Transcranial Minimally Invasive Neurosurgery for Tumors

Mark Garrett, MD, Giacomo Consiglieri, MD, Peter Nakaji, MD*

KEYWORDS

• Neuroendoscopy • Neurosurgery • Transcranial • Minimally invasive

The concept of a "minimally invasive approach," when applied to neuro-oncological surgery, continues to excite controversy. The debate over what type of approach should be used often hinges on whether a small craniotomy is intrinsically less invasive or whether a larger craniotomy results in less morbidity and therefore is a more appropriate choice. The most common goals of neuro-oncological surgery are to obtain a diagnosis, to achieve maximum tumor reduction, and to avoid neurologic deficits. Whether these goals can be accomplished as well as or better through minimally invasive approaches often cannot be answered meaningfully without large and well-designed clinical studies, which are as lacking in this field as in many other fields of neurosurgery. A similar problem exists for the related field of endoscopic intracranial extraventricular surgery in general.

The avid practitioner of minimally invasive and endoscopic neurosurgery often wryly considers the history of microneurosurgery, in which pioneer users of the operating microscope, such as Kurze, Pool, and Yasargil, had to convince skeptical colleagues of the value of microscopy, which is now accepted as a standard of care in many cases. Adherents to the minimally invasive philosophy believe that excellent outcomes can be achieved by coupling keyhole approaches and the endoscope in cases traditionally approached through larger craniotomies. In this age, the idea of a tailored craniotomy that exactly fits the pathologic condition, rather than a standard or one-size-fits-all approach, should not seem revolutionary. As for the endoscope, it is simply a tool for enhancing visualization. Neurosurgeons should welcome any tool that improves visualization.

This article discusses common minimally invasive craniotomy approaches and the role of neuroendoscopy in the removal of extra-axial and intra-axial brain tumors, excluding those of the ventricle. The use of the transsphenoidal and extended transsphenoidal approaches is considered only briefly, because they are addressed elsewhere in this issue.

HISTORY

Minimally invasive cranial neurosurgery represents a history of challenges and periodic successes. For decades, the primary concern of neurosurgery has been to minimize the neurovascular impact of surgery. Adequate exposures, which have usually

Division of Neurological Surgery, Barrow Neurological Institute, St Joseph's Hospital and Medical Center, 350 West Thomas Road, Phoenix, AZ 85013, USA
* Corresponding author. c/o Neuroscience Publications, Barrow Neurological Institute, 350 West Thomas Road, Phoenix, AZ 85013.
E-mail address: neuropub@chw.edu

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meant large exposures, were seen as the key to good outcomes. Skull base microsurgery developed around the belief that better outcomes are achieved by moving bone and soft tissue rather than brain and nerves. The minimally invasive neurosurgery paradigm evolved out of the recognition by many surgeons that, in many cases, they did not use or need much of the exposure provided by extensive approaches, and they began to seek alternatives to the soft tissue trauma, healing, and recovery time involved with extensive approaches. To this end, a few pioneers began to explore smaller approaches to achieve the same neurosurgical goals.

One such approach, the supraorbital transbrow craniotomy, was an adaptation of the orbitozygomatic approach first proposed by Jane and colleagues.[1,2] Popularized by Reisch and Perneczky[4] and by Jho,[3] the technique has become widely practiced by some schools of neurosurgery but has not been accepted universally. The minimally invasive keyhole principles promulgated by these practitioners have gradually been applied to other areas of cranial neurosurgery, where they excite ongoing debate.

Neuroendoscopy has been the foundation of many minimally invasive approaches, although it too has had an on-again, off-again history. In neurosurgical terms, most of the applications of neuroendoscopy proposed to date have been focused on addressing intraventricular pathologies.[5] The first description of a neuroendoscopy procedure was by L'Espinasse in 1910. As described by Walker,[6] L'Espinasse cauterized the choroid plexus in 2 hydrocephalic infants with the assistance of a cystoscope. Dandy[7] described his use of the endoscope to remove the choroid plexus, with results that were similar to those of his experience with formal craniotomy for open choroid plexectomy. The growth of neuroendoscopy was slowed by the significant limitations associated with the lighting and magnification available for early endoscopes. Furthermore, the advent of ventricular shunts and advances in microneurosurgery reduced interest in neuroendoscopy.

