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# DISCLAIMER

# A HELIUM-ION BEAM FOR STEREOTACTIC RADIOSURGERY OF CENTRAL NERVOUS SYSTEM DISORDERS

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## ABSTRACT

A new radiation beamline configuration for stereotactic heavy-ion Bragg peak radiosurgery of patients with intracranial deep arteriovenous malformations, including carotid-cavernous fistulas, has been developed using the 230 MeV/u helium-ion beam at the 184-inch Synchrocyclotron at the University of California, Berkeley. The modified beam has five characteristics: (1) uniform field between 10 and 40 mm in diameter; (2) variable depth of penetration between 40 and 140 mm; (3) stopping region for primary ions that can be broadened up to 40 mm; (4) sharply defined lateral and distal borders; and (5) dose-rate greater than 2 Gy/min. It is adapted to the ISAH (Irradiation Stereotactic Apparatus for Humans) at the Synchrocyclotron, with effective stereotactic localization of defined volumes within the brain, and is designed to reach all intracranial targets. It has proven suitable for all patients with intracranial vascular disorders treated with stereotactic radiosurgery at our laboratory.

## INTRODUCTION

The experimental treatment of intracranial vascular disorders, primarily inaccessible and inoperable deep arteriovenous malformations (AVM), including carotid-cavernous fistulas (CCF), using stereotactically-directed heavy charged particle or gamma beam focal irradiation in the brain is new, and holds significant promise for alleviating the risks of morbidity and of mortality in selected neurological patients (1-5). The intracranial deep AVMs have three important features. (_1_) They have a significant incidence of spontaneous intracranial hemorrhage that leads either to severe morbidity or to mortality. (_2_) Even in the absence of serious hemorrhage, nevertheless, due to progressive cerebral ischemia, patients develop progressive and irreversible neurological deficits, including motor and sensory dysfunctions, mental deterioration and blindness. (_3_) The abnormal intracerebral blood flow dynamics, mass effect, and brain ischemia frequently induce seizures, which are refractory to medication because of the chronic venous hypertension in the brain. The present report describes the development of a charged-particle helium-ion beam for stereotactically-directed Bragg peak irradiation of brain disorders in patients at the Donner Laboratory and, particularly, for application to treatment of deep AVMs.

The physical properties of heavy charged-particle beams offer some unique advantages in neuroscience research. The beams have Bragg ionization peaks with increased release of energy at the end of their range, minimal scattering, finite range and small range straggling (7). Investigations using proton, deuteron and helium-ion beams have shown that these beams can be used effectively in brain research in animals and in treatment of selected human brain disorders (5,8-11). The 184-inch Synchrocyclotron at the University of California, Berkeley, was first used for biological studies in 1948 (8) and for the treatment of patients in 1954 (9) using proton or deuteron beams. The helium-ion beam from the 184-inch Synchrocyclotron has been used since 1958 for stereotactic irradiation of the pituitary gland in patients with endocrine and metabolic disorders; here, the plateau portion of the Bragg curve has been utilized (12-14). In addition, other sites in selected neurological or cancer patients have been irradiated using the high-energy plateau portion (15) of the Bragg peak (12,16,17) of the helium-ion beam. In 1975, following modifications to produce a beam for large-field cancer radiotherapy (18), a heavy particle cancer radiotherapy program was initiated (17,19). For cancer therapy, in this configuration, field sizes as large as 30 cm circles are used with residual ranges as great as 26 cm. The capability for treating eye tumors (ocular melanomas) was later added to the readily available beam conditions (20). This radiotherapy setup is for beam diameters less than 2.5 cm and residual ranges less than 3 cm.

In 1980, we began investigations on stereotactic radiosurgery (1,4,21) in the central nervous system using the Bragg peak of the helium-ion beam at the

184-inch Synchrocyclotron, primarily for intracranial vascular disorders (22). The use of stereotactically-directed focal radiation beams for the treatment of inoperable intracranial deep arteriovenous malformations has been applied by Leksell and his colleagues (1,2) using multiple cobalt-60 gamma beams at the Karolinska Sjukhuset, by Kjellberg and colleagues (3) using the proton beam at the Harvard cyclotron, and by Barcia-Saloria (23) using a cobalt therapy unit at the University of Valencia, Spain (24). Recent work has shown the feasibility of using high energy X-ray machines (25,26).

