Application of Technology for Minimally Invasive Neurosurgery

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KEYWORDS

• Endoscopy • Minimally invasive neurosurgery
• Neuroendoscopy • Neurosurgery • Skull base
• Technology

The application of endoscopic techniques has changed the field of neurosurgery. The earliest use of an endoscope in neurosurgery dates back 100 years ago when Victor Lespinasse used a cystoscope to fulgurate the choroid plexus in two infants.[1] Twelve years later, Walter Dandy[2] reported the use of a cystoscope to inspect the lateral ventricle and a ventriculoscope to remove and fulgurate the choroid plexus. In 1923, Jason Mixter[3] was the first to report the use of the endoscope to perform a third ventriculostomy. These early neuroendoscopic procedures, however, were limited by poor image quality and suboptimal illumination. With the introduction of microneurosurgical techniques and cerebrospinal fluid shunting procedures, the development and use of the endoscope in neurosurgery decreased.

Numerous technological developments in the 1960s revolutionized endoscopy and formed the basis of current endoscopic systems. The first of these was the invention of a new rod-lens optical system by Harold Hopkins, PhD, in 1959.[4,5] Coupled with the development of the fiberoptic cold-light source by Karl Storz, this led to a new era in endoscopy.[4,5] The development of charge-coupled devices (CCD) was another technological innovation that improved the quality of transmitted images.[6]

In the 1970s, neuroendoscopic procedures were re-examined and reports began surfacing in the neurosurgical literature.[7–11] Over the past few decades, there has been tremendous application of endoscopy to all aspects of neurosurgery.[12–16] Most recently, endoscopic techniques have expanded the armamentarium of skull base neurosurgeons and otolaryngologists in the surgical treatment of skull base pathologies.[17–25] This issue of the *Neurosurgery Clinics of North America* focuses on minimally invasive intracranial neurosurgery. The purpose of this article is to highlight current technologies as well as comment on the transition from microneurosurgical to neuroendoscopic techniques.

ENDOSCOPY IN NEUROSURGERY

Various endoscopic techniques have been described and are generally categorized into endoscopic, endoscopic-assisted, and endoscopic-controlled neurosurgery.[26] In pure endoscopic neurosurgical procedures, instruments are passed through working channels. There are usually

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multiple channels, including one or more for instrumentation and a separate port for irrigation. Endoscopic third ventriculostomy, septum pellucidotomy, cyst/ventricular fenestration, and surgical treatment of intraventricular pathology are examples of pure endoscopic procedures. In endoscopic-assisted neurosurgical procedures, both the microscope and endoscope are used during the same procedure. The endoscope is used for improved visualization or illumination. Instruments are passed along side the endoscope. In endoscopic-controlled neurosurgery, the procedure is performed solely with the endoscope and instruments are passed along side the scope. Endonasal endoscopic skull base surgery is operationally included in this category, though the procedures are performed through the nasal cavity.

There are several types of endoscopes available that are broadly classed as rigid or flexible scopes. Rigid scopes, also referred to as rod lens endoscopes, are more commonly used and are available in a variety of sizes and shaft lengths. Scopes used for transcranial intraventricular procedures are longer than those used for endoscopic-assisted and endoscopic-controlled procedures, and are placed through a sheath that also contains the instrument channel through which the instruments pass (**Fig. 1**). For other endoscopic procedures, the scopes are shorter and are used without the sheath and working ports; instruments are inserted alongside the shaft of the endoscope. The lenses of rigid endoscopes come in various angles of view. The most commonly used endoscope is the 0° scope. Angled scopes of 30°, 45°, and 70° aid in intraoperative visualization (**Fig. 2**).

Flexible endoscopes are also available. Such scopes rely on flexible fiberoptic illumination. These scopes also have operative channels for instrumentation and are used in transcranial endoscopic procedures. One of the main disadvantages of flexible endoscopes is that the quality of the optics is inferior to that of rigid scopes.

