Surgical approaches to the petrous apex

Kevin L. Li, Vijay Agarwal, Howard S. Moskowitz, Waleed M. Abuzeid

Department of Otorhinolaryngology — Head and Neck Surgery, Albert Einstein College of Medicine, Bronx, NY, USA
Department of Neurosurgery, Albert Einstein College of Medicine, Bronx, NY, USA

Received 1 July 2019; accepted 27 November 2019
Available online 3 June 2020

Keywords: Petrous apex; Anterior approaches; Endoscopic endonasal approach; Lateral approaches; Surgical approaches

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.

Copyright © 2020 Chinese Medical Association. Production and hosting by Elsevier B.V. on behalf of KeAi Communications Co., Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

The petrous apex is a complex region of the temporal bone that can harbor lesions which are difficult to access surgically. 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. Of the petrous apex pathologies, asymmetric pneumatization and effusion are the most common, outnumbering cholesterol...
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

Petrus 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.15,20–22 Certain lesions, such as cholesterol granuloma, can be managed with drainage while neoplastic lesions, for example, must be fully resected.24 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.21,22 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.57–59 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.61 The pterygospheonidial 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).59
transtemporal or middle fossa approaches. 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.

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 paraclovial 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. 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 transpterygoid infrapetrous 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. 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. The ICA

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.
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 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/para-vertebral 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.\textsuperscript{1}

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

\section*{Lateral approaches}

\subsection*{Translabyrinthine approach}

The translabyrinthine approach was first popularized by House.\textsuperscript{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 labyrinthineectomy is performed and then 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.\textsuperscript{52}

\subsection*{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 suprageniculolate corridor. However, the transcanal infracochlear approach is the only approach that reaches the petrous apex.\textsuperscript{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
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 transcanal infracochlear 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 extender 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.

References

1. Fournier HD, Mercier P, Velut S, Reigner B, Cronier P, Pillet J. Surgical anatomy and dissection of the petrous and peripetrous area. Anatomic basis of the lateral approaches to the skull base. Surg Radiol Anat. 1994;16:143–148.
2. Marchioni D, Alicandri-Ciufelli M, Rubini A, Presutti L. Endoscopic transcanal corridors to the lateral skull base: initial experiences. Laryngoscope. 2015;125(Suppl 5):S1–S13.
3. Sugimoto H, Hatano M, Noda M, Hasegawa H, Yoshizaki T. Endoscopic management of petrous apex cholesteatoma. Eur Arch Otorhinolaryngol. 2017;274:4127–4130.
4. Frank G, Sciarretta V, Calbucci F, Farneti G, Mazzatenta D, Pasquinii E. The endoscopic transnasal transphenoidal approach for the treatment of cranial base chordomas and chordrosarcomas. Neurosurgery. 2006;59:ONS50–ONS57. discussion ONS50-57.
5. Presutti L, Alicandri-Ciufelli M, Rubini A, Gioacchini FM, Marchioni D. Combined lateral microscopic/endoscopic
approaches to petrous apex lesions: pilot clinical experiences. *Ann Otol Rhinol Laryngol*. 2014;123:550–559.

6. Jacquesson T, Berhouma M, Tringali S, Simon E, Jouanneau E. Which routes for petroclival tumors? A comparison between the anterior expanded endoscopic endonasal approach and lateral or posterior routes. *World Neurosurg*. 2015;83:929–936.

7. Mehta GU, Raza SM. Endoscopic endonasal transpterygoid approach to petrous pathologies: technique, limitations and alternative approaches. *J Neurosurg Sci*. 2018;62:339–346.

8. Eytan DF, Kshettry VR, Sindyadani W, Woodard TD, Recinos PF. Surgical outcomes after endoscopic management of cholesterol granulomas of the petrous apex: a systematic review. *Neurosur Focus*. 2014;37:E14.

9. Tutar H, Goksu N, Aydil U, et al. An analysis of petrous bone cholesteatomas treated with translabyrinthine transotic petrosectomy. *Acta Otolaryngol*. 2013;133:1053–1057.

