NEUROSURGICAL OPERATING ARM: FRAMELESS LOCALIZATION SYSTEM FOR PLANNING AND PERFORMING TUMOR SURGERY

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Prior to the advent of CT, stereotactic localization was used primarily for functional neurosurgery and entailed the use of head frames or similar devices attached to the skull. When CT was invented, stereotactic neurosurgeons were already familiar with the concept of localization, so it is not surprising that these surgeons were generally the first to see the applicability of CT to stereotaxy. It follows, therefore, that the early CT-based stereotactic systems were adaptations of pre-existing stereotactic frames. At that time, stereotactic neurosurgeons were a very much in the minority, and their trade was poorly understood by the general neurosurgeon. This undoubtedly has contributed to the relatively slow acceptance of digital image-guided localization. One can only wonder what kind of CT-based localization system would have emerged from neurosurgeons who understood the exquisite potential of CT but had never heard of head frames.

The explosion of image and computer technology, computer-wise neurosurgeons and the undeniable advantage and safety of stereotactic technique has gradually allowed frame-based stereotaxy to establish a wide base in neurosurgery. Early digital image-guided stereotaxy generally involved selecting a point on the CT scan at which the stereotactic equipment was then aimed in the operating room. The subsequent concept of interactive stereotaxy was manifested in two ways. Perhaps the most "pure" was the use of the CT in the operating room or performance of the procedure in the CT suite, so that the progress of the operation could be monitored with actual CT scans of the operative field. This CT-interactive arrangement remains to impractical or too expensive for most hospitals today. Computer interactive CT-guided frame-based stereotaxy differs from CT-updated frame-based stereotaxy in that the computer tracks the progress of the frame-mounted instrument and displays it to the surgeon superimposed on graphic representation of the operative equipment and lesion derived from preoperative images. The most developed application of this form of stereotaxy is the work of Kelly et al (5). His computer-interactive volume resection techniques utilize complex multiplanar views of volume reconstructions to orient the surgeon to preoperatively selected tumor edges as the lesion is resected.

These techniques have not gained wide use. First, such a system is relatively expensive and complex. Secondly, the progress of the operation requires repetitive manipulation of the surgical and computer equipment. This requires that the surgeon leave the operative field or have someone in the operating room to assist with the system. The computer localization system itself depends entirely on input from the surgeon to generate accurate information about the location of the surgical equipment. Third, the bulk and restriction of the head frame and arc system are significant and may often exceed the advantage of localization for more common cases.

In the mid-1980's, Roberts and his colleagues reported a frame-less localization process that calibrated the operating microscope to the patients head and a preoperative CT of the head (8). Using ultrasonic localization, the position of the patients head and microscope were kept in register so that an appropriate CT-derived cross section of the lesion in question was actually superimposed on the patients head. Using similar concepts, several groups independently developed frameless localization systems that utilized a digitizing arm, instead of the microscope, that could be calibrated between the patient's head and a preoperative CT scan of the head. (1,4,6,9). In these systems, three or more common reference points are defined anywhere on the head and preoperative CT scan. In the operating room, the digitizer is attached to the table and the reference points are touched with the device, thus 'calibrating' the system. As the surgeon moves in and around the head, the location of the tip of the digitizer is displayed on the CT scan. Recently, several such frameless localization systems have emerged, some utilizing ultrasound or laser light as a localization mode (7, 10, Bucholz RD: personal communication, Heilbrun MP: personal communication).

The advantages of frameless localization are numerous. No head frame need be attached to the patient, making the procedure much more comfortable. Positioning of the head on the operating table is unlimited and nor restricted by the head frame. There are no localization arcs to impede the surgeons access. Perhaps most importantly, the device is moved in a freehand fashion while the computer itself tracks its position. These features allow for tremendous flexibility and broadens the range of cases typically felt to be "stereotactic" to include virtually any cranial procedure. The Neurosurgical Operating Arm System, to be described, uses the Arm itself, plus a foot pedal, to give the surgeon complete control of the system, alleviating the need technical assistance in the operating room.

THE NEUROSURGICAL OPERATING ARM SYSTEM

The Neurosurgical Operating Arm system is a frameless planning and localization system that utilizes preoperative digital scanning images of the patient's head (2,3,4). The current system has two basic components: a multi-jointed digitized localization and operating arm with a resolution of well under a millimeter (Radionics, Inc, Boston, MA and a graphics computer with which the arm communicates (Silicon Graphics, Inc., Mountainview, CA). Functionally, the operation of the system can be divided into four components: 1) preoperative patient imaging (data acquisition), 2) initialization and calibration, 3) localization and metrics, and 4) user interface.

PREOPERATIVE PATIENT IMAGING

Preoperatively, the patient must receive a CT scan of the head that maximally demonstrates the region of interest. Currently, three scalp staples are placed on the patient's head prior to the scan to serve as fiducials or reference points. The scan can be obtained at any time prior to surgery, but the localization marks should remain in place until the time of surgery. The CT data, including an AP and lateral scout view, are loaded onto the computer and the reference points are identified on the AP and lateral scout views.

INITIALIZATION AND CALIBRATION

At the time of surgery, the Operating Arm must be calibrated to the head and the previously obtained CT image of the head. The surgeon places the patient in the desired operating position. The operating arm is either attached to the operating table or fixed next to the head such that its position stable with respect to the head. The surgeon then initializes the Operating Arm, thus orienting it to itself. The surgeon then touches the calibration points with the arm, thus orienting the arm to the CT scan and the head. At this point, the location of any point in or on the head that is touched by the Operating Arm tip can be represented on the preoperative CT scan of the head.

LOCALIZATION AND METRICS

After calibration, the surgeon can use the system for presurgical planning, intraoperative assistance or both. Perhaps the most difficult development aspect of this system is to render three dimensional operating space (as stored in CT data) on two dimensional medium (the computer screen). Several solutions have been devised and the following paragraphs depict the better of those.

PRESURGICAL PLANNING

Most surgeons have a general idea about the surgical plan prior to bringing the patient into the operating room. The Operating Arm System allows modification and fine-tuning of the surgical plan with regard to location and size of the scalp incision and craniotomy and optimization of operative approach for virtually any cranial procedure. With the patient in the operating position, the surgeon places the tip of the arm on the head and its location is graphically rendered simultaneously in several was. First, the patients head is rendered in high resolution 3-D with the trajectory of the arm represented as it approaches and touches the head. This view is extremely helpful in orienting the surgeon with respect to clearly visible cranial features. Simultaneously, the appropriate axial CT slice is shown with the tip of the arm represented as a cursor. Axial CT views are familiar to every neurosurgeon and this feature is excellent for centering operations over lesions just under the scalp or skull surface. A third view is similar to the second except that the head is sectioned in the sagittal rather than the axial plane. The fourth view is a planner section of the head cut away such that the full trajectory of the arm is shown. This view is useful for planning trajectories to deeper lesions, cysts or ventricles (such as passing a shunt catheter). The fifth view is an 'Arms-eye' view, which shows the contents of the head at varying depths and widths as if one were looking into the head along the trajectory of the arm. This view is useful for planning the size of craniotomies (since the width of the view can be adjusted). These combinations of interactive data display give the surgeon unique capability for 'real-time' pre-surgical modification and optimization of the planned procedure, using the patients head as positioned for surgery.