In addition to endoscopes, the basic endoscopic set-up also includes a video camera, monitor, light source, and recording devices. The endoscope is connected to the video camera, several of which are available. The majority of current systems use a three-chip CCD. This produces a better quality picture than the single-chip CCD cameras. The picture is then displayed on one or several monitors in the operating room. Recently, high-definition monitors have been introduced that provide spectacular image quality. The current illumination sources used are xenon light sources that are connected to the endoscope via flexible cables. Minimal heat is transmitted through the fiberglass bundles, which significantly reduces thermal injury. Video documentation of intraoperative still photographs or movie clips is extremely valuable, and enables review of operative procedures and serves as a great teaching tool.

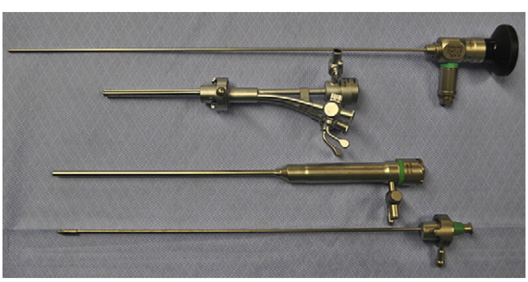

Fig. 1. Rigid 0° endoscope with instrument channel, endoscopic sheath, and associated trocar.

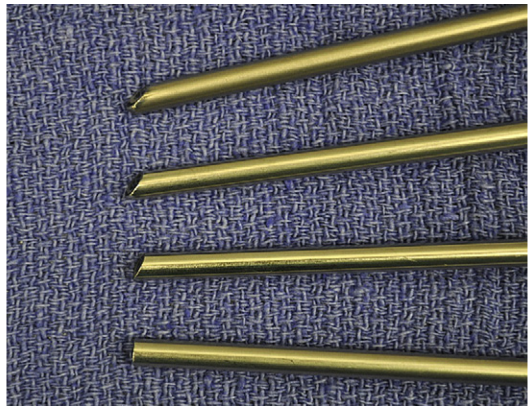

Fig. 2. High-magnification view of the endoscopic lenses, including 0° (*bottom*), 30° (*second from the bottom*), 45°, (*second from the top*), and 70° (*top*).

A drawback of current monocular endoscopes is that depth perception is impaired when viewing a surgical field.[27] Depth information must be inferred from visual cues and the interaction of surgical instruments with the environment. Stereoscopic endoscopes, endoscopes that can present separate spatially shifted images to the left and right eyes, overcome this limitation by allowing the surgeon to recover natural depth cues from stereo image pairs.[28,29] A number of recent technologic advancements have improved this class of endoscopes and they are now beginning to be used clinically for endoscopic skull base procedures. No differences in surgical time and extent of resection were noted between monocular and stereoscopic matched cases in a recent case series.[29] The inability to rotate an angled scope independently from the image sensor is a limitation of current stereoscopic endoscope designs.

ENDOSCOPIC INSTRUMENTATION

Instruments available for pure endoscopic techniques include scissors, grasping forceps, biopsy forceps, and monopolar and bipolar probes (**Fig. 3**). Additionally, a Fogarty balloon (#3 French) can be passed down in the working channel and is useful for dilation and fenestrations.

Endonasal instruments are varied in number and design (**Fig. 4**), and the instrumentation set may seem overwhelming for staff and novice surgeons at first. There are guidelines, however, that help organize the instruments and simplify instrument choice during surgery. In general, instruments are divided into those that grasp and those that cut. Grasping and cutting instruments are of similar design and structure with the exception of a blade so only cutting instruments are discussed below. Cutting instruments can be further subdivided into scissors and punches. The weight of endoscopic scissors varies; the choice of weight depends on the resilience of the tissue being dissected, with microscissors reserved for cutting

