LBL-25666
Preprint

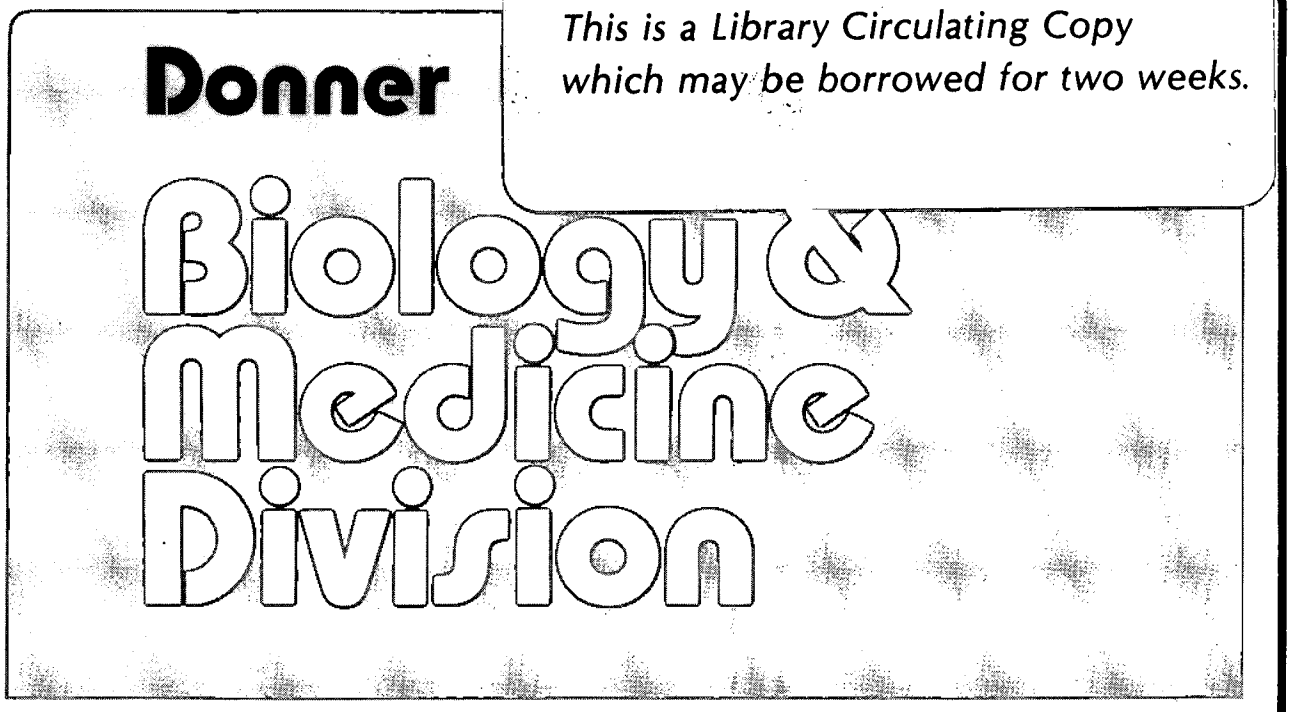
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to International Journal of Radiation Oncology, Biology, Physics

Stereotactic Frame for Neuroradiology and Charged Particle Bragg Peak Radiosurgery of Intracranial Disorders

J.T. Lyman, M.H. Phillips, K.A. Frankel, and J.I. Fabrikant

March 1988



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

STEREOTACTIC FRAME FOR NEURORADIOLOGY AND CHARGED PARTICLE BRAGG PEAK RADIOSURGERY OF INTRACRANIAL DISORDERS*

John T. Lyman, Ph.D.†
Mark H. Phillips, Ph.D.
Kenneth A. Frankel, Ph.D.
Jacob I. Fabrikant, M.D., Ph.D.‡

Donner Laboratory and Donner Pavilion
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Department of Radiology
University of California Medical Center
San Francisco, CA

March 15, 1988

*This research was supported by the Office of Health and Environmental Research, U.S. Department of Energy contract DE-AC03-76SF00098.