INTRAOPERATIVE LOCALIZATION

After the operative procedure has begun, the Operating Arm System can be used to keep the surgeon oriented and provide localization. With the progression into the head, the 3-D rendered head will cut away showing the location of the arm tip in relation to the surrounding structures. This provides immediate orienting feedback. The progress of the surgery can be monitored on the axial and saggital planar views. It is these representations that can give the surgeon feedback about location with regard to tumor edges or vital structures such as the carotid or basilar arteries. The trajectory planar cutaway and the 'arm's-eye' view are also available to provide a look at structures ahead of and around the operative field. Trajectory displays can be shown with metric cross hatches on the trajectory line to measure distance along, or perpendicular (arm's eye view), to the surgeons approach. This is helpful in keeping the surgeon oriented as to real distance within the operative region.

USER INTERFACE

Perhaps the most accommodating feature of the Operating Arm System is the user interface. It is designed to give the surgeon complete control of system operation without leaving the operative area or touching the computer. This is accomplished by allowing the Operating Arm to toggle between localization instrument and 'mouse' to control program flow. A foot pedal is used to initiate the desired function. The user is first presented with a face screen which guides him through the initial steps of the program (patient selection, identification of fiducials on the image, etc) using a hand-operated mouse and menu options. After the surgeon is at the operating table, the arm is used as a mouse to control the program via menus and the foot pedal. After the arm is calibrated to the head, it can be used as a localizer or mouse as follows. When the tip is in the 'operating region' the location of the tip (including all the views described above) are shown when the pedal is pushed. The arm is not continuously active in the localization mode. If the arm is moved out of the operating region (about a foot away from the center of the head), it automatically becomes a mouse, and selected menu actions that control program flow are implemented by pushing the foot pedal. When the arm is moved back into the operating region, it resumes its localization function.

Excluding development, the Operating Arm System has been used to resect tumors. The device has proved to be convenient and accurate. In every case, the scalp incision was minimized and a linear incision was used for most. The craniotomy was tailored to fit the lesion with respect to the regional skull configurations and to delineate tumor margins with better accuracy. As with any system that uses preoperative data for localization, the extent to which the tissue was moved introduces error. However, it was the experience of this surgeon (BLG), that the real value of the Arm was in directing the approach to the lesion because for the vast majority of cases, the actual handling of the lesion is controlled by direct vision, with or without the microscope. Although patient numbers are small so far, healthy patients required a very short hospital convalescence, with discharges at 2 to 4 days postoperatively. Patients ill from their disease required appropriately longer hospital stays. Experience with the prototypic system is extremely encouraging such that active development is underway to continually improve the system and simplify it to the extent that its localization function is relatively 'transparent' to the surgeon.

References

1. Adams L, Krybus W. Meyer Ebrecht D, Rueger R, Gilsbach J, Moesges R, Schloendorff G., Computer assisted surgery. IEEE Comp Graph App **:43-51, 1990.

2. Guthrie BL, Adler JR, Jr., Computer-assisted peroperative planning, interactive surgery and frameless stereotaxy. Clin Neurosurg In Press.

3. Guthrie BL, Adler JR, Jr., Frameless stereotaxy: computer interactive neurosurgery. Perspectives Neurological Surg 2:1122, 1991.

4. Guthrie BL, Kaplan R. Laws ER, Jr., Three-dimensional cranial image reconstruction for interactive freehand stereotaxy. AANS (Abstr) p357, 1990.

5. Kelly PJ, Kall BA, Goerss S, Earnest F., Computer-assisted stereotaxic laser resection of intra-axial brain neoplasms. J Neurosurg 64:427-439, 1986.

6. Kosugi Y, Watanabe E, Goto J. Watanabe T, Yoshimoto S, Takakura K, Ikebe J. An Articulated neurosurgical navigation system using MRI and CT images. IEEE Trans Biomed Eng 35:147-152, 1988.

7. Maciunas RJ, Galloway RL, Fitzpatrick M, Mendava VR, Allen GS. A universal intraoperative surveying device for interactive neurosurgical localization. CNS (Abstr) p122, 1990.

8. Roberts DW, Strohben JW, Hatch JF, Murray W, Kettenberger H. A frameless stereotaxic integration of computerized tomographic imaging and the operating microscope. J Neurosurg 65: 545-549, 1896.

9. Watanabe E, Watanabe T, Manaka S, Mayanagi Y, Takakura K, Three-Dimensional Digitizer (Neuronavigator): New equipment for computed tomography-guided stereotaxic surgery. Surg Neurol 27:543-547, 1987.

10. Zinreich J, Nick B, Leggett B, Long D. 3D CT/MRI and a compuer oriented sensor for guidance of neurosurgery. Neurosurg Soc Am (Abstr) p77, 1991.

FRAMELESS STEREOTAXIC RADIOSURGERY

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INTRODUCTION

Stereotaxic radiosurgery is an important new treatment for many brain tumors and vascular malformations. By coupling stereotaxic localization techniques with a sharply collimated beam, specialized instrumentation makes it possible to target an ablative dose of ionizing radiation to a well-circumscribed lesion. With an accuracy approaching 1 mm, a very large, and in many instances "necrosing", dose of radiation (1,000 to 5,000 Rad) is delivered as a single fraction. Relatively extensive clinical experience has shown stereotaxic radiosurgery to be an efficacious and cost-effective treatment for many brain tumors.

The radiosurgical principle of confining radiation as much as possible only to the volume of a brain tumor is a significant and timely concept. Nevertheless, there are limitations to present methods of radiosurgery. For example, with lesions which are larger than 3 to 4 cm in diameter, there is a significant risk of radiation injury. To safely treat such larger tumors, some measure of fractionation will be necessary. Furthermore, the length of time required to presently carry out radiosurgical treatment is problematic; a neurosurgeon must be available for a relatively extended period of time. In addition, while stereotaxic radiosurgery has the potential to be a much safer method of irradiating lesions within a developing brain, such treatment is now exceptionally lengthy and cumbersome. Current techniques for radiosurgery in children require general anaesthesia throughout the 5 to 10 hour procedure.

The above limitations to the use of radiosurgery stem largely from the reliance of present day instrumentation on conventional stereotaxic localization. More specifically, the major obstacle is the need for an external frame attached to the patient's head. This device provides a fixed reference plane upon which a coordinate base can be built for radiologic localization and radiosurgical treatment. The need for a frame makes all current methods of stereotaxic radiosurgery quite cumbersome and multiple fraction treatment virtually impossible.