In the 1960s and 1970s, technological advances in lens development and the application of fiberoptics improved neuroendoscopic visualization significantly. In 1963, Guiot and colleagues[8] used ventriculoscopy to explore a patient with a colloid cyst. In 1973, Fukushima and colleagues[9] described the first ventricular biopsy. In 1983, Powell and colleagues[10] reported the first endoscopic resection of a colloid cyst, and the technique was popularized throughout the late 1990s.[11–13] The use of endoscopy to address selected intraventricular tumors for biopsy or resection is now a widely accepted therapeutic option.[5]

Subsequently, the application of minimally invasive principles and endoscopy to extra-axial tumors was popularized by Perneczky and Fries.[14] They promoted the endoscope as a means to minimize retraction on the brain and to avoid resection of the dura and bone, which they argued increased operative time and operation-related trauma. In 1998, Fries and Perneczky[15] reported 380 endoscope-assisted cases, 242 of which involved either the subarachnoid space or the cerebral parenchyma. The investigators found that endoscopy improved visualization of perforators during aneurysm surgery and permitted exploration of the ventral brainstem, ventral side of cranial nerves, and ventral aspect of the cervical spine while minimizing retraction. They reported no complications associated with the use of the endoscope itself.

Endoscopic transsphenoidal surgery has been the largest area of recent growth in neuroendoscopy. The field was pioneered by Guiot and colleagues,[8] although Guiot later abandoned it because visualization was poor. In the 1970s the use of neuroendoscopy was again reported[16,17] as an adjuvant to transsphenoidal microneurosurgery, but it was not until 1992 that Jankowski and colleagues[18] reported a purely endoscopic transsphenoidal approach to the sella turcica. Jho and Carrau,[19] who are considered early pioneers of the field, reported 46 purely endoscopic endonasal procedures in 1997. This area continues to expand rapidly, with an increasing number of intradural lesions being approached through an endonasal route. This topic is explored more fully elsewhere in this issue.

The most recent intracranial application of neuroendoscopy is endoscopic resection of intraparenchymal brain tumors. In 2008, Greenfield and colleagues[20] described the use of METRx tubular retractors (Medtronic Inc, Memphis, TN, USA) in combination with frameless stereotactic navigation for complication-free removal of 10 deep lesions. The next year, Kassam and colleagues[21] reported the use of a nonfixed transparent conduit to remove 21 subcortical lesions with no new neurologic complications.

The forays from the ventricles into the subarachnoid and intraparenchymal spaces hardly constitute a mature field. However, these forays are an intriguing direction for minimally invasive neurosurgery. The remainder of this article considers the current state of and future applications for minimally invasive and neuroendoscopic neurosurgery beyond the intraventricular and endonasal routes.

INDICATIONS

The general indications for a minimally invasive approach are the same as those for any other neurosurgical approach to a given tumor. Often the decision to use a keyhole approach depends more on the specific pathologic condition and on the practitioner's experience than on any other factor. Although use of the endoscope depends entirely on the specifics of a case, the addition of the endoscope is often complementary in many keyhole approaches.

The appropriate trajectory is the single most important factor in the success of a minimally invasive tumor approach. Various factors must be considered: (1) the planned extent of resection for the tumor being addressed (complete removal vs debulking vs biopsy); (2) the nature of the tumor involved, particularly the distinction between the tumor and normal brain tissue; (3) the vascularity of the tumor and whether vascular control can be achieved from the chosen trajectory; (4) the surface structures that will be penetrated and whether cosmesis or intervening structures (eg, venous sinuses or bony sinuses) may force deviation from an otherwise ideal trajectory; and (5) the depth of the tumor, which at times can prevent the lesion from being accessed via a small craniotomy. The 2-point method is a simple technique for estimating the best trajectory.[22] A point is placed at the geographic center of the lesion, and a second point is placed where the lesion comes closest to the surface. A line drawn through these 2 points to the surface of the head constitutes the best approach trajectory, subject to modification by the previously mentioned considerations.

The absolute minimum size of the craniotomy is constrained by the instruments that will be used, but it typically is no smaller than the size of an open bipolar forceps.

NEUROENDOSCOPY: APPROACH OR ADJUNCT?