†Professor of Radiation Oncology, University of California, San Francisco
‡Professor of Radiology, University of California, San Francisco

ABSTRACT

The application of heavy charged particle Bragg peak radiosurgery for the treatment of intracranial vascular and other disorders requires a system of precise patient immobilization and stereotactic localization of defined intracranial targets. The process of using stereotactic neuroradiological procedures (including cerebral angiography, CT scanning and magnetic resonance imaging) for target definition and localization, and complex treatment planning constrain such a system to be adaptable and reusable. A stereotactic frame appropriate for neuroradiological and radiosurgical procedures has been developed as an integral component in the process. This paper describes the frame. It consists of four parts–a plastic mask for immobilizing the patient's head; a lucite-graphite mounting frame; a set of fiducial markers; and interfaces between the frame for immobilization and fixation to various diagnostic and therapeutic patient couches. The relationship between each component and the radiosurgical procedure is discussed. This system has proven to be safe, reliable, and noninvasive; it does not require fixation to the bones of the face or skull; and it is capable of reliably repositioning the patient to 1 mm in each of three planes and contouring the intracranial target reliably to this accuracy. The application of this stereotactic system in heavy charged particle radiosurgery of intracranial arteriovenous malformations is described in other reports.

Key Words: Radiotherapy, AVM, Stereotaxis, Charged particles

1 INTRODUCTION

At our clinical research laboratory at Lawrence Berkeley Laboratory, we have developed stereotactic radiosurgery utilizing the Bragg peak of the helium-ion beam at the 184-inch Synchrocyclotron and the Bevatron for the treatment of intracranial vascular disorders, including arteriovenous malformations [3] [4] [5]. Stereotactically-directed narrow beams of radiation have been used by several investigators for the treatment of inoperable deep arteriovenous malformations. Leksell and his colleagues (for review, see [14]) have used 179 convergent cobalt-60 gamma beams ("Gamma Knife") at the Karolinska Sjukhuset in Stockholm. Similar programs are beginning in Pittsburgh and in Leeds, England. Kjellberg and his colleagues (for review, see [7]) have used the proton beam at the Harvard cyclotron. In Valencia, Spain Barcia-Salario and colleagues [1] have used a collimated cobalt-60 radiotherapy rotational unit. Recently, several other groups in Heidelberg [15] and Essen, West Germany, and in Boston [10], have used the photons generated by clinical linear accelerators for the stereotactic treatment of intracranial vascular disorders.

Heavy charged particle beams offer a number of unique advantages for the delivery of dose to defined intracranial targets; the beams have sharp Bragg peaks, minimal scattering, finite well-defined ranges and small range straggling [18] [4] [12]. The heavy charged particle beams from the 184-inch Synchrocyclotron and the Bevatron at the Lawrence Berkeley Laboratory (LBL) have now been used to treat a number of brain disorders, including pituitary tumors and other neurometabolic disorders [16], to suppress pituitary function in metastatic breast cancer and diabetic retinal angiopathy [17] [8] [9], intracranial AVMs [3] [4] and uveal melanomas [13].

The safe, reliable, and reproducible placement of a sharply defined focal beam of charged particles with a definite range deep within the brain requires precise three-dimensional positioning information. In addition, accurate knowledge of the physical characteristics of the tissue along the beam path is essential in order to place the Bragg peak of the ion beam at the proper depth within the head. This information is obtained from several stereotactic neuroradiological procedures and is applied to the radiosurgical procedure, which requires an

accurate fixation system for correlating these data [2] [6].

We have developed a stereotactic fixation system to correlate the images and information obtained from multiple-vessel cerebral angiography, CT scanning, and magnetic resonance imaging (MRI), and to transfer this information to CT images for the calculation of optimal treatment plans for the delivery of the narrow radiation beams in the clinical situation. This stereotactic system does not rely on the fixation of studs in the bones of the face or skull, and is completely removable. A number of important considerations for reliable correlation have played roles in the development of this system, viz., (1) the patient must be repositioned for a series of neuroradiological and radiosurgical procedures over the course of several days; (2) the frame must be adapted to a number of different imaging procedures, including cerebral angiography, X-ray computed tomography, MRI, and the radiosurgical treatment procedure; and (3) information regarding the size, shape and position of the target volume must be correlated with the data detailing the physical characteristics of the tissue; (4) the system must be designed to be tolerated without discomfort by the patient for periods of up to 1.5 hr and must be easily released and removed in the case of patient distress. The importance of these considerations and the means by which they have been satisfied are discussed.

