Upper, Middle, and Lower Clivus

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BACKGROUND Carefully tailoring the transclival approach to the involved parts of the upper, middle, or lower clivus requires a precise understanding of the focal relationships of the clivus.

OBJECTIVE To develop an optimal classification of the upper, middle, and lower clivus and to define the extra and intracranial relationships of each clival level.

METHODS Ten cadaveric heads and 10 dry skulls were dissected using the surgical microscope and endoscope.

RESULTS The clivus is divided into upper, middle, and lower thirds by 2 endocranial landmarks: the dural pori of the abducens nerves and the dural meati of the glossopharyngeal nerves. Useful surgical landmarks exposed in the transnasal approach that aid in locating the junction of the clival divisions are the lower limit of the paraclival segment of the internal carotid artery, which is located 4.9 mm above the posterior opening of the vidian canal, and the pharyngeal tubercle. The upper, middle, and lower clival approaches provide access to the anterior midline parts of the previously described upper, middle, and lower neurovascular complexes in the posterior fossa. The nasal and nasopharyngeal relationships important in expanding the transnasal approach to the borders of the clivus are reviewed.

CONCLUSION The transclival approach can be carefully tailored to expose focal lesions in the anterior part of the posterior fossa.

Introduction

The anterior midline region in the posterior cranial fossa, including the

clivus and the anterior surface of the brainstem, is one of the most difficult areas to access. A variety of microsurgical approaches such as the subfrontal transbasal, subtemporal anterior transpetrosal (Kawase), presigmoid, retrosigmoid, and far lateral provide limited access to the region while having significant disadvantages.[1-6] These disadvantages include the extensive resection of the skull base structures, the brain retraction required to reach the neurovascular structures in the deep midline, and the limited view of the midline structures provided by the lateral and posterolateral approaches.[1-6]

The endoscopic transnasal transclival approach to the posterior fossa overcomes some of these disadvantages.[7-14] It provides a direct route to midline structures and allows them to be viewed without retraction of the brain. The approach offers a panoramic view of the anterior surface of the brainstem by drilling the whole or a part of the clivus. However, wide opening of the clivus and the clival dura increases the risk of cerebrospinal fluid (CSF) leak. A recent surgical series had a high rate (33%) of postoperative CSF leaks.[10]

A focal, carefully tailored opening of the clivus based on the site of the lesion is a logical approach to minimize CSF leak.[15] The clivus is customarily classified into upper, middle, and lower parts to facilitate focal approaches. Such classifications of the clivus have been based largely on the exocranial landmarks exposed in the transnasal approach. However, an accurate transnasal approach to the endocranial structures requires a thorough understanding of the relationships between the exocranial and endocranial structures. In this study, we focus on the microsurgical and endoscopic anatomy of exocranial and endocranial relationships of the clivus and the adjacent cisterns and brainstem. The objective of this study was to refine the classification of the upper, middle, and lower clivus and to explore the surgical anatomy of the focal transnasal transclival approach to each clival division.[16-22]

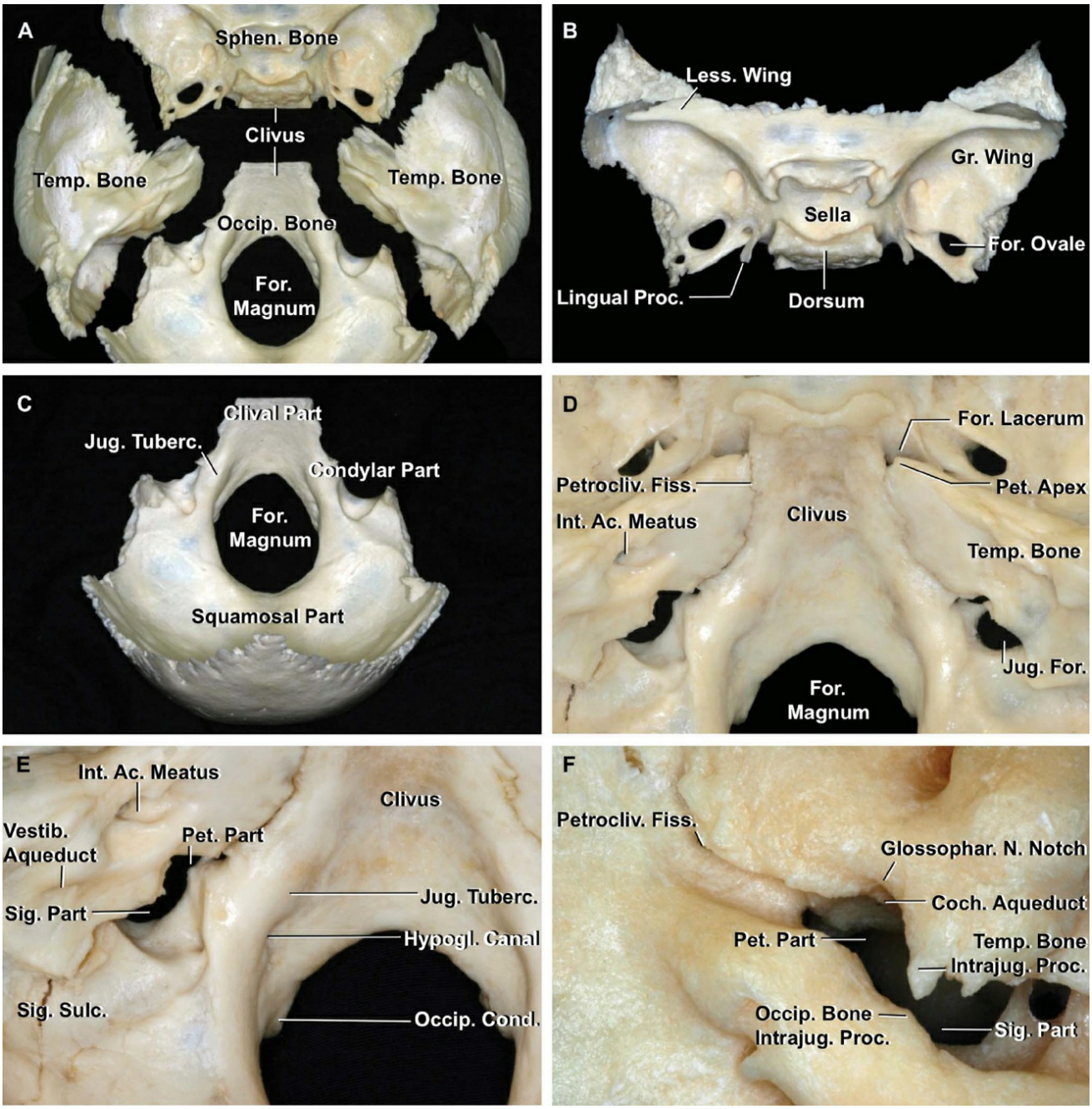

FIGURE 1. Osseous relationship of the endocranial surface of the clivus and the adjacent part of the posterior cranial base. A, superior view of the posterior cranial fossa. The cranial base has been separated into individual bones while maintaining the relationship between the bones. The posterior cranial fossa is formed by the occipital, sphenoid, and temporal bones and the clivus by the sphenoid and occipital bones. B, superior view of the sphenoid bone. The area below the dorsum sellae forms the upper third of the clivus. The lingual process is the site of attachment of the petrolingual ligament, which sits at the junction of the petrous and cavernous parts of the carotid artery. C, superior view of the occipital bone. The basal (clival) part forms the lower two-thirds of the clivus. The paired condylar parts are situated along the anterolateral

margin of the foramen magnum and connect the clival and squamosal parts of the occipital bone. D, posterior superior view. The petroclival fissure, which extends from the foramen lacerum above to the jugular foramen below, is positioned between the clivus and the petrous part of the temporal bone. The petrous apex articulates with the clivus near the junction with the sphenoid and occipital bones. E, enlarged posterior superior view of the left jugular foramen and the adjacent area. The jugular tubercle projects into the posterior fossa just above the hypoglossal canal. The jugular foramen is a sutural foramen located between the temporal and occipital bones. The sigmoid part, the larger lateral part of the jugular foramen, receives the drainage of the sigmoid sinus, and the petrosal part, the smaller medial part, receives the drainage of the inferior petrosal sinus. Cranial nerves IX, X, and XI exit the skull between the sigmoid and petrosal parts of the foramen. F, posterior superior view of a right jugular foramen. The intrajugular processes, the bony prominences that protrude into the jugular foramen from the temporal and occipital bones, are joined by a fibrous or osseus bridge that separates the jugular foramen into petrosal and sigmoid parts. The intrajugular process of the occipital bone is usually smaller than the process on the temporal bone. There is a small bony notch for the glossopharyngeal nerve at the upper border of the jugular foramen. In life, this notch corresponds to the site of the dural glossopharyngeal meatus, where the glossopharyngeal nerve penetrates the dura. The cochlear aqueduct opens into the upper margin of the petrosal part below the glossopharyngeal notch. Ac., acoustic; Coch., cochlear; Cond., condyle; Fiss., fissure; For., foramen; Glossophar., glossopharyngeal; Gr., greater; Hypogl., hypoglossal; Int., internal; Intrajug., intrajugular; Jug., jugular; Less., lesser; N., nerve; Occip., occipital; Pet., petrosal, petrous; Petrocliv., petroclival; Proc., process; Sig., sigmoid; Sphen., sphenoid; Temp., temporal; Tuberc., tubercle; Vestib., vestibular.

Methods

Ten cadaveric specimens in which the vessels were injected with colored silicone and 10 dry skulls were used for this study. Several of the specimens were sectioned in the coronal plane perpendicular to the hard

palate using image guidance (Stealth Station, Medtronic Sofamor Danek) to facilitate the focus on structures encountered at each stage of the approach. Dissections were completed with both the surgical microscope (Carl Zeiss Corp, Oberkochen, Germany) and rigid 0°, 45°, and 70° endoscopes 4 mm in diameter (Karl Storz Co, Tuttlingen, Germany). The dissections proceeded from the upper to the lower and finally to the middle clival area. Each area was first exposed unilaterally and then bilaterally.

Results

Endocranial Surface of Clivus and Adjacent Cranial Base

Osseous Relationships

The clivus, formed by the sphenoid and occipital bones, consists of a broad, shallow groove inclined upward and forward from the anterior border of the foramen magnum (Figure 1). The sphenoid bone forms the upper third of the clivus, which corresponds to a sloping area behind and below the dorsum sellae. It continues uninterrupted to blend into the basilar (clival) part of the occipital bone, which forms the majority of the clivus. These 2 bones join just below the dorsum sellae at the spheno-occipital synchondrosis, which closes in adolescence and is invisible in adults.[23] The petroclival fissure and the jugular foramen, located between the petrous part of the temporal bone and the adjacent clival and condylar parts of the occipital bone, sit at the lateral edge of the clivus (Figure 1). The inferior petrosal sinuses course along the intracranial surface of the petroclival fissures. The paired occipital condyles, which project downward from the condylar part of the occipital bone, are situated along the anterolateral edge of the foramen magnum. On the intracranial surface of the condylar part, an oval eminence, the jugular tubercle, sits just superior to the hypoglossal canal and just medial to the lower part of the petroclival fissure.

Dural and Cranial Nerve Relationships

The dural porus of the abducens nerve and the glossopharyngeal meatus

are landmarks on the endocranial surface of the clivus that divide the clivus into 3 parts.