The decision to apply neuroendoscopy to a given tumor surgery requires a major distinction to be made, that is, whether the operation is endoscopically controlled, whereby the endoscope is the sole or primary means of visualization, or whether it is endoscopically assisted. In the latter, microsurgical techniques are the mainstay of dissection and tumor resection, while endoscopy is used to help visualize areas of the tumor that are otherwise difficult to see with the uniaxial view provided by the operative microscope. Endoscopy is also used to examine the tumor bed for completeness of resection. With image injection, endoscopic images can be inserted into the microscope eyepiece, allowing both to be used together. Many surgeons, however, find this technique to be distracting.[23]

Endoscopically controlled techniques have become the approach of choice for many neurosurgeons for transsphenoidal surgery.[24–28] In most of these applications, the microscope is never used during the operation. A completely endoscopic surgical approach is less commonly used during transcranial neurosurgery. The nose is lined with mucosa, and the risk of damaging structures as one passes instruments is low. Two surgeons can work in concert, introducing and removing instruments with ease. In the cranium, the corridor to the tumor is often lined with brain and neurovascular structures, which poorly tolerate even slight manipulation by passing endoscopes or instruments. Furthermore, the microscope provides an excellent view in a direct line and frees both hands to participate in the dissection. In contrast, in these applications the endoscope often occupies the space of 1 instrument and must be held by the primary surgeon. Therefore, the endoscope tends to be used in a supporting role after access is obtained through microneurosurgery.

However, with a holder or a good assistant, 2-handed work is possible through the endoscope. The instruments are introduced along the endoscope and kept just in front of its tip so that they are always in view. This technique differs from the purely endoscopic approach, in which the instruments travel through the shaft of the endoscope, as is common in intraventricular endoscopic surgery. In the endoscopically assisted technique, the endoscope can be used in multiple stages to inspect the approach, better define the anatomy, see parts of the tumor not in the direct line of vision, and inspect the tumor bed for residual tumor. Particularly, when combined with minimally invasive approaches, smaller craniotomies, and an effort to preserve overlying neural structures, the advantage of the endoscope for working in small spaces and for seeing angles perpendicular to the line of sight can be invaluable. In some instances, both intracranial extra-axial and intra-axial tumors have been removed without the use of the microscope in an endoscopically controlled fashion, but doing so remains relatively unusual.

During tumor resection, the endoscope may be valuable for removing a small amount of residual tumor in a difficult location. For example, Chang and colleagues[29] reported the use of the endoscope to remove the last fragments of a large ecchordosis physaliphora from the clivus that could not be seen with the microscope.

EQUIPMENT

For endoscopically assisted or endoscopically controlled tumor surgery, handheld endoscopes are used and usually held in the nondominant hand or in a rigid holder. Various endoscopes are available. In the authors' opinion, the most suitable endoscope for endoscopically assisted intracranial surgery is the Perneczky endoscope. The right-angle pistol-grip configuration of this endoscope allows it to be held comfortably in the hand for long periods. The rigid shaft of the endoscope allows precise control of its position.

The endoscope is usually held in one hand while the other hand is used for working. An assistant can also hold the endoscope, freeing the surgeon to work with both hands. If needed, the endoscope can be fixated with the use of one of many available retractor arms (see another article elsewhere in this issue). Many other types of endoscopes can be used for endoscopically assisted or endoscopically controlled work. The main issue is ergonomic: it is helpful to have an endoscope that stays out of the way so that other instruments can be used simultaneously. At minimum, an appropriately sized suction device is a necessary second instrument. If possible, 2 additional instruments offer greater surgical possibilities.

New technologies continue to improve the image produced by endoscopes. For example, with the appropriate endoscope, viewing apparatus, and image processing, a 3-dimensional image can be produced. The surgeon can then view the image with the aid of polarized glasses. As an alternative to standard-definition video, new high-definition images are available and more closely approximate the view that most neurosurgeons are familiar with from the operating microscope.

In addition to endoscopes, specialized instruments are helpful for minimally invasive cranial work, regardless of whether the work is performed with an endoscope or microscope. These instruments include narrow-shafted bipolar instruments; various slim dissectors; and single-shafted bayoneted scissors, pituitary forceps, and graspers. Angled dissectors, bipolar forceps, and a suction device that can operate around corners are highly advantageous. Without these instruments, the endoscope may reveal areas of residual tumor that remain out of reach due to the working angles available to straight-shafted instruments.

OPERATING TECHNIQUE

The principal issue for operating with the endoscope is maintaining the appropriate orientation. The novice endoscopist may find the view from the endoscope disorienting compared with the view provided by the microscope. This problem improves with experience. Familiarizing oneself with the endoscopic view during laboratory or practical courses is invaluable. Looking at known objects through the endoscope also can help one to adapt more rapidly to the endoscopic perspective.

