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Review Article

Surgical approaches to the petrous apex

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Abstract The petrous apex is a difficult to reach surgical area due to its deep position in the skull base and many vital surrounding structures. Petrous apex pathology ranges from extradural cholesterol granulomas, cholesteatomas, asymmetric pneumatization, and osteomyelitis to intradural meningiomas and schwannomas. Certain lesions, such as cholesterol granulomas, can be managed with drainage while neoplastic lesions must be completely resected. Surgical options use open, endoscopic, and combined techniques and are categorized into anterior, lateral, and posterior approaches. The choice of approach is determined by the nature of the pathology and location relative to vital structures and extension into surrounding structures and requires thorough preoperative evaluation and discussion of surgical goals with the patient. The purpose of this state-of-the-art review is to discuss the most commonly used surgical approaches to the petrous apex, and the anatomy on which these approaches are based.

Introduction

The petrous apex is a complex region of the temporal bone that can harbor lesions which are difficult to access surgically.[1–5] Pathology of the petrous apex is divided into extradural and intradural etiologies. Extradural pathology includes cholesterol granulomas, cholesteatomas, or epidermoid cysts, and osteomyelitis. Intradural pathologies include meningiomas and schwannomas.[6–10] Of the petrous apex pathologies, asymmetric pneumatization and effusion are the most common, outnumbering cholesterol

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granulomas, which themselves have an incidence of 0.6 cases per million, 500 to 1.[11,12] Cholesterol granulomas are 10 times more common than cholesteatomas of the petrous apex and, together, these are the most common destructive lesions of the petrous apex.[13,14]

Petrous apex pathology is usually found incidentally on imaging for unrelated symptoms.[15] Symptoms, if present, are heterogeneous. The most common otolaryngologic complaint is hearing loss, but aural fullness and vertigo secondary to compression of the 8th cranial nerve are also common.[9,16] These symptoms are present in approximately 65% of patients with petrous apex pathology[15]. Other symptoms include headaches due to involvement of the trigeminal nerve, diplopia from compression of the sixth cranial nerve, and seventh nerve-related facial spasm or weakness. Severe infection may result in Gradenigo's syndrome: purulent otorrhea, abducens palsy, and otalgia.[17,18]

Evaluation of petrous apex lesions involves a comprehensive evaluation of cranial nerve function and audiometry. Computed tomography (CT) is routinely used to determine the optimal surgical approach if surgical intervention is warranted. Magnetic resonance imaging (MRI) can narrow the differential diagnosis without the need for tissue biopsy.[14,19]

Lesions of the petrous apex are difficult to resect due to their deep position within the skull base and close anatomical proximity to vital structures such as the internal carotid artery (ICA), cavernous sinus, and Meckel's cave.[4,20–22] Certain lesions, such as cholesterol granuloma, can be managed with drainage while neoplastic lesions, for example, must be fully resected.[20] Surgical options use open, endoscopic, and combined techniques categorized into anterior, lateral, and posterior approaches to establish an adequate corridor to the target lesion (Fig. 1).[6,20,23] Each of these approaches has distinct advantages and disadvantages such as surgical access and sacrifice of vital structures. The most commonly used surgical approaches to the petrous apex, and the anatomy on which these approaches are based, are discussed in this state-of-the-art review.

Anatomy of the petrous apex

In the skull base, the temporal bone is divided into the squamous, petrous, styloid, tympanic, and mastoid portions. The petrous portion is the most medial aspect of the temporal bone and encloses the vestibule, semicircular canal, facial canal, carotid canal, and the cochlea. It is comprised of three surfaces and margins, a base, and an apex and is located between the greater wing of the sphenoid and the occipital bone.[15,24] Within the petrous portion, the petrous apex is a triangularly shaped area that is comprised of an anterior apex with borders defined superiorly by the petrous ridge, which contains the sulcus of the superior petrosal sinus, and inferiorly by the petroclival suture, which is the groove for the inferior petrosal sinus. The base of the triangle is a virtual line drawn vertically down from the anterior edge of the porus acousticus.[25] The petrous apex is bounded anteriorly by the ICAs and the bony labyrinth, posteriorly by the posterior cranial fossa, superiorly by Meckel's Cave and the middle cranial fossa, and inferiorly by the jugular bulb and inferior petrosal sinus (Figs. 1 and 2).[26]