The Abducens Dural Porus

The abducens nerve, after emerging from the medial part of the pontomedullary sulcus, courses upward and laterally to pierce its dural porus located just below the upper edge of the petrous apex (Figure 2). The mean vertical distance between the upper edge of the petrous apex and the abducens dural porus averaged 3.4 mm. After piercing the dura, the abducens nerve enters Dorello's canal, a narrow, triangular interdural space bounded by the petrosphenoid (or Gruber's) ligament superiorly, the petrous apex inferolaterally, and the clivus inferomedially.[24,25] The nerve courses beneath the Gruber's ligament, which extends from the lower part of the lateral edge of the dorsum sellae to the upper edge of the petrous apex. The canal surrounding the nerve is filled with the venous confluence at the junction of the cavernous, basilar, and superior and inferior petrosal sinuses.[24] The abducens nerve courses upward in Dorello's canal to reach the upper end of the petroclival fissure, where it enters the cavernous sinus and turns laterally around the proximal portion of the cavernous carotid artery.

The trigeminal nerve exits the posterior fossa by passing through the dural trigeminal porus, located superolateral to the abducens dural porus and beneath the tentorial attachment, to enter Meckel's cave, which sits in the trigeminal impression on the upper surface of the petrous part of the temporal bone.

The Glossopharyngeal Meatus

The dura roofing the jugular foramen has 2 perforations: a glossopharyngeal meatus through which the glossopharyngeal nerve passes and a vagal meatus through which the vagus and accessory nerves pass (Figure 2). Both are located on the medial side of the intrajugular processes of the temporal and occipital bones, which are bony prominences that protrude into the jugular foramen from its anterior and posterior edges and separate the jugular foramen into petrosal and

sigmoid parts (Figures 1F and 2E).[26] The glossopharyngeal meatus is located superior to the vagal meatus. The glossopharyngeal meatus sits at the upper border of the petrosal part of the jugular foramen, where there is a small bony notch along which the glossopharyngeal nerve descends and into which the cochlear aqueduct opens. After piercing the dura, the nerve enters the intrajugular dural compartment (between the petrosal and sigmoid parts of the foramen) with the vagus and accessory nerves, but courses downward through the jugular foramen separate from the vagus and accessory nerves.[26,27] Eventually, the glossopharyngeal nerve exits the jugular foramen along the anterior wall of the internal jugular vein, whereas the vagus and accessory nerve exit along the medial wall of the vein.

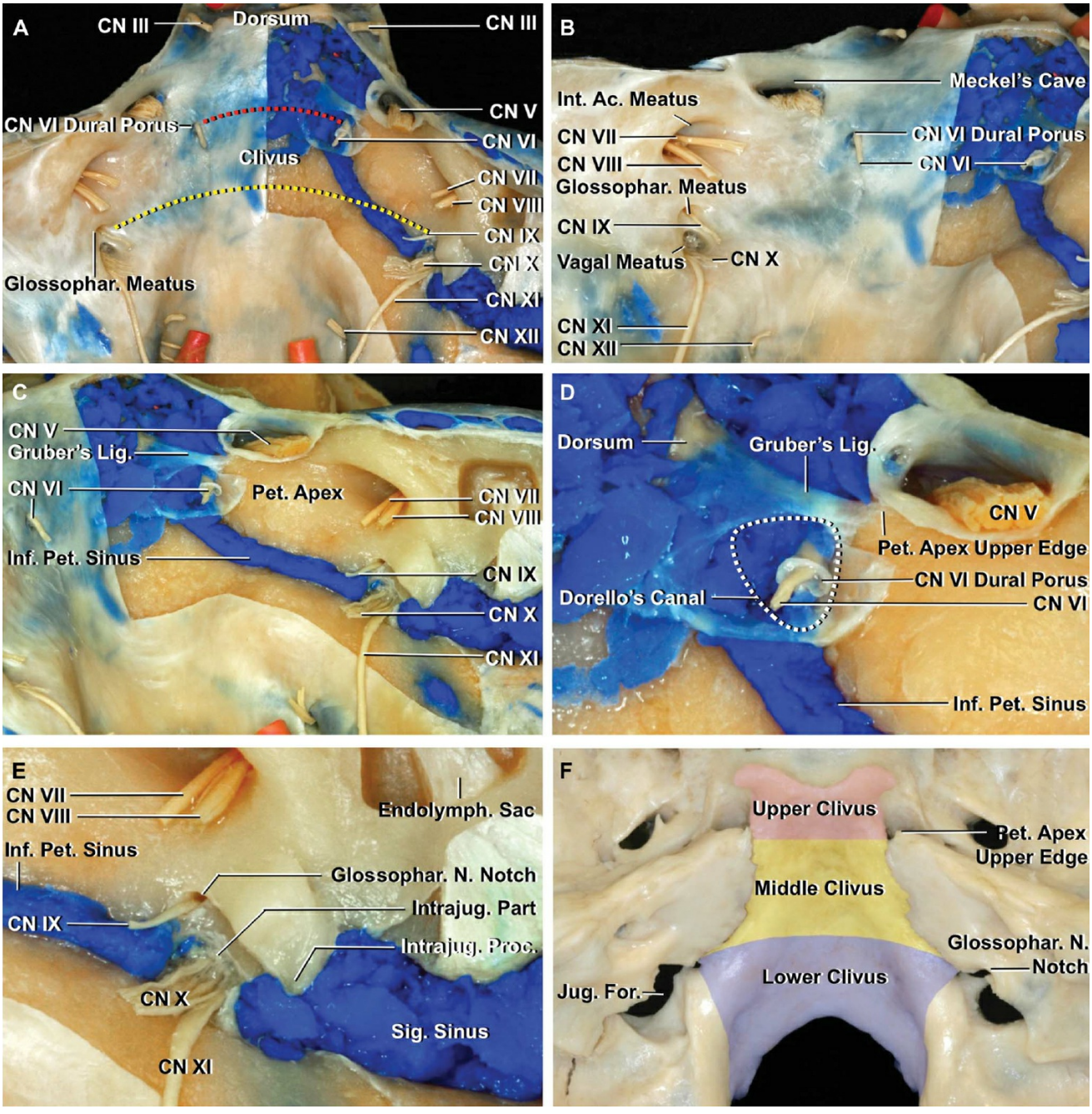

FIGURE 2. Osseous, dural, and cranial nerve (CN) relationships. A, posterior superior view. The dura on the right half of the floor of the posterior fossa has been removed while preserving the CNs. CNs V through XII pierce the posterior fossa dura. The upper clivus and middle clivus are separated at the axial plane of the dural pori of the abducens nerve formed where the abducens nerves penetrate the dura. The middle clivus and lower clivus are separated by the axial plane of the dural glossopharyngeal meati, through which the glossopharyngeal nerves pass to enter the jugular foramen. A red dotted line shows the demarcation between the upper and middle clivus, and a yellow dotted line shows the demarcation between the middle and lower clivus. The intradural space behind the upper clivus includes CNs III and V; behind the middle clivus includes CNs VI, VII, and VIII; and behind the lower clivus includes CNs IX, X, XI, and XII. B, posterior oblique view, left side. Meckel's cave, through which the trigeminal nerve passes, is located superolateral to the dural porus of the abducens nerve. The dura over the jugular foramen has 2 perforations: a glossopharyngeal meatus through which the glossopharyngeal nerve passes and a vagal meatus through which the vagus and accessory nerves pass. The glossopharyngeal meatus is located superior to the vagal meatus. C, posterior oblique view after removing the dura on the right side. The inferior petrosal sinus courses along the intracranial surface of the petroclival fissure. D, enlarged view focusing on the dural porus of the abducens nerve and Dorello's canal. Gruber's ligament extends from the lower part of the lateral edge of the dorsum sellae to the upper edge of the petrous apex. Dorello's canal (white dotted line) is a narrow, interdural, triangular space bounded by Gruber's ligament superiorly, the petrous apex inferolaterally, and the clivus inferomedially. After piercing the dura, the abducens nerve courses beneath Gruber's ligament and through a large venous confluence at the junction of the cavernous, basilar, and the superior and inferior petrosal sinuses. The dural porus of the abducens nerve is located just below the upper edge of the petrosal apex. E, enlarged view focusing on the jugular foramen. The glossopharyngeal, vagus, and accessory nerves enter the intrajugular part of the jugular foramen, which is located between the petrosal and sigmoid parts. The glossopharyngeal nerve, after reaching

the bony notch at the upper border of the jugular foramen, courses downward through the jugular foramen separate from the vagus and accessory nerve. F, the demarcation between the upper and middle clivus corresponds to the level 3.4 mm below the upper edge of the petrous apex. The demarcation between the middle and lower clivus corresponds to the level of the notch for the glossopharyngeal nerve at the upper medial edge of the jugular foramen. Ac., acoustic; Endolymph., endolymphatic; For., foramen; Glossophar., glossopharyngeal; Inf., inferior; Int., internal; Intrajug., intrajugular; Jug., jugular; Lig., ligament; N., nerve; Pet., petrosal, petrous; Proc., process; Sig., sigmoid.

The Upper, Middle, and Lower Clivus

The upper clivus is situated between the dorsum sellae and the dural pori of the abducens nerve, the lower clivus between the level of the glossopharyngeal meati and the anterior border of the foramen magnum, with the middle clivus located between the upper and lower clivus (Figure 2A and 2F).[21] The distance between the posterior clinoid process and the dural porus of the abducens nerve averaged 13.2 mm (range, 12-17 mm); between the porus of the abducens nerve and the glossopharyngeal meatus, 21.4 mm (range, 19-24 mm); and between the glossopharyngeal meatus and dural porus of the hypoglossal nerve, 25.4 mm (range, 23-30 mm). In relation to the osseous structures, the demarcation between the upper and middle clivus corresponds to a level 3.4 mm (range, 1.5-6.0 mm) below the upper edge of the petrous apex, and the demarcation between the middle and lower clivus corresponds to the level of the notch for the glossopharyngeal nerve at the medial part of the upper edge of the jugular foramen (Figure 2F).

Exocranial Surface of the Clivus

Osseous Relationships

The clivus, when viewed through the nasal cavity, is convex from side to side and slopes downward and backward toward the foramen magnum. It is formed largely by the exocranial surface of the clival part of the occipital bone (Figure 3). The inferior surface of the body of the sphenoid bone is

seen anterior to the clival part of the occipital bone and provides the site where the vomer attaches. The upper border of the vomer is expanded into paired ala that fit against the lower surface of the sphenoid bone. The lateral border of each ala reaches a thin bony lamella, the vaginal process, which projects medially from the root of the medial pterygoid plate. A tiny canal, the vomerovaginal canal, lies between the ala of the vomer and the vaginal process. The inferior surface of the vaginal process is marked by an anteroposterior groove that is converted into a canal, the palatovaginal canal, by the upper surface of the sphenoidal process of the palatine bone. This palatovaginal canal opens anteriorly through the medial part of the posterior wall of the pterygopalatine fossa and transmits the pharyngeal branch of the pterygopalatine ganglion and a small pharyngeal branch from the maxillary artery. The vomerovaginal canal is positioned medial to the palatovaginal canal and leads forward into the anterior end of the palatovaginal canal.

The petroclival fissure, which sits along the lateral edge of the clivus, separates the occipital bone and the petrous part of the temporal bone (Figure 3B). The petroclival fissure forms a deeper cleft on the exocranial than on the intracranial surface and is filled with cartilage, a remnant of the primitive chondrocranium. This fissure extends from the foramen lacerum above to the jugular foramen below. The foramen lacerum is located at the junction where the sphenoid, temporal, and occipital bones join together. The foramen lacerum is bounded anteriorly by the junction of the body, greater wing, and adjoining roots of the pterygoid process of the sphenoid bone, posterolaterally by the apex of the petrous part of the temporal bone, and medially by the clival part of the occipital bone. The internal carotid artery, after exiting the petrous apex, occupies the upper part of the foramen lacerum. The posterior end of the vidian canal, which conveys the vidian artery and nerve, opens into the upper part of the anterolateral edge to the foramen lacerum.28 The foramen is where the deep petrosal nerve from the carotid sympathetic plexus joins the greater petrosal nerve to form the vidian nerve.