In general, the endoscope is held in the nondominant hand and the working instrument or suction is held in the dominant hand. A 30° endoscope is most often used. This endoscope provides enough of an angle to be useful for looking around corners while still allowing the user to see straight ahead. Each time instruments are introduced into the field, the endoscope is removed so that the instruments can be followed into the head. This strategy prevents conflicts between the instruments and neurovascular structures.

The angled endoscope is readjusted alternately to inspect each direction where additional visualization is needed. Each time such an adjustment is made, the endoscope is withdrawn from the head, the angle is changed, and the endoscope is reinserted to prevent the tip from wandering into structures as the endoscope is rotated.

Tumor removal proceeds in a standard fashion, either with the use of the endoscope or with microsurgical instruments, such as scissors, a bipolar device, and dissectors. The endoscope is especially used at the end of surgery to check the completeness of resection and repair.

MINIMALLY INVASIVE CRANIOTOMIES

Various craniotomies are classified as keyhole approaches. The keyhole approach is usually defined by comparison to an alternative conventional craniotomy. For example, an eyebrow supraorbital craniotomy is a variation of the pterional or orbitozygomatic approach. A keyhole subtemporal approach is a variation of the traditional temporal approach. The important intellectual distinction between a conventional craniotomy and a keyhole approach is that in a conventional craniotomy, the size of the opening is typically larger than the target, with its circumference contracting as the depth of the approach increases. In a keyhole craniotomy, the surface opening can be smaller than the target, and the target is completely exposed by subtending different angles of approach (**Fig. 1**). Any approach may be made more minimally invasive by making an opening that requires the surgeon to take advantage of the various angles of view offered compared with a single trajectory. When no surface opening can expose the target without undue manipulation of neurovascular structures, the endoscope may offer additional opportunities for exposure.

The retrosigmoid approach is a common craniotomy that many neurosurgeons are familiar with as a keyhole approach. The surface opening is often modest because of the constraints of the local anatomy. The target is often deep. The cranial nerves are laid out in a "picket fence," that is, their exposure from top (usually the trochlear nerve) to bottom (spinal accessory nerve) can best be achieved by sweeping the view from one side to the other through the craniotomy. In the hands of many surgeons, only a very small craniotomy (often of the order of 1 cm or slightly more) is necessary to expose this region.

Fig. 1. Two hypothetical masses at different depths show the effect of depth on the cranial opening required. In the example on the left, the mass is deeply located and the craniotomy shown is therefore more than adequate to allow it to be exposed through a small cortical opening. Although the more superficial lesion located on the right is of the same size as the lesion on the left, full use of the same size craniotomy and an even larger cortical opening are needed. (*Courtesy of* Barrow Neurological Institute, Phoenix, AZ.)

Supraorbital Eyebrow Craniotomy for Tumors

Different names have been given to the craniotomy made through an incision in or around the eyebrow, such as the supraciliary, transbrow, transciliary, and supraorbital, among others.[3,4,30–34] Regardless of the name, it consists of an incision in the eyebrow through which a low frontal craniotomy is made, with or without removal of the orbital rim. The approach can be used to access the frontal pole, subfrontal region, suprasellar region, and retrosellar region. In most cases, the supraorbital approach can substitute for the orbitozygomatic approach and its variants.[4,34]

A prototypical tumor for which this approach can be considered is the craniopharyngioma,[35] for which various approaches have been applied. In general, a simple distinction determines the best route to the tumor. For retrochiasmatic and predominantly sellar or suprasellar tumors, the endonasal approach is preferred. For prechiasmatic tumors, a supraorbital eyebrow approach is usually preferred.[36–38]

Meningiomas, which involve neurovascular structures in the anterior cranial fossa, are usually best approached from above. The more posteriorly the meningiomas are located in the anterior cranial fossa, the more amenable they are to removal via an eyebrow approach because the olfactory groove tends to remain below the plane of the roof of the orbit, which may obstruct the access from an eyebrow craniotomy. If there is no attachment between a midline tumor and the anterior cerebral artery complex or optic nerves, the lesion also can be approached via an endonasal approach.

The access afforded by the eyebrow craniotomy is usually restricted to the anterior cranial fossa and to the structures immediately deep to the fossa in the upper basilar trunk and basilar cisterns. The incision cannot easily be extended laterally for these reasons: (1) the nature of overlying soft tissues, (2) a desire to avoid transecting too much of the temporalis muscle transversely, and (3) cosmetic concerns related to the consequences of sectioning the frontalis branch of the facial nerve. Therefore, the eyebrow craniotomy is not favored for lesions that fall below the sphenoid wing or that lie in the lower mesial temporal region. As noted, the olfactory groove can be accessed, but doing so is awkward at its most anterior reaches.