To perform intracranial stereotactic radiosurgery with the Bragg peak, it was necessary to develop a small field beamline configuration at the 184-inch Synchrocyclotron, since the existing stereotactic irradiation facility used for pituitary irradiation of patients (27) was not optimized for use with the Bragg peak. The major requirements in developing a helium-ion beam for stereotactic radiosurgery were: (1) uniform field between 10 and 40 mm in diameter; (2) variable depth of penetration between 40 and 140 mm; (3) stopping region for the primary ions that could be broadened up to 40 mm; (4) sharply defined lateral and distal borders; and (5) dose-rate greater than 2 Gy/min.

## METHODS AND MATERIALS

The range in water of the 230-MeV/u helium-ion beam at the 184-inch Synchrocyclotron is 316 mm. This range is greater than that needed to reach any intracranial target; therefore, it is necessary to degrade the beam energy in order to obtain the required residual range. This must be done in a manner that minimizes the beam straggling, the multiple scattering and the loss of the primary ions due to nuclear interactions (28).

### Beam Edge Sharpness

To achieve a sharp lateral edge to the beam and, thus, to the treatment volume, the penumbra of the beam is kept as small as is practical, consistent with all other requirements, and the beam passing through the final collimator is kept essentially parallel. These conditions are met by placing all the beam degrading material about 3.8 m upstream of the final beam collimator (Fig. 1). The beam striking the degrader is approximately 30 mm by 40 mm (FWHM). Immediately after the degrading material, the beam is collimated by a 22 mm brass collimator. This geometry produces a geometric penumbra of 0.9 mm at a position 150 mm downstream of the final collimator. The angular spread of the beam collimated to a 30 mm diameter is less than 0.5 deg.

## Beam Energy Degradation

The beam energy must be reduced from 230 MeV/u to about 145 MeV/u for the maximum desired residual range (29,30). For a given energy loss, high atomic number (Z) materials scatter the beam more than lower Z materials (30). At the position selected for the degrading material, polyethylene alone does not result in sufficient multiple scattering to provide the uniformity of dose-distribution desired over the treatment field at the isocenter of the patient positioner. Due to space limitations, it is not practical to place the polyethylene absorber further upstream of the irradiation position. Therefore, some of the degrading of the beam energy is accomplished with copper. Using only a copper absorber scatters the beam more than is required for the appropriate beam diameter and reduces the dose-rate below the minimum acceptable level. Thus, a combination of materials was selected to provide sufficient scattering of the beam to obtain an acceptable uniform irradiation field while minimizing the loss of the useful beam. An additional consideration was to limit the amount of induced radioactivity with long half-lives. The induced activity in the polyethylene is carbon-11, with a 20.5 min half-life. Therefore, the beam is degraded by, first the polyethylene, then the copper absorbers before the initial collimation with a brass collimator.

The energy degradation is accomplished with a composite absorber consisting of 153 mm of polyethylene followed by 3.4 mm of copper. While this combination of degraders may not be the only way to achieve the desired goal, it was the only one we tested since we achieved a satisfactory result with this approach.

Not all treatment plans will need the maximum available range of the beam because of different depths of the target volume from different beam directions. The beam range can be shortened with an appropriate thickness of polyethylene added to the front of the fixed degrader to achieve the required residual range.

Adjustments in the depth of penetration in the phantom or patient are made with an additional thickness of polyethylene added to the front of the fixed degrader. The modulation of the stopping region of the beam is controlled by a rotating variable-thickness acrylic absorber (32) located upstream of the beam degraders. The beam current is monitored by two parallel-plate transmission-type ionization chambers (33) located upstream of the beam modulator and degrader, and by a third transmission ionization chamber located behind an intermediate collimator (7.0 cm dia). All three chambers (Fig 1. lower) monitor the central 1 cm of the beam. In addition, the first chamber monitors the distribution of the beam between the two sides. The second chamber monitors the dose on separate annular segments of the ionization chamber. These data on beam size are presented as the standard deviation of a fitted Gaussian distribution.

