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Open and Endoscopic Skull Base Approaches

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Abstract

Purpose of Review Surgical approaches to the skull base have been evolving at an incredible rate in the past 30 years. The advent of the endoscope has multiplied the available approaches while reducing morbidity. Otolaryngologists and neurosurgeons performing these operations must stay updated in recent trends and techniques to determine the best options for patients.

Recent Findings Twenty years have passed since the adoption of the endoscope in skull base surgery but new techniques are still being introduced on an annual basis. Most notably are the "cross court" techniques utilizing the contralateral transmaxillary (CTM) approach and transorbital neuroendoscopic surgery (TONES). Both approaches allow the surgeon increased angulation and access to lateral structures limited by the endonasal approach.

Summary Surgeons must understand the patient factors, pathology, and available resources as well as the armamentarium of approaches to the skull base to offer the best option for individual patients.

Keywords Skull base · Endoscopic approaches · Open approaches · Anterior cranial Fossa · Middle cranial Fossa · Posterior cranial Fossa

Introduction

History

Skull base surgery and sinonasal endoscopy both have their origins in the early twentieth century. In 1901, German otolaryngologist Alfred Hirschmann used the Nitze cystoscope to examine the sinuses and perform a limited sinus surgery [1]. M. Reichart is credited with the first sinus surgery in 1910 when he treated maxillary sinus disease through an oroantral fistula [2]. However, endoscopy was greatly limited by poor illumination and poor optics. It was not until after World War II in the 1960s, when Harold Hopkins, PhD, of Reading University developed the glass rod-lens endoscope which significantly improved visualization and light transmission, that endoscopy made a leap forward [3]. Walter Messerklinger, MD, of Austria began working with the Hopkins endoscope which allowed him to study mucociliary clearance and sinonasal procedures that were published in 1978 [4]. This work paved the way to modern day sinus endoscopy and surgery.

The bifrontal craniotomy was first described as an approach to the hypophysis in 1913 [5]. A few years later, the transbasal approach to the anterior ventral skull base was developed [5, 6, 7]. Not until the end of the twentieth century were major developments made in open approaches. In 1988, the subcranial approach was described for excision of fronto-orbital and anteroposterior skull base tumors. This approach was highlighted by its minimal frontal lobe retraction [8]. Three years later, a more extensive transbasal approach was described as creating access to tumors extending into the lateral anterior cranial fossa [9]. Sekhar et al. also described an extended frontal approach in 1992. This approach included orbito-fronto-ethmoidal osteotomies that improved access to the clivus with decreased frontal lobe retraction [10].

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In the late 1990s, otolaryngologists and neurosurgeons worked together to perform the first fully endoscopic surgeries of the sella in lieu of the commonly accepted microscopic approach. The advantages of the endoscopic endonasal approach (EEA) were readily apparent. As endoscopic surgery of the sella and parasellar region improved, the approaches expanded to include the anterior skull base and eventually certain parts of the middle and posterior cranial fossae as well. While open cranial approaches provide wide exposure to numerous pathologies along the skull base, the EEA has truly revolutionized the field of skull base surgery. Compared with transcranial and transfacial approaches, EEAs to anterior skull base tumors have led to decreased hospital and ICU stays, decreased blood loss, and faster recovery. This has led to the majority of sinonasal and ventral skull base tumors now being treated with an EEA [11]. Despite some of the advantages that an endoscope may offer, not all pathologies will be suitable for an EEA. Understanding the advantages, disadvantages, limitations, and complex anatomy of the various regions of the skull base are critical in selecting the best approach.

General Principles

Choosing the best surgical approach for a case must consider factors associated with the patient, the pathology, and available resources. While considering these factors, the surgeon should have an ultimate goal of addressing the lesion while minimizing unnecessary harm to surrounding structures. The concept of multidisciplinary teams to treat complex pathologies has shown improved outcomes especially in oncology [12]. Skull base surgery should be approached in a similar manner with a group of specialists such as neurosurgeons, otolaryngologists, anesthesiologists, neuropathologists, endocrinologists, oncologists, and diagnostic and interventional neuroradiologists [13]. The neurosurgeon and otolaryngologist should have extensive training in open and endoscopic approaches. The team should be prepared and capable of managing all potential complications, hence the need for an interventional neuroradiologist. The proper equipment should be available including the proper instruments and stereotactic computer-assisted surgery capabilities [14]. The proper level of postoperative care is required in these high acuity cases which include an intensive care unit with ancillary staff comfortable with neurological conditions.