Transfalcine and Transtentorial Approaches

The principles of minimally invasive neurosurgery support not just smaller openings but also ones with less impact on neurovascular structures. For lesions located deep to the convexities of the skull and adjacent to the falx cerebri or tentorium, the option of crossing these structures has advantages. The patient should be positioned so that the brain on the side of the entry falls away from the dural fold by gravity so that gravity brings the target closer to the falx or tentorium. A small craniotomy then provides access to the gap between the brain and dural fold, and image guidance can be used to localize the lesion. The falx or tentorium can be opened and the lesion accessed, often without traversing any normal brain tissue (**Fig. 2**). Neuroendoscopy is often helpful for full evacuation of the extent of such resections, because the working angles are limited by the dura or by neurovascular structures that must be preserved.

Minimally Invasive Craniotomy for Removal of Intra-axial Brain Tumors

Minimally invasive craniotomies are well suited for addressing intra-axial pathologies. Regardless of its size, the deeper into the brain that any lesion lies, the smaller the arc that must be subtended to access it (**Fig. 3**). A larger craniotomy often merely exposes a larger area of the brain to potential harm. The chief concern is usually the brain tissue that must be transversed to reach the tumor, and this concern is the same for both minimally invasive craniotomies and conventional openings. The endoscope can be used to work within the cavity, allowing the surface opening to be even smaller.

To aid with exposure, various tubular retractors are available for access to deep tumors.[20,39] A tubular retractor has theoretical advantages because its placement should require a smaller scalp and bone opening and be less traumatic to transgressed brain tissue compared with the placement of conventional retractors. Tubular retractors also can facilitate the removal of intra-axial lesions in an endoscopically controlled fashion. Kelly and colleagues[40] pioneered the stereotactic tubular retractor system for resection of deep brain tumors. Otsuki and colleagues[41] described a method of using a similar retractor fixed to a Leksell stereotactic frame. The tube had a side port through which the instruments were placed for tumor resection. The investigators achieved gross total resection of 7 small lesions and partial resection of 8 larger lesions. Other than transient aggravation of hemiparesis in 1 patient, there were no significant complications.

More recently, Kassam and colleagues[21] reported their results after intra-axial resection of 21 lesions, including 12 metastases, 5 glioblastomas, 3 cavernous malformations, and 1 hemangioblastoma, using only the endoscope. Gross total resection was achieved in 8 cases, near-total resection in 6 cases, and subtotal resection in 7 cases. There were no complications directly caused by the use of the endoscope and no postoperative hematomas, worsened neurologic deficits, or postoperative seizures. As the investigators discussed, there are 2 keys to resecting intra-axial lesions with the endoscope in this manner. First, the retractor must be dynamic and capable of being placed at multiple angles to see different views of the lesion. Second, the tubular retractor must be a conduit that allows bimanual use of instrumentation so that tumor can be resected using standard microsurgical techniques.

Similarly, Akai and colleagues[42] used a clear tubular retractor to remove intrinsic brain tumors from 3 patients. The tube was integrated with image guidance. The investigators were able to perform biopsy and coagulate tissue but noted that limitations associated with the instruments for coagulation limited the scope of what they could accomplish surgically. This point highlights that the evolutionary goal of minimally invasive approaches must be bimanual surgery with techniques that are equal to or better than traditional microsurgical techniques.

Although tubular retractors have their advocates, they are not entirely essential for endoscopically assisted minimally invasive resection of intrinsic tumors. In some cases, the working cavity is created as tumor removal proceeds. However, these studies do demonstrate that endoscopically controlled removal of intra-axial tumors is feasible in appropriately selected patients. Whether it will prove an improvement on prior techniques remains to be seen.