2 MATERIALS AND METHODS

All stereotactic neuroradiological and radiosurgical procedures are carried out with the patient's head comfortably immobilized in the stereotactic frame system. The stereotactic frame system is comprised of four components: the patient head mask, the frame that supports the mask, the fiducial markers that define the coordinate system, and the adapters to a variety of patient positioning couches and equipment for the neurodiagnostic and radiosurgical procedures.

Patient Head-Mask: The original masks were made of polystyrene vacuum-formed on plaster of paris casts of each individual patient's head; these were very satisfactory, labor-intensive, and required at least two days for complete fabrication. With recent development of thermoplastic materials which are malleable at temperatures in the range of $60 - 70°$ C and which become

rigid when cooled to room temperature, we have found advantages of these materials for use in application to the complex sequence of neuroradiological and radiosurgical procedures. We find that masks made of such thermoplastic more accurately reproduce small but important bony and other contour characteristics of the patient's head, are more comfortable to the patient, and require less time and and are less complex to fabricate. The resulting mask is only slightly less rigid than the polystyrene type, but with proper preparation of the patient this feature has not proven to be an undesirable feature.

The procedure of fabrication is discussed with the patient prior to beginning the process. The patient is required to have a very short haircut (less than 1 inch) in order to minimize repositioning errors. The mask is constructed in two halves, divided coronally. With the patient lying supine, a sheet of thermoplastic[1] is heated to $60-70°$ C in a water bath and draped over the face. A pre-cut hole allows for breathing through the mouth. The warm plastic is carefully molded around the patient's head and face, with particular attention paid to prominent bony structures such as the mandible, zygomatic arches, frontal ridges, and the nose. The plastic hardens in 2-3 min and is removed. Holes are cut for the eyes and nostrils. The patient then sits in a chair and leans forward, with the face prone into the front of the mask. The procedure is then repeated for the back of the head, with the mask extending from the crown of the head to the upper cervical region, again with attention paid to molding prominent structures, such as the mastoid processes, and the occipital protuberance.

The mask is removed, and a few simple procedures are then required to mount the mask in the frame. Figure 1 illustrates a completed mask, mounted in the stereotactic frame.

Stereotactic Frame: The stereotactic frame is the central component of the stereotactic positioning system (Figure 1). It holds the mask that immobilizes the patient's head in a fixed position relative to a well-defined coordinate system. The entire frame is constructed of lucite with graphite supporting rods. The lucite is lightweight, easily machined, and relatively similar to tissue composition in its radiographic characteristics so that imaging artifacts are minimized.

[1]Thermoplast, Rolyn Corp, Menomonee Falls, WI

The graphite rods are used in two places where additional structural strength is necessary. The graphite is also lightweight and contributes no radiographic or MR imaging artifacts. The stereotactic frame has been designed so that it will fit into a 30 cm bore, and the fiducial markers and head are imaged in a 25 cm circular reconstruction field. This is important so that CT and MRI scanning parameters can be used which provide the maximum resolution.

The top cross-member of the frame, lucite, is positioned at the top of the patient's head. The two graphite rods, anchored in the top of the frame near the back of the head, extend axially along the patients head, and support a small lucite yoke that extends around the dorsal half of the neck. The mask is fitted into the frame by means of holes which fit over three positioning pins placed in the top cross-member and yoke of the frame. Three screw and nut assemblies, anchored to the frame at the sides and top of the head, clamp the two halves of the mask together and securely hold the entire mask in the frame. In addition to the two graphite rods, two thin (0.25 inch thick) lucite sideplates extend between the top cross-member and yoke. These plates are directly on either side of the patient's head, and the dimensions are approximately the length and height of a head (20 x 13 cm). Finally, a lucite arch joins the two sideplates, passing over the forehead of the patient.