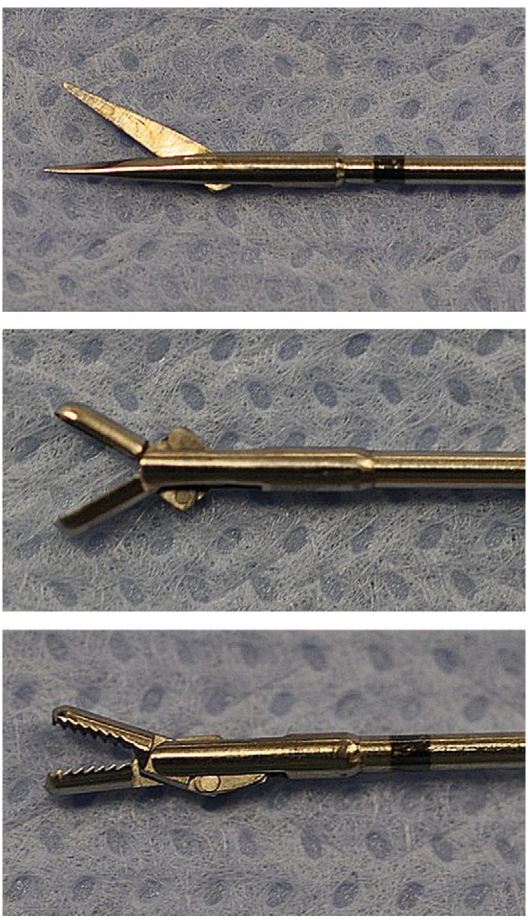

Fig. 3. Endoscopic instruments, including scissors, grasping forceps, and biopsy forceps.

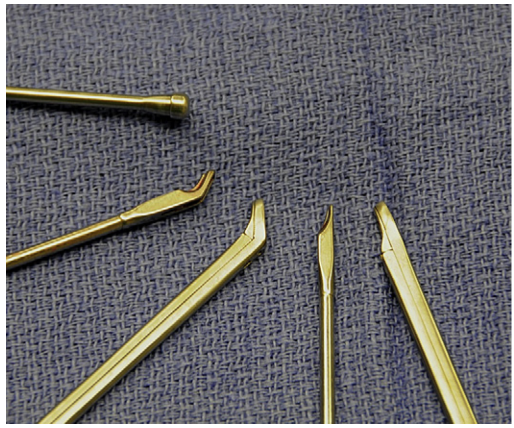

Fig. 4. Endonasal endoscopic instruments, including mushroom punch (*left*), up-biting (*second and third from left*), and straight cutting forceps (*two on right*).

dura and dividing bands during extracapsular dissections, for example. The heaviest scissors are reserved for maneuvers such as turbinate resections. Scissors are curved and straight. We recommend choosing an instrument that places the major axis of the cutting blade perpendicular to the cut direction with the hand placed in the most neutral position.

Punches come in four varieties: straight, up-angled, right-angled, and specialty. Straight instruments place the cutting head in line with the shaft of the instrument. Up-angled deflect the cutting head roughly 45° off line with the shaft of the instrument, while right-angled instruments deflect the biting head 90° off line; that is, they are side-biting. Punches are optimized to cut or divide tissue in plane with the instrument's cutting head, but perform well with any tissue oriented within 45° of the cutting surface. The surgeon must look at a target structure and determine what plane that structure is in with respect to the instrument's shaft and cutting head. The surgeon's goal is to always pick an instrument that places the cutting head inline or parallel with the object she or he is cutting. If, for example, the structure is oriented 45° off axis with the shaft of the instrument then an up-angled instrument is ideal. The degrees of freedom of an instrument in the nose is greatly restricted; that is, one can advance or withdraw an instrument, translate it, or rotate it. It is important to pick the correct instrument because it is hard to compensate for poor instrument choice by instrument manipulation as it is in open surgery.

Specialty instruments have been developed to simplify anterior skull base dissections. These instruments have a bend in the shaft that direct the cutting head toward the skull base. Here the same principles apply orienting the cutting head to the tissue of interest. Back-biting punches and side-biting punches also exist for addressing special cases.

There are numerous other instruments that have been developed for endonasal skull base surgery. Various blunt and sharp dissectors are available, as well as ring curettes for pituitary tumor surgery. In addition, rotatable microscissors are available for fine sharp dissection.