Considerations for the patient's overall health, pre-existing symptoms, age, goals of care, and quality of life are important factors when choosing the appropriate approach. Skull base surgery is high risk and the patient must be able to tolerate the anesthesia of a potentially long surgery. Baseline visual, olfactory, and vestibulocochlear function must be considered as well, choosing an approach that maximizes preservation of function. The goals of care should be discussed with the patient while factoring in their age and quality of life. A thorough conversation with the patient and family members as well as medical clearance should be mandatory before performing surgery.

Finally and most importantly, the pathology and its location must be carefully analyzed. Malignant lesions should be treated differently than benign lesions. Benign lesions should be carefully dissected with preservation of important surrounding structures. Radiation may sometimes be used to treat any residual disease [15]. While the treatment of some malignant lesions may be histology driven, the current gold standard is still for complete removal with negative margins [16]. If gross total resection is not possible with an approach, an alternative approach or combined approaches should be considered. The consistency of a mass may make endoscopic removal technically difficult, in which case an open approach may be preferred.

The location of the lesion is an important factor in choosing the approach. The surgeon should have a thorough understanding of the anatomy surrounding the lesion and choose the approach that minimizes damage and achieves the stated goals. Vasculature of a tumor should also be considered and approach should be tailored accordingly. A highly vascular tumor being fed by superiorly based vessels is made more difficult if an inferior approach is utilized. A durable multilayered reconstruction should be available and planned prior to making an incision for an uncomplicated recovery [17]. The experienced surgeon should consider all aspects of the approach and decide the best route after thorough consideration of the various factors involved.

There are many available approaches to any part of the skull base. Open and endoscopic approaches should not be thought of as competing approaches, and may be used in combination in a complementary fashion. Endoscopic instruments can be used in conjunction with open approaches to better visualize hidden areas in the sinuses or skull base. An open approach may allow clearance of a tumor margin following endoscopic resection or facilitate reconstruction. These approaches should be utilized in a manner that is the least invasive while best achieving the stated goals of surgery and minimizing damage to surrounding structures.

Anterior Cranial Fossa

Anatomy

The anterior cranial fossa (ACF) is composed of the ethmoid and frontal bones anteriorly and the sphenoid bone posteriorly. The fovea ethmoidalis and cribriform plate of the ethmoid bone form the roof of the nasal cavity and house the olfactory foramina. Just posterior to the last of the olfactory foramina begins the planum sphenoidale, which is the roof of the sphenoid sinus. The anterior clinoid processes and lesser sphenoid wings serve as the posterior limits of the ACF, separating it from the middle cranial fossa (MCF). The lamina papyracea separates the ethmoids from the orbits laterally.

A number of important structures are located in the anterior cranial fossa. The communicating veins of the nasal cavity are found in a small midline depression at the base of the frontal bone called the foramen cecum. The ethmoidal vessels run across the ethmoid roof bilaterally at the level of the frontoethmoidal suture line. This suture line guides the surgeon to the level of the ethmoid roof and floor of the anterior fossa when viewed from the orbit. The anterior ethmoid artery (AEA) is located along the fovea ethmoidalis between the 2nd and 3rd lamellae, or in a coronal plane tangential to the posterior surface of the globe. The posterior ethmoid artery (PEA) is located at the junction of the fovea ethmoidalis and planum sphenoidale. The AEA and PEA are approximately 24 mm and 36 mm, respectively, from the anterior lacrimal crest, with the optic nerve another 6 mm posterior. The olfactory bulbs lie at the base of the frontal lobes on either side of midline, just above the cribriform plate. The olfactory fibers run through the olfactory foramina of the cribriform plate along with a small amount of dura as they pass through. At the posterior aspect of the ACF, the optic nerves and internal carotid arteries lie between and inferior to the anterior clinoid processes.

