Technologic Advances in Surgery for Brain Tumors: Tools of the Trade in the Modern Neurosurgical Operating Room

Christopher M. McPherson, MD, and Raymond Sawaya, MD

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Abstract
Surgery is an essential part of the oncologic treatment of patients with brain tumors. Surgery is necessary for histologic diagnosis, and the cytoreduction of tumor mass has been shown to improve patient survival time and quality of life. Ultimately, the goal of any oncologic neurosurgery is to achieve maximal safe resection. Over the years, many technologic adjuncts have been developed to assist the surgeon in achieving this goal. In this article, we review the technologic advances of modern neurosurgery that are helping to reach this goal. (JNCCN 2005;3:705–710)

The surgical treatment of brain tumors has advanced considerably. The addition of the operating microscope, computed tomography (CT), and magnetic resonance imaging (MRI) brought neurosurgery into the modern era and allowed the safe surgical treatment of tumors throughout the central nervous system. Technologic advances over the past 20 years have gone even farther to assist the neurosurgeon in achieving the goals of neurosurgery. Ideally, these goals include the ability to remove the entire gross tumor using the smallest, least invasive approach possible, leaving the patient without worsening neurologic deficits. In this article, we discuss how the tools of modern neurosurgery, although not without disadvantages, are helping to make these goals possible.

Frameless Stereotaxis
To accomplish an effective resection, the tumor must first be localized in relationship to the scalp, and the approach must be planned so as not to harm functional areas of the brain. This goal remains the same whether the tumor is on the surface of the brain or in deep-seated structures such as the pineal gland, thalamus, or brainstem.

However, accurate localization of lesions has long been a problem in neurosurgery. In 1908, Horsley and Clarke1 developed a system using a fixed frame attached to the patient's head to better define a coordinate system for the brain that could then be compared to an atlas for localization of specific structures. The advent of the frame and frame-based stereotaxis changed neurosurgery forever. The frame, however, is not without limitations. The frame itself can be bulky, uncomfortable for the patient, and restrictive for the surgeon. In addition, frame-based stereotaxis is most useful for designating a point and the trajectory to it, such as in a biopsy. It is not as good at helping to identify the 3-dimensional relationships needed for a volumetric resection.

Advances in computer technology and digitization led to the development of what is now referred to as frameless stereotaxis. Frameless stereotaxis uses the addition of computer technology to achieve the same results as frame-based stereotaxis, but without the added difficulties and inconveniences of the frame. In addition, frameless stereotaxis allows the surgeon greater freedom of localization and the ability to visualize 3-dimensional representations of a lesion in space, through computer models.
Frameless stereotaxis works as follows: A patient with a brain tumor undergoes preoperative imaging (usually MRI, although CT can be used) with markers (fiducials) containing a contrast-enhancing agent placed on the head. These images are then digitized and sent to a computerized system. In the operating room after anesthesia is induced, the patient's head is fixed to the operating room table, and registration is performed using a probe with light-emitting diodes (LEDs) that can be detected by a camera attached to the computerized system. The computer then matches the fiducials as registered on the head to the fiducials on the MRI scan. After this, the surgeon can use the probe to locate the tumor and for surgical planning. This allows the surgeon to plan an accurate approach to the tumor before the incision is ever made and allows for smaller, more accurately placed incisions and smaller craniotomies.

Frameless stereotaxis has been widely reported and shown to be both accurate and effective for localization and planning surgical approaches to various intracranial lesions. It has been used for stereotactic biopsy as well as for stereotactic volumetric resection of tumors, although frame-based stereotaxis continues to be useful in some situations. For tumor resection, the surgeon can use frameless stereotaxis not only to localize the lesion but also to localize important structures, such as cortical veins that are important to avoid when planning the surgical trajectory. Frameless stereotaxis can also be used during resection to aid the surgeon in detecting tumor borders and ultimately can help the surgeon achieve a maximal resection (Figure 1).

Frameless stereotaxis also has limitations, however, mainly caused by the development of brain shift. Brain shift is a deformation of the brain caused by intraoperative changes from tumor resection, such as loss of cerebrospinal fluid, use of brain retractors, and brain swelling. Therefore, frameless stereotaxis becomes less accurate as the surgery proceeds, making it less useful for localizing residual tumor after most of the tumor has been resected. Despite this limitation, frameless stereotaxis has proved to be a useful adjunct for the neurosurgeon and is considered a standard neurosurgical tool in the modern operating room.