10. Mattos DE. Endoscopy-assisted surgery of the petrous apex. *Otolaryngol Head Neck Surg*. 2004;130:229–241.

11. Arriaga MA. Petrous apex effusion: a clinical disorder. *Laryngoscope*. 2006;116:1349–1356.

12. Lo WW, Solti-Bohman LG, Brackmann DE, Gruskin P. Cholesterol granulomas of the petrous apex: CT diagnosis. *Radiology*. 1984;153:705–711.

13. Arriaga MA, Brackmann DE. Differential diagnosis of primary petrous apex lesions. *Am J Otol*. 1991;12:470–474.

14. Chang P, Fagan PA, Atlas MD, Roche J. Imaging destructive lesions of the petrous apex. *Laryngoscope*. 1998;108:590–604.

15. Isaacs B. Cholesterol granuloma and other petrous apex lesions. *Otolaryng Clin North Am*. 2015;48:361–373.

16. Gimenez VF, Cano CB, Lazaro R, Perez CF, Garcia RI, Aldasoro J. [Recurrent paralysis as the first manifestation of chordoma of the petrous apex]. *Acta Otorrinolaringol Esp*. 1999;50:239–242.

17. Gadre AK, Chole RA. The changing face of petrous apicitis—a 40-year experience. *Laryngoscope*. 2018;128:195–201.

18. Tornabene S, Vliet GM. Gradenigo’s syndrome. *J Emerg Med*. 2010;38:449–451.

19. Bruchhage KL, Wollenberg B, Leichtle A. Transsphenoidal and infralabyrinthine approach of the petrous apex cholesterol granuloma. *EUR Arch Otorhinolaryngol*. 2017;274:2749–2756.

20. Patron V, Humbert M, Micault E, Emery E, Hitter M. How to perform microscopic/endoscopic resection of large petrous apex lesions. *EUR Ann Otorhinolaryngol Head Neck Dis*. 2018;135:443–447.

21. Feng K, Qiuang Z, Wei Z, et al. Anatomy of the petrous apex as related to the endoscopic endonasal approach. *J Clin Neurosci*. 2012;19:1695–1698.

22. Park KC, Wong G, Stephens JC, Saleh HA. Endoscopic transsphenoidal drainage of an aggressive petrous apex cholesterol granuloma: unusual complications and lessons learnt. *J Laryngol Otol*. 2013;127:1230–1234.

23. Zanation AM, Snyderman CH, Carrau RL, Gardner PA, Prevedello DM, Kassam AB. Endoscopic endonasal surgery for petrous apex lesions. *Laryngoscope*. 2009;119:19–25.

24. Rhoton AL. The temporal bone and transtemporal approaches. *Neurosurgery*. 2000;47:5211–5265.

25. Fournier HD, Mercier P, Roche PH. Surgical anatomy of the petrous apex and petroclival region. *Adv Tech Stand Neurosurg*. 2007;32:91–146.

26. Aubry K, Kania R, Sauvaget E, Huy PT, Herman P. Endoscopic transsphenoidal approach to petrous apex cholesteatoma. *Skull Base*. 2010;20:305–308.

27. Kassam AB, Gardner P, Snyderman C, Mintz A, Carrau R. Expanded endonasal approach: fully endoscopic, completely transnasal approach to the middle third of the clivus, petrous bone, middle cranial fossa, and infratemporal fossa. *Neurosurg Focus*. 2005;19:E6.

28. Miyamura S, Yamaguchi S, Tominaga A, et al. A case of petrous apex cholesterol granuloma successfully treated with endoscopic endonasal surgery. *Hiroshima J Med Sci*. 2014;63:39–42.

29. Dhanasekar G, Jones NS. Endoscopic trans-sphenoidal removal of cholesterol granuloma of the petrous apex: case report and literature review. *J Laryngol Otol*. 2011;125:169–172.

30. Patel CR, Wang EW, Fernandez-Miranda JC, Gardner PA, Snyderman CH. Contralateral transmaxillary corridor: an augmented endonasal approach to the petrous apex. *J Neurosurg*. 2018;129:211–219.