The top cross-member, yoke and graphite support rods provide the structural strength to support the patient's head in the mask, in a fixed position relative to the neuroradiological imaging equipment or the treatment beam line. The top and yoke components lie superior and inferior, respectively, to the cranium, and hence pose no obstacle to the precise delivery of the radiation within the head. The top cross-member does preclude treatment ports directed along the cranial-caudal axis of the body. However, as the stereotactic alignment procedure is derived from orthogonal lateral and AP cerebral angiograms, axial ports are very rarely necessary. Practically, then, these stabilizing frame elements pose little or no problem, and only occasionally, when the target volume is either located extremely superior or inferior, must special modifications be made.

The graphite rods run the length of the head, and they are positioned posterior to the occiput well beyond the extent of the head on either side. Therefore, any straight lateral or AP beam ports are not obstructed. Other ports are de-

livered at some angle from these direct ports, but are generally limited to $\pm 30°$ from the lateral or AP directions. As the mask is fit over the skin and hair of the head and relies on friction for immobilization, it is found that some slippage can occur for large rotations around the localization position. Thus, the limitation on port angles. One result of this is that only rarely are the graphite support rods blocking a desired beam port.

The frame sideplates and arch hold the fiducial markers. The fiducial markers defining the coordinates in the AP direction are located on the graphite rods and on the arch. The sideplates and arch are removed during the radiosurgical procedure after beam localization is completed and before the beam is delivered, and so provide no obstacle.

Coordinate System: The coordinate system is defined by fiducial markers, located on the frame, that are distinctly imaged on all neuroradiological procedures. For X-rays, e.g. cerebral angiography, CT, and positioning radiographs, radio-opaque markers are required; for MRI, markers with unique and imageable relaxation times are necessary. The radio-opaque markers are made of 26-gauge (0.016 inches) copper wire; these are clearly visible on radiographs and CT images, without producing artifacts. For MRI, the fiducial markers are 2 mm diameter plastic beads filled with olive oil. These can be made small enough so that there is no loss of accuracy, and they provide sufficient contrast to be easily seen. The type of appropriate fiducial marker can easily be mounted depending on the imaging procedure, since the sideplates and arch are detachable.

The fiducial markers mounted on each sideplate are arranged in two lines at right angles to one another. This cross is oriented at 45° relative to the superior-inferior axis of the head, and the center of the cross is located near the position of the sella. The wires are placed in thin grooves machined in the sideplates. These grooves are visible in Figure 1. Figure 2, orthogonal lateral and AP views of a cerebral angiogram, shows the fiducial markers as they appear in a radiographic image. The coordinate system used has its origin at the bisector of the line joining the origins of the crosses positioned on either side of the head. The magnification of the images are obtained by comparing the positions of the endpoints of the fiducial wires with the known separations

of the wires. The coordinates of the center of the target volume are determined from measurements relating the target volume image and the images of the fiducial markers. (To be described in a forthcoming report.)

Interfacing Adapters: Each particular imaging procedure requires a separate interfacing adapter by which to attach the stereotactic frame to the patient couch. A separate aluminum interface is required for the ISAH (Irradiation Stereotactic Apparatus for Humans, [11] in the experimental cave where the radiosurgical procedure is carried out. The frame is designed to be extremely adaptable and currently can be mounted on at least six different systems of imaging and treatment equipment (including cerebral angiographic, CT, MRI, and cyclotron equipment) using appropriately designed interfaces. The interfaces attach to the top cross-member, the yoke, or both, depending on the equipment. For some CT scanners, an interface has been constructed that attaches to the yoke of the stereotactic frame, mounts on the CT table much as the conventional head holder, and cantilevers the frame beyond the couch for CT scanning, e.g. with the GE 8800 and GE 9800 units. The patient couch in the cerebral angiography suites tend to have small, narrow platforms for the head, and bar clamps are attached to the top cross-member and yoke of the stereotactic frame which are then slipped over the head holder portion of the angiography couch and clamped. At the treatment facility, the interface between the frame and ISAH mounts onto the top cross-member of the frame, directly superior to the head. This interface is then positioned by pins and clamped in place.