When viewed from anteriorly along the axis of the hard palate, the lateral part of the osseous skull base is largely hidden by the maxillae (Figure 3C

and 3E). However, the clival part of the occipital bone can be seen through the lower part of the nasal cavity and through the posterior nasal apertures called choanae, through which the nasal cavity opens into the nasopharynx. The clivus, from below to above, leans approximately 45 forward. The sphenoid sinus is also accessible through the upper part of the nasal cavity. Thus, the whole clivus can be accessed through the nasal cavity because the posterior wall of the sphenoid sinus forms the upper part of the clivus. The hard palate is positioned at the axial level of the foramen magnum. Gaining the expanded nasal access needed for some clival lesions requires an understanding of the relationships along the nasal corridor to the clivus (Figures 3 and 4).

Sphenoid Sinus

The anatomy and a new classification of the sphenoid sinus were well described by Wang et al.[29] The anterior wall of the sphenoid sinus consists of 2 areas. An upper and lateral area shares its wall with the posterior ethmoid cells and cannot be seen from the nasal cavity (Figure 3L). A lower and medial smooth, triangular area, called the sphenoid conchae, forms much of the anterior face of the sphenoid and can be viewed from the nasal cavity behind the superior turbinate. The ostia of the sphenoid sinus are located near the lateral border of the superior angle of the sphenoid conchae and medial and slightly above the posterior inferior end of the superior turbinate (Figure 4G). The anterior wall in the median plane has a crest, the sphenoid crest, that forms a small part of the nasal septum. The anterior border of this crest articulates with the perpendicular plate of the ethmoid bone.

The posterior wall of the sphenoid sinus is hidden superiorly by the sellae and is limited laterally by the carotid prominences, behind which the cavernous portion of the carotid arteries rest (Figure 4I, 4J, and 4L). This vertical segment of the internal carotid artery is also called as the paraclival segment because the posterior sinus wall corresponds to the part of the clivus located between the dorsum sellae and basilar part of the occipital bone (Figures 4L and 5). When followed distally, the carotid exits the carotid canal and turns upward and medially above the foramen

lacerum to form the “anterior genu.” The anterior genu is also referred to as the lacerum segment because of its relationship to the foramen lacerum. The paraclival carotid begins and extends upward from the flexion point where the artery turns vertically at the distal end of the lacerum segment (Figures 4L and 5).[28,30] The sinus often extends posteriorly beyond the vertical coronal plane of the posterior wall of the pituitary fossa to form a clival recess, found in 68% of the sinuses examined by Wang et al.[29] This recess may extend superiorly into the dorsum sellae and/or inferiorly to the basilar part of the occipital bone.

The paired vidian canals course in the osseous floor of the sphenoid sinus, or they may protrude into the sphenoid sinus, especially into the anterior part of a well-pneumatized sinus (Figure 4K). According to Osawa et al,[28] a bony prominence overlying the vidian canal in the floor of the sphenoid sinus was seen in 60% of the sinuses.

Occipital Bone

When the exocranial surface of the clival part of the occipital bone is viewed anteriorly, a small elevation, the pharyngeal tubercle, is observed in the midline (Figure 3). The tubercle gives attachment to the pharyngeal raphe, into which the superior constrictor muscle is inserted. The pharyngeal tubercle was seen in all 20 specimens examined in this study. It was located an average of 17.4 mm posterior to the posterior edge of the vomer and 10.8 mm anteriorsuperior to the anterior edge of the foramen magnum. The longus capitis muscle attaches to the clivus lateral to the pharyngeal tubercle. The rectus capitis anterior, a small muscle located deep to the longus capitis, is attached above in a small depression, the supracondylar groove, located above the occipital condyle and below to the lateral mass of the atlas. This groove for the attachment of the rectus capitis anterior, which sits an average of 9.0 mm above the anterior edge of the foramen magnum, may be replaced by a small prominence called the precondylar tubercle.[20,31,32] This supracondylar groove provides a reliable landmark for estimating the position of the hypoglossal canal and its external orifice. The hypoglossal canal lies deep to the groove. The extracranial orifice of the hypoglossal canal and the jugular

foramen are situated just lateral to the groove. The anterior margin of the foramen magnum gives attachment to the anterior atlanto-occipital membrane.

The paired condylar parts of the occipital bone are situated at each side of the foramen magnum. The occipital condyles, which articulate with the atlas, are located lateral to the anterior half of the foramen magnum, are oval in shape, convex downward, face downward and laterally, and have their long axes directed forward and medially. A tubercle that gives attachment to the alar ligament of the odontoid process is situated on the medial side of each condyle. The hypoglossal canal is situated above the middle third of the anteroposterior axis of the condyle and is directed forward and lateral from its intracranial opening.

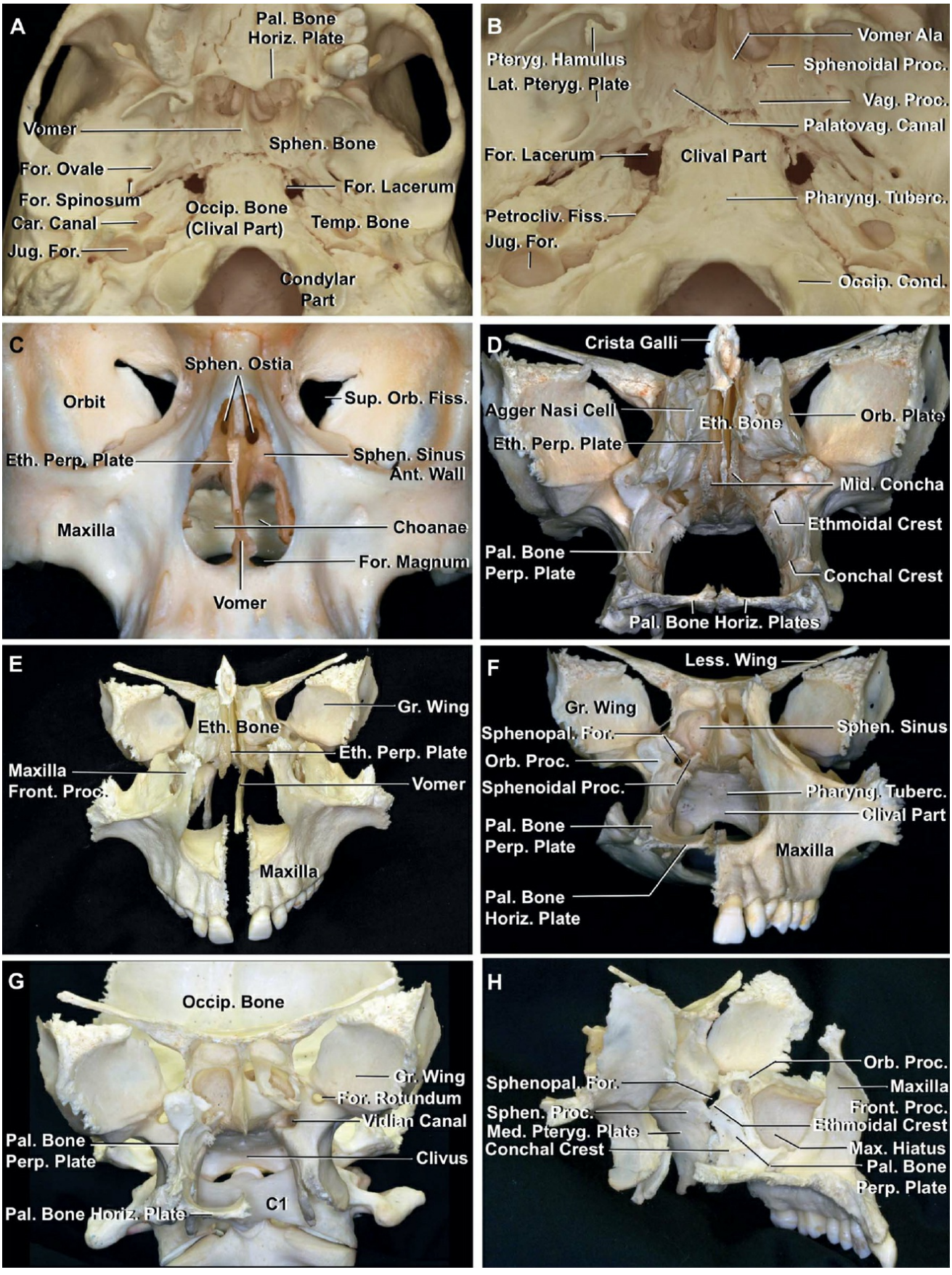

FIGURE 3. A-H. Osseous relationships of the exocranial surface of the clivus and the adjacent cranial base. A, inferior view. The exocranial surface of the clival part of the occipital bone is convex from side to side and has an irregular surface. It is wider above than below at the foramen magnum. B, enlarged view. The petroclival fissure separates the lateral

edge of the clivus from the petrous part of the temporal bone. This fissure extends from the foramen lacerum above to the jugular foramen below. There is an anteroposterior groove along the inferior surface of the vaginal process of the sphenoid bone. This groove joins with the upper surface of the sphenoidal process of the palatine bone to form the palatovaginal canal, which opens anteriorly into the pterygopalatine fossa. An inconsistent vomerovaginal canal may lie medial to the palatovaginal canal between the ala of the vomer and the vaginal process of the sphenoid. C, anterior view. The middle and inferior conchae have been removed. The clival part of the occipital bone is seen through the lower part of the nasal cavity and the posterior nasal apertures (choanae), the opening between the nasal cavity and nasopharynx bounded below by the horizontal plate of the palatine bone, superiorly by the body of the sphenoid, and laterally by the medial pterygoid plates. The sphenoid sinus occupies the upper part of the view through the nasal cavity. The hard palate is positioned at the level of the foramen magnum posteriorly. The lateral part of the cranial base is hidden behind the maxillae. D, anterior view. The sphenoid, ethmoid, and both palatine bones have been fitted together. The ethmoid bone forms the roof of the nasal cavity in front of the sphenoid bone. The middle nasal conchae are parts of the ethmoid bone, whereas the inferior nasal concha is a separate bone. The posterior end of the middle conchae articulates with the ethmoidal crest of the perpendicular plate of the palatine bone. E, the sphenoid, ethmoid, and maxillary bones and the vomer have been fitted together. The perpendicular plate of the ethmoid forms the upper part of nasal septum and the vomer forms the lower part. The frontal processes of the maxillae form the anterior part of the lateral wall of the nasal cavity. F, anterior view. The sphenoid, occipital, and left palatine bones have been fitted together. The pharyngeal tubercle is exposed in the midline on the clival part of the occipital bone. The sphenopalatine notch of the palatine bone, located between the orbital and sphenoid processes, is closed superiorly by the inferior surface of the sphenoid bone to form the sphenopalatine foramen. The anterior end of the vidian canal is sometimes seen through the sphenopalatine foramen. G, anterior view. The occipital, sphenoid, and left palatine bones and the axis and atlas

have been fitted together. The clivus and atlas (C1) can be viewed through the nasal cavity between the body of the sphenoid above, the horizontal plate of the palatine bone below, and the vertical plate of the palatine bone and pterygoid process of the sphenoid bone laterally. H, oblique view of the left lateral wall of the nasal cavity. The sphenoid and left maxillary and palatine bones have been fitted together. The lower half of the lateral nasal wall is composed of, from anterior to posterior, the maxilla, the perpendicular plate of the palatine bone, and the medial pterygoid plate. The sphenopalatine foramen is located just above the ethmoidal crest of the palatine bone. The maxillary hiatus, a large opening in the medial wall of the maxillary sinus, is formed by the maxilla anteriorly and the perpendicular plate of the palatine bone posteriorly. The hiatus is partially closed by the inferior nasal concha and the ethmoid bone.