Approaches

Approaches to the anterior cranial fossa range from exclusively open to exclusively endoscopic and various combinations in between (Table 1). Examples include the bifrontal craniotomy; transfacial approaches via the lateral rhinotomy incision, Weber-Fergusson incision, Lynch incision, Dieffenbach incision, or midfacial degloving; subcranial approach alone or in combination with a transorbital, pteronial, orbito-zygomatic, or supraorbital eyebrow approach; and additional techniques such as Le Fort type I and II osteotomies, maxilla splitting, and craniofacial resection [11, 18]. Many of the craniofacial techniques were originally developed by plastic and reconstructive surgeons to address congenital craniofacial deformities [19]. For pathology of the ACF, the craniofacial and subcranial approaches are the most commonly utilized open approaches [20–23]. The main advantage of the open approach is wide exposure, which often allows for resection of intradural and extradural tumors with easier reconstruction [18, 24]. Frontal lobe retraction with potential neurologic dysfunction and facial incisions are the primary disadvantages of some of the open approaches. EEA is ideal for centrally located lesions, and minimizes manipulation of surrounding critical neurovascular structures that are typically situated laterally, with the exception of the olfactory apparatus [25]. The main limitations of endoscopic procedures are larger lesions with adherence or encasement of important structures, significant lateral extension, and intraparenchymal extension [25].

The transcribriform approach is the ideal EEA for ACF midline pathology involving the olfactory groove or crista galli, or sinonasal tumors with superior extension. This has not always been common practice; as Schroeder et al. previously suggested, the endonasal approach is only indicated if the tumor extends into the nasal cavity and the patient is anosmic [11, 26]. If the patient has intact preoperative olfaction, this is often lost with the endoscopic approach. In fact, most studies do not even report preservation of olfaction, assuming it is always lost [27]. Youssef et al. suggest, however, that with a unilateral approach, the contralateral olfactory apparatus may be preserved, potentially sparing some olfaction [28]. For lesions with intradural extension, a bilateral approach is often required.

Tumors extending laterally over the orbits can be difficult to address through a purely EEA. In selected cases, a superomedial orbitectomy can be performed endonasally by decompressing the orbit and removing part of the orbital roof without violating the periorbita [29, 30]. This modification should extend no further than the meridian of the orbit and the surgeon must be prepared for a repair with higher degree of difficulty [30]. Supraorbital eyebrow craniotomy, a type of “keyhole” approach, can supplement access to pathology with greater lateral extension. Cases with significant lateral extension should be considered for an open approach or possibly combined approach.

The transtuberculum-transplanum approach addresses lesions involving the planum sphenoidale, tuberculum sellae, suprasellar cistern, the optic chiasm, and the optic nerves. Lesions of this region can occupy both the ACF and MCF. One must remain cognizant of the optic nerves and carotid arteries when drilling, which are located superolaterally from an endonasal approach. Additional landmarks to be cautious of during intradural dissection include the carotid arteries in the paraclinoid region, the anterior cerebral arteries, the anterior communicating artery, and the recurrent artery of Heubner. The main limitations of this approach are lesions extending lateral to the ICA. A conchal type sphenoid sinus pneumatization can also make an endonasal approach challenging and time consuming given the extensive drilling necessary, but is not an absolute contraindication [31].

Lateral anterior cranial fossa lesions involving the orbital apex, supraorbital region, and lateral frontal lobe can be accessed by a variety of open approaches. The open options are infratemporal, transfacial, temporal, pteronial, and supraorbital craniotomy [32]. However, EEA is the preferred approach to access the medial orbital apex and optic canal for decompression [33]. Transcranial approaches are limited for lesions that are inferomedial to the optic canal. Total resection is possible, but could result in vision deficits due to potential manipulation of the optic nerve and poor visualization of hypophyseal arteries. One strategy to improve exposure and avoid the optic nerve via an open approach is to drill the anterior clinoid process and cut the falciform ligament. The other option is EEA, which may be optimal in such cases since it eliminates retraction of neurovascular structures and provides superior visualization and preservation of hypophyseal vessels [26, 32]. Ultimately, the ophthalmic arteries and optic nerves are the lateral limits of access endonasally by the nature of their inability to be mobilized [33].

Transorbital neuoro-endoscopic surgery (TONES) approach to the ACF is one of the newest endoscopic techniques addressing skull base pathology. Moe and colleagues [34, 35•] first described the transorbital technique in 2010 as four separate access ports—precaruncular, preseptal lower eyelid, superior eyelid crease, and lateral retrocanthal. With each port, a different orbitotomy can be made to access pathology of varying locations [34]. In addition to orbital lesions, TONES permits access to the ACF, MCF, and lateral cavernous sinus [34, 35•]. Ramakrishna et al. [35•] recommend the transorbital approach as more of a supplementary tool for challenging lesions that cannot be accessed by standard approaches. TONES also presents a unique set of complications including enophthalmos, epiphora, and ptosis [35•].