## Radiation Dose Measurement

The dose at the stereotactically-determined isocenter of the patient positioner, i.e., within the patient's brain, is obtained by calibration of the transmission chambers with a tissue-equivalent (TE) ionization chamber (Far West Technology, Goleta, CA), located at the isocenter of the patient positioner. Depth-dose curves are obtained by scanning the TE ionization chamber alonq the beam path in an acrylic box filled with water. Measurements are also made by scanning a diode (34,35) in the water-filled box. Beam profiles are obtained from diode scans across the beam axis and from densitometry of X-ray films exposed at different depths of penetration in a polyethylene phantom.

## RESULTS

Depth-dose measurements with the parallel plate ionization chamber indicated a maximum range to the Bragg peak of 145 mm in water; this included the wall thickness of the water column (Fig. 2). The dose beyond the Bragg peak decreased from 90 percent of the maximum to 10 percent within 6 mm. The peak-to-plateau ratio was 3.09.

The depth-dose distribution with the stopping region broadened by 21.6 mm is shown in Fig. 3. The beam profile was measured with a diode and with X-ray film at the midpoint of a 27 mm broadened stopping region (Fig. 4). The lateral edge of the beam is sharpest at all depths when the final collimator is placed in contact with the entrance surface of the polyethylene or water phantom (Table 1).

A dose-rate of 4.0 Gy/min is regularly and uniformly delivered in the modified Bragg peak, allowing treatment times of 1-3 min duration per portal for stereotactic radiosurgery in the brain.

## DISCUSSION

A new beamline configuration, intended primarily for stereotactic radiosurgery in the brain with the Bragg ionization peak of the 230-MeV/u helium-ion beam at the 184-inch Synchrocyclotron, has been developed. This modified beam has a 145 mm range in water to the Bragg peak with sharply delimited lateral and distal borders. The practical limits on beam diameter range from 6 mm to 40 mm. The unmodulated Bragg peak maximum dose is greater than 3 times the entrance dose, and the width of the peak at 80 percent of the maximum is 7.8 mm. The energy of the beam can be modulated by a rotating acrylic variable-thickness absorber to increase the width of the high-dose region to as much as 40 mm. The physical properties of this beam are similar to that of the proton beams that have been available for stereotactic radiosurgery at the Harvard Cyclotron Laboratory (32) and at the Gustaf Werner

Institute in Uppsala, Sweden (4,5). The maximum range of the helium-ion beam is greater than that of these proton beams; therefore, more energy degradation is necessary to obtain the same residual range. But since the nuclear charge and mass of helium is larger than the proton, the multiple scattering and the range straggling is comparable to the proton beams.

This helium-ion beam has proven suitable for fundamental and clinical neuroscience research to induce focal lesions in the central nervous system (22). It provides improved dose localization and dose-distribution for stereotactic radiosurgery of the neurological patients with intracranial deep arteriovenous malformations, including carotid-cavernous fistulas, thus far treated at the 184-inch Synchrocyclotron (37,38). Studies are in progress to develop beam characteristics of heavier ions, such as carbon, with small uniform transverse profile and modified Bragg peak for improved dose distribution at the Lawrence Berkeley Laboratory Bevalac, a high energy, heavy-ion accelerator (28,39-43). These heavier ion beams have physical characteristics with unique advantages for application to stereotactic radiosurgery of the central nervous system, such as a sharper Bragg peak and smaller beam dispersion (22,43).