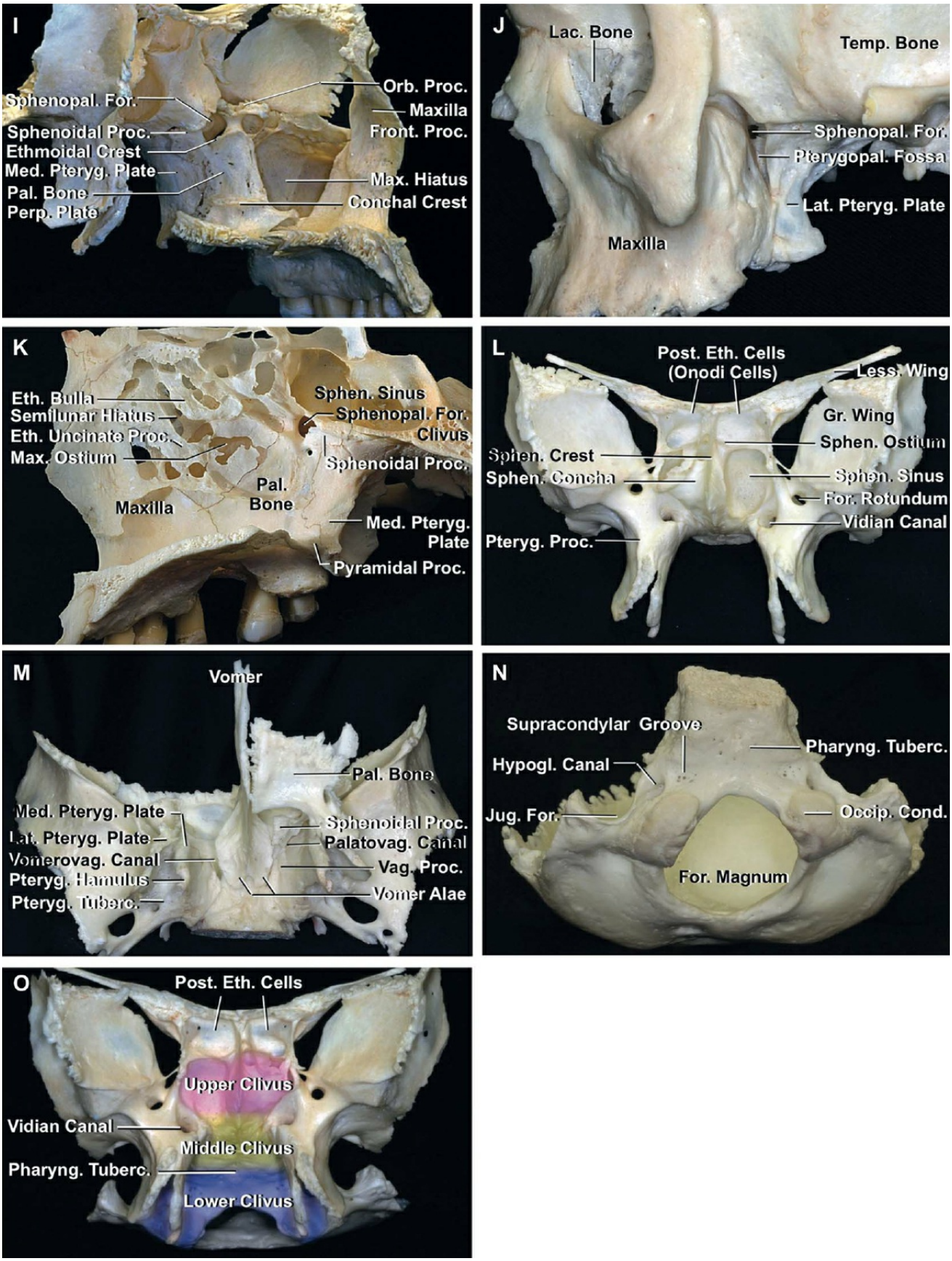

FIGURE 3. I-O. I, enlarged view. J, lateral view of the cranial base. The pterygopalatine fossa is the narrow space between the superior half of the posterior wall of the maxillary sinus and the pterygoid process of the sphenoid bone. The sphenopalatine foramen opens through the medial wall of the fossa into the nasal cavity. K, right lateral nasal wall in a

sagittally sectioned specimen. The superior, middle, and inferior nasal conchae have been removed. A thin, curved bar of bone, called the uncinate process, bridges the anterior part of the maxillary hiatus and divides the maxillary hiatus into anterior and posterior spaces. The posterior space, called the semilunar hiatus and situated between the uncinate process and ethmoid bulla, is characterized by its arc-like shape. The anterior space is closed by the mucosa in life. The posterior space is also closed by mucosa except at the ostia draining the maxillary, ethmoidal, and frontal sinus into the nasal cavity. The sphenopalatine foramen is located behind the ethmoid bulla. L, anterior view of the sphenoid bone. The left half of the anterior wall of the sphenoid sinus has been opened. The anterior wall of the sphenoid sinus consists of 2 areas, an upper and lateral depressed area, which shares its wall with the posterior ethmoid cells, and is hidden behind the ethmoid air cells. In this specimen, the most posterior ethmoid cells extend into the sphenoid sinus and are called Onodi cells. A lower and medial smooth triangular area that can be viewed through the nasal cavity behind the superior turbinate corresponds to the sphenoid conchae. The ostia of the sphenoid sinus are located near the superior angles of the sphenoid concha. The sphenoidal crest forms a small part of the nasal septum and articulates with the perpendicular plate of the ethmoid bone. M, inferior view of the sphenoid and palatine bones and the vomer. The upper border of the vomer is expanded into an ala on each side and attaches to the sphenoid bone. The lateral border of each ala articulates with a thin bony lamella, the vaginal process of the sphenoid bone, which projects medially from the root of the medial pterygoid plate to complete the palatovaginal canal. The pterygoid hamulus, around which the tensor veli palatini muscle turns medially to insert into the soft palate, projects laterally from the tip of the medial pterygoid plate. N, inferior view of the occipital bone. The pharyngeal tubercle is located in the midline of the clivus approximately 1 cm anterior to the anterior edge of the foramen magnum. The occipital condyles project downward along the anterolateral margin of the foramen magnum. There is a small bony groove, the supracondylar groove, for the insertion of the rectus capitis anterior muscle in front of each occipital condyle. The extracranial end of

the hypoglossal canal opens above the occipital condyle. O, anterior view. The sphenoid and occipital bones are fitted together. The areas corresponding to the upper, middle, and lower clivus are shown on the exocranial aspect. The anterior end of the vidian canals sits at the junction of the upper and middle clivus. The pharyngeal tubercle can be used to estimate the junction of the middle and lower clivus. Car., carotid; Cond., condyle; Eth., ethmoid; Fiss., fissure; For., foramen; Front., frontal; Gr., greater; Horiz., horizontal; Hypogl., hypoglossal; Jug., jugular; Lac., lacrimal; Lat., lateral; Less., lesser; M., muscle; Max., maxillary; Med., medial; Occip., occipital; Orb., orbital; Pal., palatine; Palatovag., palatovaginal; Perp., perpendicular; Petrocliv., petroclival; Pharyng., pharyngeal; Proc., process; Pteryg., pterygoid; Pterygopal., pterygopalatine; Sphen., sphenoid; Sphenopal., sphenopalatine; Sup., superior; Temp., temporal; Tuberc., tubercle; Vag., vaginal, Vomerovag., vomerovaginal.

Extracranial Landmarks

Certain landmarks on the exocranial surface can be useful during the transnasal approach (Figure 5).

Upper and Middle Clival Border

In most cases, the demarcation between the upper and middle clivus, defined as the level of the dural pori of the abducens nerve, approximates the floor of the sphenoid sinus. The relationship between the pori and the sphenoid sinus floor, however, varies according to the extent of the pneumatization of the sinus. The lower limit of the paraclival internal carotid artery, or the junction between the lacerum and paraclival segment, provides the landmark for the dural pori.[33]

The abducens nerve arises at the pontomedullary junction and ascends in the prepontine cistern to reach its dural porus (Figures 6 and 7). It then ascends between the 2 leaves of dura, passes behind the midpoint of the paraclival carotid coursing almost perpendicular to the artery, and passes below Gruber's ligament to enter the cavernous sinus.[33] The dural porus is located at the same level of the lower limit of the paraclival segment of

the carotid (Figure 5L). This point corresponds to “the upper limit of the lacerum segment,” regarded as a landmark for the abducens porus by Barges-Coll et al.[33] The posterior end of the vidian canal opens at the inferolateral surface of the anterior genu, or lacerum segment, of the internal carotid artery.[28] This anatomic relationship makes the vidian canal an important landmark for reaching the lacerum segment of the carotid in the expanded transnasal approach.[19,28,34] In our study, the dural porus of the abducens nerve was located an average of 4.9 mm (range, 4-6 mm) above the posterior end of the vidian canal.

The vidian nerve, when followed posteriorly from the pterygopalatine fossa and through the vidian canal, reaches the lateral surface of the lacerum segment of the internal carotid artery and the anteromedial part of the cavernous sinus (Figures 5-7). Here, the nerve turns slightly upward in the foramen lacerum (Figure 6E) and is continuous with the greater petrosal nerve and the deep petrosal nerve. The greater petrosal nerve, which arises from the geniculate ganglion, runs above the horizontal segment of the petrous carotid and below the trigeminal ganglion toward the vidian canal. As it proceeds medially, it turns downward along the anterior part of the carotid canal and joins the deep petrosal nerve, a branch from the carotid sympathetic plexus, to form the vidian nerve. Although the posterior ends of the vidian nerve and the canal are both important landmarks for the anterior genu of the internal carotid artery, their locations on the petrous carotid artery are different. The vidian nerve, when followed anteriorly from its origin, turns downward along the carotid to enter the posterior end of the vidian canal, which is positioned at the inferolateral edge of the foramen lacerum and inferolateral to the terminal petrous carotid (Figure 7I-7L). Misunderstanding these relationships may cause carotid artery injury.

Middle and Lower Clival Border

The middle and lower clivus are demarcated at the axial level of the glossopharyngeal meati, which corresponds to the upper medial border of the jugular foramina. When the extracranial orifice of the jugular foramen is viewed from the anterior direction, the glossopharyngeal nerve can be

seen exiting the foramen at the anterior edge of the sigmoid part. The extracranial orifice of the jugular foramen is not, however, considered to be an operative landmark between the middle and lower clivus in the transnasal approach because the jugular foramen is located too far lateral. The pharyngeal tubercle, a consistent bony projection in the midline, is a better landmark for estimating the border between the middle and lower clivus. When viewed from anterior and parallel to the hard palate, the border between the middle and lower clivus approximates the level of the anterior edge of the pharyngeal tubercle (Figure 5); the border averaged 3.9 mm (range, 2-8 mm) above the tip of the tubercle. The border sat an average of 7.0 mm (range, 4-10 mm) above the supracondylar groove for attachment of the rectus capitis anterior. Opening the clivus just below the anterior tip of the pharyngeal tubercle exposes the cisternal portion of the glossopharyngeal nerve just before it exits the dura.

Focal Approach to the Upper, Middle, and Lower Clivus

Stepwise opening of the clivus, in which the right and then left half of the upper, middle, and lower clivus are opened in sequence, clearly displays the relationship between the exocranial and endocranial structures (Figure 5E-5L). The vertical length of the upper clivus averaged 17.3 mm; the middle clivus, 13.7 mm; and the lower clivus, 15.2 mm. The brainstem demarcation between the upper and middle clivus corresponds to the midlevel of the pons, and the demarcation between the middle and lower clivus corresponds to the pontomedullary sulcus. Opening the upper, middle, and lower clivus exposes the anterior surface of the upper half of the pons, the lower half of the pons, and the medulla, respectively.