Table 1 Open and endoscopic approaches to ACF

ACF	Approach	Advantages	Disadvantages	Limitations
Open	Anterior Craniofacial Resection	Wide exposure, access to MCF	Osteotomies, hypesthesia, hyposmia	Orbit
	Lateral rhinotomy/Weber-Fergusson	Ease of approach, exposure of sinuses, inferior exposure	Cosmesis, lacrimal injury	Access limited to ipsilateral maxilla
	Midface degloving	Inferior exposure	Nasal vestibule stenosis, cosmesis	Access superiorly
	Midface split	Wide exposure	Poor cosmesis	Carotid arteries
	Bifrontal craniotomy	Wide exposure	Brain retraction, Neurologic sequelae	Need for frontal lobe retraction
	Subcranial	Superior exposure	Osteotomies, facial incisions	Lateral access
	Supraorbital Craniotomy	Lateral lesions	Poor exposure, difficult reconstruction	Specific lesions
	Le Fort osteotomies	Wide exposure	Dental sensory dysfunction, cosmesis	Not used alone
	Pteronial	Visualization of neurovascular structures	Brain retraction, possible neurologic sequelae	Sinonasal extension
Endoscopic	Transcribriform	Inferior midline exposure, no brain retraction	Anosmia, sinonasal morbidity	Lateral access
	Supermedial orbitectomy	Lateral exposure	Orbital injury	Meridian of the orbit
	Supraorbital "Keyhole"	Lateral exposure, cosmesis	Limited exposure, difficult reconstruction	Midline lesions
	Transtuberculum-transplanum	Inferior midline exposure	Hyposmia, risk of CSF Leak	Carotid arteries, optic nerve
	Transorbital neuroendoscopic	Cosmetically favorable, lateral access	Orbital complications	Midline lesions

ACF, anterior cranial fossa; *CSF*, cerebrospinal fluid; *MCF*, middle cranial fossa

Middle Cranial Fossa

Anatomy

The middle cranial fossa (MCF) is bounded by the sphenoid and temporal bones. Its anterior most border is the posterior edge of the lesser sphenoid wing, and posterior border is the posterosuperior edge of the petrous temporal bone. Medial and lateral compartments have been used to describe the middle cranial fossa to simplify surgical approaches [32]. These are generally defined by parasagittal lines projected through the medial pterygoid plates extending posteriorly to the occipital condyles bilaterally. The lateral compartment contains the greater wings of the sphenoid and the petrous and squamous portions of the temporal bone. Centrally is the body of the sphenoid which contains the pituitary fossa, sphenoid rostrum, sphenoid sinus, and nasopharynx.

In the midline, the junction of the ACF and MCF is marked by a bony ridge called the limbus of the sphenoid. This also separates the planum sphenoidale and the prechiasmatic sulcus, a depression between the two optic canals. The optic nerves pass through the optic canals which are bounded laterally by the anterior clinoid processes. Each optic canal is separated from the superior orbital fissure by the optic strut. The prechiasmatic sulcus sits superior and slightly anterior to the sella turcica which is a saddle-shaped depression that houses the pituitary gland. The tuberculum sellae and dorsum sellae are the bony ridges that make up the anterior and posterior borders of the sella turcica, respectively. The dorsum sella also makes up the upper clivus which then becomes part of the posterior cranial fossa (PCF) [36].

In the lateral compartment, the inferior portion of the lesser wing and the greater wing of the sphenoid create the superior orbital fissure. Several important structures pass through this fissure including the oculomotor nerve (III), trochlear nerve (IV), ophthalmic division of trigeminal nerve (V1), abducens nerve (VI), sympathetic fibers from the cavernous sinus, and ophthalmic vein. Foramen rotundum sits inferior to this transmitting the maxillary division of the trigeminal nerve (V2). Foramen ovale and spinosum sit posterolateral and transmit the mandibular division of the trigeminal nerve (V3) and the middle meningeal artery, respectively. Foramen lacerum is found posterior to these structures which contains the ascending pharyngeal artery. The greater superficial petrosal nerve and deep petrosal nerve join in foramen lacerum to form the vidian nerve. The carotid artery is situated immediately superior and slightly posterior to foramen lacerum.