It is essential that the interfaces hold the frame securely, do not obstruct imaging or beam delivery, and position the frame in the same orientation on each unit of equipment. The first requirement is readily achieved. The second requirment is easily met if the interfaces attach to the top cross-member of the frame and/or yoke, which were designed to eliminate as many obstructions as possible. The interfaces have been designed with the third requirement in mind as each new system of equipment has been used.

3 RESULTS AND DISCUSSION

The overall clinical research program in our laboratory of stereotactic heavy charged particle Bragg peak radiosurgery for intracranial vascular disorders involves extensive stereotactic neuroradiological imaging, multistage radiosurgical procedures, and follow-up neurodiagnostic studies to assess the radiation response of brain tissue and cerebral blood flow conditions with time over long intervals following therapy. Accordingly, we have not found it possible to use a method of head immobilization of bone studs or screws which must be secured into the skull or facial bones. We have therefore developed a system which incorporates an individualized thermoplastic head mask and stereotactic frame. The system permits accurate and reproducible positioning of the head of the patient for the different neuroradiological procedures required for treatment planning prior to radiosurgical treatment and for multifraction stereotactic heavy charged particle radiosurgical procedure at the 184-inch Synchrocyclotron and the Bevatron.

The goal is to immobilize the head in a reproducible manner within the stereotactic frame. The reproducibility of the positioning of the head for each of these procedures depends on the closeness of the fit of the mask, the uniqueness of each patient's cranial and facial features, and the cooperation of the patient. The closeness of the fit is affected by the amount of soft tissue on the face and head, the amount of hair, and the presence of edema or fluid following a neurosurgical procedure. The second and third factors can be controlled. The amount of soft tissue and the uniqueness of cranial features are related and greatly affect the reproducibility of positioning. Prominent facial characteristics such as strong cheekbones or frontal processes are always helpful for immobilization, as is an absence of excessive soft tissue around the head. Rotations left and right around the cranial-caudal axis are not frequently a problem, but we have found that rotations of the head around the left-right axis are more likely. Special attention must be given to keeping the jaw closed during the mask fabrication and making sure that the mask adequately covers the lower jaw. Careful attention to visual landmarks, e.g. nose, chin, and frontal processes, and to the comments of the patient regarding the comfort of the fit aid in the proper

positioning of the patient in the mask from procedure to procedure.

Stereotactic information obtained from the cerebral angiograms, CT scans, and MRI scans must be correlated to obtain the exact size, shape and position of the intracranial lesion. To position the AVM at the isocenter of the radiosurgery patient positioner, ISAH, the stereotactic information obtained from the neuroradiological studies is correlated with localization radiographs taken in the treatment facility at the time of radiosurgery. The target volume for radiosurgical cerebral irradiation is determined from selected orthogonal pairs of radiographs from the cerebral angiographic procedure. From these films, the appearance of the fiducial markers provides the geometric factors used for the radiographic exposures, and measurements of the imaged AVM relative to the fiducial markers provides the coordinates of the intracranial target and its exact dimensions. Figure 2, lateral and AP angiographic films, illustrate the appearance of the fiducial markers. Correlation of the fiducial markers imaged by cerebral angiography and CT permits the transfer of the target volume and location to the CT scans. Similarly, correlation between MRI and CT fiducial markers allows one to transfer information from one set of procedures to the other[2]. Once the AVM is located within the three-dimensional volume of CT data, treatment planning parameters are calculated, and the coordinates of ISAH necessary to put the center of the lesion at the isocenter of ISAH are obtained. The CT data provide the information necessary to construct a set of beam ports that will yield the desired dose distribution at the site of the vascular lesion. Final positioning of the patient on ISAH for stereotactic radiosurgery is accomplished by comparing localizing radiographs taken on ISAH to computer-generated overlays of digitized angiographic radiographs, and correlated with MRI scans where necessary (e.g. cryptic AVMs). With this system, we find that we are able to reposition the head in the mask in repeated sessions to approximately 1 mm in each of three orthogonal directions. Misalignments, either in translation or rotation, are then corrected to 0.5 mm or less with the use of localizing radiographs. Once the target center is located at isocenter, the beam is delivered through a number of ports by rotating the patient to a predetermined fixed position. These rotations are accurate to a tenth of a

[2]Phillips MH, et al, in preparation

degree.