31. Kohanski MA, Palmer JN, Adappa ND. Indications and endonasal treatment of petrous apex cholesterol granulomas. *Curr Opin Otolaryngol Head Neck Surg*. 2019;27:54–58.

32. Beer-Furlan A, Ewins AI, Rigante L, Anichini G, Stieg PE, Bernardo A. Dual-port 2D and 3D endoscopy: expanding the limits of the endonasal approaches to midline skull base lesions with lateral extension. *J Neurosurg Skull Base*. 2014;75:187–197.

33. Loyo M, Kleriga E, Mateos H, de Leo R, Delgado A. Combined supra-infrasellar approach for large pituitary tumors. *Neurosurgery*. 1984;14:485–488.

34. Alleyne CH, Barlow DL, Oyesiku NM. Combined transsphenoidal and pterional craniotomy approach to giant pituitary tumors. *Surg Neurol*. 2002;57:380–390. discussion 390.

35. Cavallo LM, Cappabianca P, Galzio R, Lacioneta G, de Divitiis G, Tschabitscher M. Endoscopic transnasal approach to the cavernous sinus versus transcranial route: anatomic study. *Neurosurgery*. 2005;56:379–389. discussion 379-389.

36. Herzallah IR, Casiano RR. Endoscopic endonasal study of the internal carotid artery course and variations. *Am J Rhinol*. 2007;21:262–270.

37. Vescan AD, Snyderman CH, Carrau RL, et al. Vidian canal: analysis and relationship to the internal carotid artery. *Laryngoscope*. 2007;117:1338–1342.

38. Wang WH, Lieber S, Mathias RN, et al. The foramen lacerum: surgical anatomy and relevance for endoscopic endonasal approaches. *J Neurosurg*. 2018;1–12.

39. Sandu K, Monnier P, Pasche P. Anatomical landmarks for transnasal endoscopic skull base surgery. *Eur Arch Oto-rhinolaryngol*. 2012;269:171–178.

40. Aubry K, Kovac L, Sauvaget E, Tran BHP, Herman P. Our experience in the management of petrous bone cholesteatoma. *Skull Base*. 2010;20:163–167.

41. Shin M, Kondo K, Hanakita S, et al. Endoscopic transsphenoidal anterior petrosal approach for locally aggressive tumors involving the internal auditory canal, jugular fossa, and cavernous sinus. *J Neurosurg*. 2017;126:212–221.

42. Kassam AB, Vescan AD, Carrau RL, et al. Expanded endonasal approach: vidian canal as a landmark to the petrous internal carotid artery. *J Neurosurg*. 2008;108:177–183.

43. Schwartz TH, Fraser JF, Brown S, Tabae A, Kacker A, Anand VK. Endoscopic cranial base surgery: classification of operative approaches. *Neurosurgery*. 2008;62:991–1002. discussion 1002-1005.

44. de Lara D, Ditzel FLF, Prevedello DM, et al. Endonasal endoscopic approaches to the paramedian skull base. *World Neurosurg*. 2014;82:S121–S129.

45. Raza SM, Gidley PW, Kupferman ME, Hanna EY, Su SY, DeMonte F. Site-specific considerations in the surgical management of skull base chondrosarcomas. *Oper Neurosurg (Hagerstown)*. 2018;14:611–619.

46. Maza G, AMM O, Subramaniam S, Otto BA, Prevedello DM, Carrau RL. Modified endoscopic endonasal approach with a minimally invasive transoral approach—an adjunct to infrapetrous approaches. *Laryngoscope*. 2019;129:339–343.

47. Taniguchi M, Akutsu N, Mizukawa K, Kohta M, Kimura H, Kohnura E. Endoscopic endonasal translacerum approach to the inferior petrous apex. *J Neurosurg*. 2016;124:1032–1038.
48. Van Gompel JJ, Alikhani P, Tabor MH, et al. Anterior inferior petrosectomy: defining the role of endonasal endoscopic techniques for petrous apex approaches. J Neurosurg. 2014;120:1321–1325.