OUTCOMES

The literature on clinical outcomes after resection of intra- or extra-axial lesions of the cranium is sparse. Most data are in the form of case reports or small retrospective reviews. Given the paucity of conclusive outcome data, it is difficult to compare endoscopic neurosurgery with standard microneurosurgical techniques. To date, no studies have conclusively demonstrated the superiority of the endoscopic approach for tumor removal. Nevertheless, a review of the literature offers some insight into the progress of

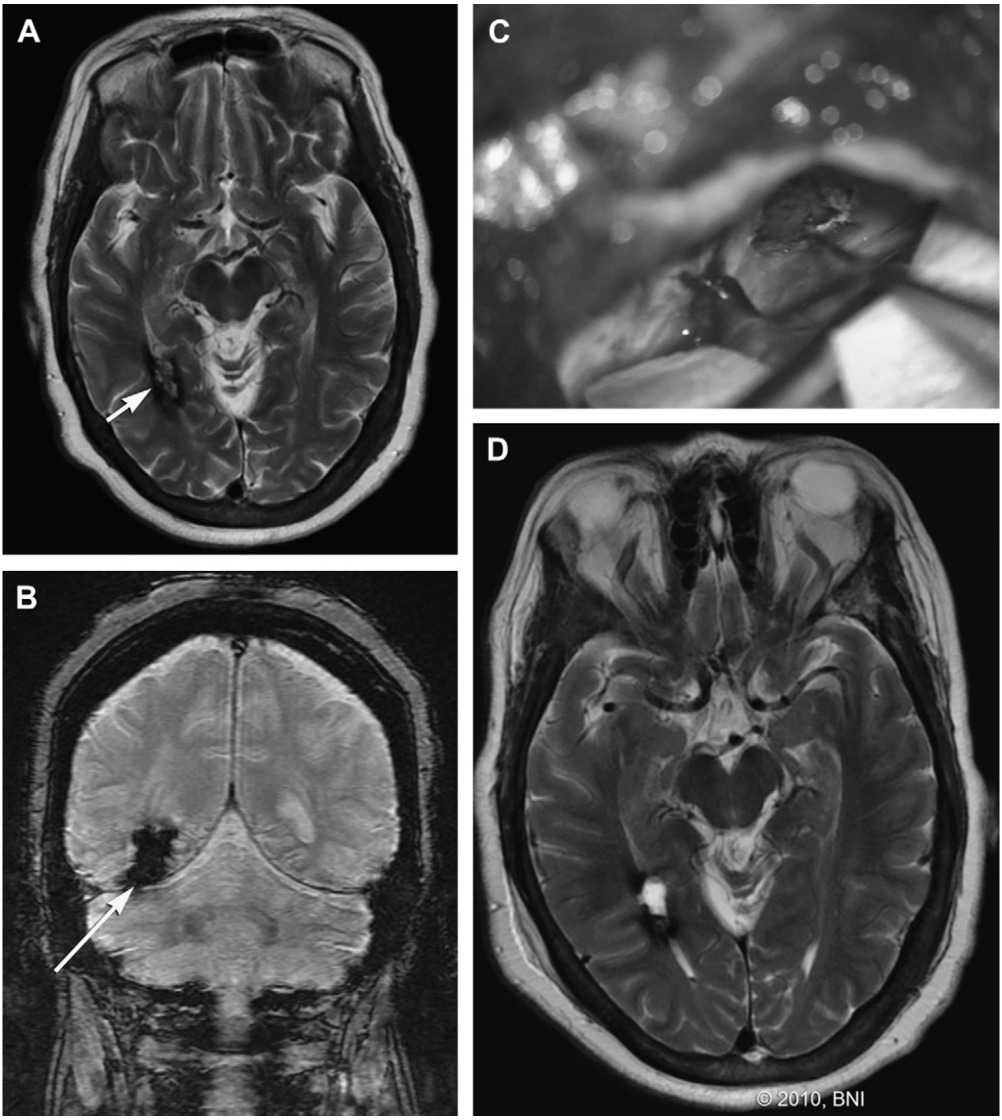

Fig. 2. The contralateral interhemispheric transfalcine approach and retrosigmoid transtentorial approaches take advantage of the natural space created between the brain and these fixed dural structures by gravity. In this example, a cavernous malformation medial to the ventricles is approached transtentorially to avoid harming the visual fibers. (*A*) Axial T1-weighted magnetic resonance (MR) image shows the lesion (*arrow*). (*B*) Coronal T2-weighted gradient-recalled echo MR image shows that the lesion reaches the tentorium. The trajectory to the lesion is shown with an arrow. (*C*) Still image from the intraoperative video shows the opening being made in the tentorium. (*D*) T2-weighted MR image shows the resection cavity of the cavernous malformation and preservation of the surrounding brain. (*Courtesy of* Barrow Neurological Institute, Phoenix, AZ.)

neuroendoscopic surgery and some of the successes and failures associated with the technique.

