Extending the Limits of Endoscopic Endonasal Surgery of the Skull Base

Carl H. Snyderman, MD, MBA¹⁾, Eric W. Wang, MD¹⁾,
Georgios A. Zenonos, MD²⁾, Paul A. Gardner, MD²⁾

¹⁾Departments of Otolaryngology, University of Pittsburgh School of Medicine,
200 Lothrop Street, Pittsburgh, Pennsylvania, USA

²⁾Neurological Surgery, University of Pittsburgh School of Medicine,
200 Lothrop Street, Pittsburgh, Pennsylvania, USA

Endoscopic endonasal surgery (EES) of the skull base has evolved beyond the sella to include the entire ventral skull base. In the sagittal plane, surgical modules extend from the frontal sinus to the craniovertebral junction in a midline corridor. Access to the superior clivus is achieved with a pituitary transposition without loss of pituitary function. Coronal plane modules extend laterally to provide access to the anterior, middle and posterior cranial fossae. In the anterior coronal plane, a superomedial orbitotomy provides access to the anterior cranial base as far laterally as the mid-sagittal plane of the orbit. In the middle coronal plane, the transpterygoid approach provides access to the lateral recess of the sphenoid sinus and Meckel's cave. In the posterior coronal plane, transjugular tubercle and transcondylar approaches extend beyond the hypoglossal canal in an infrapetrous plane. Access to the petrous apex for chondromatous tumors is limited by the internal carotid artery (ICA). A new approach, the contralateral transmaxillary approach, allows complete dissection of the petrous apex deep to the petrous ICA as far as the internal auditory canal and jugular foramen. Inferiorly, tumors of the parapharyngeal space may be dissected to the parapharyngeal ICA.

The limitations of EES are determined by multiple factors. Anatomical limits include the major neural and vascular structures of the skull base. Other limits are imposed by patient, surgeon, and institutional factors. EES may be applied to all patient populations; the principles are the same for young pediatric patients despite the unique challenges of the pediatric population (decreased pneumatization of sinuses, smaller blood volume, etc.). Vascular tumors including aneurysms can be managed safely with EES. Oncological principles can be preserved with the management of sinonasal malignancy, often with superior outcomes. Improved methods of reconstruction allow reliable repair of large dural defects with acceptable morbidity. In particular, the employment of vascularized flaps (nasoseptal flap, extracranial pericranial flap, lateral nasal wall flap) in combination with selective use of lumbar spinal drainage, has dramatically lowered the risk of postoperative cerebrospinal fluid leak. EES is also limited by the training of surgeons. A systematic approach to training based on increasing levels of complexity and risk has been validated and is correlated with clinical outcomes. Surgical simulation allows teams to train for rare events such as vascular injury.

Further improvements in anatomical knowledge, surgical technology, and enhanced surgical training will further extend the limits of EES of the skull base.

Key words : Endoscopic endonasal surgery, Limitations, Petrous apex, Skull base

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Evolution of Skull Base Surgery

Endoscopic endonasal surgery (EES) of the skull base has evolved through multiple stages over the last few decades: (I) endoscopic sinus surgery, (II) endoscopic pituitary surgery, (III) parasellar approaches, (IV) sagittal plane approaches, and (V) coronal plane approaches. At the same time, there have been several distinct stages of development. In the first stage, the feasibility of *endoneurosurgery* was established through description of endonasal skull base anatomy, development of new instrumentation, and design of new surgical techniques. In the second stage, safety was addressed by investigating causes of mortality and morbidity. In the final stage, a critical analysis of outcomes has reported on recurrence and survival rates, and quality of life issues. Comparison of results with traditional open approaches allows skull base surgeons to select the best approach based on pathology and location.

The evolution of a discipline may occur incrementally or by giant leaps. Although we envision a timeline of progress as one of continuous improvement, some evolutionary paths are dead ends and one must take a step back to choose a different path in order to reach a higher level. Thus, many paradigm shifts may not appear to be an improvement at first glance; more time is needed to address early problems. This was the case with EES, with a high incidence of cerebrospinal fluid (CSF) leaks in early years¹⁾.

