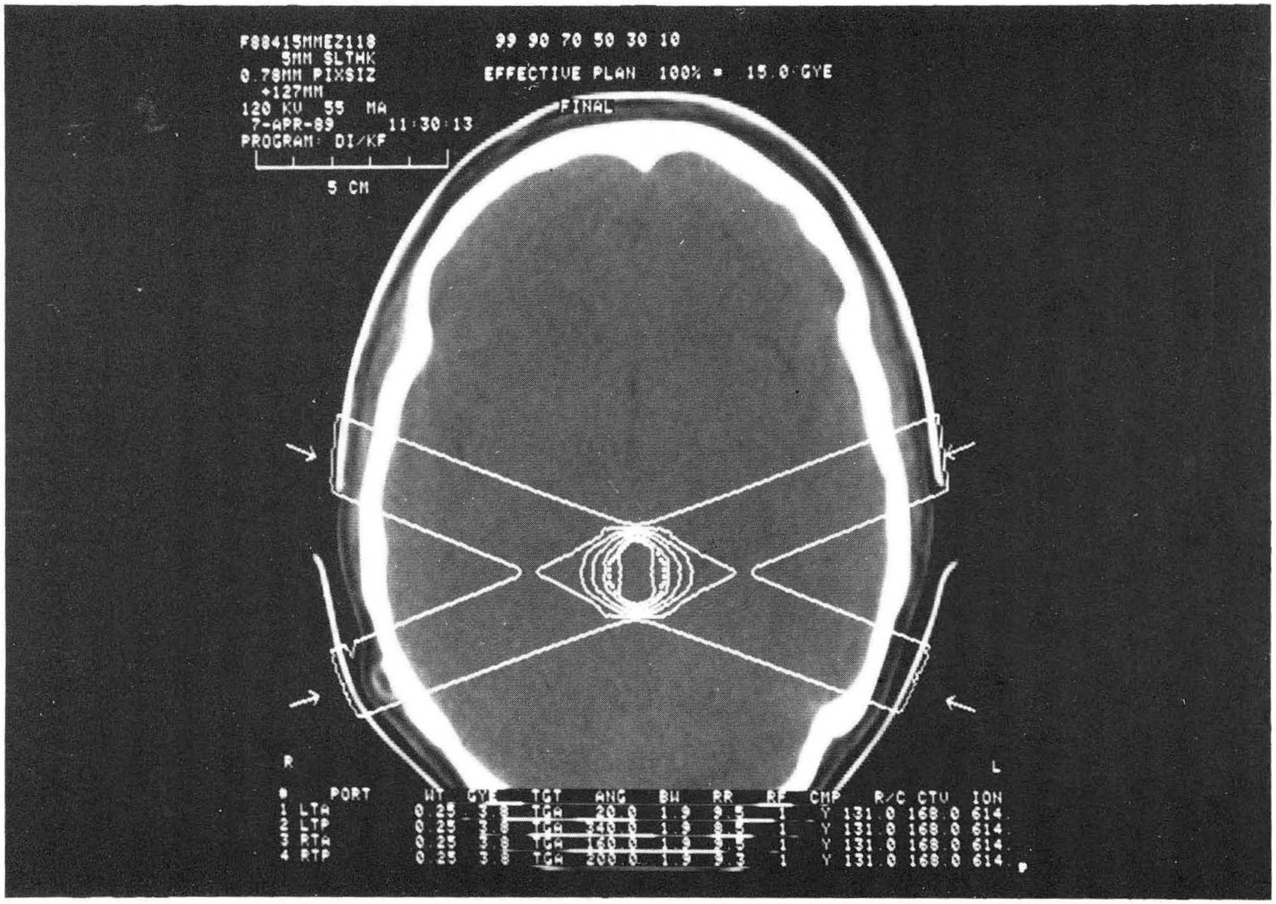

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Fig. 1

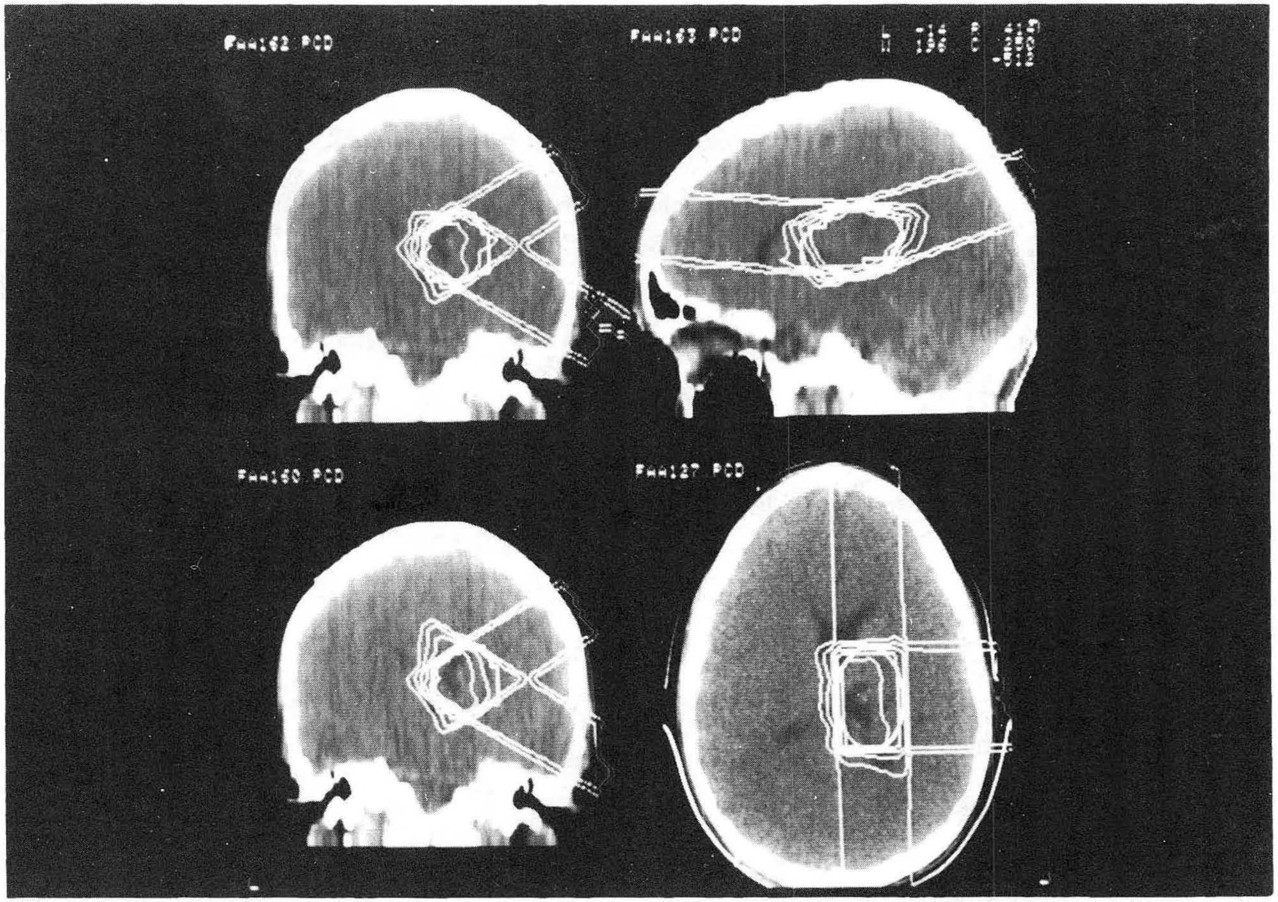