Approach to the Upper Clivus

Exposure of the Upper Clivus

The whole upper clivus can usually be exposed by opening the anterior wall and part of the floor of the sphenoid sinus. In exposing the upper clivus, the straight endoscope was advanced into the nasal cavity along the superior nasal meatus toward the sphenoid ostium (Figure 7). The right middle turbinate was crushed laterally (lateralized) or removed, and

the inferior turbinate was lateralized. The posterior part of the nasal septum was detached from the sphenoid crest, and approximately 1 cm of the posterior edge of the nasal septum was resected to provide the view for binostril instrumentation. Opening of the anterior wall of the sphenoid sinus at the level of the sphenoid conchae and the sphenoid crest provides a triangular corridor to the sphenoid sinus, limited laterally by the superior turbinate and the posterior ethmoid cells. Removing the superior turbinate and posterior ethmoid cells (posterior ethmoidectomy) widens the surgical route through to the sphenoid sinus.

The vidian canal is identified by drilling the sinus floor from medial to lateral. The canal is often identified as a prominence in the sinus floor (Figure 4K). There are 3 canals coursing through the sphenoid sinus floor in anteroposterior direction: from medially to laterally, the vomerovaginal, palatovaginal, and vidian canals (Figures 6 and 7F). The most medial canal, the vomerovaginal canal, is more of a shallow bony groove than a canal. When drilling the floor of the sphenoid sinus from medial to lateral part, one usually first encounters the palatovaginal canal, also called the palatosphenoidal canal, which can be mistaken for the vidian canal because both canals have nerves and arteries within them and open into the pterygopalatine fossa.35 The palatovaginal canal transmits the pharyngeal nerve from the pterygopalatine ganglion and the pharyngeal artery from the third part of the maxillary artery, which are much smaller than the vidian nerve and artery in the vidian canal. The other difference between the palatovaginal canal and the vidian canal is that the palatovaginal canal courses at a medial angle to the sagittal plane when followed from its anterior to posterior end, whereas the vidian canal courses at a slight lateral angle. The anterior opening of the vidian canal is located approximately 2 mm lateral to that of the palatovaginal canal,35 but they may share the same anterior opening. The laterally directed 45 endoscope may facilitate visualization of the vidian canal through the sphenoid sinus (Figure 4K).

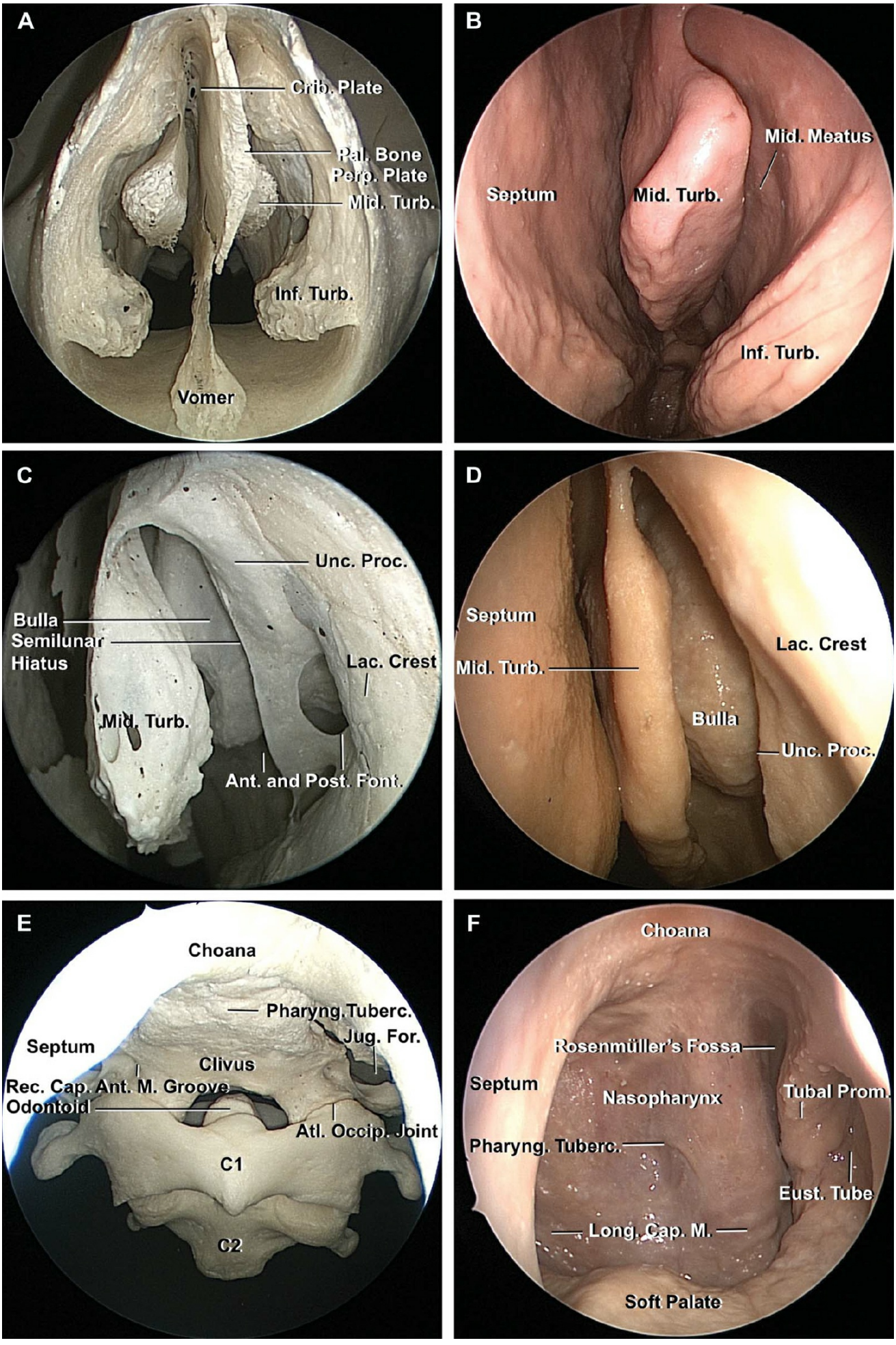

FIGURE 4. A-F. A, endoscopic view through the anterior nasal aperture of the osseous nasal cavity. The perpendicular plate of the ethmoid bone,

vomer, and sphenoid crest forms the osseous nasal septum. The middle and inferior concha project into the nasalcavity. B, nasal cavity with intact mucosa. The endoscope has been inserted into the left nostril. The ethmoid bullae and the uncinate process, to be exposed as the endoscope advances, are hidden under the middle turbinate in the middle nasal meatus. C, enlarged view of A. The left ethmoid bulla, a rounded bony protrusion overlying the ethmoid air cells, is situated posterior to theuncinate process on the superolateral wall of the middle meatus. The uncinate process arises from the agger nasi cell, the most anterior air cell of the ethmoid bone, and projects downward and backward to attach to the inferior concha. The uncinate process divides the maxillary hiatus into a smaller anterior part and a larger posterior part called the anterior and posterior fontanelles, respectively. In life, the anterior part is closed by the mucosa, whereas the posterior part forms the infundibulum, leading to themaxillary, frontal as ethmoid ostia. The uncinate process obscures the direct view of the maxillary ostium and semilunar hiatus inthe view through the 0° endoscope. D, view with intact mucosa. The ethmoid bullae and uncinate process are positioned lateral tothe middle turbinate in the middle meatus. E, anterior view of the clivus. The pharyngeal tubercle, a good landmark for the demarcation between the middle and lower clivus, is seen in midline, whereas the anteromedial edge of the jugular foramen, which sits at the junction of the middle and lower clivus, may be difficult to see through the nasal cavity. The small groove for the insertion of the rectus capitis anterior muscle is seen at the upper anterior edge of the occipital condyle. F, anterior view of the opening from the nasal cavity into the nasopharynx. The tubal prominence is seen behind the ostium of the eustachian tube. The fossa of Rosenmüller projects laterally behind the tubal elevation. The pharyngeal tubercle and longus capitus underlie the mucosa.

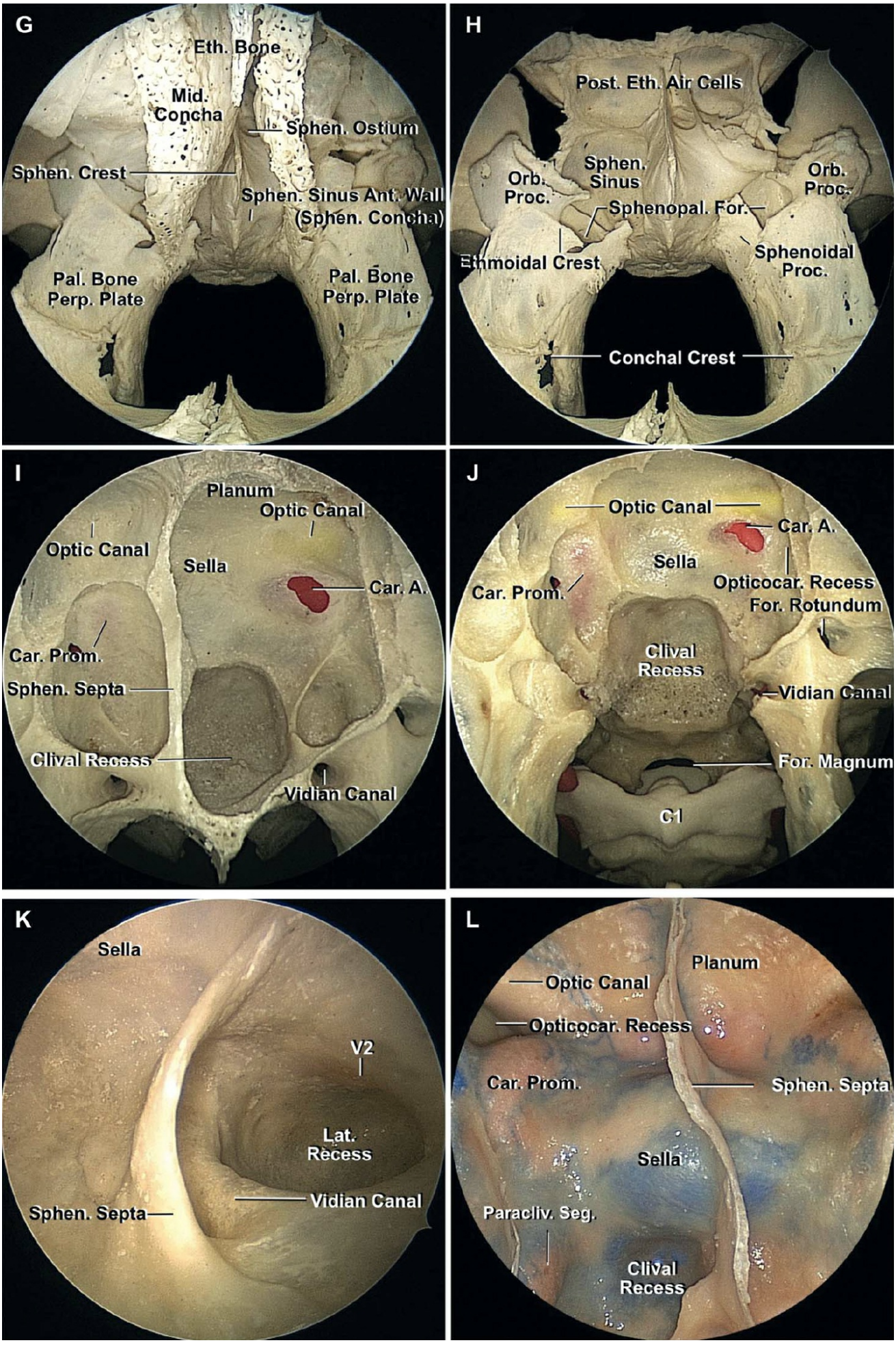

FIGURE 4. G-L. G, anterior endoscopic view of reconstructed sphenoid, ethmoid, and both palatine bones. Only the lower medial part of the

