No Access Surgery: The Gamma Knife

L. DADE LUNSFORD, M.D., FRCS, PROFESSOR & VICE CHAIRMAN, DEPT. OF NEUROSURGERY, PROFESSOR OF RADIOLOGY, PROFESSOR OF RADIATION ONCOLOGY
DOUGLAS KONDZIOLKA, M.D., FRCS(C), ASSISTANT PROFESSOR OF NEUROSURGERY & RADIATION ONCOLOGY
JOHN C. FLICKINGER, M.D., ASSOCIATE PROFESSOR OF NEUROSURGERY
DEPARTMENTS OF NEUROLOGICAL SURGERY, RADIOLOGY, AND RADIATION ONCOLOGY
UNIVERSITY OF PITTSBURGH SCHOOL OF MEDICINE
AND THE SPECIALIZED NEUROSURGICAL CENTER
UNIVERSITY OF PITTSBURGH MEDICAL CENTER
PITTSBURGH, PA

Swedish neurosurgeon Lars Leksell, frustrated by the invasiveness of existing surgical tools and the morbidity some neurosurgical patients endured, created the field of stereotactic radiosurgery in 1951.[1,2] He subsequently pioneered the development of the dedicated multi-source Cobalt 60 Gamma Knife®. During the 27 year interval from its first clinical use in 1967 to its latest application in 1994, single fraction, closed skull irradiation of deep intracranial targets has been performed in more than 20,000 patients worldwide. The goals of radiosurgery are obliteration or prevention of further growth of the target coupled with reduced patient risk in comparison to more invasive procedures.

CURRENT TECHNOLOGY AND APPLICATIONS

Across the world by mid-1994, 63 sites worldwide were using or installing the Gamma knife® to treat benign and malignant brain tumors, cerebral vascular malformations, or manage functional disorders (Table 1). Individual photon beams generated by up to 201 Cobalt-60 sources are arrayed around the patient's head in a hemisphere (U style unit) or an O ring (B style unit) (Figure 1). The beams converge on a target volume within the brain. The target is defined by various modern neurodiagnostic imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), angiography, and positron emission tomography (PET). In contrast to surgical tools that

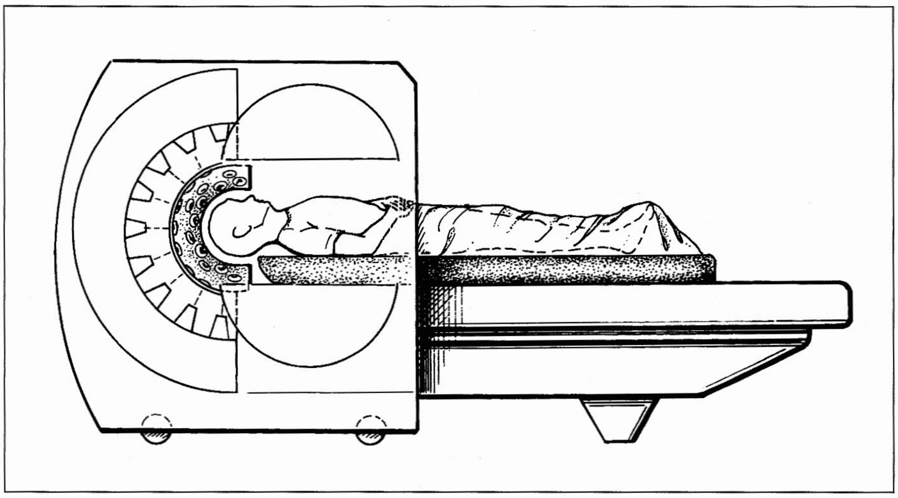

Figure 1: Side view of the Gamma knife model B. The O-ring array of 201 Cobalt 60 sources crossfires photon beams to the target.