OTHER TECHNOLOGIES

Microdebriders are commonly used in nasal surgery and represent a major technical advancement for the field. They are used to expeditiously remove tissue in a precise fashion. Originally used by the House group in the 1970s for morselizing acoustic neuromas, microdebriders gained popularity in the orthopedic community for arthroscopic surgery.[30] Setliff[31] and Parsons[32] introduced this technology to nasal surgery in 1994. The basic design of a tissue shaver consists of a hollow shaft attached to a vacuum with a hole at one end. Tissue to be removed is sucked into the hole and sheared off by a rotating, oscillating, or reciprocating inner cannula. The resected tissue and blood are cleared from the surgical field through the hollow shaft. The microdebrider does not alter the morphologic features of the tissue passed though the shaver, making the captured specimens useful for histopathological analysis.[33] Recent advancements in microdebrider technology allow for 360° rotation of the cutting aperture and the ability to control bleeding with bipolar cautery incorporated into the blade. The shaft of the microdebrider blade can either be straight or is available at prebent angles to facilitate access to hard-to-reach areas. Microdebriders have certain limitations that must be recognized. They are inefficient at removing thick bone and, due to their mass and powered nature, they diminish tactile feedback during the removal of soft tissue.[30] Microdebriders are used in the safest fashion when resecting tissue that was deliberately and easily sucked into the cutting aperture. We use them extensively during the approach and often for debulking large tumors. Finer tissue shavers are in development and are better suited for tumor debulking around critical neurovascular structures.

Coblation is an electrosurgical process used to disrupt tissues. There is controversy surrounding the exact mechanism of action of these devices.[34] The major benefit of this technology is its low thermal footprint; that is, it heats the surrounding tissues to a lower temperature[35] (40–70°C) than traditional electrocautery (400°C) devices.[36] This is beneficial when operating near critical structures. Commercial handpieces include a suction port and bipolar cautery. It is hypothesized that the ability to rapidly change between ablation and cautery modes reduce surgery time and blood loss.[36] A recent clinical trial involving skull base and sinonasal tumors supports this conjecture.[37]

Removal of bone is necessary in endoscopic procedures. Pure endoscopic procedures are typically performed via a burr hole. Endoscopic-assisted and transcranial endoscopic-controlled procedures are performed through a craniotomy, often a keyhole craniotomy. The bony work for these procedures is performed with standard perforating drills and craniotomy. For endonasal endoscopic skull base surgery, new drills capable of reaching the skull base have been developed. These drills come in both straight and angled tips. Various burrs are also available, including cutting, diamond, and hybrid bits. For bone removal at the skull base, the hybrid bit is optimal. Recently, irrigation adapters have been developed that help disperse heat when drilling about the optic nerve or other neurovascular structures. The drills can also be registered to the neuronavigation system and, with the CT bone windows, the location along the skull base can be monitored during the bone removal.

Ultrasonic surgical devices were originally developed by the dental industry to remove plaque from hard surfaces.[38,39] In 1967, ophthalmologists started using ultrasonic aspirators to emulsify the lens during cataract surgery.[40,41] Approximately a decade later the technology was adapted by neurosurgeons[42] for the removal of intra-axial and extra-axial tumors. Ultrasonic aspirators are useful for the removal of firm tumors that are not freely suctionable. These devices were modified to disrupt and cut bone[37,39,43–49] and were miniaturized so that they can be used endonasally.[44,45,49] Bone emulsifying aspirators work by delivering vibrations of sufficient amplitude and frequency to disrupt rigid structures. They are designed to exploit differences in tissue properties to minimize injury to soft tissue during the bone emulsification process. This safety feature is not absolute and appropriate technique is required to prevent tissue injury near vital structures.[45,46,50] In general, ultrasonic surgical devices are less efficient at removing bone than drills, so the technology is thought to be complementary rather than a replacement for the drill.[45]

IMAGING: PREOPERATIVE AND INTRAOPERATIVE STEREOTAXIC NEURONAVIGATION

Imaging is essential in all aspect of neurosurgery. Preoperative radiographic evaluations include CT scans, MRI, and angiography. The CT scan is used to define bony anatomy during the approach and the MRI scan is used to provide soft tissue contrast during the tumor resection. Additionally, CT and MRI angiography are useful evaluations. These studies provide information of anatomic landmarks and extent of pathology. Careful review of these studies is crucial for preoperative surgical planning and anticipated intraoperative findings.