anteriorwall of the sphenoid sinus, which corresponds to the sphenoid conchae, is seen through the nasal cavity. The remainder of theanterior wall of the sphenoid sinus is hidden behind the ethmoid bone, which shares its posterior wall with the anterior wall of thesphenoid sinus. The sphenoid ostium is exposed near the superior angle of the sphenoid concha. The posterior ethmoid air cells share a common wall with the upper lateral part of the anterior wall of the sphenoid sinus. H, the ethmoid bone has been removed.The right half of the anterior wall of the sphenoid sinus has been opened. The sphenopalatine foramen is located just above theethmoid crest in the lateral wall of the nasal cavity between the sphenoid and orbital processes of the palatine bone. I, posterior wallof the sphenoid sinus. There is a spontaneous dehiscence of bone over the left carotid artery. The posterior sinus wall is limitedsuperiorly by the sellae and laterally by the prominences overlying the cavernous carotid. The posterior sinus wall corresponds tothe part of the clivus formed by the sphenoid bone. The sinus wall often extends posteriorly beyond the vertical coronal plane ofposterior wall of pituitary fossa to form a clival recess. The vidian canal is located at the lower lateral corner of the sphenoid sinus.J, view extending to the clivus, foramen magnum, and C1. In this specimen, the opticocarotid recesses, the recess located betweenthe optic canal and the carotid prominence that extends into the optic strut, is shallow. K, left lateral wall of the sphenoid sinusviewed with a 45° endoscope. In this specimen, the pneumatization extends laterally beyond the vidian canal into the greater wingto form a lateral recess. The left vidian canal underlies a bony ridge in the lateral part of the floor of the sphenoid sinus. L, posteriorwall of the sphenoid sinus in another specimen. The vertical paraclival segment of the carotid artery ascends along the lateral limitof the posterior wall of the sphenoid sinus. A., artery; Ant., anterior; Atl., atlanto; Cap., capitis; Car., carotid; Crib., cribriform;Eth., ethmoid; Eust., eustachian; Font., fontanelles; For., foramen; Inf., inferior; Jug., jugular; Lac., lacrimal; Long., longus; M.,muscle; Mid., middle; Occip., occipital; Opticocar., opticocarotid; Orb., orbital; Pal., palatine; Paracliv., paraclival; Perp., perpendicular; Pharyng., Pharyngeal; Post., posterior; Proc., process; Prom., prominence; Rec., rectus; Seg., segment; Sphen., sphenoid;

Sphenopal., sphenopalatine; Tuberc., tubercle; Turb., turbinate; Unc., uncinate.

Drilling the Upper Clivus

The sphenoid septa are removed, and the clival recess is drilled in a medial to lateral direction to expose the dura of the clivus and parallel to the internal carotid to prevent arterial injury. The upper clivus articulates with the petrous apex approximately 10 mm lateral to the midline and behind the internal carotid artery. Fibrocartilage fills the vertical groove along the articulate between the petrous apex and clivus (Figure 7I). Care is required to avoid injuring the abducens nerve when drilling the most lateral part of the upper clivus because the nerve crosses the upper edge of the petroclival junction.

The dura of the upper clivus is easily separated into 2 layers: a periosteal layer facing the bone and a meningeal layer facing the brainstem (Figure 8). The basilar and superior and inferior petrosal sinuses course between the 2 layers of the dura. Opening the basilar venous plexus, which sits on the posterior surface of the upper clivus and connects the posterior ends of the paired cavernous sinuses, may result in significant bleeding. This venous plexus becomes less prominent as it descends toward the foramen magnum. The posterior end of each cavernous sinus forms a characteristic venous confluence or gulf with the superior and inferior petrosal and basilar sinuses. The abducens nerve penetrates the meningeal dura and courses through the venous confluence before passing below the sphenopetrosal (Gruber's) ligament. The nerve then turns around the lateral aspect of the internal carotid artery to reach the medial aspect of the ophthalmic nerve in the lateral wall of the cavernous sinus. Preserving Gruber's ligament with drilling of the clivus may aid in maintaining the position of the abducens nerve (Figure 7K).

Opening of the upper clival dura has the potential risk of injuring the abducens nerve, especially the interdural segment, because the interdural segment may be difficult to locate and venous bleeding may further obscure its identification. The distance between the paired abducens dural pori averaged 20.9 mm (range, 18-25 mm). Barges-Coll et al[33] reported

that the horizontal distance between the abducens nerves at the pontomedullary sulcus was 10 mm and at the venous confluence was 18.5 mm. The interdural segment of the abducens nerve is often accompanied by the dorsal meningeal artery, which usually arises at the level of the dorsum sellae from the meningohypophyseal branch of the internal carotid artery. Six percent of dorsal meningeal arteries arise directly from the intracavernous carotid below the origin of the meningohypophyseal trunk.[36] The artery distal to the origin passes posteriorly through the cavernous sinus with the abducens nerve to reach the dura on the dorsum and clivus, where it courses medially along the abducens nerve and below Gruber's ligament (Figure 7K). The 45 endoscope directed laterally aids in the visualization of the interdural segment of the abducens nerve, the dorsal meningeal artery, and Gruber's ligament.

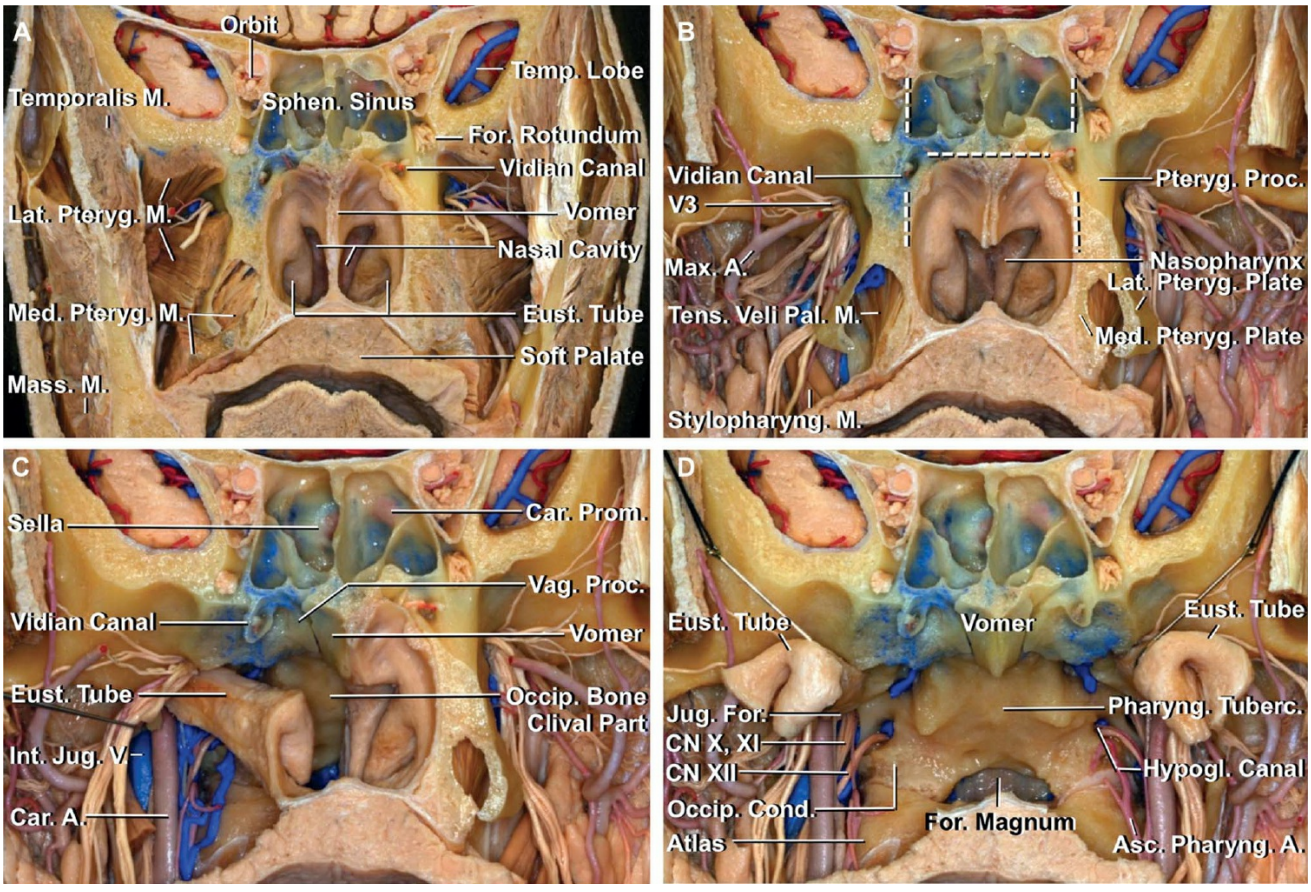

FIGURE 5. A-D, stepwise dissection of the nasopharynx and clivus. A, anterior view of a coronal section just in front of the pterygoid process. The sphenoid sinus, nasal cavity, and nasopharynx offer corridors to the clivus. The infratemporal fossa, containing the lateral and medial pterygoid muscles, branches of the maxillary artery, mandibular nerve, and pterygoid venous plexus, is located lateral to the nasal cavity and

nasopharynx. B, the pterygoid muscles, lower part of the temporalis muscles, and vomer have been removed. The vidian canal is located at the lower lateral corner of the sphenoid sinus floor, where a horizontal line along the sinus floor meets a vertical line along the lateral wall of the sphenoid sinus and the medial pterygoid plate. C, the right pterygoid process, tensor, and levator veli palatini muscles and the nasopharyngeal structures, except the right eustachian tube, have been removed while preserving the vidian canal. The eustachian tube extends from the middle ear, passes along the posterior edge of the medial pterygoid plate, and opens into the nasopharynx. The internal carotid artery and internal jugular vein are positioned behind the foramen ovale and branches of the mandibular nerve. D, the pterygoid processes have been removed on both sides, and the eustachian tubes have been retracted laterally to provide an anterior view of the clivus and the adjacent area. The anterior edge of the exocranial orifice of the jugular foramina is located at almost the same level as the anterior edge of the pharyngeal tubercle. The soft palate sits at the level of the foramen magnum.