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## FIGURE LEGENDS

Figure 1. The medical cave at the 184-inch Synchrocyclotron (upper) illustrating the helium-ion beam delivery line in relation to the stereotactically-determined isocenter of the patient positioner (ISAH: Irradiation Stereotactic Apparatus for Humans) (27) (lower) used for stereotactic radiosurgery of intracranial vascular disorders. (XBL 824-486A, XBL 8312-4763)

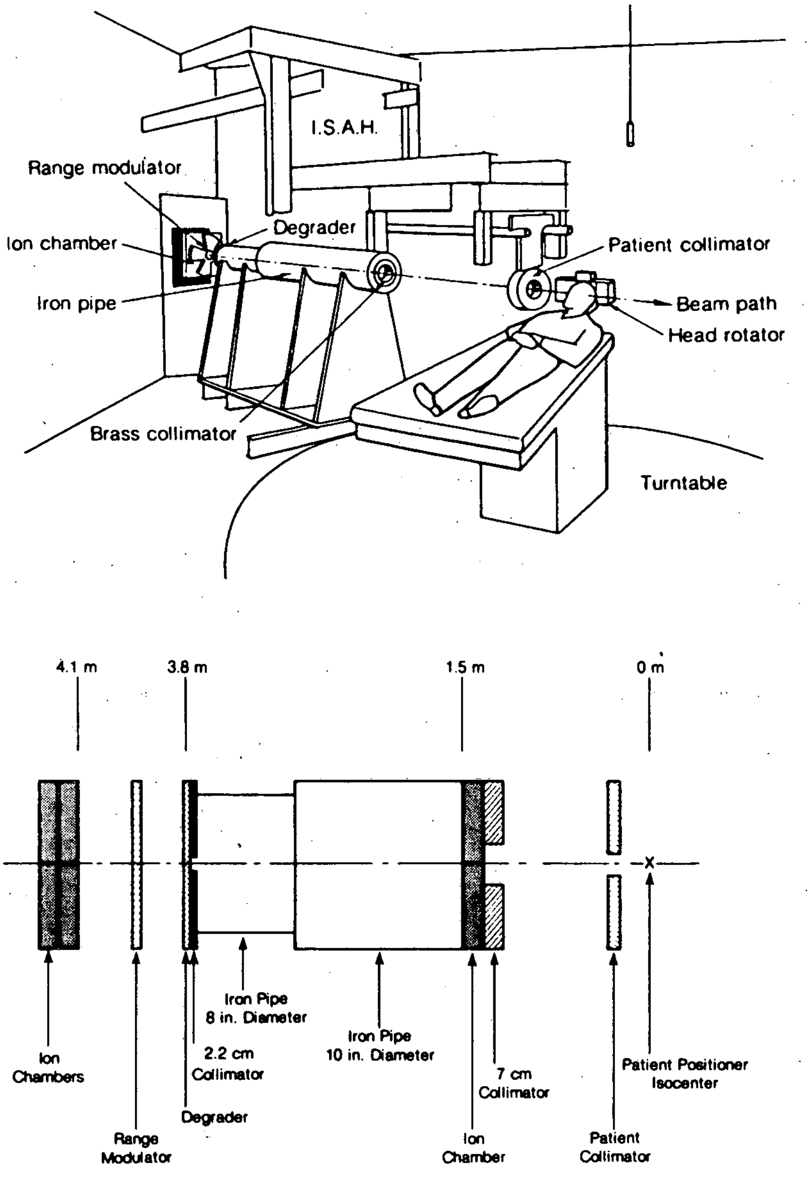
Figure 2. Depth-dose measurements of the 230-MeV/u helium-ion beam at the 184-inch Synchrocyclotron using the parallel plate ionization chamber. The maximum range to the Bragg peak is 145 mm in water. The oscillations in the histogram are a property of the measuring device, not statistical fluctuations. (XBL 8312-4762A)

Figure 3. The depth-dose distribution of the 230-MeV/u helium-ion beam with the stopping region broadened by 21.6 mm. (XBL 8212-7366)

Figure 4. The beam profile of the 230 MeV/u helium-ion beam at the midpoint of a 27 mm broadened region. The beam was collimated with a 12.7 mm aperture. (XBL 843-10207)