Endoscopic surgical landmarks important for indentifying vital structures are often distorted or obscured by large skull base lesions. This makes it easy for a surgeon to become disoriented. Disorientation can often be minimized with a systematic surgical approach relying on the sequential identification of important landmarks to maintain orientation. A strong understanding of the three-dimensional surgical anatomy is required to perform these surgeries well. Image-guided surgery is useful in this regard, as it can instantly recall multiplanar reconstructions of a patient's anatomy using images uploaded before surgery (**Fig. 5**). Often this includes a preoperative MRI scan and CT scan. The disadvantage of this technology is that the preoperative scans lose relevance as the surgery progresses as the surgical process itself changes the anatomy. Intraoperative imaging mitigates this problem (**Fig. 6**). It is thought that intraoperative imaging technologies may enhance the effectiveness of endoscopic procedures and reduce morbidity.[51,52] There are two competing intraoperative imaging modalities: MRI[53–56] and CT scans.[51] In pituitary surgery, intraoperative MRI was shown to identify residual tumor after the surgeon thought tumor resection was complete in 58% to 83% of cases.[54,57,58] The use of intraoperative MRI increased the operative times by 1.8 hours on average. CT scan imaging modalities can be further subdivided into cone beam, multidetector, and fluoroscopy.[52] In general, cone bean CT scanners are smaller, more portable and cheaper than multidetector CT scans. In a similar fashion to intraoperative MRI, intraoperative CT scan was shown to change