Classification of Approaches

Endonasal approaches to the ventral skull base are classified into modules in sagittal and coronal planes, corresponding to radiological planes (Table 1)²⁾. The sagittal plane extends from the frontal sinus to foramen magnum and upper cervical spine in a midline corridor. Coronal planes extend laterally corresponding to the cranial fossae (anterior, middle, posterior). Endonasal modules can be combined like building blocks to tailor the approach to the pathology. For example, an endonasal resection of the anterior cranial base for sinonasal malignancy combines transfrontal, transcribriform, and transplanum approaches.

Limits of Endonasal Surgery

Age

The limits of endoscopic endonasal surgery are not just anatomical. Age may be a consideration, especially for young

pediatric patients. The most common pediatric conditions include angiofibroma, chordoma, craniopharyngioma, fibro-osseous lesion, meningo-encephalocele, and pituitary adenoma^{3,4)}. Due to a small nasal aperture, there is less room for endoscopic instrumentation and a greater risk of injury to the nasal tissues (e.g., burn injury to the nasal sill from powered instrumentation). In practice, this has not been a limiting factor and a sublabial approach is seldom necessary. There is also poor pneumatization of the sinuses with few anatomical landmarks, requiring greater reliance on image-based navigation. Reconstructive options are limited due to less body fat and cosmetic concerns. Up until age 14, there is a growth disparity between the nasal septum and the anterior cranial base, resulting in a smaller nasoseptal flap⁵⁾. Although there have been concerns about delayed effects on facial growth, studies of facial growth following EES have not confirmed this⁶⁾.

Table 1 Classification of Endonasal Approaches to the Skull Base

Sagittal Plane
Transfrontal
Transcribriform
Transplanum/transtuberculum (suprasellar)
Transsellar
Transclival
Superior: dorsum sellae, posterior clinoid processes
Middle: mid clivus
Inferior: foramen magnum
Transodontoid/transcervical
Coronal Plane
Anterior (anterior cranial fossa)
Supraorbital
Transorbital
Middle (middle cranial fossa)
Medial Transcavernous
Medial petrous apex
Contralateral transmaxillary
Transpterygoid
Suprapetrous
Meckel's cave
Lateral transcavernous
Infratemporal skull base
Posterior (posterior cranial fossa)
Infrapetrous ("far medial")
Transjugular tubercle
Transcondylar
Parapharyngeal space

In a review of our youngest cohort of patients (<7 years old), we treated 36 patients with EES (4 staged EES; 2 combined endoscopic/open surgery)⁷⁾. Most frequent diagnoses included 12 encephalocele/traumatic CSF leaks, 11 craniopharyngiomas, 3 dermoids, 3 chordomas, and 2 rhabdomyosarcomas. Reconstruction included 16 nasoseptal flaps and 2 other vascularized flaps (temporalis muscle and nasopharyngeal). Postoperative CSF leaks occurred in 8% of primary EES.

Pathology

EES offers a clear advantage for certain tumor types and locations. Superior results have been demonstrated for pituitary tumors, craniopharyngiomas, suprasellar meningiomas, petrous apex lesions, chordomas, and C1/C2 compression⁸⁾. Advantages of EES include better access, improved oncologic resection, greater preservation of vision, and less morbidity.

One of the most controversial areas has been the management of sinonasal malignancy⁹⁾. There are a wide variety of tumor types with different biologic behaviors and requiring different treatment strategies. The goal of most surgeries is a complete oncological resection. Although it has been shown that endoscopic resection of sinonasal malignancy is technically feasible and safe, questions remained regarding long-term oncological outcomes. For a proto-typical skull base malignancy such as olfactory neuroblastoma, systematic reviews with meta-analysis demonstrate equivalent (no difference in locoregional control and metastasis-free survival) or superior outcomes (improved overall survival and increased disease-specific survival)^{8, 10)}.