The patient may experience discomfort when immobilized in the mask for a prolonged period, usually approximately one hour, and this may result in patient movement. CT and MRI scans usually present no problem. The cerebral angiography procedure is often more protracted, so the mask is not fastened onto the patient until the catheterization is complete, and the injection-filming sequence is about to begin. The radiosurgical procedure typically takes 30 to 60 minutes. A simulation of the actual treatment is carried out beforehand in order to anticipate any patient problems; this tends to shorten the time necessary for the actual treatment.

4 SUMMARY AND CONCLUSIONS

The stereotactic immobilizing mask and frame designed for stereotactic heavy charged particle radiosurgery of intracranial arteriovenous malformations at the 184-inch Synchrocyclotron and the Bevatron at Lawrence Berkeley Laboratory is described. Stereotactic neuroradiological procedures– cerebral angiography, computerized X-ray tomography, and magnetic resonance imaging–are performed with the patient fixed the mask-frame unit. The stereotactic information obtained from these neuroradiological procedures is used to calculate the size, shape and location of the AVM. Using these calculated physical values, beam apertures are designed and fabricated, port angles and ranges for the delivery of the charged particle radiation are calculated, and the coordinates of the patient positioning couch at the radiosurgical procedure are calculated.

The radiosurgical procedure is carried out at the 184-inch Synchrocyclotron and the Bevatron with the patient immobilized in the stereotactic mask-frame unit. This unit, coupled with the very accurate and reproducible patient positioner (ISAH), results in the delivery of the charged particle beam radiation to the intracranial arteriovenous malformation with an accuracy of 1 mm.

References

[1] Barcia-Salorio JL, Hernandez G, Broseta J, et al: Radiosurgical treatment of a carotid-cavernous fistula. Case Report. In *Stereotactic Cerebral Irradiation*, Szikla G (Ed). INSERM Symposium No. 12, Elsevier/North-Holland Press, 1979, pp. 251-256.

[2] Bergström M, Greitz T, Steiner L: An approach to stereotaxic radiography. *Acta Neurochir* **54**: 157-165, 1980.

[3] Fabrikant JI, Lyman JT, Hosobuchi Y: Stereotactic heavy-ion Bragg peak radiosurgery: Method for treatment of deep arteriovenous malformations. *Br J Radiol* **57**:479-490, 1984

[4] Fabrikant JI, Lyman JT, Frankel KA: Heavy charged-particle Bragg peak radiosurgery for intracranial vascular disorders. *Radiat Res* **104**: S244-S258, 1985

[5] Fabrikant JI, Frankel KA, Phillips MH, Levy RP: Stereotactic heavy charged-particle Bragg peak radiosurgery for intracranial arteriovenous malformations. In *Cerebral Vascular Diseases of Childhood and Adolescence*, Edwards MSB, Hoffman HJ (Eds), 1987, pp 23.1-23.40.

[6] Greitz T, Bergström M, Boëtheius J, et al: Head fixation system for integration of radiodiagnostic and therapeutic procedures. *Neuroradiology* **19**: 1-6, 1980.

[7] Kjellberg RN, Hanamura T, Davis KR, et al: Bragg peak proton-beam therapy for arteriovenous malformations of the brain. *N Engl J Med* **309**: 269-274, 1983

[8] Lawrence JH, Tobias CA, Born JL, et al: Heavy particle irradiation in neoplastic and neurological disease. *J Neurosurg* **19**: pp. 717-722, 1962

[9] Lawrence JH: Heavy particle irradiation of intracranial lesions. In *Neurosurgery*, Wilkins RH and Rengcharry SS (Eds), Philadelphia, McGraw-Hill, 1984.

[10] Lutz W, Winston KR, Maleki N: A system for stereotactic radiosurgery with a linear accelerator. *Med Phys* **13**: 611, 1986.