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Fig. 2

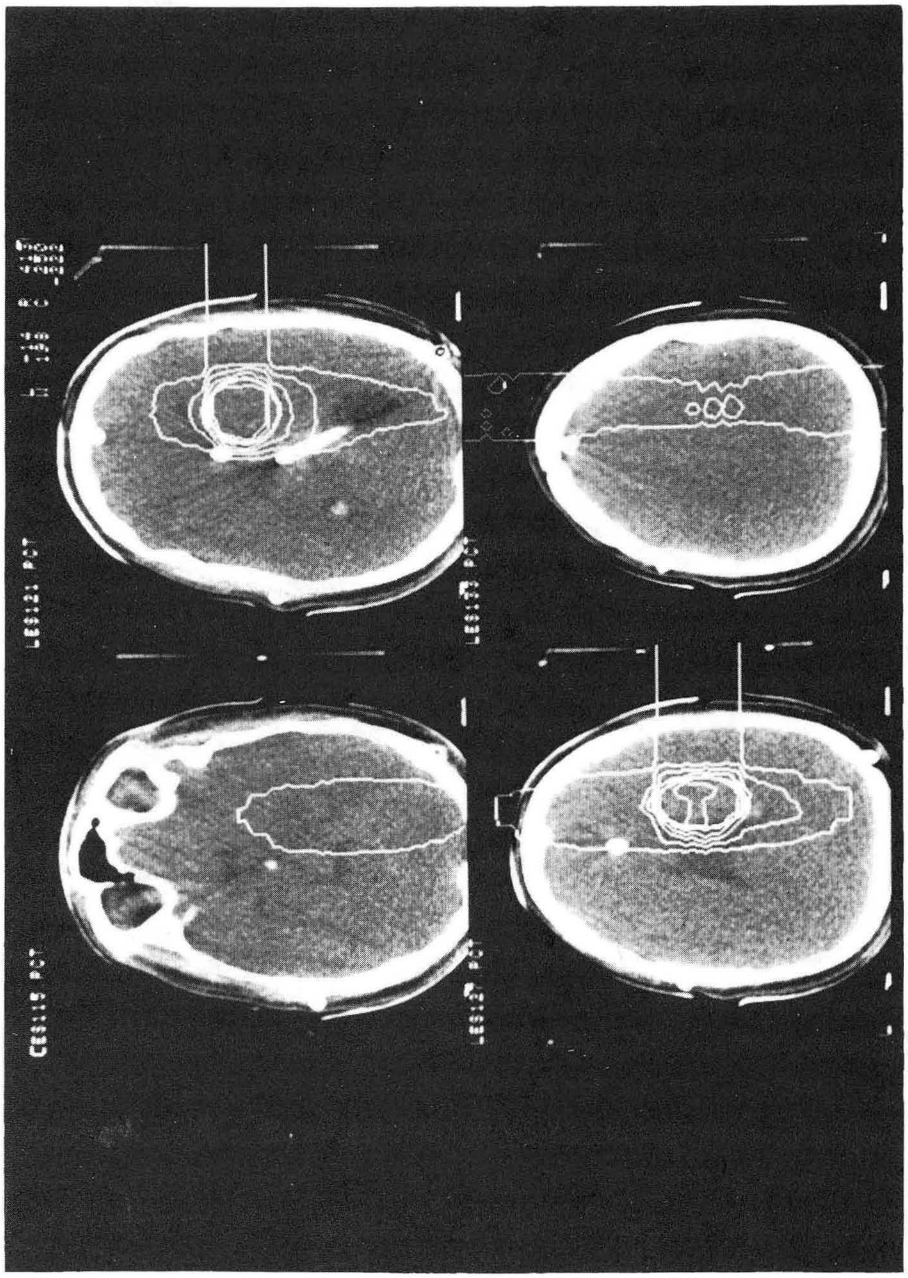

Fig. 3

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