Access (anatomy)

The golden rule of EES is to avoid crossing the plane of major vascular and neural structures (Figure 1). If tumor is on the other side of a vessel or nerve, an alternate approach or combination of approaches may be necessary. The risks of surgery increase inversely relative to the proximity of the tumor to the cerebral vessels. Tumor encasement of vessels generally precludes a complete resection and the goals of surgery are modified. An additional consideration with large olfactory groove meningiomas is the amount of brain manipulation that would be necessary to remove the tumor. Large vertical tumors with intervening frontal lobes are best managed with EES. Petroclival meningiomas are a particular challenge and often require multiple staged surgical ap-

Figure 1 Axial T1 MRI demonstrates a large chordoma with encasement of the internal carotid arteries and basilar artery (arrows). Superiorly, this tumor was limited by the pituitary gland and optic chiasm. Laterally, it was limited by the internal auditory canal. Inferiorly, it extended to the craniovertebral junction.

proaches. The surgeon must not lose sight of the goals of surgery. Subtotal resection with observation/radiation therapy may be the best strategy in some patients, depending on multiple factors.

In the sagittal plane, the anterior limit of EES is the posterior table of the frontal sinus. If tumor is filling the sinus, a combined approach may be necessary. Inferiorly, the nasopalatine line (line tangential to the nasal bones and hard palate) is a rough estimate of the limit of endonasal access¹¹⁾. The use of curved drills and angled instrumentation reliably extends access to the body of C2. Tumor below the body of C2 necessitates a transoral or transcervical approach.

In the anterior coronal plane, access to the orbital roof is limited by the medial wall of the orbit and the ethmoidal arteries. A medial orbital decompression with sacrifice of the ethmoidal arteries allows dissection of the periorbita to the mid-sagittal plane of the orbital roof¹²⁾. This provides an extended lateral margin for access to osteomas arising from the orbital roof, tumors with a dural tail such as meningiomas, or clearance of dural margins for malignant neoplasms such as olfactory neuroblastoma.

In the middle coronal plane, access to the petrous apex

is limited by the petrous segment of the internal carotid artery (ICA). Anatomical studies show that an endonasal approach provides superior access to all regions of the petrous apex (superior, anterior, posterior) compared to an infracochlear approach and provides a larger drainage pathway for lesions such as cholesterol granulomas¹³. For tumors that involve the petroclival region such as chordomas, the most important prognostic factor is the ability to achieve a gross total resection. This is significantly less likely when there is tumor involvement of the lower third of the clivus with lateral extension¹⁴. Although access to the petrous apex is enhanced with decompression and lateralization of the ICA, this poses additional risk to the ICA and exposure is still limited. The contralateral transmaxillary (CTM) approach was designed to provide access to the petrous apex without manipulation of the ICA¹⁵. Anatomical studies demonstrate that the CTM approach improves the trajectory relative to the petrous ICA by approximately 25 degrees as well as a *reach* advantage (Figure 2). Anatomical limits are the jugular bulb inferiorly and the cochlea and internal auditory canal superiorly.

Reconstruction

In the early stage of EES, reconstruction of dural defects was a limiting factor, with unacceptable rates of postoperative CSF leaks¹. The introduction of the vascularized naso-

Figure 2 The contralateral transmaxillary (CTM) approach improves the trajectory of surgery relative to the petrous internal carotid artery (Int Carotid Art) by approximately 25 degrees compared to a transnasal approach (TNA). The CTM approach also has a reach advantage for the petrous bone (red bar). Pteryg Fossa = pterygopalatine fossa

septal flap (NSF), in combination with other measures, dramatically decreased the leak rate¹⁶. For those cases where a NSF is not available, other local and regional flaps provide reconstructive options. The lateral nasal wall flap is well-suited for defects of the sellar region and clivus¹⁷. For large defects of the anterior cranial base, the extracranial pericranial flap provides a large well-vascularized flap with minimal morbidity and avoids the need for a craniotomy¹⁸. The reconstruction of large clival defects is a particular challenge. Transclival approaches have a higher incidence of postoperative CSF leak and are reconstructed using a 4-layer technique: inlay collagen graft, onlay fascia lata graft, fat graft, and vascularized flap. Interposition of the fat graft prevents pontine herniation with large dural defects¹⁹.