The intersinus aspect of the MCF is important to discuss whether surgical approaches are done open or endoscopically. The most direct access to the medial MCF is through the sphenoid sinus. Pneumatization of the sphenoid sinus varies among individuals and is characterized as conchal, presellar, and sellar. This classification is important to understand because of the degree of bone that will have to be removed to enter the MCF. In well-pneumatized individuals, the indentation of the optic nerve and carotid arteries are visualized and the optico-carotid recess that separates them. This represents the optic strut discussed earlier. The midline bulge in the sphenoid sinus represents the sella turcica which the pituitary gland sits in. Inferior to that is the clivus which makes up the anteromedial PCF. Lateral to the clival recess runs the paraclival segment of the carotid artery. The pterygopalatine fossa is located behind the posterior maxillary sinus. The maxillary division of the trigeminal nerve can be traced from the pterygopalatine fossa through foramen rotundum to enter the MCF. The infratemporal fossa is located lateral to the pterygopalatine fossa and the mandibular division of the trigeminal nerve can be traced through foramen ovale entering the MCF.

Approach

Surgery of the MCF is difficult because of the complex neurovascular structures within it. Open approaches require large incisions and craniotomies to access these deeper areas of the skull base, and with it comes longer healing times, patient discomfort, and brain retraction leading to neurological sequelae [37]. Endoscopic approaches have provided surgeons with minimally invasive approaches but there is a significant learning curve. While endoscopic approaches to this region have been gaining in popularity, not every case is amenable to one (Table 2).

Open approaches to the anterior cranial fossa can be extended posteriorly to gain access to the MCF. Anterior craniofacial resection can be used to gain access to the ACF and the MCF by extending the approach posteriorly. The lateral rhinotomy and Weber-Fergusson incisions allow access and exposure to one side of the midface, and the sublabial or midface degloving approach provides access to the midface bilaterally. The midface split approach is cosmetically inferior to these above approaches but can give wide access to the central face. Once the midface has been exposed, osteotomies can be tailored to the lesion to gain the required exposure. Le Fort osteotomies and maxillectomies can give wide access to the nasal cavity which can extend posteriorly to the MCF. While these techniques allow for wide exposure allowing for gross total resection, the large osteotomies and incisions cause significant morbidity to the patient. The patient may experience varying degrees of postoperative pain, numbness, hyposmia, malocclusion, visual disturbances, neurological sequelae, and poor cosmesis after surgery [37, 38].

The MCF can also be accessed through lateral approaches. Exposure can be achieved through the intracranial, transtemporal, infratemporal, and transfacial approaches. The intracranial approach includes the traditional temporal craniotomy but can also be combined with the various transtemporal approaches like the presigmoid, translabyrinthine, and transcochlear approaches to access the posterior and medial MCF. The internal carotid artery limits the translabyrinthine and transcochlear approaches anteriorly so these approaches are more often used for posterior cranial fossa access. Additionally, sacrifice of hearing is necessary and patients may experience significant vertigo. The presigmoid approach allows for exposure of the petroclival region with preservation of hearing; however, anatomic variability may limit access [39]. Infratemporal approaches include the infratemporal fossa, transparotid, or extended rhytidectomy approach. These approaches all require dissection of the facial nerve and the infratemporal approach requires closure of the ear canal causing conductive hearing loss. Transfacial approach utilizes a facial translocation technique with hemicoronal and lateral rhinotomy incisions followed by osteotomies to give wide exposure to the infratemporal space and medially to the sphenoid. This however requires transection of the frontal branch of the facial nerve which can be anastomosed at the end of the case.

Endoscopic approaches to the middle cranial fossa are largely transnasal, although extended and combination approaches provide increased angulation to increase access. The most common EEA is a transsphenoidal transsellar or transtuberculum approach for midline pathologies. The EEA for management of pituitary lesions has been widely accepted because of decreased complications of facial swelling, septal perforation, and numbness to the incisors as well as shorter hospital stay [40]. These approaches can also be used for more