As long as radiosurgery was used to treat benign lesions which are somewhat unusual diseases, its shortcomings could be ignored. However, radiosurgery is increasingly being used to treat malignant brain tumors with considerable success. In selected patients, radiosurgery can substitute for surgical resection, brachy therapy, or radiation therapy. As a consequence, the number of patients who might benefit from radiosurgery is growing immensely. This situation has made the limitations of radiosurgery more glaring and as a result, provides the rationale for a radically new "frameless" approach to stereotaxic radiosurgery.

FRAMELESS STEREOTAXY

Among stereotaxic surgeons there is increasing interest in frameless methods for intraoperative stereotaxis. Several such methods have been developed, all of which utilize a series of scalp fiducials visible on imaging studies. These markers provide a reference system for head orientation. After anaesthetizing the patient and fixing their head, the spatial location of these fiducials is registered. Various 3-D digitizers (articulating arms, sonic, optical) have been used for this purpose.

During surgery the same digitizing technology provides the surgeon with real time localization. While this technique is a straight-forward solution to "frameless localization", accuracy is limited by its reliance on scalp markers. Consequently, it is probably best-suited for the anaesthetized patient whose skull is fixed.

FRAMELESS IMAGE-BASED STEREOTAXY

Given the above limitations of existing frameless stereotaxic technologies, the Stanford Program in Computerized Stereotaxy has been investigating image-based cranial localization. This proposed frameless method of orientation will determine head position from digitial x-rays. No skeletal fixation will be used. The basic assumption behind image-based localization is that brain contents, including brain tumors, have a fixed relationship with respect to the cranium. Consequently, if one can determine the location of the skull, tumor position will be known.

The basic premise of image-based localization is that head position can be established by finding at least 3 corresponding features on both a preliminary CT, and at the time of treatment, a pair of orthogonal x-rays. The identified structures define a unique spatial frame of reference with which the skull and target can be oriented. Mathematical comparisons between these sets of images must be calculated by high speed computer. However, to accomplish this task the computer must have a mathematical understanding of the treatment geometry. A precise definition of 3-D the space present at radiosurgical treatment is critical to automatic cranial localization. Spatial parameters such as source to image plane, distortion within the digital receiver, distance between x-ray sources etc. must therefore be described to the computer. The basic design of a system for image-based frameless stereotaxy makes realtime tracking of a target feasible. Such realtime tracking substitutes for rigid skeletal fixation.

Three different methods for image-based stereotaxic targeting have been explored. This first technique involves the implantation of metallic markers (i.e. fiducials) into the skull. These markers are both visible on both CT and non co-linear (optimally orthogonal) x-rays obtained at the time of radiosurgical treatment. Given the significant difference in x-ray density between the fiducials and skull, markers can be easily and automatically identified by the computer. After localizing corresponding markers within a know treatment geometry, triangulation (using trigonometry) determines head position. Although this is the simplest solution to image-based frameless localization, it has much in common with the other 2 methods which will be discussed below.

The second approach to image-based stereotaxy investigated at Stanford involves the automatic recognition of natural skull landmarks. Instead of recognizing artificial implanted markers, software has been constructed which automatically detects at least 3 cranial features. At present, those landmarks which can be detected include the mastoid processes and the anterior clinoid. Analogous to the approach taken with implanted fiducials, such features are found automatically on both a preliminary thin cut CT and digital non co-linear (optimally orthogonal) x-rays obtained during treatment. Information regarding the general location, shape and density of cranial landmarks is included in the recognition algorithm. In many ways this process mirrors its human counterpart, as exemplified by the standard (non-stereotaxic) positioning of a patient's head for surgery. Given the computer's prior knowledge of the radiosurgical treatment geometry, target location is determined by triangulation. The precision of this system has been tested with conventional stereotaxic frames in both phantoms and patients. Localization accuracy is better than 2 mm.

The above approaches will solve the problem of frameless image-based stereotaxy. Nevertheless each has some drawback. Localization with implanted fiducials requires both an additional procedure and that any relevant imaging studies be repeated with skull markers in place. Furthermore, any dislodgement or loss of a fiducial would necessitate yet another repetition. Meanwhile, feature recognition software is extremely complex. Although that written to date has worked well under experimental conditions, it would seem quite a challenge to write software that would quickly recognize cranial landmarks in all patients all the time. This is even difficult for the knowledgeable neurosurgeon. As a consequence, we have explored a third somewhat more general solution to the problem of image-based stereotaxy, image to image correlation.

Image to image correlation relies on the tremendous speed of modern microprocessors. This process begins with a 3-D computer model of the skull assembled from CT axial images. With a comprehensive knowledge of radiosurgical treatment geometry, the computer uses its model of the skull to calculate a series of different x-ray projections. Each projection represents a slightly different head orientation. At the time of radiosurgical treatment, a computer compares, i.e. correlates, the actual images obtained against the previously calculated synthetic images. A series of mathematical comparisons is made until a best fit is found. This process, which is carried out for 2 non colinear projections, provides sufficient spatial information to precisely locate a patient's head. Computer modeling suggests that this technique will permit head localization to an accuracy of better than 1 mm. The computation involved is fast enough to permit realtime tumor location obviating the need for rigid skull fixation. As a consequence, only passive head restraints using velcro will be utilized.

RADIATION SOURCE

To optimize the focus of radiation, the ideal radiosurgical system targets its collimated beam(s) at a brain lesion from as many different directions as possible; the more closely the volume covered during radiosurgery approximates a sphere, the better the dosimetry. Present day radiosurgical instruments, using either arcs from linear accelerators or fixed Co^{60} beams as in the Gamma-knife, target over somewhat less than a hemisphere. This situation results from the inherent design of the latter as well as the fixed geometry and size of medical linear accelerators. Since frameless stereotaxy removes many of the mechanical constraints confronted by current radiosurgical techniques, is it possible to increase the flexibility with which the beam is targeted? At Stanford we have tried to design such a radiosurgical system.

Present day medical linear accelerators were designed to meet the needs of radiation oncology. Perhaps the principal design criteria has been the necessity of irradiating large fields, as big as 20 x 20 cm, with a homogenous dose of energy. For this purpose an S-band accelerator wave guide has been used in all medical accelerators. However, the large size of this device results in an overall weight of several thousand pounds. This massive weight of current medical accelerators is counterproductive when attempting to design a flexible targeting system. As a result, mechanical systems used to manipulate them have been necessarily quite simple. In general both the accelerator and the treatment couch have only a single degree of rotational freedom.

Unlike conventional radiation therapy, the need to irradiate large fields is clearly unnecessary in radiosurgery. As a consequence the instrument under development at Stanford will utilize an ultra low weight 6 MeV linear accelerator as a radiation source.

This device, which weighs 60lbs, was designed for portable industrial radiography or large concrete and steel structures. The low weight is made possible by the small size of the accelerator's X-band wave guide. Despite its size, this device can irradiate small areas with comparable performance as the much larger standard medical accelerators.