Many groups have published their experience with endoscopically assisted procedures. As mentioned, Fries and Perneczky[15] reported 380 cases of endoscopically assisted brain surgeries, which included 205 tumors. Excluding intraventricular and sellar lesions, the investigators operated on 242 lesions in the brain parenchyma or subarachnoid space. Conclusions were primarily subjective evaluations of the utility of the endoscope in each case. Although there was no comparison group, Fries and Perneczky concluded that the endoscope decreased operating time because the visualization it provided precluded the need for more extensive dural and bony resection. Two cases were presented to

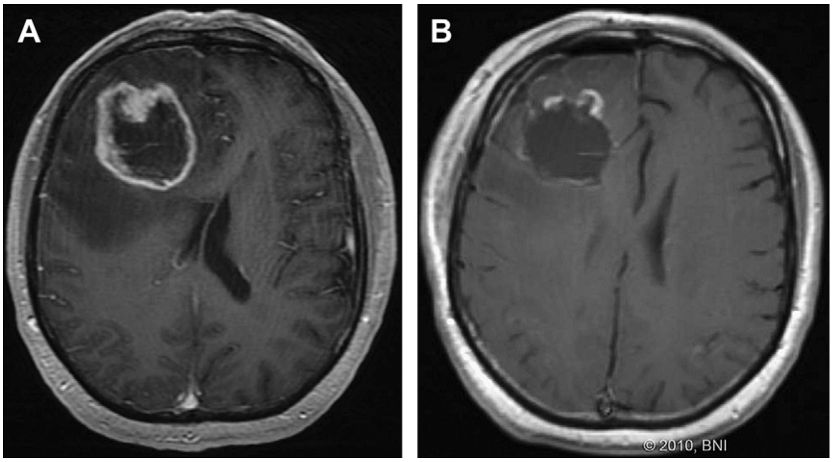

Fig. 3. Precautions for minimally invasive approaches. Axial T1-weighted magnetic resonance (MR) image with gadolinium shows a glioblastoma multiforme (*A*) approached through a small incision in a forehead crease. Removal of the bulk of the tumor was simple. Paradoxically, however, a small residual was missed on the surface nearest to the surgeon, as seen on the postoperative MR image (*B*). The residual tumor lay under the edge of the opening outside the view of the trajectory of the microscope. An endoscope with a highly oblique view (eg, 70°) would have been a useful adjunct in such a case. (*Courtesy of* Barrow Neurological Institute, Phoenix, AZ.)

illustrate this point. The investigators estimated that the time saved ranged from 10 minutes to 2 hours. Although there was no objective evidence confirming the benefit of the endoscope, the investigators demonstrated that the improved visualization can be valuable during intracranial surgery. Furthermore, there were no complications attributable to the endoscope. They described the use of the endoscope to visualize and preserve perforators during aneurysm surgery as well as to inspect tumor beds in deep-seated regions, such as the brainstem parenchyma, highlighting the potential improvement in visualization provided by the endoscope.

Others have reported similar benefits for visualizing intracranial regions that are otherwise difficult to access. Taniguchi and colleagues[43] reported 3 jugular foramen schwannomas that were removed primarily with the operating microscope. The endoscope was then used to visualize and resect residual tumor extending into the jugular foramen. Selvapandian[44] reported 4 cases of simultaneous thalamic glioma biopsy and cerebrospinal fluid diversion by ventriculostomy with no complications.

Complications

Complications of minimally invasive tumor neurosurgery are similar to those related to any standard craniotomy. Because the approaches are smaller and have more restricted working angles, concern is often raised about the risk of injury to neural or vascular structures caused by working in a small space. However, at present there is little evidence in the literature for or against this proposition. Proper surgical planning and meticulous technique are the keys to obtaining a low rate of complications.

Specific complications associated with keyhole approaches have been documented. For the supraorbital eyebrow craniotomy, the small surgical field and technical difficulty often make adequate dural closure difficult. Consequently, extra emphasis should be placed on obtaining a good closure, especially a good primary closure, supplemented with the use of sealants or fibrin glue and pericranial flaps as needed. Warren and Grant[34] reported that only 2 of 105 patients (1.9%) who underwent supraorbital craniotomy experienced a cerebrospinal fluid leak.