Table 2 Open and endoscopic approaches to MCF

MCF	Approach	Advantages	Disadvantages	Limitations
Open	Temporal craniotomy	Ease of approach, infratemporal access	Brain retraction	Limited access to medial MCF
	Presigmoid	Preservation of hearing, less brain retraction	Anatomical variability in exposure	Vestibular structures, sinodural angle
	Translabyrinthine/transcochlear	Less brain retraction	Sacrifice of hearing	ICA, limited exposure of MCF
	Transcanal infracochlear	Access to petrous apex, small incision	Limited working angle and exposure	Jugular bulb, ICA
	Infratemporal fossa	Wide exposure to medial MCF	Closure of EAC, facial nerve risk	Petrous ICA, sigmoid sinus
	Facial translocation	Wide exposure	Cosmesis, sacrifice of frontal branch	Orbit
Endoscopic	Transellar/transtuberculum	Minimally invasive	Limited working angle	ICA, optic nerve
	Transplanum	Increased anterosuperior exposure	Possible hyposmia/anosmia	Olfactory nerves, anterior circulation
	Transpterygoid	Increased lateral exposure	Possible hypesthesia, Vidian nerve injury	Lateral access limited by structures in PPF
	Anteromedial maxillectomy	Improved access to maxillary sinus and lateral sphenoid sinus/MCF floor	Possible hypesthesia	Nasolacrimal duct
	Denker's maxillotomy	Access to anteroinferior maxillary sinus	Cosmesis, epiphora	Still requires working through nostril
	Contralateral transmaxillary	Improved working angle to lateral petrous apex	Sublabial incision	May require SPA sacrifice, CN VI

EAC, external auditory canal; *ICA*, internal carotid artery; *MCF*, middle cranial fossa; *PPF*, pterygopalatine fossa; *SPA*, sphenopalatine

extensive pathology, often allowing the surgeon to follow the pathology into the middle cranial fossa. This approach can extend anteriorly utilizing a transplanum or transcribriform approach which facilitates not only anterior but superior exposure [41]. The optic chiasm sits just above the pituitary gland and its location relative to the pathology is critical to choosing the best approach. Olfactory tracts run parallel in an anterior direction above the planum.

Laterally, the ICAs and cavernous sinuses limit access, but inferior and anterior dissection of the middle fossa floor is possible with extended approaches. The transpterygoid approach gives access to the lateral recess of the sphenoid, middle fossa floor, and petrous apex. The sphenopalatine artery is often sacrificed during this approach and its implication on reconstruction should be considered, especially if utilizing a nasoseptal flap. The transpterygoid approach places structures in the pterygopalatine fossa at risk, including the maxillary division of the trigeminal nerve (V2), greater and lesser palatine nerves, vidian nerve, pterygopalatine ganglion, and the terminal branches of the internal maxillary artery.

While the transpterygoid approach can improve lateral access from an endonasal approach, additional corridors can be introduced to further extend lateral access [42, 43]. Working through these different corridors can allow for a greater working angle and exposure. Examples of this include the medial maxillectomy, anteromedial maxillectomy (Denker's maxillotomy), and sublabial transmaxillary approach. An endoscopic Denker's approach can be used for greater access to the anteroinferior maxillary sinus, pterygopalatine fossa, and infratemporal fossa [44]. While the Denker's maxillotomy extends access, it still requires the surgeon to work through the nostril. Also given the need to take down the pyriform aperture, there is some risk of cosmetic deformity as well as epiphora from lacrimal duct injury.

The endoscopic transmaxillary approach can be performed through a sublabial incision and used to access even further lateral structures in the infratemporal fossa [45]. This requires a secondary incision but provides a second working corridor for endoscopy and instrumentation. This approach introduces risk to the infraorbital nerve but eliminates the risk of cosmetic deformity and epiphora. These various approaches can improve access to Meckel's cave and foramen ovale [46].

Additional extended approaches have been described as "cross court" approaches. The most familiar "cross court" approach is utilizing both nostrils and making a posterior septectomy to access the sphenoid sinus [47]. This technique allows for a two surgeon, four-handed surgery to be performed and increases working angle into lateral structures. Transseptal approaches have also been described for improved access anteriorly where non-overlapping septal flaps are elevated, followed by removal of bony and cartilaginous septum to provide improved angulation by as much as 15 degrees. The opposing flaps are then sutured back to the remaining septum to avoid large septal defects [48]. The modified hemi-Lothrop procedure is another approach developed by Eloy et al., that utilizes an anterior septectomy to access the contralateral frontal sinus while preserving the ipsilateral frontal recess [49]. A newer approach developed by Patel et al. is the contralateral transmaxillary corridor (Fig. 1) [50••]. The lateral petrous apex has been a difficult area to reach endonasally because of the paraclival carotid arteries. Displacement of the paraclival carotid arteries is sometimes required to access more lateral lesions within the petrous apex [51, 52]. The contralateral transmaxillary approach utilizes the sublabial transmaxillary corridor from the side opposite the pathology which allows for a better working angle and a trajectory that is more parallel with the petrous carotid artery. This helps achieve greater lateral access with less manipulation of the ICA. Access to the lateral clivus and hypoglossal canal has also been described using this approach [53, 54].