MECHANICAL DESIGN

The combination of frameless stereotaxic localization with a low weight linear accelerator provides the basis for a system of radiosurgery with much greater flexibility. To take advantage of these possibilities, Stanford's instrument will include a robotic arm to target the accelerator. This commercially available arm incorporates 5 degrees of freedom and is capable of manipulating up to 200 lb. payloads with millimeter precision. Using image-based stereotaxy to provide realtime head and tumor spatial localization, the robot is capable of redirecting the accelerator in response to small patient movements. This mechanical system will ultimately be capable of performing very complex arc-like movements which can further enhance the "sharpness" with which radiation can be deposited.

SUMMARY

In response to the expanding indications for radiosurgery, Stanford is currently developing a novel radiosurgical instrument. The device being built will include a frameless image-based system for tumor localization and targeting. A very low weight linear accelerator and a flexible robotic manipulator are also being utilized. We expect such a device to significantly simplify the process of radiosurgery and potentially lead to new treatment applications.

SUGGESTED READING

1. Guthrie BL, Adler JE, Jr. Computer-assisted preoperative planning, interactive surgery and frameless stereotaxy. Clin Neurosurg In Press.
2. Guthrie BL, Adler JR, Jr. Frameless stereotaxy: computer interactive neurosurgery. Perspectives Neurological Surg 2:1122, 1991.
3. Lee B. Stereo Matching of Skull Landmarks. Dissertation submitted to the Department of Electrical engineering and the Committee on Graduate Studies of Stanford University, June 1991.
4. Watanabe E, Watanabe T, Manaka S, Mayanagi Y, Takakura K. Three-Dimensional Digitizer (Neuronavigator): New equipment for computed tomography-guided stereotaxic surgery. Surg Neurol 27:543-547, 1987.
5. Winston KR, Lutz W. Linear Accelerator as a Neurosurgical Tool for Stereotactic Radiosurgery. Neurosurgery 22(3) 454-464, 1988.

TECHNOLOGICAL ADJUNCTS FOR FUNCTIONAL AND STRUCTURAL LOCALIZATION IN BRAIN TUMOR SURGERY

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The objectives of localization in brain tumor surgery include the planning of operative approaches, intraoperative tumor localization, intraoperative localization of the tumor to specify brain landmarks, the relationship of the tumor to functionally eloquent brain regions, and the mapping of zones of tumor-associated epileptogenicity. In recent years, many technical adjuncts have been added to the neurosurgical armamentarium so as to assist with each of these objectives. These will be reviewed individually, including future perspectives allowing the integration of anatomic and functional localization in brain tumor surgery.

PLANNING OF OPERATIVE APPROACH AND INTRAOPERATIVE TUMOR LOCALIZATION

Classical neurosurgical planning of craniotomoies has traditionally included general regional localization, an operative approach aimed at exposing the region of pathology, and more specific intradural inspection so as to reveal the specific site of the neoplasm. Intraoperative ultrasound techniques have greatly enhanced the ability to localize a tumor which has not altered significantly the cortical surface.

Conventional anatomic landmarks and the pursuit of anatomic "pathways" have been used with great skill and ingenuity by neurosurgeons for many years. Mesial temporal regions have been approached through the inferior temporal gyrus, atrial lesions have been approached through parietal occipital corticectomies and a transventricular route, and thalamic lesions have been approached via transcallosal transventricular routes. Craniotomies can be precisely planned around "localization marks" indicating the precise localization of a lesion as revealed by preoperative imaging.

However, these conventional techniques fall short in the localization of many deep-seated tumors. Frame-referenced stereotaxy has added a new level of sophistication and precision of the localization of tumors. It has allowed precise needle biopsies, and track-guidance in the open excision of many deep lesions previously thought to be inaccessible.

Frameless stereotaxy is currently being developed at several institutions. Several "surgical localizers" are now on the market, and many more will be available in upcoming years, so as to provide the neurosurgeon with a user-friendly and helpful guide at localization and planning of operative approaches for a variety of intracranial lesions.

INTRAOPERATIVE LOCALIZATION OF TUMOR TO SPECIFIC BRAIN LANDMARKS

For the purpose of maximal safe excision of neoplasms, the neurosurgeon should ideally have an intraoperative reference of the relationship of tumor margins to specific brain landmarks. Such referencing should be dynamic, providing the surgeon with real-time feedback as to the extent of resection and proximity to various anatomic landmarks within the brain. The "volumetric guided resection" advocated by Kelly is one such approach to this problem. Others are adapting various frame-referenced and frameless localizers to preoperative imaging data, so as to provide the surgeon with instant spacial orientation during intracranial surgery.

The glabella-inion reference system can provide precise orientation of any landmark in the midsagittal cranial plane, with immediate geometric translation from skull x-ray to MRI coordinates. The Talairach grid system allows parasagittal extension of this referenced plane, providing the surgeon with immediate localization in three dimensions of any point within the skull. These and other techniques will undoubtedly be integrated into any scheme of interactive image-guided neurosurgery which is marketed in upcoming years.

RELATIONSHIP OF TUMOR TO FUNCTIONALLY ELOQUENT BRAIN REGIONS

Several techniques have been used by neurosurgeons in recent years to localize the rolandic sulcus, and functional motor, sensory and speech areas intraoperatively for the purpose of assisting in brain tumor resection.

Techniques have included the use of intraoperative evoked potentials, with the rolandic sulcus localized by phase reversal on the cortical surface as described by Luders, et al. This can provide instantaneous identification of the rolandic fissure, and can assist in orienting the surgeon toward specific gyral landmarks relevant to a particular plan of resection.

Stimulation mapping has been used extensively to identify cortical and subcortical structures associated with specific functions. Intraoperative stimulation mapping provides "real-time" functional information to guide specific operative maneuvers. When performed under local anesthesia, it allows further verification in "real-time" of the functional impact of specific operative maneuvers. This technique was described by Penfield and later popularized by the Montreal and Seattle schools, and has greatly enhanced the surgeons' ability to maximize tumor resection near eloquent areas of the brain. Intraoperative stimulation mapping is, however, limited by the time and milieu constraints of the operative environment, by anesthetic constraints, and by constraints of the operative exposure with relative lack of correlative anatomic information.

Extraoperative mapping using subdural grids has been used extensively at the Cleveland Clinic and at several other institutions for mapping of motor, sensory, and speech areas. It allows detailed, unhurried and unrestrained functional testing with limitless potential to verify and repeat specific and sophisticated tests extraoperatively and outside the constraining environment of the operative room. Subdural plates can be "slid" beyond the edges of a craniotomy, allowing mapping beyond the operative exposure. Radiographic verification of electrode location, including more recently magnetic resonance imaging or electrode location, has allowed precise and reliable anatomic correlation of the functional data to specific gyri and to the radiographic coordinates of the neoplasm. Extraoperative mapping allows the chronic recording of intercital tumor-associated epileptogenic activity, and allows the recording of ictal-onset epileptiform activity. Intraoperative mapping allows the limited recording of intercital activity (within the time constraints of craniotomy) and does not allow the recording of ictal-onset epileptiform activity (the occurrence of a seizure during craniotomy is a highly undesirable phenomenon). As will be pointed out later, the zone of ictal-onset often requires resection along with the neoplasms so as to insure maximal chance of control of tumor associated epilepsy.