The supraorbital eyebrow craniotomy also carries some risk of frontalis paresis related to retraction or section of the frontal branch of the facial nerve. This problem can be avoided by keeping the incision small and not extending it laterally over the keyhole region. Temporary paresis is common; however, in Warren and Grant's[34] series, only 2 patients experienced long-standing forehead asymmetry. Concerns about cosmesis are often cited by detractors of the eyebrow approach; however, the authors have found that the incision is actually favored by plastic surgeons and the cosmetic results are usually excellent.

Complications that arise during procedures involving the endoscope most often occur during introduction or lateral movements of the rigid scope within the surgical field. Focusing only on the endoscopic image can lead to neglect of the other instruments in the field and of the impact of the endoscope shaft on structures that the tip has already passed. If 2 surgeons are performing the procedure, it is imperative that 1 observes and be responsible for avoiding such injuries. Another possible solution, as suggested by Kassam and colleagues,[23] involves simultaneous visualization of the images from the endoscope and from the surgical microscope. The image from the endoscope can be placed in the ocular pieces of the microscope along with the image from the microscope so that the surgeon can constantly monitor the position of the endoscope shaft in the surgical field. However, for many practitioners, monitoring both images simultaneously is difficult.

To avoid causing trauma with a second instrument, the surgeon should maintain the habit of keeping all instruments in use within the view of the endoscope at all times. The endoscope should be withdrawn whenever the instrument is withdrawn and used to visualize the replacement of the instrument (**Fig. 4**).

As noted, the endoscope itself potentially presents the greatest danger to neurovascular structures. Endoscope-related trauma can be prevented by inserting and removing the endoscope in a straight line. The endoscope should not be swung side to side, particularly in the depth of a surgical field. Whenever the direction of view is altered, the endoscope should only be rotated around its long axis. For major changes of orientation or trajectory, the endoscope should be removed from the cranium, the new direction chosen, and the endoscope reinserted.

With care and attention to these principles, injuries directly caused by the endoscope should be rare. In their series, Fries and Perneczky[15] noted no complications related to the use of the endoscope itself. With experience, operating under endoscopic visualization becomes quite natural. The image provided by modern high-definition endoscopes is excellent. Further, the use of a binocular 3-dimensional endoscope provides a view that appears more like the view from the microscope, offers improved depth perception, and may be associated with a shorter learning curve.

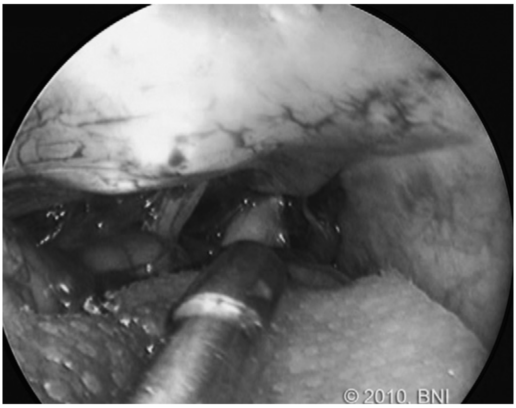

Fig. 4. Endoscopic view of a left retrosigmoid approach to the cerebellopontine angle. The endoscope is held in the right hand. A suction device is held in the left hand and kept in front of the endoscope so that it is in constant view to prevent inadvertent contact between the instrument and the cerebellum or cranial nerves. (*Courtesy of* Barrow Neurological Institute, Phoenix, AZ.)

SUMMARY

The approaches discussed in this article are all refinements of standard or traditional approaches. At the conclusion of any tumor surgery, it behooves the neurosurgeon to examine the approach and ask whether a less-invasive approach would have been adequate. Conversely, it is fair to consider whether a smaller approach would leave the surgeon with fewer options. However, it is also important to ask whether the larger approach is associated with so much additional morbidity that its use cannot be justified. For many intrinsic tumors, only a small corticotomy is required, and a smaller bony opening actually prevents damage to the overlying brain. For extrinsic tumors, the route chosen depends mostly on tumor location and the tumor's relationship to intervening neurovascular structures.

Minimally invasive approaches are applicable to a broad range of intracranial tumors. Through the use of the keyhole concept and careful choice of trajectory, many tumors can be removed through a small craniotomy with fewer traumas to soft tissue and bone. The decision to use a minimally invasive approach must be individualized based on the patient and tumor. All cranial neurosurgeons should be familiar with the advantages and limitations of these approaches to use them where necessary. The addition of endoscopy can improve the removal of tumor and help protect neurovascular structures. The principles involved in using these techniques in brain tumor surgery are potentially applicable to almost all intracranial tumors and form an important part of the neurosurgical armamentarium.

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