TONES, discussed in the ACF section, can also be applied to gain access to the MCF. Ramakrishna noted the ability to access the MCF dura and lateral cavernous sinus based on his clinical experience [35•]. Several studies out of Korea have documented successful access to the MCF with TONES alone or in combination with endonasal approaches [55–57]. These benign lesions involved the cavernous sinus and Meckel's cave. Additional anatomic feasibility studies have been published allowing access to the infratemporal fossa, parapharyngeal space, mesial temporal structures, and petrous apex [58–60]. Lateral transorbital approaches have also been described to extend the exposure by removing the bone lateral to the superior orbital fissure [61, 62]. The medial limits in the MCF with TONES alone include the ICA and trigeminal nerve. The greatest utility is likely with combined endonasal approaches.

Posterior Cranial Fossa

Anatomy

The posterior cranial fossa is bounded by the posterior surface of the petrous temporal bone and the occipital bone. It houses the cerebellum and brainstem. The internal auditory canal (IAC) is located on the posteromedial aspect of the temporal bone and transmits the facial nerve and vestibulocochlear nerve. The jugular foramen is made of the temporal bone and occipital bone and transmits the glossopharyngeal nerve, vagus nerve, accessory nerve, inferior petrosal sinus, and sigmoid sinus. The hypoglossal nerve passes through the hypoglossal canal in the occipital bone. The medulla oblongata, accessory nerve, and spinal and vertebral arteries pass through the foramen magnum.

The anterior limit of the posterior fossa is the dorsum sella of the sphenoid bone which articulates with the occipital bone to form the clivus. The clivus can be divided into upper, middle, and lower portions. The upper or "sellar" clivus is made of the dorsum sellae and posterior clinoid process and extends down to the level of Dorello's canal that transmits the abducens nerve as it enters the cavernous sinus. The middle or "sphenoidal" clivus extends from the floor of the sella to the choanae (floor of the sphenoid sinus). The paraclival carotid arteries run laterally and foramen lacerum divides the middle and lower clivus. The petrous apex can be found lateral and posterior to the paraclival and horizontal petrous portions of the carotid arteries. The lower or "nasopharyngeal" clivus extends down to foramen magnum.

Removing the middle clivus reveals the prepontine cistern where the basilar trunk, anterior inferior cerebellar artery, abducens nerve, and the ventral surface of the pons are located. The inferior clivus can be accessed through the nasopharynx by going through the pharyngobasilar fascia, longus capitis muscle, and rectus capitis muscles. Deep to these muscles are the foramen magnum, anterior ring of C1, occipital condyles, and atlanto-occipital joint. This provides access to the vertebral arteries, vertebrobasilar junction, posterior inferior cerebellar artery, anterior spinal artery, hypoglossal canal and nerves, lower cranial nerves, and ventral medulla. The eustachian tube limits access to the jugular foramen.

Approach

Surgical access to the posterior cranial fossa can be through lateral and posterior approaches (Table 3). Expert anatomical knowledge and surgical technique of the vestibulocochlear system is necessary when approaching the posterior cranial