[11] Lyman JT, Chong CY: ISAH: A versatile treatment positioner for external radiation therapy. *Cancer* **34**: 12-16, 1974

[12] Lyman JT, Kanstein L, Yeater F, Fabrikant JI, Frankel KA: A helium-ion beam for stereotactic radiosurgery of central nervous system disorders. *Med Phys* **13**: 695-699, 1986

[13] Saunders WM, Char DH, Quivey JM, et al: Precision high dose radiotherapy: Helium ion treatment of Uveal Melanoma. *Int J Rad Onc Biol Phys* **11**: 227-233, 1985.

[14] Steiner L: Treatment of arteriovenous malformations by radiosurgery. In *Intracranial Arteriovenous Malformations*, Wilson CB and Stein BM (Eds),

Baltimore, Williams and Wilkins, 1984, pp 295-313.

[15] Sturm V, Kober B, Höver KH, et al: Stereotactic percutaneous single dose irradiation of brain metastases with a linear accelerator. *Int J Rad Onc Biol Phys* **13**: 279-282, 1987.

[16] Tobias CA, Anger HO, Lawrence JH: Radiologic use of high energy deuterons and alpha particles. *American Journal of Roentgenology, Radium Therapy and Nuclear Medicine*, **67**: 1-27, 1952.

[17] Tobias CA, Lawrence JH, Born JL, et al: Pituitary irradiation with high energy proton beams: A preliminary report. *Cancer Res* **18**:121-134, 1958

[18] Tobias CA: Future of heavy ion science in biology and medicine (Failla Memorial Lecture). *Radiat Res* **103**: 1-33, 1985.

FIGURE CAPTIONS

Figure 1: Stereotactic frame and patient mask system. The mask is formed of thermoplastic and molded individually to each patient's head. The letters (A-F) denote components of the frame, described more fully in the text. (A) Top cross member, (B) Yoke, (C) Graphite support bar– an identical bar is also present on the other side of the frame. A fiducial marker is present on each bar. (D) Sideplates with fiducial markers–the clear lucite sideplates have two grooves machined at right angles. Markers are fine copper wires glued into the grooves, and are imaged on lateral radiographs. (E) Arch with fiducial markers–arch supports two copper wire markers that are imaged on AP radiographs. (F) Positioning pins–mask is reliably positioned by means of holes that fit onto the three pins.

Figure 2: Lateral and AP views of cerebral angiogram of patient with an intracranial arteriovenous malformation. The angiogram was performed with the patient in an individually molded mask which is held in place in the stereotactic frame. The arrows point to the fiducial markers (copper wire). Analysis of the location and separation of each of the fiducial markers yields the position, size and angle of the AVM and other structures in the head. The white stripes visible on the lateral view are the flanges of the mask viewed edge on, and can be removed by trimming the mask if they obscure important structures. Other frame structures, e.g. positioning pins, screws, etc., are also seen.