Anterior approaches

The endoscopic endonasal approach (EEA) is typically indicated for extradural and anterior pathologies of the petrous apex with recent innovations allowing for lateral lesions to be accessed that would have, traditionally, been inaccessible due to the location of the ICA.[25,27–31] The EEA minimizes risks to hearing or the facial nerve, which are typically elevated with lateral approaches, reduces surgical morbidity, and shortens hospitalization.[23] The EEA can also be combined with other approaches to more effectively treat pathology.[32–34]

All EEA to the petrous apex begin with a bilateral extended sphenoidotomy to facilitate binostril, four-handed surgery.[23,27] Careful note must be made of sphenoid surface anatomy. The ICA is usually visible as the bony protuberance lateral to the sellar floor and the clival indentation. The medial and lateral optico-carotid recess (OCR) are consistent landmarks delineating the borders of the ICA and the optic nerve.[35,36] The vidian canal lies superior and medial to the lacerum portion of the ICA and, thus, drilling along the inferomedial aspect of the canal allows for a safe approach to the ICA.[37–39] Feng et al demonstrated that the torus tubarius, carotico-optic recess, foramen rotundum, and foramen ovale all act as reliable anatomic landmarks with consistent distances to the foramen lacerum and the internal carotid artery.[21] The pterygosphenoidal fissure is another effective landmark to help find and expose the foramen lacerum as it is located anteriorly.[38]

In cases of petrous apex cholesterol granuloma, the use of angled endoscopes and hand instrumentation allows for complete resection of the lesion with the capsule wall, decreasing overall morbidity and recovery time compared to open approaches, and making the EEA an attractive initial option[8].

Medial transsphenoidal approach

The medial transsphenoidal approach is best suited for lesions with medial expansion into a well-pneumatized sphenoid sinus placing a portion of the lesion medial to the vertical segment of the ICA (Fig. 3). As described by Zanation et al, this approach is begun with a bilateral sphenoidotomy.[23] The sphenoid mucosa is stripped to facilitate identification of the sella, clival recess, optic canal, medial and lateral OCR and carotid canal. Image guidance can be used to facilitate identification of the ICA. A posterior septectomy is performed to enhance the angle of approach and to allow for a binostril, four-hand technique. The bone overlying the lesion is meticulously drilled using a diamond burr. If necessary, the ICA can be exposed by careful drilling of the overlying bone to further widen the operative window. Once thinned enough, the bone can be fractured and removed with Kerrison rongeurs until the lesion is exposed for drainage or resection (Fig. 4).[23]

Aubry et al concluded that the endoscopic endonasal transsphenoidal approach facilitated better access to the petrous apex cholesteatoma and had less risk for vascular or nervous injury as compared to the lateral