**Intraoperative Ultrasound**

Intraoperative ultrasound (IOUS) has gained widespread acceptance in neurosurgery and has been shown to offer significant benefits. IOUS is useful for lesion localization as well as for evaluating the progress of resection and determining if any residual tumor exists (Figure 2). The advantage of IOUS is that it gives real-time feedback and avoids the problems of brain shift that can alter the accuracy of frameless stereotaxis.

However, IOUS also has limitations. Because IOUS is ineffective at penetrating bone, unlike frameless stereotaxis, it is not useful for surgical planning before the craniotomy. IOUS is especially difficult to use for visualizing recurrent tumors and in patients who have already undergone radiation therapy because the tumor margin becomes indistinct, and it is difficult to distinguish tumor tissue from peritumoral edema. Also, blood and hemostatic products left in the tumor bed are difficult to distinguish from residual tumor. Despite these limitations, IOUS has proved to be a useful tool for both lesion localization and real-time localization of residual tumor, thereby assisting the surgeon in obtaining a maximal resection. In addition, IOUS has been combined with frameless neuronavigation technology to create a computerized neuronavigation system that can be used for image-guided tumor resection.

**Intraoperative MRI**

Both frameless stereotaxis and IOUS are useful tools to assist the surgeon in locating residual tumor intraoperatively to maximize resection, but both have disadvantages. Frameless stereotaxis image-guidance is limited to the images obtained preoperatively. Thus, no real-time update is available. The technique can also become less accurate as the resection proceeds, because of brain shift. IOUS provides real-time updates and avoids problems caused by brain shift, but ultrasound imaging does not provide the same resolution of detail as MRI.

Starting in the late 1990s, many medical centers developed different versions of intraoperative MRI designed to provide intraoperative updates on tumor resection using the gold standard for tumor imaging, MRI, as well as to update the frameless neuronavigation system to account for brain shift. In most cases, intraoperative MRI is used after the surgeon believes that maximal resection has been achieved, to confirm the degree of resection and to locate any residual tumor. Image information can then be transferred to update frameless stereotaxis. In a few instances, such as brain biopsy procedures and stereotactic...
aspirations, intraoperative MRI has been used in real-time to provide immediate feedback.\textsuperscript{16,17}

Intraoperative MRI has been shown to be most useful for the resection of intracranial tumors, especially gliomas and pituitary adenomas, and has been shown to increase the rates of gross-total or maximal resection.\textsuperscript{12–15} In addition, a recent retrospective review comparing patients with historic controls suggests that increased resection achieved with the use of intraoperative MRI led to an improvement in long-term survival rates in patients with low-grade gliomas.\textsuperscript{18}

Several disadvantages to intraoperative MRI exist, such as increased cost and longer surgical times. However, as intraoperative MRI has evolved, imaging technologies such as functional MRI, diffusion tensor imaging, and magnetic resonance spectroscopy have been added, all of which provide additional information useful to the neurosurgeon during resection.

Cortical Mapping

In addition to tools for localizing tumors and tools to assist with achieving maximal resection, techniques have been developed for mapping the brain’s cortex to assist the neurosurgeon in locating the areas of the brain that control critical sensory and motor functions (eloquent brain). These modern tools owe their development to pioneers from the late nineteenth and early twentieth centuries. Fritsch and Hitzig, Bartholow, Sir Victor Horsley, and Penfield and Boldrey played key roles in showing that electrical stimulation of the brain’s cortical surface evokes visible responses that enable the surgeon to minimize injury to eloquent brain regions during surgical resection of tumors.\textsuperscript{19}

Cortical mapping is performed either by direct cortical stimulation or via the monitoring of somatosensory evoked potentials (SSEP’s). Direct cortical stimulation is mostly used for speech mapping while the patient is awake, but it can also be used to directly stimulate the motor cortex during tumor resection. This has the advantage of allowing the surgeon to map descending motor pathways during the actual tumor resection. Cortical mapping with SSEP monitoring allows the surgeon to localize the sensorimotor cortex while the patient is under general anesthesia (Figure 3).