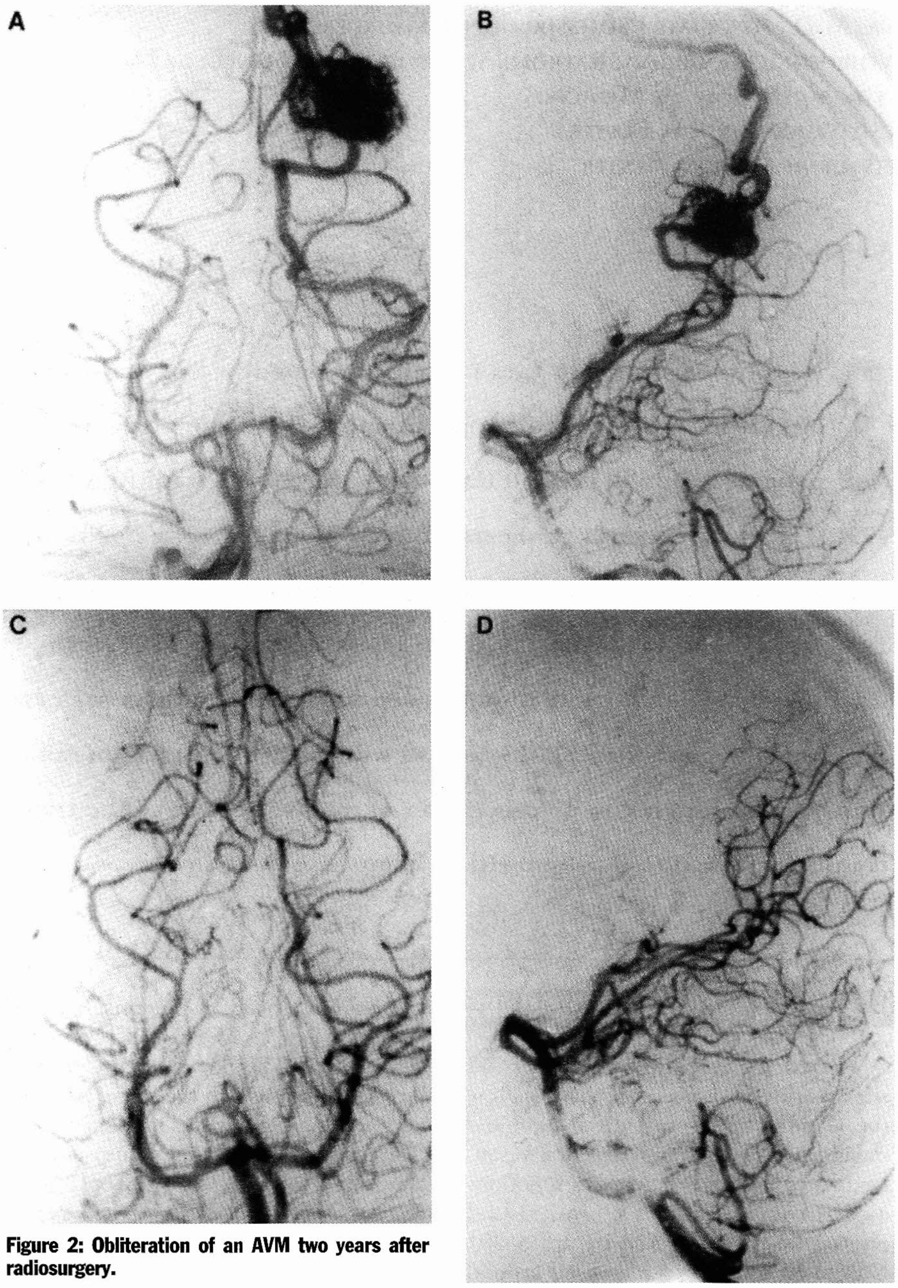

Figure 2: Obliteration of an AVM two years after radiosurgery.

require opening the skull in order to focus the destructive energy (e.g. mechanical, focused ultrasound or lasers), photon irradiation can be collimated precisely and focused predictably through the intact scalp, skull and brain. Stereotactic radiosurgery is a procedure of no access, and minimal invasion.