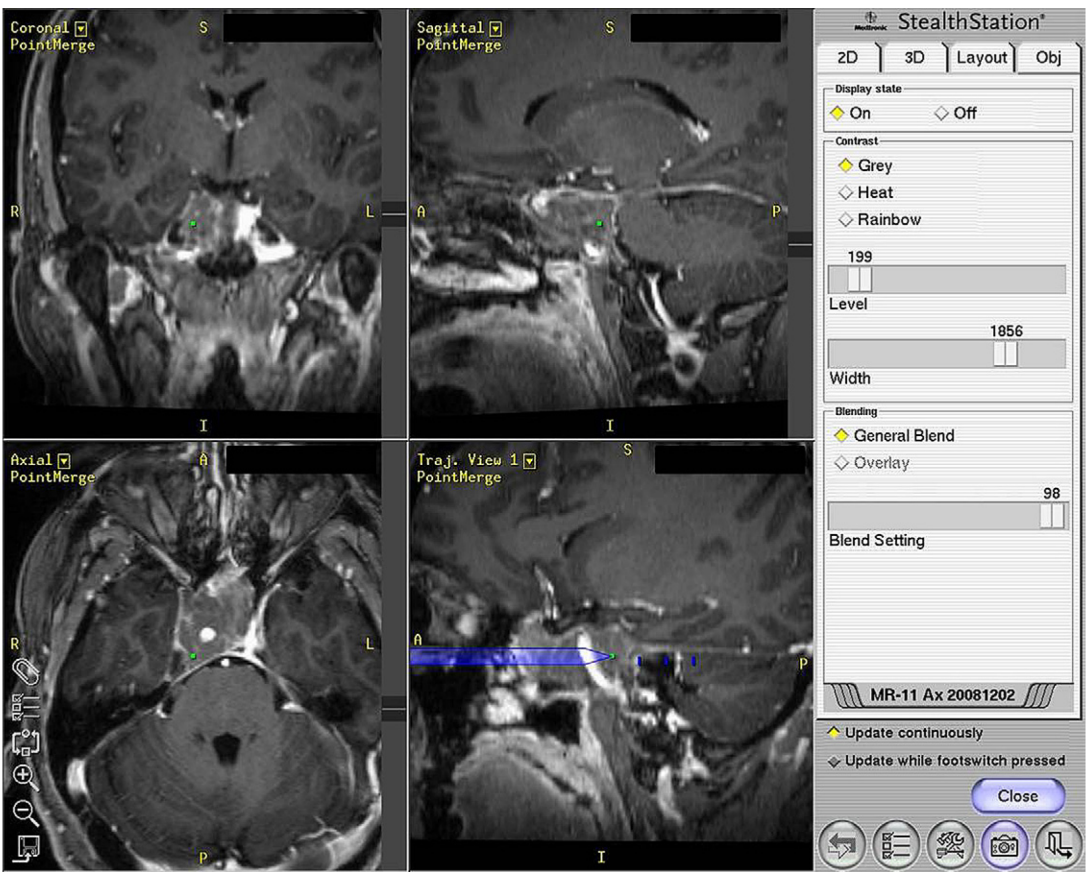

Fig. 5. Intraoperative neuronavigation screenshot during resection of a large pituitary adenoma; taken during the resection of the tumor posterior and lateral to the carotid artery.

Fig. 6. Intraoperative CT scanner and integrated neuronavigation system.

surgical planning in 24% of endoscopic sinonasal and skull base procedures.[51]

HEMOSTASIS

Hemostasis is one of the major concerns during endoscopic procedures. Most bleeding during pure endoscopic neurosurgical procedures is venous. This can often be managed by irrigation and patience. Monopolar and bipolar coagulation are also useful when the site of bleeding is visible. If bleeding cannot be controlled with these maneuvers, conversion to an open craniotomy should be considered. For endonasal endoscopic surgical procedures, a variety of tools are available.[59] Monopolar and suction cautery are useful during the nasal stages of the surgery. Pistol grip bipolar forceps (**Fig. 7**) are useful for coagulation of the dura, tumors, and small vessels. There are numerous hemostatic materials available for venous bleeding, including microfibrillar collagen, Gelfoam-soaked in thrombin, and oxidized cellulose. Warm irrigation is also effective for mucosal bleeding. For vascular tumors such as juvenile nasopharyngeal angiofibromas, preoperative embolization may also be considered. Injury to large arterial vessels is a major concern especially when the tumor involves these structures. Intraoperatively, the vessel injury site is focally packed with hemostatic materials when possible; in cases where control is unachievable, the vessel may need to be occluded with an aneurysm clip. Any patient with an arterial injury should have a postoperative angiogram and potential definitive endovascular intervention.

FLUORESCEIN

Leakage of cerebrospinal fluid (CSF) into the nasal cavity can lead to life-threatening complications; therefore, it is important to accurately diagnose the presence of a CSF fistula. Several clinical tests can be used to confirm the diagnoses and generally fall into two categories: biochemical analysis (beta 2 transferrin and beta trace) and radiographic methods (CT scan imaging, MRI, and nuclear medicine imaging). Often a combination of techniques is used. Once the diagnosis is confirmed, the precise location of the leak must be identified for repair. Introduced by Kirchner and Proud[60] in 1960, intrathecal fluorescein injection is a commonly used method for localizing low-flow and intermittent leaks. Sodium fluorescein is a fluorescent compound[61] that dyes the CSF green so

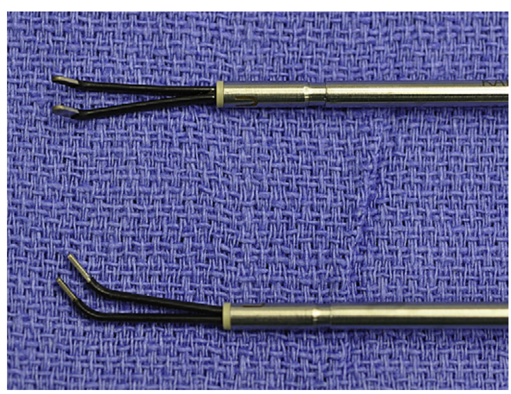

Fig. 7. Pistol grip endoscopic bipolar forceps come in various tip configurations and are essential for precise coagulation.