Duration of Surgery

The duration of surgery may be a limiting factor in some patients, especially those with co-morbidities. Long surgeries increase the risk of pulmonary complications, blood loss requiring transfusion, and deep venous thrombosis. Operating late in the day with secondary operative staff is less efficient and increases the risk of errors. In some cases, an open approach may be more expedient (e.g., large olfactory groove meningioma). In other cases, staging of the surgery should be considered. Indication for staging of a surgery include: (I) uncertain diagnosis requiring pathologic confirmation, (II) excessive blood loss with coagulopathy, (III) complication such as a vascular injury, (IV) changes in neurologic status measured with neurophysiological monitoring, (V) allow descent of giant tumor (pituitary adenoma, meningioma), (VI) team issues (fatigue, unskilled personnel, lack of resources), and (VII) prevention of patient morbidity (pulmonary complications, deep venous thrombosis, pressure ulcers/neuropathy).

Blood Loss

A variety of techniques help to minimize intraoperative blood loss and prevent the development of coagulopathy²⁰. This is a critical issue with intradural dissection of tumor. Reverse Trendelenburg positioning to lower venous pressure, endoscopic bipolar electrocautery, application of hemostatic materials such as Surgiflo and Floseal for cavernous sinus bleeding, and warm saline irrigation (40–45° C) are standard during ESS. For vascular tumors, a variety of hemostatic instruments are available: Harmonic scalpel, Aquamantys

irrigating bipolar, and coblation.

For highly vascular tumors such as angiofibromas, intraoperative blood loss is the limiting factor. Proper staging using the UPMC staging system better stratifies patients into high risk groups (Table 2)²¹⁾. Those patients with residual tumor vascularity following tumor embolization of the external carotid branches have higher blood loss and are more likely to have residual/recurrent disease. Even advanced UPMC stage tumors can be effectively removed using EES through a combination of preoperative embolization, hemostatic techniques, sequential dissection of vascular territories, and staging of surgeries (if necessary). EES can also be used for treatment of vascular lesions such as arteriovenous malformations and selected aneurysms (Figure 3)²²⁾.

Morbidity/Complications

The morbidity of EES can be categorized as *common*, *“almost never”*, and *unknown* events. The most common event is a postoperative CSF leak. A time series plot (run chart) is a useful method for tracking results and detecting variations in outcomes²³⁾. Further evaluation with a root cause analysis provides a learning opportunity and opportunity for quality improvement. A prospective randomized controlled trial has demonstrated the benefit of postoperative lumbar drainage, especially for large defects of the anterior cranial base and posterior fossa²⁴⁾. In the event of a postoperative CSF leak, it is considered an emergency and warrants return to the operating room for endoscopic repair within 24 hours. Early repair minimizes the risk of meningitis.

Table 2 UPMC Staging System for Angiofibroma

Stage	Stage Criteria
I	Nasal cavity, medial pterygopalatine fossa
II	Paranasal sinuses, lateral pterygopalatine fossa No residual vascularity
III	Skull base erosion, orbit, infratemporal fossa No residual vascularity
IV	Skull base erosion, orbit, infratemporal fossa Residual vascularity
V	Intracranial extension
	Residual vascularity
	M: Medial extension L: Lateral extension

Vascular injury is the most feared complication of EES and represents an *almost never* event. Surveys of skull base surgeons demonstrate that approximately 20% have had at least one ICA injury in the last 12 months²⁵⁾. A root cause analysis is useful in identifying the possible contributing factors. A review of 2015 sequential EES demonstrated injury of the ICA in 0.3% of cases²⁶⁾. Risk factors included left side (right-handed surgeons), chondromatous tumors, and para-clival segment of ICA. There was no association with stage of the learning curve. Most injuries required sacrifice of the ICA without neurologic deficits. There is a significant risk of pseudoaneurysm when the vessel is preserved. Successful management of a vascular injury requires a team approach with neurophysiological monitoring and access to interventional neuroradiology²⁷⁾. Training with a vascular model in the laboratory can improve the skills of the team for dealing with such an emergency²⁸⁾.