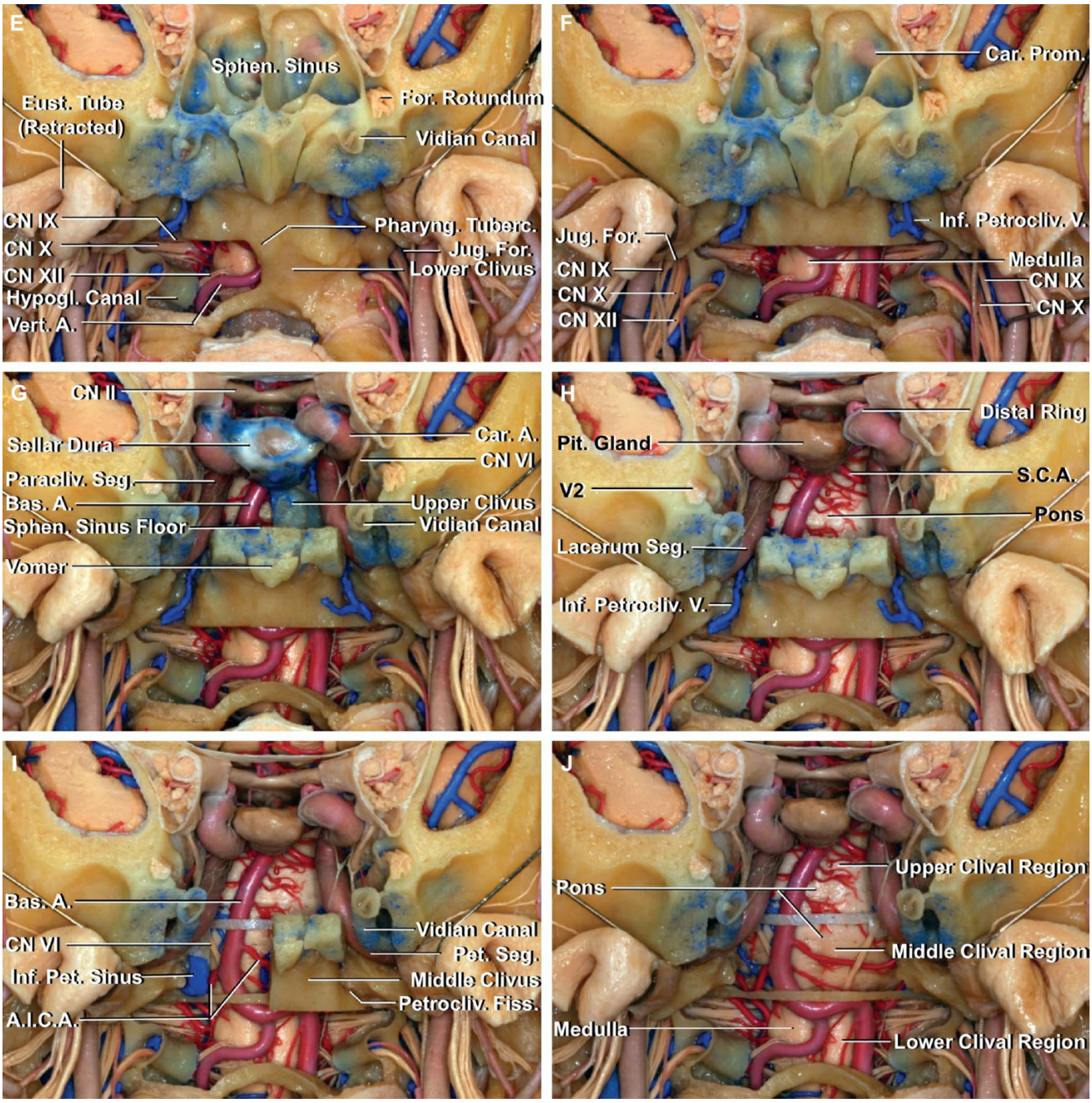

FIGURE 5 E-J. E-L, stepwise dissection showing the relationship between exocranial landmarks and endocranial structures. E, the right half of the lower clivus has been opened. The border between the middle and lower clivus approximates the level of the anterior edge of the pharyngeal tubercle. The glossopharyngeal and vagal nerves are exposed above the hypoglossal canal. F, the left half of the lower clivus has also been opened, and the medulla has been exposed. The intracranial demarcation between the middle and lower clivus is just above the glossopharyngeal nerve at the level of the pontomedullary sulcus. G, the bone and dura of the right half of the upper clivus has been opened. The vertical segment of the internal carotid artery, which ascends along the lateral limit of the posterior wall of the sphenoid sinus, is referred to as the paraclival segment. The border between the upper and middle clivus is located at

the same level of the lower limit of the paraclival segment of the internal carotid artery. H, removing the left half of the upper clivus and opening the dura exposes the upper part of the pons. The lacerum segment of the petrous carotid is positioned at the anterior genu below the paraclival segment. I, the right half of the middle clivus has been opened. A thin dural bridge has been preserved at the junction of the upper and middle clivus, and a thin bony bridge has been preserved at the junction of the middle and lower clivus. J, the left half of the middle clivus has been opened to expose the intradural structures in the upper, middle, and lower clival regions. The middle clival opening exposes the lower pons.

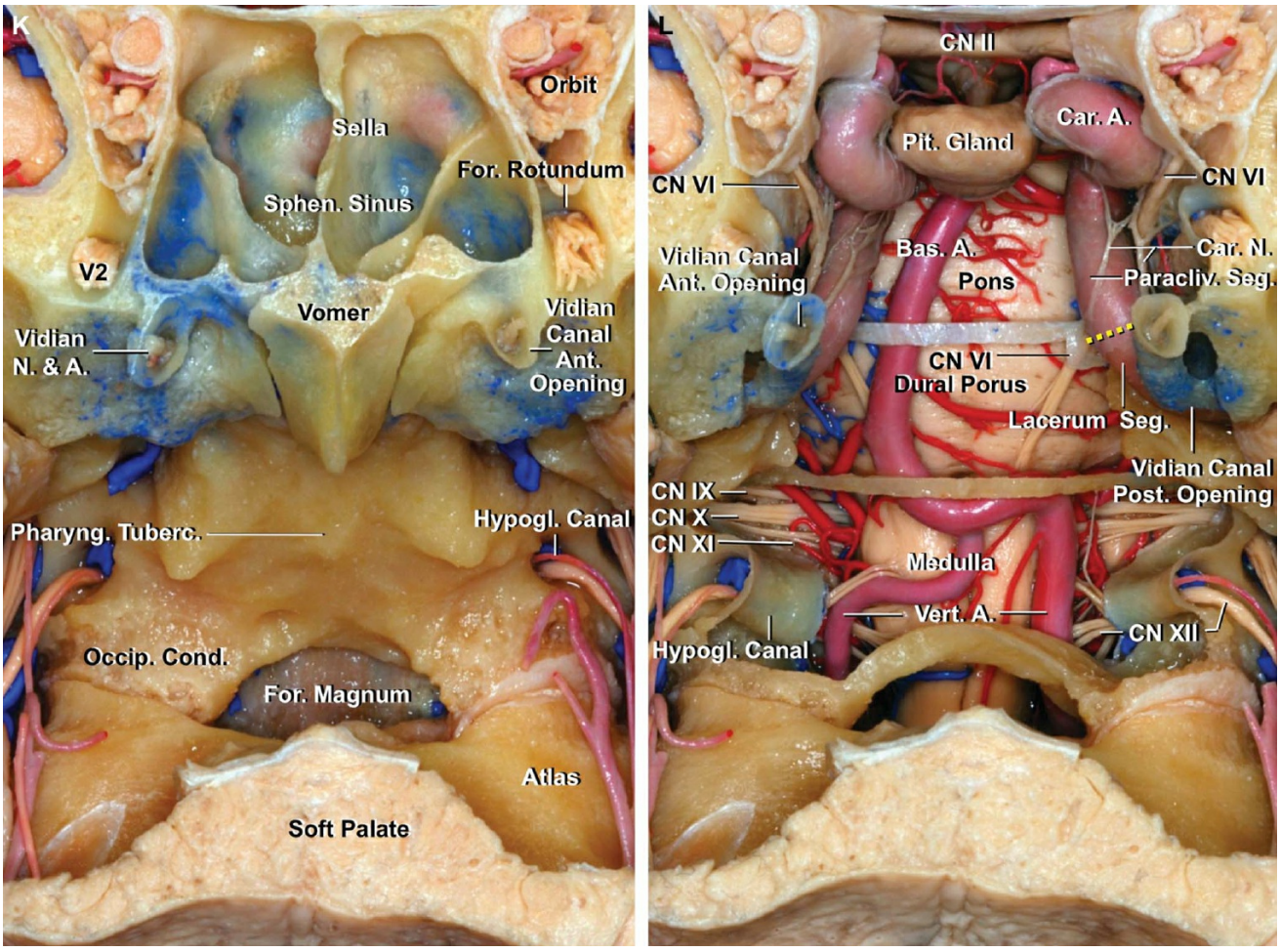

FIGURE 5. K and L, enlarged anterior views of the midline cranial base before (K) and after (L) opening the clivus. A thin dural bridge separates the upper and middle clivus, and a thin bony bridge separates the middle and lower clivus. The border between the upper and middle clivus is located at the junction of the paraclival and lacerum segments of the petrous carotid (yellow dotted line), which is approximately 5 mm above the posterior end of the vidian canal. The border between the middle and lower clivus is situated approximately 4 mm above the top of the

pharyngeal tubercle. Opening the upper, middle, and lower clivus exposes the anterior surface of the upper half of the pons, the lower half of the pons, and the medulla, respectively. When followed from its anterior to posterior end, the vidian canal courses in a slight lateral angle to the sagittal plane and almost parallel to or at a slight downward angle in relation to the plane of the hard palate. The posterior end of the vidian canal is located inferolateral to the anterior genu, or the lacerum segment, of the internal carotid artery. A., artery; A.I.C.A.; anterior inferior cerebellar artery; Ant., anterior; Asc., ascending; Bas., basilar; Car., carotid; CN, cranial nerve; Cond., condyle; Eust., eustachian; Fiss., fissure; For., foramen; Hypogl., hypoglossal; Inf., inferior; Int., internal; Jug., jugular; Lat., lateral; M., muscle; Mass., masseter; Max., maxillary; Med., medial; N., nerve; Occip., occipital; Pal., palatini; Paracliv., paraclival; Pet., petrous, petrosal; Petrocliv., petroclival; Pharyng., pharyngeal; Pit., pituitary; Post., posterior; Proc., process; Prom., prominence; Pteryg., pterygoid; S.C.A., superior cerebellar artery; Seg., segment; Sphen., sphenoid; Stylopharyng., stylopharyngeus; Temp., temporal; Tens., tensor; Tuberc., tubercle; V., vein; Vag., vaginal; Vert., vertebral.

Intradural Structures

Opening the upper clival dura below the pituitary gland exposes the upper half of the anterior surface of the pons and prepontine cistern (Figures 7L and 8). The upper limit of this exposure is the pontomesencephalic junction and the mesencephalic leaf of Liliequist's membrane if not extended upward behind the pituitary gland. The exposure of the cerebellopontine cistern on the lateral side of the anterior pontine membrane is limited by the internal carotid artery and petrous apex. The upper basilar artery and its perforating branches to the pons are visualized unless the artery is markedly elongated (Figure 7L). The anterior pontomesencephalic segment of the superior cerebellar artery (SCA), which encircles the brainstem near the pontomesencephalic junction, may be seen at the upper limit of the exposure with an upper 45 endoscope.

No cranial nerves are exposed in the exposure limited to the upper clivus.

The trigeminal nerve, which originates at the level of the upper clivus and courses in the cerebellopontine cistern, passes lateral to the exposure. Extending the exposure by drilling the lingual process of the sphenoid bone and the petrous apex with or without transposition of the internal carotid artery provides an anterior view of the trigeminal nerve and Meckel's cave, but it is not seen in the exposure limited to the clivus.37,38 The oculomotor nerve, which arises from the anterior aspect of the midbrain and courses above the SCA, is not seen unless the exposure is extended superiorly.

Superior Extension of the Upper Clival Approach

The superior extension of the upper clival approach with elevation of the pituitary gland and removal of the dorsum sellae will expose the interpeduncular cistern. However, it is difficult to elevate the pituitary gland with the sellar dura intact through the simple upper clival route because the periosteal layer of the sellar floor dura blends into the dura around the internal carotid artery and the diaphragma sellae, forming a roof of the pituitary fossa that blends into the upper dural ring, which surrounds and tightly adheres to the internal carotid artery. Separating the pituitary capsule from the medial wall of the cavernous sinus, a procedure well described by Kassam et al,[18] aids in elevating the gland and exposing the dorsum sellae.

The periosteal and meningeal dural layers line the sellar floor and the lower surface of the pituitary gland (Figure 8). The periosteal layer is adhered to the sphenoid bone, and the meningeal layer extends down from the diaphragm around the pituitary gland. The double-layer structure of the dura is apparent at the floor of the sella, especially at the intercavernous sinuses, which course between the 2 layers. The medial wall of the cavernous sinus, which separates the lateral surface of the pituitary gland from the internal carotid artery, is formed by a single thin layer of meningeal dura (Figure 8B).[39] The pituitary capsule, a very thin, semitransparent membrane, is tightly attached to the pituitary gland adjacent to the medial wall of the cavernous sinus and can be separated from the medial wall of the cavernous sinus by careful dissection. The

sellar part of the medial wall of the cavernous sinus covers the lateral surface of the anterior lobe, but the posterior lobe is positioned behind both the anterior lobe and the medial wall of the cavernous sinus in the concave anterior surface of the dorsum sellae, behind where the sellar part of the medial wall of the cavernous sinus blends into the dura along the lateral edge of the inner surface of the dorsum.