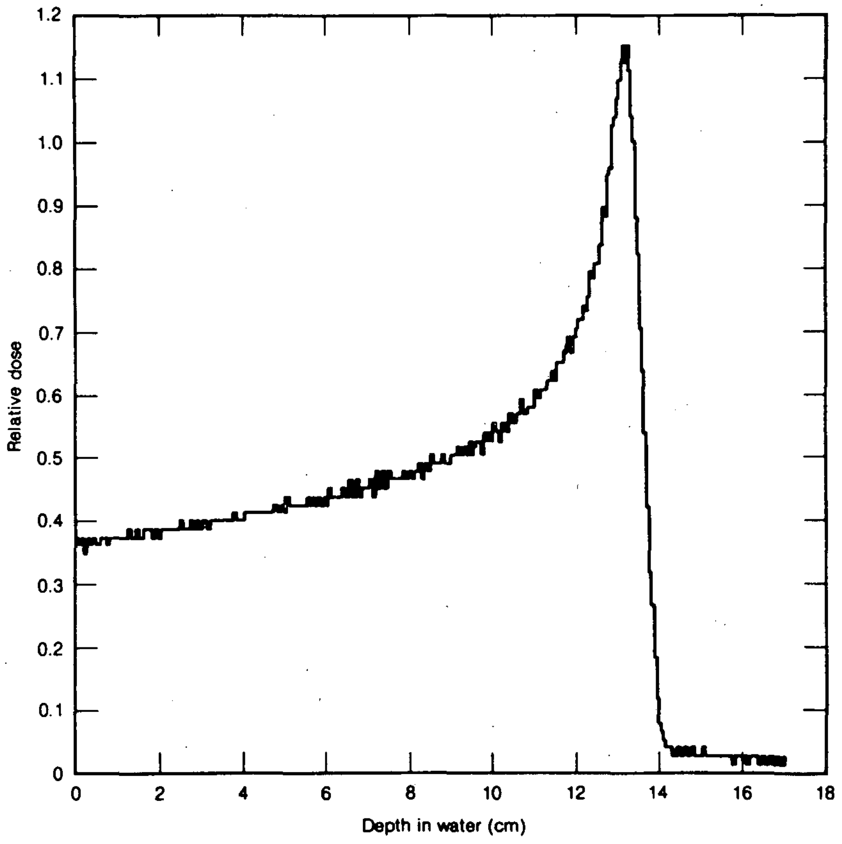
Table 1. Distance between 90 and 10 percent points on lateral profile for a beam with a 21.6 mm modulated stopping regions and scan at midpeak

| Residual Range, mm | Collimator-to-Phantom Distance, mm | |
|---|---|---|
| | 0 | 10 |
| 60 | 1.5 | 1.9 |
| 90 | 2.4 | 2.7 |
| 120 | 3.4 | 3.8 |