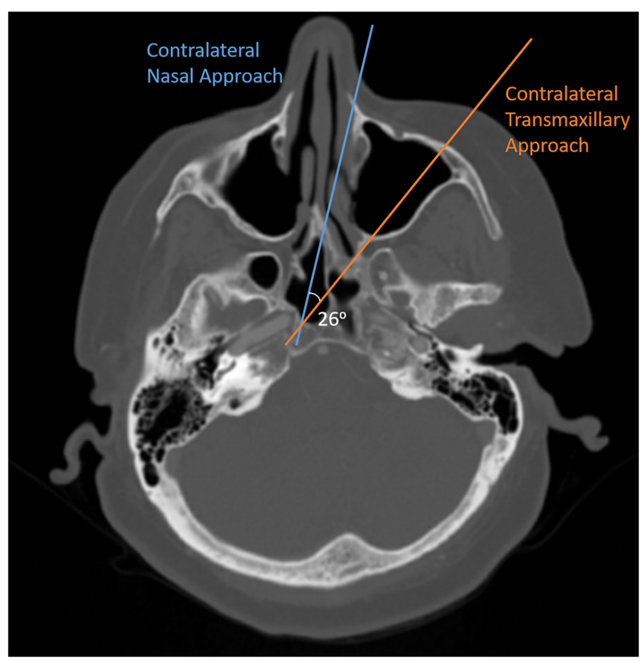

Fig. 1 Contralateral approach corridors

Table 3 Open and endoscopic approaches to PCF

PCF	Approach	Advantages	Disadvantages	Limitations
Open	Retrosigmoid	Preservation of hearing	Access to IAC	Facial, vestibulocochlear nerves
	Far-lateral approach	Exposure down to craniocervical junction	Lower cranial neuropathies	Brainstem, lower cranial nerves
	Midline suboccipital	Ease of approach, access to midline PCF	Lower cranial neuropathies	Brainstem, lower cranial nerves
Endoscopic	Transclival	Minimally invasive	Limited lateral access, vidian neuropathy	Petroclival ICA, eustachian tube
	Pituitary transposition	Wide view of interpeduncular cistern	Risk of CSF leak, risk of pituitary dysfunction	Optic nerves, cavernous sinus
	Transoral	Direct access to craniocervical junction	Limited working angle, usually requires combined approach	Vertebral arteries, spine

IAC, internal auditory canal; *ICA*, internal carotid artery; *PCF*, posterior cranial fossa

fossa through the temporal bone. Open approaches to the medial posterior cranial fossa include transcochlear and transotic approaches. These approaches require sacrifice of hearing on the surgical side. The facial nerve also limits exposure and may result in temporary facial nerve paresis. The intracranial approaches include the extended middle cranial fossa, retrosigmoid, and the transpetrosal approaches [63]. While these latter approaches allow hearing preservation, temporal lobe and cerebellar retraction is required. If the lesion extends inferiorly, the far-lateral approach allows exposure to the foramen magnum and craniocervical junction [64, 65] Access to the most posterior portion of the posterior cranial fossa is possible through the midline suboccipital approach.

Endoscopic endonasal approaches are very useful for midline pathologies. Both transnasal transclival and transoral approaches have been described. The transnasal approach provides access from the upper clivus to the craniocervical junction. Visualization of the upper clivus can be improved with a pituitary transposition [66]. The middle clivus requires significant trepanation of the vomer and floor of the sphenoid. The vidian canal is found within the floor of the sphenoid sinus below the lateral recess and often needs to be sacrificed for adequate exposure laterally. The abducens nerve runs just laterally to the paraclival ICA and both of these limit lateral access in the middle clivus. As discussed previously, the contralateral maxillary approach can improve the ability to access areas behind the carotid, but care must still be taken to avoid injuring the abducens nerve [50••]. The lower clivus is approached through the nasopharynx. The hypoglossal nerve and branches of the ascending pharyngeal arteries run on the lateral edge of the rectus capitis muscles and should be saved [67]. The hypoglossal canal is the demarcation of the jugular tubercle above and the occipital condyle below. Lateral limit of dissection in this area is the cartilage of the eustachian tube [68]. The cartilaginous eustachian tube can be divided for improved access but this carries the risk of creating chronic middle ear dysfunction [69]. Further inferior access is possible through transoral and transpharyngeal approaches if access to the cervical vertebrae is required.

Conclusion

Surgical approaches to the skull base have evolved over time and surgeons have learned to perform surgery in an increasingly efficient, safe, and minimally invasive way. Open and endoscopic approaches are at the two ends of the spectrum when considering the invasiveness of the procedure. Surgeons should think of utilizing this entire spectrum while considering patient factors, pathology, and available resources when choosing an approach. Many studies have attempted to compare the various approaches but there are far too many variables to consider, making a comparative study difficult.

Ultimately, the approach should be chosen by the surgeon that has a complete understanding of the available options, consideration of the disease process, all while keeping the best interest of the patient in mind.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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•• Of major importance

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