In several studies, SSEP mapping has been shown to be at least as useful for identifying the sensorimotor cortex as direct cortical stimulation.\textsuperscript{20–22} Today, both techniques are used for differing indications. For lesions near the motor strip, SSEP mapping helps to locate the sensorimotor cortex, allowing the neurosurgeon to plan a resection that will avoid worsening the patient’s neurologic function. Use of direct cortical stimulation during awake craniotomy is most practical for tumors in the dominant hemisphere that are close to eloquent speech areas, but it is also valuable for tumors that directly involve portions of the sensorimotor cortex, such as low-grade gliomas. The neurosurgeon can obtain direct

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\caption{Preoperative T1-weighted contrast-enhanced magnetic resonance (MR) image of a 55-year-old man with a history of seizures who was found to have a large glioblastoma multiforme in the left frontal lobe (Left). The postoperative T1-weighted contrast-enhanced MR image shows gross-total resection of the lesion (Right).}
\end{figure}
feedback during the resection by performing direct cortical and subcortical stimulation. Cortical mapping has become an essential tool for the neurosurgical oncologist for achieving the goal of maximal tumor resection without worsening the patient’s neurologic status.

**Endoscopy**

Attempts to use endoscopes as adjuncts to neurosurgery have been made since at least the 1920s, when both Dandy and Mixter used urological endoscopes for ventriculoscopy.\(^{23,24}\) Over the years, endoscopic technology has improved, allowing for smaller fiberoptic scopes with better image quality. In addition, the availability of endoscopes with greater flexibility that offer a view from various angles (allowing neurosurgeons to effectively “see around corners”) and endoscopes with working channels for suction, monopolar cautery, and grasping instruments, has increased the utility of neuroendoscopy, although some concerns regarding control of bleeding remain.

Endoscopes are most suited for procedures within the brain’s ventricles, where a natural anatomic space affords excellent working room as well as good light and image transmission. Endoscopic third ventriculostomy has become an accepted alternative to ventriculoperitoneal shunting, with low risk to the patient and proved efficacy.\(^{25}\) In addition, endoscopic techniques have been effectively applied to the resection of colloid cysts.\(^{26,27}\) In one series comparing endoscopic resection of colloid cysts with open resection, patients undergoing the endoscopic procedure had shorter operating room times, shorter hospitalizations, fewer complications, and less risk of needing to undergo ventriculoperitoneal shunting.\(^{27}\) Other ventricular applications include tumor biopsy, tumor cyst aspiration, and (in some cases) solid tumor resection.\(^{26}\)
Endoscopes have also been used in resection of pituitary tumors. Otolaryngologists have a long history of using endoscopes for sinonasal procedures, even more so than neurosurgeons. This and the common partnership between neurosurgeons and otolaryngologists for transsphenoidal procedures has led to the development of an endonasal endoscopic procedure that allows access to the sellar compartment without disrupting the nasal mucosa. This endoscopic approach has been shown to be comparable to the microsurgical approach in terms of patient safety and efficacy. Furthermore, the endoscopic approach has the advantage of reducing patient discomfort by eliminating nasal packing and shortening hospital stay.

Other applications of neuroendoscopy include endoscope-assisted procedures. Because endoscopes have varying angles of view, they can be used to look around corners and into surgical blind spots to detect and remove tumor tissue that otherwise might be left behind. This is especially effective for tumors located in the cerebellopontine angle and suprasellar region. Also, newer so-called “minimally invasive” approaches are being developed that use endoscopes to minimize brain retraction. The keyhole supraorbital approach has documented the use of endoscopes for resection of suprasellar tumors, including craniopharyngiomas and pituitary adenomas, through an incision over the eyebrow and a small craniotomy.

Robotics
The burgeoning field of modern surgical technology is surgical robotics. Robots have numerous advantages applicable to surgical procedures. They can perform with precision that exceeds human capacity with microscopic assistance. They can counteract the normal human tremor and magnify surgical movements, allowing for levels of dexterity never encountered before. In addition, robots are relatively impervious to biohazards and can work in locations distant from the surgeon. Thus, robots are being considered for potential medical use on the International Space Station. Robotics has been most successfully applied to cardiothoracic, abdominal, and prostate surgical procedures. The da Vinci system (Intuitive Surgical, Inc., Sunnyvale, CA) is the most well-known system currently approved. Although robotics has not been as widely accepted in neurosurgery, potential applications exist. Systems are being developed that would allow work within an intraoperative MRI system, with the advantage of allowing the surgeon to perform fine microneurosurgery from outside of the MRI field.

Conclusions
The neurosurgical operating room today uses many technologically advanced tools that would have seemed like science fiction only 25 years ago. By combining these tools, the neurosurgeon can more accurately localize lesions, perform surgery with smaller incisions and craniotomies, and more safely achieve maximal tumor resection. The ultimate goal of every oncologic neurosurgeon is to be able to stealthily remove a tumor without the patient’s knowing he or she was there. In the future, technology will no doubt play...
an even larger role in neurosurgery, ultimately improving the outcomes for patients in general.

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References