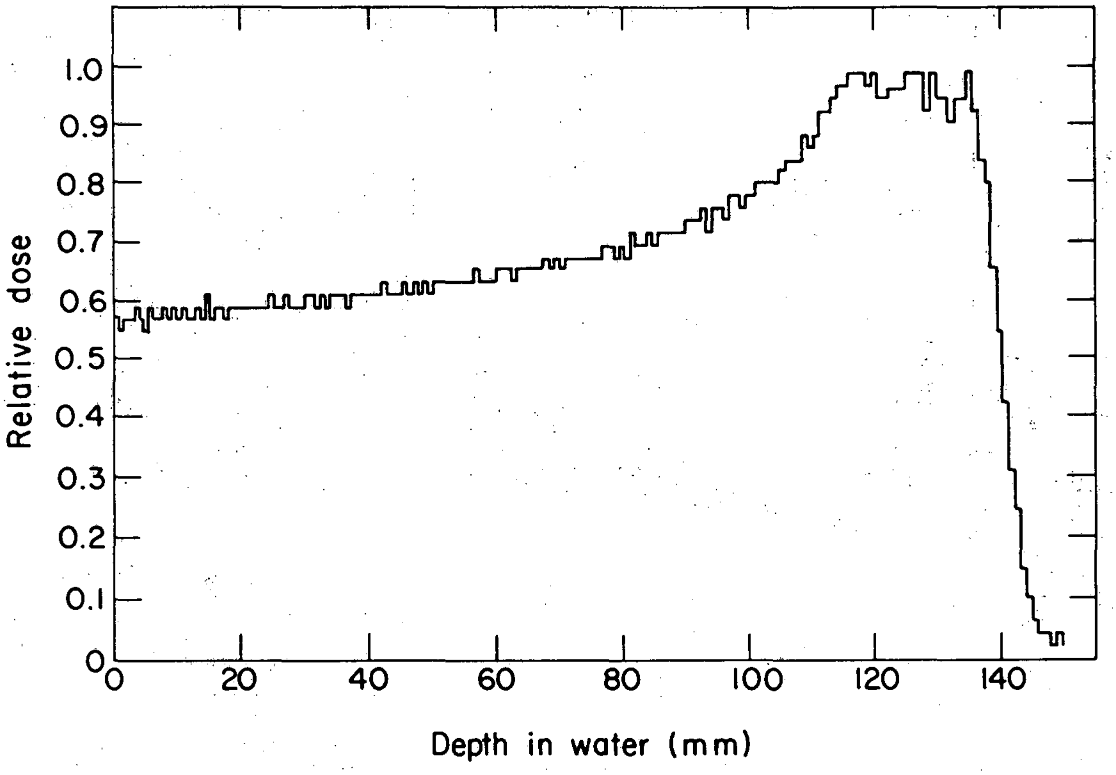
XBL 8312-4763A

Fig. 1



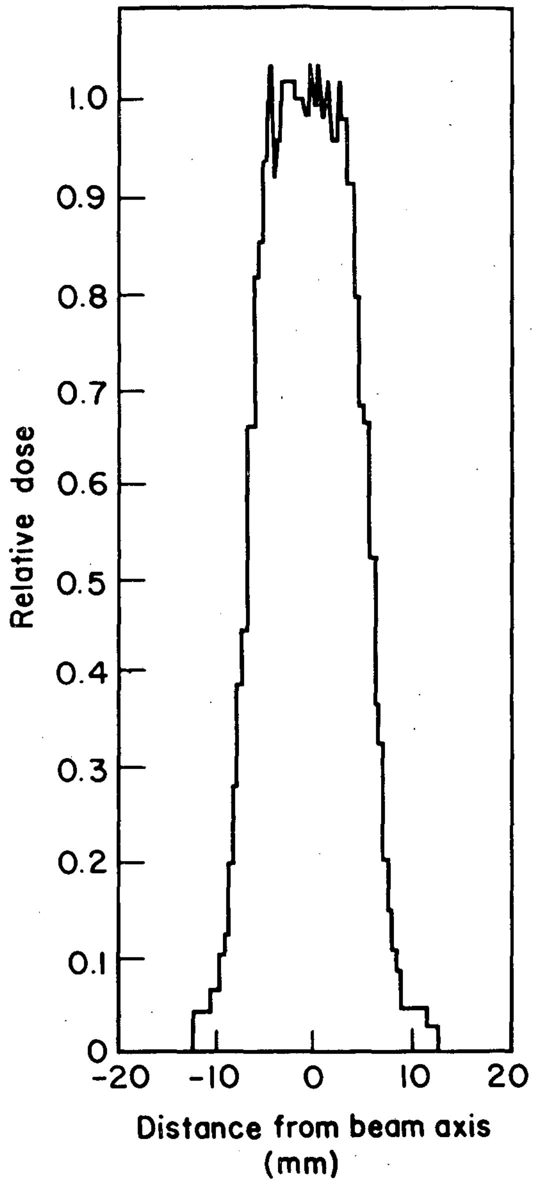
XBL 8312-4762A

Fig. 2



XBL8212-7366

Fig. 3



XBL 843-10207

Fig. 4

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