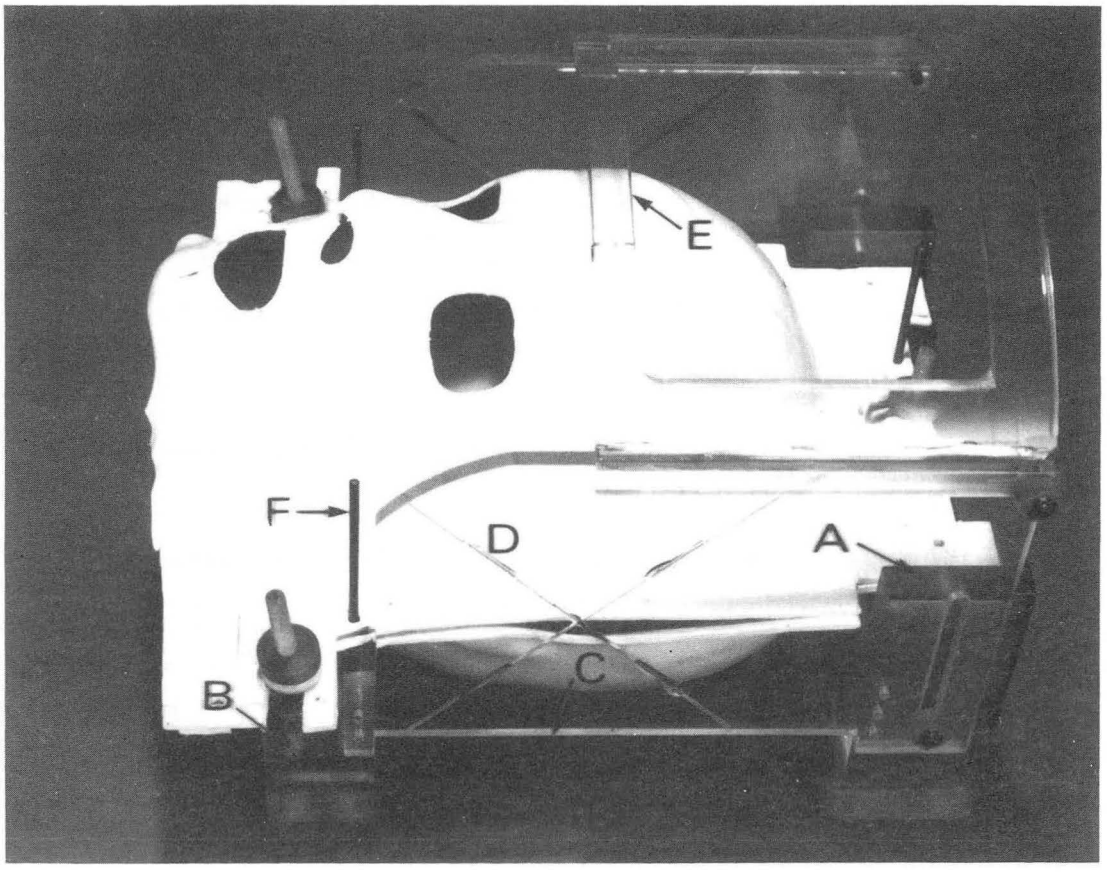


Fig. 1 CBB 877-5479A

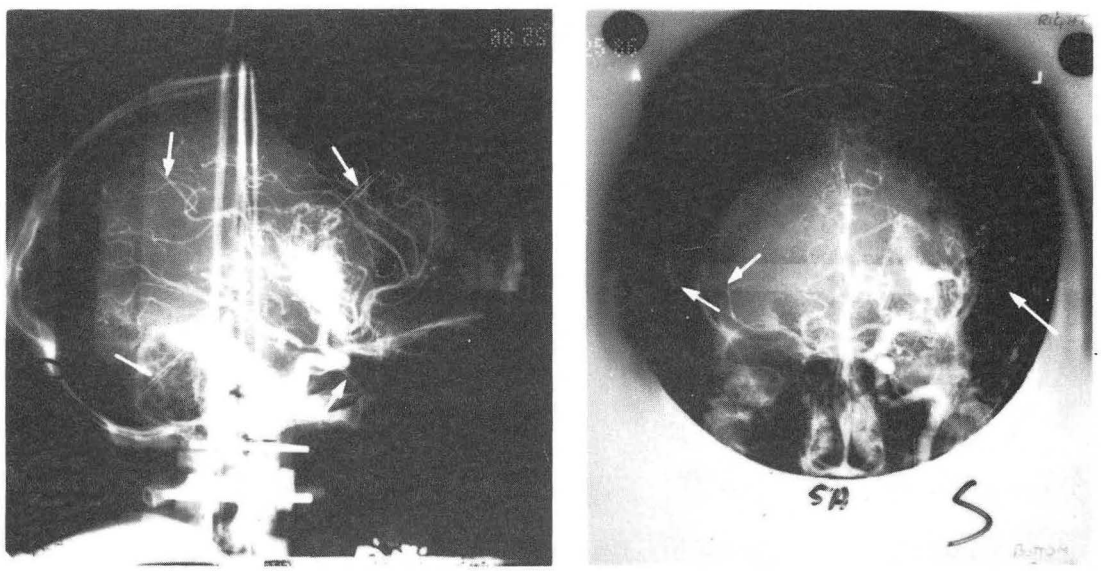


Fig 2. XBB 877-5438A

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720