The techniques of intraoperative and extraoperative stimulation mapping have been perfected at different centers. In experienced hands, they are both easy and reliable. Clearly, the two techniques are complementary, with intraoperative mapping providing decided advantages of precise real-time information, while extraoperative mapping provides the advantages of prolonged unhurried gathering of functional information. Either could be useful in individual situations, and most large centers are currently gaining experience in the use of both techniques for individual situations.

While cortical stimulation can be quite reliable in identifying precentral primary motor areas, postcentral primary sensory areas, and frontal and temporal speech ares, it must be cautioned that the evoking of movements or sensations by cortical stimulation does not necessarily imply "eloquence." For example, stimulation of mesial frontal areas will invariably evoke motor movements in the contralateral arm and leg, which are often difficult to distinguish from movements evoked by stimulation of the primary foot area in the paracentral lobule. However, only resection of the paracentral lobule on the medial hemisphere has been associated with permanent paresis of the contralateral foot. Similarly stimulation of the temporal tip and of the fusiform gyrus have been shown to evoke speech arrest in certain patients. However, there has been no evidence that resection of these regions has ever resulted in permanent dysphasia in any patient. Conversely, resection of stimulation-confirmed Broca's or Wernicke's areas invariably result in the expected dysphasia. Therefore, functional eloquence must be interpreted in light of the precise anatomic localization of the area stimulated, and stimulation induced function or dysfunction should not be relied upon solely to make decisions regarding brain resection. Ideally, these techniques should assist in anatomic definition of a specific area of the brain, in addition to its functional definition. These techniques, can however, be invaluable in situations where the anatomy has been distorted by cysts, scar or tumor. A surgeon can be more inclined to extend a resection into an area of the brain with suspected eloquence, if careful repetitive stimulation in experienced hands fails to reveal the corresponding junction or shows the expected function in an adjacent region.

TUMOR ASSOCIATED EPILEPTOGENICITY

Epileptogenicity may be the sole significant clinical manifestation of a brain tumor. In many instances, a neoplasm which is visible on radiologic studies has been present for many years, and has no functional sequelae other than epileptogenicity, including the absence of associated edema compression or demonstrable growth. Many such "neoplasm", including some benign astrocytomas and many gangliogliomas behave more like hamartomas than true neoplasms. However, the lesion-associated epileptogenicity may be significant with seizures truly intractable. The resection of the lesion alone in these instances does not achieve the desirable clinical outcome unless it also assists in seizure control.

Several workers have demonstrated that the zone of epileptogenicity may extend beyond or be remote from the pathologic tumor margin. The resection of the tumor itself is necessary but not always sufficient for control of tumor-associated intractable epilepsy. There are many reports where the tumor has been convincingly removed, but where intractable seizures persist much to the chagrin of the surgeon and the patient and family.

Tumor-associated epileptogenicity includes a zone of ictal-onset (epileptogenic zone) which is usually but not always adjacent to the pathologic tumor margin. This region is focal and consistent for every seizure type, with ictal-onset epileptiform activity recorded from the same region consistently in every recorded seizure. The resection of the zone of ictal onset in addition to tumor resection appears to greatly enhance the likelihood of control of tumor-associated seizures. In our own experience, the resection of the epileptogenic zone increased the likelihood of seizure control over simple lesion excision, and provides a chance for seizure control in cases where lesion excision alone has failed.

It must be emphasized that the lesion resection alone may be sufficient in some cases to totally control seizure activity. This may be because the epileptogenic zone is very small and is inadvertently included in the standardized tumor resection. However, in some instances, the epileptogenic zone may extend several centimeters beyond the pathologic margin of the tumor, and may not be included in a standardized tumor resection. In cases where epileptogenicity is a sole or important clinical manifestation of a brain tumor, it is our policy to map and define the zone of ictal-onset by extraoperative mapping so as to maximize its resection.

The zone of ictal-onset (epileptogeinc zone) is frequently surrounded by a much larger zone of intercital epileptiform activity (irritative zone). The irritative zone extends well beyond the tumor margin and the zone of ictal-onset, and often contains these. The zone of interictal epileptiform activity, or "spiking brain" is usually diffuse and inconsistent over time. The area of spiking may depend of the level of anesthesia, on anticonvulsant agents, and on recent seizure activity. It has been convincingly demonstrated that resection of the irritative zone is not necessary for control on intractable epilepsy. In fact, the practice of "chasing spikes" can lead to the resection of extensive brain regions unrelated to ictal-onset or epileptogenicity. However, if the whole irritative zone is resected, it is likely that the enclosed zone of ictal-onset will also be included in the resection. This explains why extensive resections guided by "spike mapping" have been used so successfully at many centers. However, the mapping of the irritative zone may be inconsistent over time, and may not relate specifically to the epileptogenic zone in every instance.

While intraoperative mapping allows a limited survey of the irritative zone and a mapping of functional areas, it does not allow the mapping of ictal-onset epileptogenicity (the epileptogenic zone). We and others have used implanted subdural electrodes for the purpose of mapping the epileptogenic zone, the irritative zone, functional areas, and correlating these areas in a neuroanatomic fashion using imaging modalities.

INTEGRATION OF ANATOMIC AND FUNCTIONAL LOCALIZATIONS: FUTURE HORIZONS

As indicated above, several teams are working on the development of user-friendly localizer systems which can greatly simplify the planning of operative approach, intraoperative anatomic localization, and provide real-time intraoperative feedback of the relationship of tumor margins to surrounding brain regions. The system currently being developed at the Cleveland Clinic utilizes an acoustic digitizer with two mounted "sparkers" on a portable wand. These provide signals which are detected by four fixed mounted spark detectors. This system allows spacial localization of the wand tip in a real-time fashion, in relation to skull and brain landmarks as previously digitized in the imaging data set. The system provides real-time visualization of the wand tip on the 3-D MRI or CT reconstruction, or on any coronal axial or sagittal cut of the CT or MRI.

Other workers are experimenting with other frameless localizers which may be attached to the operating table, or to a mechanical arm mounted on the microscope or elsewhere in the operating room. It is likely that several of these systems will accomplish the objective of integrated anatomic real-time localization in the operating room, providing the surgeon with image-guided feedback regarding operative maneuvers. These techniques should be integrated with intraoperative stimulation, and with the ability to spacially localize implanted electrodes, so as to add the dimension of functional localization in an anatomically relevant fashion.

In the next decade, the surgeon should expect to use a simple instrument which fulfills all these objectives. The technology and the concepts have all been perfected in recent years, and are awaiting effective integration in a user-friendly and cost-effective system.