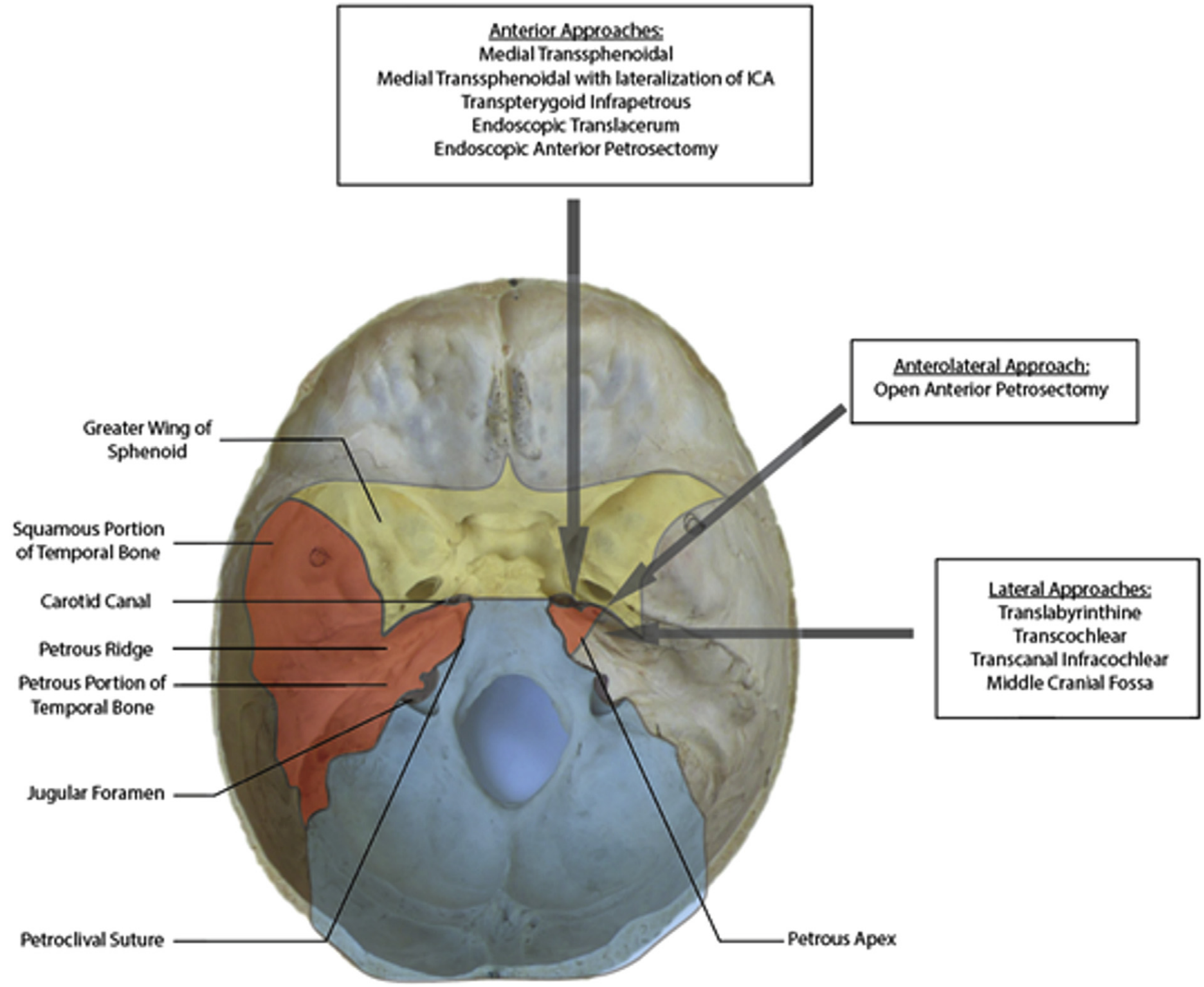

Fig. 1 An illustration of the various surgical approaches to the petrous apex with relevant anatomy. The sphenoid bone (yellow), temporal bone (red), and occipital bone (blue) are shaded.[68]

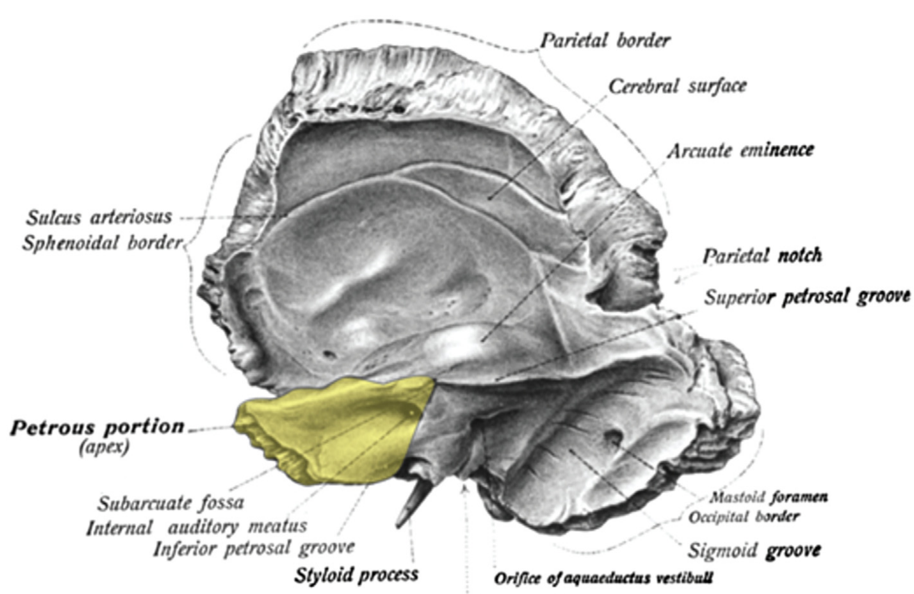

Fig. 2 Detailed anatomy of the petrous apex (yellow).[69]