The target is defined after application of a stereotactic guiding device with millimetric precision. One or more neurodiagnostic imaging studies then are performed to provide comprehensive volumetric information on both the configuration of the often irregular intracranial target as well as the surrounding brain. Normal intracranial targets have been selected when the goal is selective obliteration or destruction of a target such as trigeminal nerve fibers for tic douloureux or the thalamus for Parkinson's disease. Currently, the digitally acquired imaging target information is transferred by fiberoptic ethernet systems and down-loaded into rapid high speed computer workstations. Most targets are defined in three dimensional space by high resolution MRI. The dose planning computer rapidly integrates the various isocenters of irradiation. These isocenters of variable diameters are superimposed, weighted, selectively blocked and shaped in order to confine the most critical dose of radiation within the target volume and to spare the surrounding brain. The best possible targets are those that are relatively small since high doses can often be given with little risk to the surrounding brain. Targets within critical locations of brain function are often selected, since such lesions are

Worldwide Gamma Knife Sites
(April, 1994)

Site	Number
North America	
United States	22
Mexico	1
Europe	13
Asia	26
South America	1
Total	**63***

*47 were operational, 16 were not yet installed.

Table 1.

often high risk for more invasive surgery.

PATIENT SPECTRUM

Worldwide, approximately 45% of patients selected for gamma knife radiosurgery have arteriovenous malformations (AVMs).[3] Benign tumors, including acoustic neuromas,[4-7] meningiomas,[8] and pituitary tumors,[9] represented the next largest category of patients, approximately 40%. The application of radiosurgery as part of an overall treatment plan for malignant tumors such as brain metastases and primary glial neoplasms has begun at a wide number of centers.[10,11] The initial results are optimistic, especially when the initial tumor volume is relatively small, and radiosurgery is used in conjunction with additional other potent modalities such as fractionated radiation therapy, chemotherapeutic regimens, and aggressive attempts to control systemic disease in the case of metastatic cancer. Gamma knife radiosurgery is especially valuable in elderly or medically infirm age groups because of its extremely low perioperative risks.[12]

OUTCOME STUDIES

Comprehensive outcome studies based on Phase I/II data have been evaluated for more than 20 years. Long term studies in the management of arteriovenous malformations have been report from Sweden as well as from Pittsburgh, Buenos Aires, and Sheffield, England.

Successful obliteration of an AVM can be related to the AVM volume (Table 2). At our center we evaluated 164 patients 2 to 3 years after radiosurgery (Figure 2). Small AVMs (< 1 cm^3 volume) had an 89% total obliteration rate. Larger AVMs (>10 cm^3) usually required multimodality management to reduce the AVM volume. First, staged embolization procedures were performed in order to achieve a permanent volume reduction in the AVM.[13] Second, radiosurgery was performed in order to initiate the obliteration process. If the AVM was still visible by angiography at 3 years, a second radiosurgical procedure was recommended. Our recent review of the results of radiosurgery for otherwise "operable" AVM's indicates that the bleeding risks decreases by approximately one year after radiosurgery.[14]

In the management of acoustic neuromas, more than 90% of patients have tumor control (defined as tumor regression or prevention of further growth) without the need for further surgical intervention. We have performed stereotactic radiosurgery in 276 patients with newly diagnosed or recurrent acoustic tumors during a 7 year interval. During the same time period approximately the same number of patients underwent microsurgical removal of their tumors at our institution. The goal of radiosurgery is tumor control and reduced patient risk. Currently patients stay in the hospital a total of 8 to 18 hours afterwards. They can return to their preoperative level of function within a matter of days after discharge. Our current treatment plan is based on intraoperative high resolution MRI coupled with high speed image integrated dose planning computer systems. Cranial nerve preservation rates are carefully assessed in comparison to preoperative function. We are able to preserve useful hearing in 45% of patients with preoperative useful hearing and save some hearing in up to 70%. Preoperative facial nerve function can be maintained in 90% of patients.