SUGGESTED READING

Awad IA, Rosenfeld J, Ahl JJ, et al (1991): Intractable epilepsy and structural lesions of the brain: mapping, resection strategies, and seizure outcome. Epilepsia 32:179-186.

Bordal A (1981): The cerebral cortex. In: Neurological Anatomy in Relation to Clinical Medicine (Third Edition), by A. Brodal, pp 788-848. Oxford University Press, New York.

Debrin RA (1988): Volume Rendering. Comput Graph 22:65-74.

Djindjian M and Nguyen JP (1988): Correlation between anatomy and computed tomography in the occipito-temporal plane: appliation to cerebral lobectomy. Surg Radiol Anat 10:61-69.

Gado M, Hanaway J, and Franck R (1979): Functional anatomy of the cerebral cortex. J Comp Assist Tumor 3:1-9.

Gouaze A and Salamon G (1988): Brain anatomy and magnetic resonance imaging. Springer-Verlang, New York.

Hu X, Tank KK, Levin DN, et al (1990): Three-dimensional magnetic resonance images of the brain: application to neurosurgical planning. J Neurosurg 72:433-440.

Luders H, Lesser RP, Hahn JF, et al (1986): Basal temporal language area demonstrated by electrical stimulation. Neurology 36:505-510.

Penfield W and Roberts L (1959): Speech and brain mechanisms. Princetown University Press, Princeton, New Jersey.

Talairach J and Taurnoux P (1988): Coplanar Stereotaxic Atlas of the Human Brain. Three-dimensional proportional system: an approach to cerebral imaging. Thieme Medical Publishers, New York.

INTRAOPERATIVE BRAIN MAPPING TO ENHANCE TUMOR RESECTION

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The efficacy or radical tumor resection for gliomas continues to remain controversial. Evidence has been established to support this approach as it effects the mean time to tumor progression (MTP), survival, and the quality of life following surgery (1,3,9,25). Recurrence patterns of gliomas have predominantly involved the area contiguous with the contrast enhancing margins, and multicentric tumor or cerebrospinal fluid (CSF) dissemination is unusual at the time of recurrence (16,24). This provides another reason to encourage the concept of radical tumor resection when feasible, especially when considering predictive factors such as preoperative Karnofsky performance status and age (20).

Low grade gliomas present a difficult problem in that many of these lesions are ill-defined on imaging studies and are associated with an intractable seizure disorder. Again, there is evidence to support radical tumor resection followed by focal radiotherapy in terms of improving the MTP and survival. It would also be interesting to speculate whether the extent of tumor resection affects not only the recurrence pattern of these tumors but the phenotype of the lesion at the tumor or reoperation. Previous work from our group (4) and other investigators (10,13) indicates that the eplieptogenic focus (or foci) associated with a low grade glioma is quite likely to be located adjacent to the tumor mass. The pathophysiology of this phenomenom is secondary to a loss of inhibitory neurotransmitters in the surrounding non-tumor infiltrated cortex (15). Therefore, intraoperative electrocorticography (ECoG) may be used to maximize seizure control in patients with intractable seizures associated with low grade gliomas. Resecting the tumors alone without mapping separate seizure foci will often result in less than optimal results.

The techniques described in this section have been utilized to maximize the amount of tumor removal while minimizing the operative morbidity. Stimulation mapping has become essential when operating in the dominant hemisphere near functional language cortex (18). Also, motor pathways may be identified and avoided from the surface inward to the internal capsule, peduncle, and corticospinal tracts. Unlike during epilepsy surgery, subcortical mapping has been quite useful when dissecting large, amorphous tumors that extend deep below the surface.

MAPPING TECHNIQUES

Direct stimulation of the cortex or subcortical white matter is conducted with a bipolar electrode spaced 5 mm apart. A constant current generator is used to produce a train of biphasic square wave pulses. The pulse frequency is 60 Hz with a single phase duration of 1 msec. The current is applied to surface for 1 to 3 seconds. Under asleep conditions, a higher current may be necessary due to the anesthesia, e.g., up to 16 mA, whereas only 2 to 4 mA are usually required to elicit sensory or motor responses in an awake patient. The same current that provokes a motor movement from cortical stimulation may be used during subcortical mapping of the descending motor tracts. Following a witnessed movement, the corresponding area on the cortex or below should be documented with a numbered ticket. When removing a supplementary motor area tumor, it is often necessary to place a strip electrode along the falx to identify leg motor responses. The strip electrode may be repetitively stimulated during the tumor removal to ensure safety of the motor cortex. The strip electrodes are also used to stimulate the cortex underneath a bone flap if the craniotomy is not large enough.

Awake craniotomies for language mapping are usually done under the administration of propofol anesthesia. First, the scalp is anesthetized with a 0.5% lidocaine and 0.25% marcaine mixture. Once the scalp is opened, the propofol is given until the bone is removed. The patient is awakened prior to opening the dura so that coughing will not cause brain herniation especially if swollen initially. Once the recording electrodes are in place on the cortical surface, the brain is stimulated to evoke afterdischarge potentials e.g., 2 to 6mA usually. The optimal current used during speech mapping is that which elicits one or no afterdischarges. The patient then reads and identifies common objects from a slide projector and the cortex is stimulated to induce either speech arrest (in the region of the face motor cortex) or errors in object naming. At least three errors at a specific cortical site are necessary to identify a functional language region.

Electrocorticography usually requires 20 to 30 minutes of monitoring to obtain meaningful data unless there are numerous interictal discharges. It is often essential to place several strip electrodes under the surface of the temporal lobe when the tumor is primarily located in that area. This is due to the predominant location of epileptogenic activity in mesial temporal lobe structures, e.g., amygdala, hippocampus, and parahippocampal gyrus. Following tumor and seizure focus (foci) resection, additional ECoG is necessary to make sure that no obvious epileptogenic areas have been missed. This is especially critical when the lateral temporal cortex prevents a detailed recording of the mesial structures until the former is removed. A seizure focus (foci) far removed from the initial area of activity is not considered feasible for resection, e.g., beyond 4 to 6 cm from the active interictal areas detected at the initial recording.

CONTRAINDICATIONS TO MAPPING

Patients with well controlled seizures on antiepileptic drugs are not appropriate candidates for ECoG because the interictal seizure activity is usually minimal. Chemical activation of epileptiform discharges may be evoked with a rapid infusion of intravenous Brevital (1-mg/kg). ECoG during tumor resection is only helpful when the patient has intractable epilepsy.

Children under the age of 4 to 5 years often have an electrically inexcitable cortex thus often preventing direct stimulation mapping of the Rolandic (sensory-motor) cortex (5,6,12). Therefore somatosensory evoked potentials (SSEPs) should be available if identification of the motor cortex is necessary. Identifying phase reversal potentials across the central sulcus is not trivial and becomes more difficult as the face motor cortex is approached. Also, subcortical motor pathways cannot be located with SSEP monitoring. Another approach for this patient population is to insert a subdural electrode array several days prior to the tumor resection to stimulate the cortex while the patient is awake. Using this technique, language, motor, sensory, and seizure mapping can be performed.