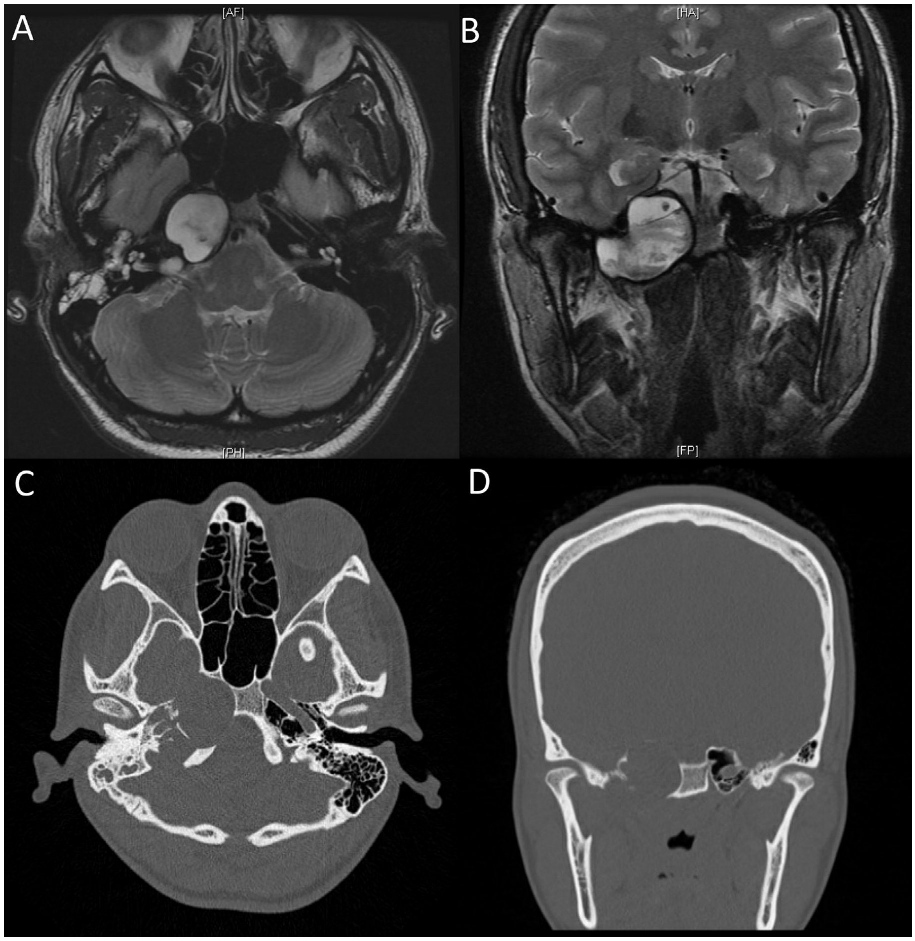

Fig. 3 A and B are T2-weighted MRI images demonstrating a multilobulated expansile lesion in the right petrous temporal bone extending to the sphenoid bone and displacing the petrous internal carotid artery consistent with a cholesterol granuloma. C and D are non-contrast high-resolution CT images re-demonstrating the right petrous apex lesion and the associated remodeling and scalloping of surrounding bones including the clivus as well as bony dehiscence of the right petrous carotid canal.

transtemporal or middle fossa approaches[26,40]. Shin et al demonstrated that this approach can also be extended by approaching through the retrocarotid space for lesions in the jugular fossa, cavernous sinus, and internal auditory canal[41].