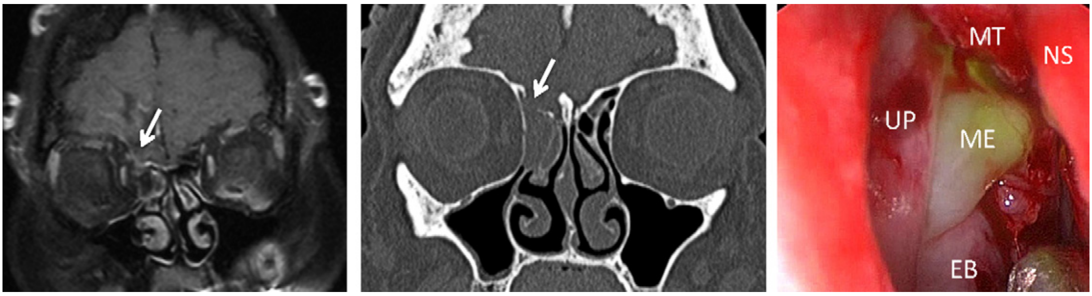

Fig. 8. From left to right, a coronal T1-weighted MRI scan, a coronal CT scan, and an endoscopic intraoperative image taken with a zero-degree endoscope. The CT scan and MRI scan correspond roughly to the same coronal slice. The images show a skull base defect (*arrows*) and a meningoencephalocele (ME). The endoscopic images show the ME turning green as it fills with fluorescein. EB, ethmoid bulla; MT, middle turbinate; NS, nasal septum; UP, uncinate process.

that it is easier to visualize as it leaks into the nose (**Fig. 8**). Fluorescein injection has not been approved by the US Food and Drug Administration for intrathecal injection and one must be aware of the complications associated with its use and appropriately inform patients of rare, but serious, side effects.[62–68] Paraparesis, numbness, and seizure are the most commonly reported side effects.[69] These are attributed to the injection of too much or too high a concentration of fluorescein,[70] the injection of fluorescein too rapidly, and the use of unsuitable fluorescein preparations.[70] Myelopathy with paraplegia has been reported.[69] Some investigators advocate the use of topical fluorescein as a method for reducing the side-effect profile of the intrathecal approach.[71]

CONVERSION FROM MICROSCOPIC TO ENDOSCOPIC PROCEDURES

As described in other articles in this issue, the endoscope has become an essential tool for neurosurgeons and there has been tremendous applications in the field of neurosurgery. As with any new surgical advancement, there is a learning curve in minimally invasive and endoscopic techniques to become proficient. This learning curve is steep for endoscopic procedures for many reasons. Endoscopic procedures are performed in three-dimensional space but viewed on two-dimensional monitors. As such, depth perception is challenging for the beginner. For endoscopic procedures, new and often unfamiliar instrumentation is required and operative times are significantly longer during the initial endoscopic cases. Additionally, for endonasal skull base procedures, the anatomy is initially unfamiliar.

As minimally invasive centers continue to grow, future generations of neurosurgeons and otolaryngologists will be trained in and become proficient with endoscopic procedures. For surgeons who are interested in mastering such techniques, some recommendations are suggested. Dedicated anatomic dissections and minimally invasive and endoscopic cadaveric courses are crucial to become more familiar with the surgical anatomy and the instrumentation. A good initial strategy is to gradually increase endoscopic use with each successive case until the entire procedure is performed endoscopically. Additionally, it is important to identify cases appropriate to the level of surgical skill. This has been nicely described by the Pittsburgh group, which has developed a training plan for acquisition of endonasal endoscopic surgical skill. This consists of a modular and incremental approach based on the difficulty of the procedure in which surgeons should not progress to the next level unless the current level of cases has been mastered.[72]

SUMMARY

The development of modern endoscopy has impacted every aspect of neurosurgery. This article highlights current technological developments, including endoscopic instrumentation and devices, imaging, and hemostatic agents. Future technologies, including robotic surgery, virtual endoscopy, and surgical simulation, will further expand the possibilities and applications of endoscopy in our field.

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