Patients who are unable to name common objects prior to surgery cannot be successfully mapped for language sites. Although we have attempted to gain some useful information by performing "conversational" mapping during stimulation, this has been an unreliable method and should be avoided. Similarly, patients with a dense hemiparesis will often not be suitable candidates for motor mapping due to unreliable results. This cannot be overcome by increasing the current beyond 16mA.

MAPPING BY FUNCTIONAL SITE

Language

Wada testing (23) should be used in any circumstance when cerebral dominance for speech is unclear. For instance, left handed individuals with left or right sided tumors, and, ambidextrous individuals. Following determination of the ideal stimulation current that does not elicit afterdischarge potentials, multiple sites within 5 to 10 mm of each other are tested. Prior to surgery, the baseline error rate for speech for each patient must be determined in order to detect meaningful naming errors. In a retrospective study conducted by our group (13) language maps from 117 patients with and without tumors were reviewed and demonstrated a wide variability in speech localization throughout the posterior frontal, temporal and anterior parietal lobes. When analyzing those patients with predominantly temporal lobe tumors it was clear that nearly 20% of this group had no language sites throughout the temporal cortex. In addition, speech was mapped anterior to the bottom of the Rolandic cortex in 15% to 20% (within 3 cm of the temporal tip) of these cases, yet was never present in the inferior temporal gyrus.

When a cortical site has tested positive for speech, the subcortical white matter cannot be undercut and the dissection needs to proceed perpendicular to the functional surface. We have also documented language localization on the insular cortex which always corresponds to overlying language sites in the superior temporal gyrus, inferior parietal and frontal lobes. Resection of adjacent cortex (within 1 cm) near functional sites will often result in temporary language deficits that may last several weeks. This may not start until 48 hours following the resection when swelling is expected postoperatively. If speech is intact at the end of the tumor resection, then a full functional outcome is expected even if a temporary deficit ensues.

Motor Pathways

The optimal current to elicit motor responses is first determined by stimulating the cortex. The same current may be used to follow the motor pathways subcortically into the internal capsule. Without proceeding in this order it may not be possible to find the subcortical motor tracts in a reliable fashion. Therefore, if the motor cortex is not optimally exposed, strip electrodes should be used to elicit the proper stimulation current. During the tumor removal, verification of intact circuits must be ascertained by repetitively stimulating the cortex. This will provide the confidence necessary to proceed in seemingly normal white matter even if subcortical motor responses are not evoked. The closer the resection comes to functional tissue the more likely the patient is to have temporary weakness. However, as long as stimulation can result in motor responses, no permanent weakness should develop.

Resection of tumors involving the supplementary motor area (SMA) will often result in a typical syndrome of transient hemiplegia and mutism (dominant SMA) (21). Return of function occurs in a stepwise fashion involving leg, arm and speech areas within several days to weeks following surgery. This syndrome is always reversible and the patient and family should be warned of these preoperatively. Complete function return may take as long as 4 months.

The non-dominant face motor cortex may be resected with impunity up to the level of the hand motor area due to bilateral cortical representation of the face (17). This is not feasible in the dominant hemisphere because of the proximity of the face cortex with Broca's speech area. Insular tumors may also be aggressively resected in the non-dominant hemisphere except posterior and mesially where the capsular motor fibers are located. Subcortical stimulation is an ideal technique to localize these pathways during tumor resection deep to the insular cortex. We have also identified motor tracts in the spinal cord during removal of intramedullary tumors. The stimulation current is reduced to 0.5 mA to 2 mA and elicits brief motor responses indicating stimulation of the anterior horn cells or corticospinal tracts.

SEIZURE MAPPING AND OUTCOME

A recent review of our experience with pediatric supratentorial tumors (4) and adults with low grade gliomas (unpublished data) revealed seizure foci that are typically adjacent to the tumor as documented with ECoG. Histologically, over 90% of these epileptogenic cortical regions were void of tumor infiltration. Further analysis of these specimens revealed a statistically significant loss of somatostatin and GABAergic immunoreactive neurons in this epileptic tissue removed at the time of the tumor resection (15). Patients with a prolonged history of intractable seizures were more likely to have multiple seizure foci.

Seizure control was greatest in the pediatric group with 93% of patients becoming seizure free off antiepileptic drugs. Most adults (85%) were seizure free, however only 62% of these patients were able to stop their antiepileptic medication with a mean followup of 27 months postoperatively. In our experience, ECoG is an important adjunct during surgery for only those patients with intractable seizures associated with low grade gliomas, although this approach has not been utilized by other investigators (8,12,22) for a similar patient population. Extraoperative recordings from subdural electrodes is another approach that may provide useful data to maximize seizure control in patients with structural lesions (2).

CONCLUSION

We have used these mapping techniques in nearly three hundred patients with primary and metastatic tumors of the Central Nervous System. This has allowed us to perform more aggressive surgical resections within and adjacent to functional cortical and subcortical tissue. Although SSEPs may be used to localize Rolandic cortex reliably (7,14,26), we prefer the method of direct stimulation mapping first described by Fritsch and Hitzig (11) and later popularized by Penfield and Boldrey (19). SSEPs may be indispensible, however, in young children to localize the Central sulcus. Language mapping requires the greatest time commitment during surgery, as the surgeon must become well versed in recognizing errors in naming and speech arrest upon repetitive stimulation. Using ECoG, seizure control is greatest in patients with intractable epilepsy when separate seizure foci are identified and removed along with the tumor nidus.

REFERENCES

1. Ammirati M, Vick N, Liao I, et al: Effect of the extent of sugical resection on survival and quality of life in patients with supratentorial glioblastomas and anaplastic astrocytomas. Neurosurgery 21: 201-206, 1987.
2. Awad IA, Rosenfeld J, Ahl J: Intractable epilepsy and structural lesions of the brain: Mapping, resection strategies, and seizure outcome. Epilepsia 32: 179-186, 1991.
3. Berger MS, Tucker A, Spece A, et al: Reoperation for Glioma. Clinical Neurosurgery, in Press.
4. Berger MS, Ojemann, GA, Lettich E: Neurophysiological monitoring during astrocytoma surgery. Neurosurgery Clinics of North America 1:65-80, 1990.
5. Berger MS, Kincaid J. Ojemann GA, et al: Brain mapping techniques to maximize resection, safety, and seizure control in children with brain tumors. Neurosurgery 25: 786-792, 1989.
6. Berger MS, Ghatan S, Geyer JR, et al: Seizure outcome in children with hemispheric tumors and associated intractable epilepsy: The role of tumor removal combined with seizure foci resection. Pediatric Neurosurgery, in press.
7. Black PMD, Ronner S: Cortical mapping for defining the limits of tumor resection. Neurosurgey 20: 914-919, 1987.
8. Cascino GD: Epilepsy and brain tumors: Implications for treatment. Epilepsia 31: S37-S44, 1990.
9. Ciric I, Ammirati M, Vick N, et al: Supratentorial gliomas: Surgical considerations and immediate postoperative results. Neurosurgery 21: 21-26, 1987.
10. Drake J, Hoffman HJ, Kobayashi J, et al: Surgical management of children with temporal lobe epilepsy and mass lesions. Neurosurgery 21: 792-797, 1987.
11. Fritsch G, Hitzig E: Verber die electricle erregbarkeit des grosshirns. Arch Anat Physiol Wissen, p.100, 1870.
12. Goldring S, Rich KM, Picker S: Experience with gliomas in patients presenting with a chronic seizure disorder. Clinical Neurosurgery 33: 15-42, 1896.
13. Gonzales D, Elvidge AR: On the occurrence of epilepsy caused by astrocytoma of the cerebral hemispheres. J Neurosurg 19: 470-482, 1962.