Medial approach with lateralization of the internal carotid artery

Lesions of the petrous apex that cannot be visualized completely due to poor pneumatization or a more posterolateral location, placing them lateral to a plane drawn through the medial border of the ICA, may require additional bone removal for adequate access. This approach is begun by executing a transpterygoid approach. In brief, the posterior wall of the maxillary sinus is removed medially to expose the contents of the pterygopalatine fossa. The sphenopalatine artery is ligated and transected, allowing the soft tissue package to be displaced laterally to expose the pterygoid bone. The vidian nerve is identified exiting the pterygoid canal and a diamond drill burr used to remove bone inferomedially along the canal, proceeding posteriorly and laterally until the second genu of the ICA is identified. The paraclival bone overlying the internal carotid artery can then be carefully dissected and removed, allowing lateral displacement of the vertical paraclival internal carotid artery segment. This approach widens the window to the petrous apex by several millimeters.[23] Medial extension of the window can be achieved by drilling through the clivus until the brainstem dura is exposed.

Transpterygoid infrapetrous approach

Certain petrous apex lesions that are laterally situated or are inferior to the petrous ICA are simply not accessible through the sphenoid sinus. In such cases, the transpterygoidinfrapetrous approach allows for exposure of the entire petrous apex along the undersurface of the petrous ICA. Some surgeons use this approach for all solid tumors of the petrous apex.[23] A transpterygoid approach is performed as described in the prior section. The vidian artery and nerve are transected and displaced laterally to expose V2 at the foramen rotundum. The superior aspect of the medial and lateral pterygoid plates are drilled down. The vidian artery is used to identify the junction of the paraclival (vertical) and petrous (horizontal) ICA.[23,37,42] The ICA

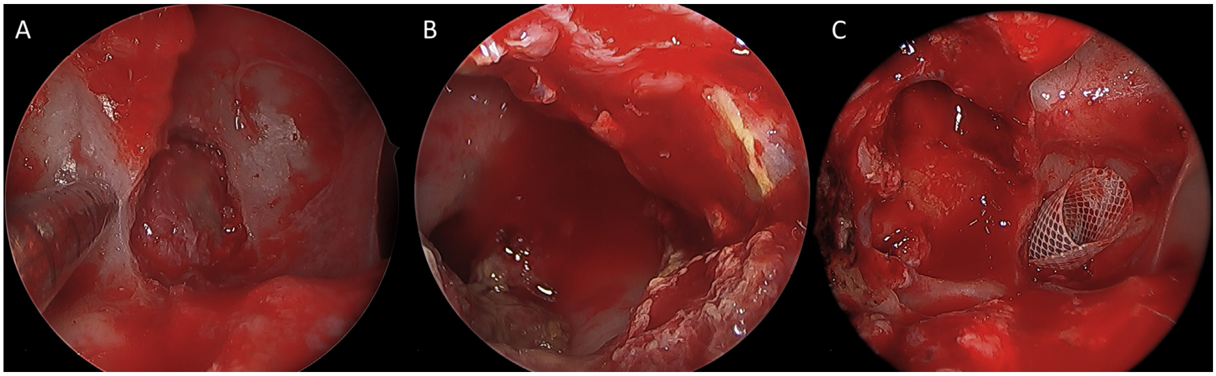

Fig. 4 Series of endoscopic images derived from the same patient. A: Initial exposure of petrous apex granuloma capsule via medial transsphenoidal approach. B: Evaluation of the expanded granuloma cavity using 30° angled endoscope demonstrating typical debris associated with this lesion within the cavity. C: View of the sphenoid and silastic stent placed across the opening into the petrous apex.

is skeletonized. A one centimeter segment of the cartilaginous eustachian tube is resected. The posterior edge of the lateral pterygoid plate is used as a landmark to identify V3. Drilling medial to this structure between the petrous (horizontal) ICA and the eustachian tube exposes the undersurface of the petrous apex. Drilling inferior to the petrous ICA allows access to the petrous apex lesion.[7,23,43,44]

The transpterygoid approach is not suitable for disease that extends posteriorly into the IAC and/or occipital condyle. These lesions may be better approached with lateral or posterior approaches.[6] Combining different approaches may tackle this issue. Raza et al found that chondrosarcomas of the petroclival region are better approached and have better outcomes with a combined endoscopic transpterygoid and transcranial approach for tumors that extend supero-lateral to the petrous ICA, have temporal bone involvement, or extend laterally beyond Meckel's cave.[45] Maza et al found that a transoral approach may supplement the transpterygoid approach, providing greater angles of approach.[46]