Sinonasal morbidity is increased in EES and should be considered in the management of patients. In most cases, it is temporary with return to baseline quality of life measures within a few months²⁹⁾. The use of a NSF has been associated with a saddle-nose deformity³⁰⁾. Loss of olfaction is not a consistent feature of ESS.

The biggest unanswered question is the impact of surgical approach on neurocognitive morbidity. A matched-pair comparison of EES and transcranial surgery for olfactory groove meningiomas demonstrated less radiographic brain injury with EES³¹⁾. Ongoing neurocognitive studies of

Figure 3 Endoscopic view of clipping of an aneurysm of the left posterior cerebral artery. Notice temporary clamps for proximal and distal control and calcification of neck of aneurysm (yellow discoloration).

patients will help to answer this question.

Training

The ability to perform EES safely and effectively requires proper training. Transition from open transcranial surgery to EES requires relearning skull base anatomy from an endoscopic perspective, adapting to 2D visualization, learning to function as a team, and mastering new surgical techniques. An incremental training program for EES has been proposed based on level of technical difficulty, potential risk of vascular and neural injury, and unfamiliar endoscopic anatomy (Table 3)³²⁾. Advancement to higher levels (with intradural dissection) is predicated on a commitment to team surgery, sufficient volume of cases, and adequate resources. Recent validation of the training program in a clinical series demonstrated good correlation of training level with out-

comes such as duration of surgery, blood loss, and major complications³³⁾. Simulation training is an important aspect of training, especially for rare but serious events such as vascular injury²⁸⁾.

Resources

Building a highly functioning team is the most important ingredient for success³⁴⁾. More than any other type of surgery, EES is *team surgery*. This requires a commitment from the members of the team and willingness to make compromises. The benefits of a co-surgeon are many: improved visualization through dynamic endoscopy, increased efficiency, second opinion for problem solving, and modulation of enthusiasm.

There needs to be an adequate volume of cases to develop surgical expertise. A commitment on the part of the institution

Table 3 Incremental Training Levels for Endoscopic Endonasal Skull Base Surgery

Level	Description	Examples
I	Sinus surgery	Endoscopic sphenoethmoidectomy Sphenopalatine artery ligation
II	Advanced sinus surgery Basic skull base surgery	Endoscopic frontal sinusotomy Cerebrospinal fluid leaks Lateral recess sphenoid Sella/pituitary (intrasellar) Medial orbital decompression
III	Extradural skull base	Sella/pituitary (extrasellar) Optic nerve decompression Transodontoid approach (extradural) Transclival approaches (extradural) Petrous apex (medial expansion)
IV	Intradural skull base Cortical cuff No cortical cuff	Petrous apex (exposure of carotid) Transplanum approach (intradural) Craniofacial resection Transclival approaches Transodontoid approach (intradural) Suprapetrous carotid approach
V	Coronal plane Vascular dissection	Infrapetrous carotid approach Parapharyngeal space Aneurysms Vascular malformations Highly vascular tumors

with dedication of adequate resources is necessary. This includes ancillary services such as neuroradiology, specialized pathology, interventional radiology, endocrinology, and critical care medicine. Obstacles to financial reimbursement need to be addressed such as coding issues and distribution of revenues³⁵⁾.

EES has been driven by advances in surgical technology, especially the introduction of the Hopkins rod lens endoscope. Technical limitations remain, however, and there is need for continued innovation in: visualization, navigation, soft tissue dissection, bone dissection, vascular surgery, reconstruction, and robotics.

Imagination

We are only limited by our imaginations. As Albert Einstein said, “If you always do what you always did, you will always get what you always got”³⁶⁾. Necessary ingredients for creativity include knowledge, technical skills, and improvisation (innovation)³⁷⁾. Our thinking processes are limited by heuristics, brain short-cuts for making decisions. In order to make room for a new idea, it is necessary to destroy old ways of thinking: “Every act of creation is first an act of destruction” (Pablo Picasso)³⁸⁾. The use of psychedelics to open the mind to new experiences is an intriguing possibility³⁹⁾.

Conflict of Interest

Drs. Carl Snyderman and Paul Gardner are consultants for SPIWay, LLC

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