14. Gregorie EM, Goldring S: Localization of fuction in the excision of lesions from the sensorimotor region. J Neurosurg 61: 1047-1054, 1984.

15. Haglund MM, Berger MS, Kunkel DD, et al: Changes in GABA and somatostatin in epileptic cortex associated with low-grade gliomas. J Neurosurg, in press.

16. Hochberg FH, Pruitt A: Assumptions in the radiotherapy of glioblastoma. Neurology 30: 907-911, 1980.

17. LeRoux PD, Berger MS, Haglund MM, et al: Resection of intrinsic tumors from nondominant face motor cortex using stimulation mapping: report of two cases. Surg Neurol 36: 44-48, 1991.

18. Ojemann GA, Ojemann J, Lettich E: Cortical language localization in left, dominant hemisphere. J Neurosurg 71: 316-326, 1989.

19. Penfield W, Boldrey E: Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. Brain 60: 389-443, 1937.

20. Quigley MR, Maroon JC: The relationship between survival and the extent of the resection in patients with supratentorial malignant gliomas. Neurosurgery 29: 385-389, 1991.

21. Rostomily RC, Berger MS, Ojemann GA: Postoperative deficits and functional recovery following removal of tumors involving the dominant hemisphere supplementary motor area. J Neurosurg 75: 62-68, 1991.

22. Spencer DD, Spencer SS, Mattson RH, et al: Intracerebral masses in patients with intractable partial epilepsy. Neurology 34: 432-436, 1984.

23. Wada J, Rasmussen T: Intracarotid injections of sodium amytal for lateralization of cerebral speech dominance. J Neurosurg 17: 266-282, 1960.

24. Wallner KE, Galicich JH, Krol G, et al: Patterns of failure following treatment for glioblastoma multiforme and anaplastic astrocytma. Int J Radiat Oncol Biol Phys 16: 1405-1409, 1989.

25. Wood CC, Green JB, Shapiro WR: The prognostic importance of tumor size in malignant gliomas: A computed tomographic scan study by the Brain Tumor Cooperative Goup. J Clin Oncol 6: 338-343, 1988.

26. Woolsey CN, Civodosan TC, Gibson WE: Localization in somatosensory and motor areas of human cerebral cortex as determined by direct recording of evoked potentials and electrical stimulation. J Neurosurg 51: 476-506, 1979.

STEREOTACTIC MRI-GUIDED INTERSTITIAL LASER THERAPY OF BRAIN TUMORS

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Three technical advances have significantly changed our ability to resect intrinsic brain tumors. Contemporary neuroimaging has improved the ability to visualize the living human nervous system. MRI can distinguish between tumor and edema, and can also establish the relationship between tumor and surrounding blood vessels by three-dimensional reconstruction techniques.

The ability to couple this imaging with manipulation has advanced neurosurgery as much as imaging itself has advanced the art of neurological diagnosis. Using a variety of stereotactic frames, it has been possible to localize virtually any lesion within the brain. Thus localization techniques have been accompanied by major advances in tumor diagnosis and resection.

Several indirect techniques have been used to establish the site of a tumor, its size and configuration, and completeness of its removal: these include ultrasound and stereotactic surgery using the Leksell, Brown-Roberts-Wells, Cosmann-Roberts-Wells, or other systems. These can be coupled with visualization systems to produce targeting systems.

A third technological advance over the last decade has been the laser as a source of energy and for extirpation of tumors. The CO_2 laser is limited in its hemostatic capabilities, and although it is a very effective vaporizing device is not effective in stopping bleeding. The neodymium YAG laser is much more effective for this but has the difficulty that its energy penetrates much deeper than can be visualized; thus its damage cannot be seen readily by the naked eye.

Technology presently being developed at Brigham and Women's Hospital combines these three trends in neurosurgical management to create real time image-directed neurosurgery. In this system the MRI is used to image the abnormality, the stereotactic system is used to direct the resection device, and a YAG laser is used to deliver energy. Closing the loop, the MR is used to image the tissue changes caused by the YAG laser.

As part of this effort there is presently underway an investigation of stereotactic technology that will work without placement of the stereotactic frame. This technology uses the MR scanner itself, or other external fiducials, to guide localization of the lesion, avoiding the discomfort of frame placement.

Date for this concept have developed in two different models. The first is a prolactinoma model in Fischer 344 rats. The implantation of estrogen seeds under the skin of such rats is followed by hyperplasia of the anterior pituitary gland. After 60 days this hyperplasia becomes autonomous and the resulting tumor evolves to kill the animal despite the removal of the estrogen implant.

For our studies rats were allowed to develop the autonomous tumor and a YAG laser was placed in the center of it using stereotactic methodology and a rat frame. The YAG laser was then used as an energy source delivered through an optical fiber. The tissue damage could be visualized with the laser as two shadows, the first with apparent necrosis and a surrounding rim of shadowed reversible change. The rats were sacrificed at varying periods after this. Histologic evaluation demonstrated that there were discrete lesions with edema around them, confirming the sharp margins of the lesion. The central concept is that the MR can be used in this circumstance to visualize directly the lesion itself and therefore can be a major change: tissue changes can be appreciated in this setting.

A second series of experiments evaluated the effect of neodynium YAG laser on C6 gliomas of varying stages in rats. The C6 gliomas is an astroglial neoplasm which infiltrates diffusely. Two weeks after implantation of gliomas cells rats had implantation of the YAG laser fiber using the same coordinates as the original implanting device for tumor. The laser was then activated for periods of up to 45 seconds and the effect of heating could be observed very readily. Three zones were identifiable in the heating: the first was the necrotizing area, which on subsequent pathology demonstrated destruction of tissue completely; the second was a surrounding region of high signal which indicated tissue that would demarcate as being an area which would ultimately be necrotic; and finally a general region of edema which will ultimately resolve.

These preliminary data suggest that the concept of using MRI technology to monitor the lesion created by a laser or other energy source is a viable one and presently preliminary studies are underway to establish the longterm feasibility of such an approach.