Endoscopic translacerum approach

Despite the advances in the endoscopic endonasal approaches, the inferior petrous apex is still a difficult region to access endoscopically. Lateral approaches to this area require various degrees of petrosectomy and sacrifice of structures. The foramen lacerum offers a potential, less morbid approach.[47] Taniguchi et al describe the endoscopic translacerum approach, which entails performance of a transpterygoid approach with dissection of the vidian nerve up to the foramen lacerum. The bone overlying the paraclival carotid was removed to the level of the foramen lacerum, as was the medial half of the base of the pterygoid. This effectively exposes the superior surface of the cartilaginous eustachian tube. From here, the fibrocartilage covering the foramen lacerum was transected near the eustachian tube and the fibrous ligament within the foramen lacerum was removed to expose the anterior genu and petrous (horizontal) ICA. The inferior petrous apex can then be accessed in the created space between the petrous ICA and the superior aspect of the eustachian tube. The authors found that the translacerum approach is a reliable way to access the inferior petrous apex and allow lateral access from the medial ICA to the jugular foramen, and the posterior vertical petrous carotid artery.[47]

Open anterior and endonasal anterior petrosectomy

One of the main limitations of the EEA is the inability to access disease that extends superiorly to the level of the petrous ICA, laterally into the temporal bone or inner ear, posteriorly into the hypoglossal canal, or inferiorly into the parapharyngeal space.[7] An anterior petrosectomy is preferred for intradural tumors with supratentorial extensions.[6] For petrous apex pathology that extends into other regions, the open anterior petrosectomy has also been described as an approach that provides access lateral to the jugular foramen, anteriorly into the preclival/paravertebral musculature, and inferiorly to the occipital condyles.

The open anterior petrosectomy begins with a linear incision anterior to the tragus and extending from the superior temporal line to the root of the zygoma. The temporalis muscle is exposed, dissected, and retracted laterally to allow for a temporal craniectomy centered over the root of the zygoma. From there, the dura is elevated and subsequently divided while preserving the greater superficial petrosal nerve. A retractor is placed at the medial petrous apex and facilitates bone resection from the trigeminal dura posteromedially to the greater superficial petrosal nerve anterolaterally. The superior petrosal sinus is next elevated and mobilized from the petrous ridge. The internal auditory canal is skeletonized as well as the posterior and medial surfaces of the internal carotid artery. From there, the bone can be removed in Kawase's quadrangle down to the inferior petrosal sinus. The anterior petrosectomy has the advantage of accessing other structures ventral to the brain stem and medial to the cranial nerves, potential exposure of the contralateral petrous apex, and preservation of hearing. However, this approach does require retraction of brain, potential CN V3 palsy, inability to access the clivus, and restricted access to the cerebellopontine angle.[1]

The endoscopic anterior petrosectomy can either start with a medial approach through the sphenoid, with or without internal carotid mobilization, or following a transpterygoidinfrapetrous approach. Once the petrous apex is exposed following ICA mobilization, 0° and 45° endoscopes are used alongside an angled drill to remove bone.[48]

Van Gompel et al found in a cadaveric study that, compared to an open anterior petrosectomy, the endoscopic anterior petrosectomy compromised volumetric resection of lesions by over 50% and, thus, may be better suited for lesions of the inferior petrous apex. The open anterior petrosectomy allowed for resection of lesions in the superior portion of the petrous apex. Consequently, the authors classified the open approach as the "superior anterior petrosectomy" and the endoscopic approach as the "inferior anterior petrosectomy".[48]