49. House WF. Transtemporal bone microsurgical removal of acoustic neuromas. Evolution of transtemporal bone removal of acoustic tumors. Arch Otolaryngol. 1964;80:731–742.

50. Mamikoglu B, Wiet RJ, Esquivel CR. Translabyrinthine approach for the management of large and giant vestibular schwannomas. Otol Neurotol. 2002;23:224–227.

51. Brackmann DE, Green JD. Translabyrinthine approach for acoustic tumor removal. 1992. Neurosurg Clin N Am. 2008;19:251–264 [vi].

52. Zanoletti E, Mazzoni A, Martini A, et al. Surgery of the lateral skull base: a 50-year endeavour. Acta Otorhinolaryngol Ital. 2019;39:1S1–1S146.

53. Sanna M, Russo A, Taibah A, Falcioni M, Agarwal M. Enlarged translabyrinthine approach for the management of large and giant acoustic neuromas: a report of 175 consecutive cases. Ann Otol Rhinol Laryngol. 2004;113:319–328.

54. House WF, Hitselberger WE. The transcochlear approach to the skull base. Arch Otolaryngol. 1976;102:334–342.

55. Angeli SI, De la Cruz A, Hitselberger W. The transcochlear approach revisited. Otol Neurotol. 2001;22:690–695.

56. House WF. Middle cranial fossa approach to the petrous pyramid. Report of 50 cases. Arch Otolaryngol. 1963;78:460–469.

57. House WF. Surgical exposure of the internal auditory canal and its contents through the middle, cranial fossa. Laryngoscope. 1961;71:1363–1385.

58. House WF, Shelton C. Middle fossa approach for acoustic tumor removal. Otolaryngol Clin North Am. 1992;25:347–359.

59. Yasargil MG. My reflections on professor Madjid Samii. World Neurosurg. 2013;80:475.

60. Brackmann DE, House JR, Hitselberger WE. Technical modifications to the middle fossa craniotomy approach in removal of acoustic neuromas. Am J Otol. 1994;15:614–619.

61. Wigand M, Haid T, Berg M, Rettinger G. The enlarged transtemporal approach to the cerebellopontine angle: technique and indications. Acta Otorhinolaryngol Ital. 1982;2:571–582.

62. Kanzaki J, Kawase T, Sano K, Shiobara R, Toya S. A modified extended middle cranial fossa approach for acoustic tumors. Arch Otorhinolaryngol. 1977;217:119–121.

63. Haid CT, Wigand ME. Advantages of the enlarged middle cranial fossa approach in acoustic neurinoma surgery. A review. Acta Otolaryngol. 1992;112:387–407.

64. Hendershot EL, Wood JW, Bennhoff D. The middle cranial fossa approach to the petrous apex. Laryngoscope. 1976;86:658–663.

65. Scheich M, Ginzkey C, Ehrmann MD, Shehata DW, Hagen R. Complications of the middle cranial fossa approach for acoustic neuroma removal. J Int Adv Otol. 2017;13:186–190.

66. Scheich M, Ginzkey C, Ehrmann-Müller D, Shehata-Dieter W, Hagen R. Management of CSF leakage after microsurgery for vestibular schwannoma via the middle cranial fossa approach. Eur Arch Otorhinolaryngol. 2016;273:2975–2981.

67. Muto J, Prevedello DM, Ditzel FLF, et al. Comparative analysis of the anterior transpetrosal approach with the endoscopic endonasal approach to the petroclival region. J Neurosurg. 2016;125:1171–1186.

68. Schädellbasis Welleschik. Adapted from Original Work with Labels and Shading. 2007.

69. Sobotta DJ. Sobo 1909 56. Sobotta’s Atlas and Text-Book of Human Anatomy 1909. 2013. An Illustration from the 1909 American Edition of Sobotta’s Anatomy with English Terminology.

70. Lalwani AK. In: Current Diagnosis & Treatment In Otolaryngology - Head & Neck Surgery. 3rd ed. New York, NY: McGraw-Hill Lange; 2011.

Edited by Yi Fang