Excellent outcomes after radiosurgery also have been reported for skull base meningiomas, especially those associated with high surgical risks for complete extirpation such as those in the cavernous sinus.[8] Gamma knife radiosurgery has been used for pituitary tumors, most often for patients who have had incomplete microsurgical resection. Laterally displaced pituitary tumors within the cavernous sinus, for which conventional surgical techniques have excessive risk, are effectively treated by radiosurgery.[9] A wide variety of other less common tumors such as hemangioblastomas, chordomas, and chondrosarcomas,[15] pineal region tumors,[16] and schwannomas of the fifth and ninth and tenth cranial nerve have also undergone radiosurgery.

MALIGNANT TUMORS

Metastatic brain cancers smaller than 3 cm in average diameter can be controlled or irradicated by a single outpatient radiosurgical procedure in more than 85% of patients. In conjunction with advanced fractionated radiation protocols and continuous infusion chemotherapy, the expected survival of patients with malignant glioma has increased at our center. Forty percent of patients with glioblastomas who complete radiation therapy, chemotherapy, and boost radiosurgery survive 2 years.

COST EFFECTIVENESS

Our studies indicate that in the management of vascular malformations, meningiomas and acoustic neuromas, gamma knife radiosurgery provides a total cost savings of between 40-70% in comparison to the costs associated with microsurgical care.[12] Since the average length of stay is less than one day in most patients, and gamma knife radiosurgery avoids high charges items such as intensive care units, operating room time, and anesthesia, third party reimbursement sources at last have begun to understand the value of this technology.

Gamma Knife Angiographic Obliteration Rates
University of Pittsburgh 1987-1994

AVM Volume	Total No. of Patients	Complete Obliteration Rate No. (%)	Subtotal Obliteration Rate No. (%)
<1 cm^3	36	32 (89)	4 (11)
1-4 cm^3	73	58 (80)	15 (20)
4-10 cm^3	47	29 (62)	18 (38)
>10 cm^3	8	4 (50)	4 (50) *
Total	164 †	123 (75)	41 (25)

* One patient had no change.
† All patients had > 24 months follow-up angiography.

Table 2.

THE FUTURE OF RADIOSURGERY

It is likely that in 1994, approximately 1,800 patients in North America will undergo gamma knife radiosurgery. In addition to the initial cost savings provided by gamma knife radiosurgery, the rapid return to work and the maintenance of long term employability in the vast majority of patients also enhances the value of radiosurgery in comparison to many other surgical techniques. Three issues must be studied further in the future.

First, gamma knife radiosurgery is not risk-free. Using both prior knowledge and current dose volume calculations, it is likely that less than 3% of patients undergoing gamma knife radiosurgery will develop any form of new permanent neurological deficits as a side effect of the treatment.[17] Unlike microsurgery, side effects are almost never instantaneous, but instead require observation intervals of six to 24 months in order to detect.

Second, significant emphasis must be provided on the initial training, and re-education of neurological surgeons, medical physicists, radiologists and radiation oncologists who constitute the essential team aspect of the procedure as performed in the United States.[18] This multidisciplinary combined knowledge base and technical expertise is vastly superior to that provided by any single member of the team. Expertise in stereotactic technology, microneurosurgery, radiobiology and imaging, constitutes some of the knowledge base essential to each member.

Third, new technology continues to emerge. The development of reverse algorithm dose planning systems will calculate the ideal radiation field in three dimensional space for any target. By the 21st century, it is likely that the computer defined target will be irradiated by robotic systems that can selectively destroy a deep intracranial target without the need to open the skull. Performed on an outpatient basis, such procedures of proven effectiveness will continue to revolutionize the treatment of a wide variety of deep brain problems previously either untreatable or associated with an excessive risk for the patient. No access surgery as exemplified by gamma knife radiosurgery will continue to revolutionize the field of neurological surgery. STI

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