Lateral approaches

Translabyrinthine approach

The translabyrinthine approach was first popularized by House.[49] This approach preserves the facial nerve, the cochlea, tympanic cavity and external auditory canal. First, a retroauricular incision is made that extends from above the pinna to the mastoid tip. The bone over the mastoid is drilled to expose the semicircular canals. The occipital bone is drilled in the retrosigmoid area to expose the retrosigmoid dura and allow retraction of the sigmoid sinus. The sigmoid sinus is uncovered and skeletonized, along with the middle fossa dura, jugular bulb, and mastoid facial nerve. A labyrinthinectomy is performed and then the internal auditory canal is uncovered 270° of the circumference with exposure of the dura of the internal auditory canal.[24] The traditional translabyrinthine approach allows for petrous bone access but the translabyrinthine-transapical approach extends the surgical field into the petrous apex. The traditional translabyrinthine approach is limited for approaching the anterior cerebellopontine angle by the anterior wall of the internal auditory canal. The additional transapical approach removes the entire petrous apex and allows larger angle access to tumors that extend anteriorly. Moreover, this approach can be useful for overcoming unfavorable anatomy such as a high jugular bulb or an anterior sigmoid sinus.[50–53]

Transcochlear approach

House and Hitselberger first described the transcochlear approach in 1976.[54] This approach was designed to reach petroclival or large median intradural lesions and cerebellopontine angle tumors, which were considered inoperable until this point. The original transcochlear approach is an anteromedial extension of the translabrynthine approach with additional posterior transposition of the facial nerve, removal of the cochlea, and removal of the petrous bone. Since this approach removes the cochlea and can potentially injure the facial nerve, it should be considered for patients with history of or presentation with hearing impairment. The transcochlear approach is useful because it gives a wide exposure of the anterior, medial, and median cerebellopontine angle and gives control of the intrapetrous internal carotid artery.[24,52,54,55]

As described by Restivo and Danesi, the transcochlear approach begins with a retroauricular C-shaped skin and subcutaneous tissue incision. Next the mastoid is exposed and the skin and cartilaginous portion of the external auditory canal is incised and dissected towards the concha respectively. From here, an enlarged mastoidectomy and skeletonization of the middle and posterior fossa dura to the sigmoid sinus is performed. The facial nerve is identified and skeletonized to the level of the geniculate ganglion and great petrosal nerve, which then allows for an open mastoidectomy to be performed to remove the superior and posterior walls of the external auditory canal. The jugular bulb is then skeletonized to begin the labyrinthectomy and vestibule opening. The vestibular nerves are identified, and the internal auditory canal is skeletonized as well to the level of the internal acoustic meatus. The tympanic bone is removed and the anterior auditory bony canal is drilled to expose and skeletonize the internal carotid artery. The cochlea is removed, and the genu of the carotid is skeletonized with removal of tympanic bone until middle fossa dura is exposed. The remaining thin layers of bone that are left on the facial nerve can now be removed using a dissector and skeletonization continues until the CN VII fundal emergence is reached. In order to reroute the facial nerve, the greater superficial petrosal nerve is sectioned and the geniculate ganglion and labyrinthine facial nerve are released in order to subsequently release the tympanic and mastoid portion of the facial nerve. The superior and inferior vestibular nerves as well as the cochlear nerve are interrupted at the fundal emergence to completely free the facial nerve. Posterior transposition of the facial nerve to the corner between the sigmoid sinus and jugular bulb can now be performed, taking care to remove all bone at the stylomastoid foramen. The rest of the internal carotid can now be skeletonized to expose the petrous apex.[52]

Transcanal infracochlear approach

Microscopic surgical approaches were developed to facilitate removal of internal auditory canal and cerebellopontine angle pathologies. The main drawback to these approaches, like many lateral approaches, is brain and vascular manipulation. To overcome this drawback, surgeons have gradually turned to endoscopic techniques for lateral skull base procedures. The transcanal approaches use the external auditory canal as a natural corridor to reach lesions and include the transcanal transpromontorial corridor, the transcanal infracochlear approach, and the transcanal suprageniculate corridor. However, the transcanal infracochlear approach is the only approach that reaches the petrous apex.[2,52] The transcanal infracochlear approach allows for treatment of disease in the petrous apex below the internal auditory canal and preserves hearing function. This corridor is created by drilling between the cochlea superiorly, the jugular bulb inferiorly, and the carotid artery anteriorly (Fig. 5). The

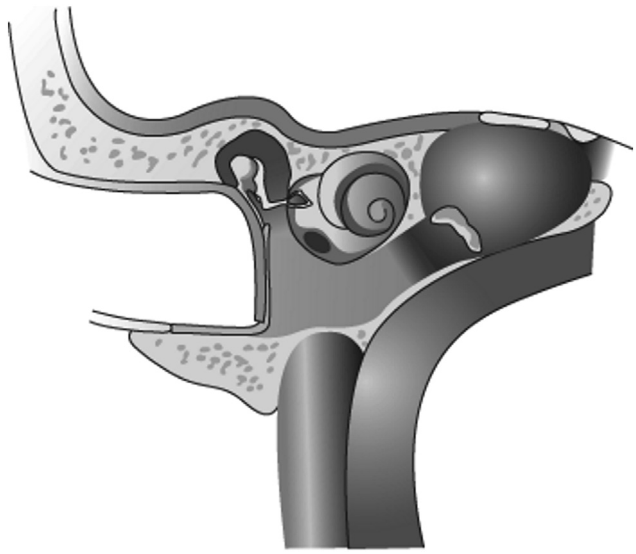

Fig. 5 Transcanal infracochlear approach. A corridor is opened to the petrous apex within the space between the cochlea, internal carotid artery and jugular bulb.[70]

inferior limit of the promontory is detected endoscopically and the subcochlear canaliculus is identified and can be followed to the petrous apex. The jugular bulb is identified as well as the vertical tract of the carotid artery by drilling into the protympanic cells below the Eustachian tube orifice. The medial aspect of the tympanic cavity is drilled into the round window fossa and the hypotympanic and protympanic cells are drilled between the jugular bulb, carotid artery, and basal turn of the cochlea.[2,5,52]

Marchioni et al noted that in 4 patients undergoing the transcanalinfracochlear approach, one patient developed CSF leak postoperatively. Moreover, though two out of the four patients had normal hearing postoperatively, one case developed middle ear conductive hearing loss.[2]

Middle cranial fossa approach

House first described the middle cranial fossa approach in 1963 as a treatment for petrositis.[56–58] Since that time, there have been modifications on the original procedure that extendor enlarge the surgical field.[59–62] This approach can also be extended to the petrous apex.[24,63] The extended middle cranial fossa approach, also known as the anterior transpetrosal approach, is typically used for larger acoustic neuromas, which need a wider opening to the posterior petrous apex. This approach begins with a reverse question mark incision beginning anterior to the tragus and a temporal muscle flap is elevated off the calvarium. The squamous temporal bone is exposed and a craniotomy is performed superior to the zygomatic root with subsequent posterior to anterior detachment of the dura of the middle fossa from the temporal bone. Next, the major petrosal nerve canal and superior semicircular canal are identified and the superior semicircular canal is removed until the "blue line" is identified. The geniculate ganglion can be exposed if necessary, and the roof of the internal auditory canal is completely removed to the level of the porus and the intrameatal dura is exposed and incised to the cerebellopontine angle. The facial nerve can be visualized at this point and the underlying bone can be drilled to expose the petrous apex.[52,64]

The most common complication for the middle cranial fossa approach is CSF leak, with rates of up to 13% reported, but facial nerve palsy, meningitis, hydrocephalus, and ataxia can also be seen. CSF leak typically presents within the first few post-operative days as leakage into the wound or posterior nasal drainage.[65,66] Muto et al compared the anterior transpetrosal approach to the endoscopic endonasal approach and found that the main advantage is avoidance of brain retraction. However, the anterior transpetrosal approach is better able to overcome difficult anatomy such as vascular encasement of tumors because of the wider surgical corridor and as such, is better for lesions located lateral or posterior to the paraclival internal carotid artery or for lesions with extension into the middle or infratemporal fossa.[67]

Conclusion

The petrous apex remains one of the most challenging areas of the skull base to reach surgically, but with multiple possible approaches, skilled teams of otolaryngologists and neurosurgeons can safely manage petrous apex lesions. The choice of approach is determined by the nature of the pathology and location relative to vital structures and extension into surrounding structures, and requires thorough preoperative evaluation and discussion of surgical goals with the patient.

Financial disclosures

None.

Declaration of Competing Interest

Waleed Abuzeid, MD is a consultant for Medtronic Inc. and Intersect ENT. Neither of these relationships is pertinent to the contents of this study.

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