The pituitary gland is detached from the dural structures by opening between the pituitary capsule and the medial wall of the cavernous sinus. This allows the gland to be transposed upward for resection of the dorsum sellae. Care is required to avoid excessive transposition and avulsion of the inferior hypophyseal artery, which arises from the meningohypophyseal trunk lateral to the dorsum sellae and courses medially to supply the posterior lobe.

This approach exposes the interpeduncular cistern and the leaves of Liliequist's membrane at the confluence of the supratentorial and infratentorial parts of the subarachnoid space (Figure 8D). The oculomotor nerve courses in the lateral wall of the interpeduncular cistern and forms the pillars to which the leaves of Liliequist's membrane attach. The origins of the SCA and posterior cerebral artery could be exposed in all specimens through this approach. Opening the diencephalic leaf of Liliequist's membrane, which extends above the interpeduncular cistern, exposes the segments of the posterior communicating and internal carotid arteries in the chiasmatic and carotid cisterns. This exposure, at the upper limit of the extended upper clival exposure, may require a 70 endoscope (Figure 8F).

Approach to the Lower Clivus

Exposure of the Lower Clivus

In contrast to the upper clivus, which is positioned behind the sella, the lower clivus is located just behind the posterior wall of the nasopharynx, which communicates anteriorly with the nasal cavity through the choanae (posterior nasal apertures; Figures 9 and 10). The choanae are paired apertures formed superiorly by the body of the sphenoid bone, laterally by the perpendicular plate of palatine bone and the medial pterygoid plates,

inferiorly by the horizontal plate of the palatine bone, and medially by the vomer at the midline. The eustachian tubes open on the lateral wall of the nasopharynx by passing along the posterior edge of the medial pterygoid plate. Several muscles, including the tensor and levator veli palatini and salpingopharyngeus muscles, attach to and act by opening the tube, which remains closed most of the time (Figure 9). Behind the orifice of the eustachian tube, there is a hard elevation beneath the mucosa, the tubal elevation (or the torus tubarius), formed by the base of the cartilaginous portion of the eustachian tube. The eustachian tube and tubal elevation are at the lateral limits for the lower clival approach. The transverse distance between the orifice of the eustachian tubes averaged 24.1 mm and between the tubal elevations averaged 14.7 mm, as reported previously.[21] The pharyngeal recess (or the fossa of Rosenmüller) projects laterally from the posterolateral corner of the nasopharynx behind the tubal elevation. The parapharyngeal internal carotid artery runs just deep to the lateral edge of the fossa of Rosenmüller.

For the approach to the lower clivus, a U-shaped or linear mucosal incision is made on the posterior nasopharyngeal wall with its upper edge located slightly above the pharyngeal tubercle. The attachment of the longus capitis muscles to the clivus usually presents as a V-shaped mucosal elevation. The pharyngeal tubercle is located in the midline at the lower end of the V (Figure 10A and 10C). There is a shallow, inverted triangular mucosal depression above the insertion of the longus capitis muscle that corresponds to where the pharyngeal tonsil or adenoid is located in childhood.

The muscular structures in the posterior nasopharyngeal wall are divided into 3 layers (Figure 9I and 9J). The pharyngobasilar fascia, the most superficial layer encountered after opening the nasopharyngeal mucosa, covers the longus capitis muscle. It is firmly connected to the lower surface of the occipital and temporal bones. As the fascia descends, it diminishes in thickness and gradually blends into the superior pharyngeal constrictor at the level of soft palate. The superior pharyngeal constrictor inserts into the pharyngeal raphe, which attaches to the pharyngeal tubercle. The upper edge of the superior constrictor is located at the C1

level and is not usually opened for exposure of the lower clivus. At its upper edge, the pharyngobasilar fascia blends into the fibrocartilage at the border between the sphenoid and occipital bones and at the foramen lacerum. The second layer is the longus capitis muscle. The parapharyngeal segment of the internal carotid artery ascends just laterally to the longus capitis muscle. Fibrocartilage fills the petroclival fissure along the lateral edge of the attachment of the longus capitis muscle. The third and deepest layer of the posterior nasopharyngeal wall consists of the rectus capitis anterior and the longus colli muscles. The rectus capitus anterior is a short, flat muscle that extends across the front of the atlanto-occipital joint. The muscle usually attaches in a groove just above the occipital condyle, but its attachments may be associated with a tubercle that can be mistaken for the medial edge of the occipital condyle. The hypoglossal nerve and neuromeningeal branches of the ascending pharyngeal artery course along the lateral edge of the rectus capitus anterior (Figure 9). The longus colli muscle is not encountered in the lower clival approach because it inserts below the exposure into the atlas. The petrosal venous confluence is situated lateral and deep to the rectus capitis anterior muscle, around the extracranial orifice of the jugular foramen and hypoglossal canal, where the lower end of the inferior petrosal sinus connects to the venous plexus of the hypoglossal canal and prevertebral venous plexus (Figures 9E and 10I).[26] It empties into the medial aspect of the jugular bulb through 1 or 2 openings in the venous walls between the glossopharyngeal and vagus nerves or into the internal jugular vein below the jugular foramen. The inferior petroclival vein courses along the extracranial surface of the petroclival fissure like a mirror image of the inferior petrosal sinus on the intracranial side and empties into the petrosal confluence. The upper end of the inferior petroclival vein connects to the venous plexus around the carotid artery through the foramen lacerum or to the cavernous sinus directly. The neuromeningeal branch of the ascending pharyngeal artery gives rise to branches just below the jugular foramen that penetrate through the petrosal confluence, hypoglossal canal, and jugular foramen to supply the surrounding dura.

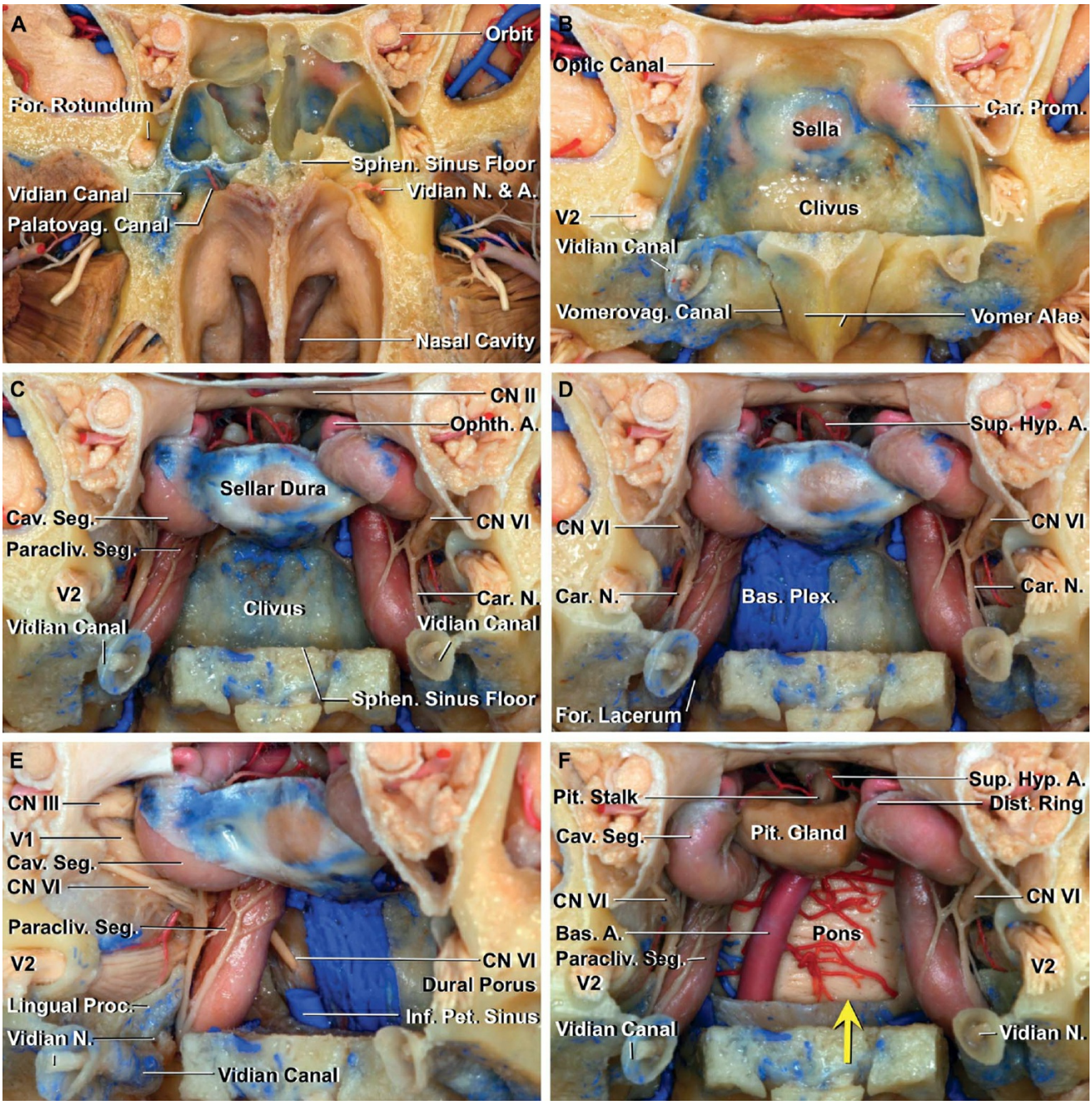

FIGURE 6. Stepwise exposure of the upper clivus. A, the vidian canal courses along the lateral edge of the sinus floor. The palatovaginal canal, located between the sphenoidal process of the palatine bone and the vaginal process of the sphenoid bone, is positioned medial to the vidian canal. B, enlarged view. The sphenoid septae and pterygoid processes have been removed. The wings (alae) of the vomer attached along the sphenoid sinus floor. The vomerovaginal canal, located between the ala of the vomer and the vaginal process of the sphenoid bone, is more of a shallow bony groove than a canal. The vomerovaginal canals are located medial to the palatovaginal canals seen in A. C, The medial wall of the cavernous sinuses has been opened, and the cavernous segment of the carotid arteries has been exposed. The posterior sinus wall, which is

limited superiorly by the sellae and laterally by the paraclival segment of the carotid arteries, corresponds to the part of the clivus formed by the sphenoid bone. D, the right half of the upper clivus has been drilled. The periosteal layer of the clival dura has also been opened to expose the basilar venous plexus. A bundle of the carotid sympathetic plexus ascends on the cavernous carotid and joins the abducens nerve. E, anterior, oblique view of the right anteromedial cavernous sinus. The venous confluence surrounding the dural porus of the abducens nerve has been removed. The vidian nerve runs below anathe cavernous segment of the abducens nerve runs above the lingual process of the sphenoid bone. The vidian nerve, when followed posteriorly, reaches the lateral surface of the lacerum segment of the petrous carotid artery. Here, the nerve turns slightly upward in the foramen lacerum and is continuous with the greater petrosal and the deep petrosal nerves. The abducens nerve, when followed anteriorly, exits its dural porus and ascends lateral to the internal carotid artery. F, the upper clivus has been opened and the dura, above the level of the dural porus of the abducens nerve (yellow arrow), has been removed. The basilar artery and the upper half of the pons are exposed. A., artery; Bas., basilar; Car., carotid; Cav., cavernous; CN, cranial nerve; Dist., distal; For., foramen; Hyp., hypophyseal; Inf., inferior; N., nerve; Ophth., ophthalmic; Palatovag., palatovaginal; Paracliv., paraclival; Pet., petrosal; Pit., pituitary; Plex., plexus; Proc., process; Prom., prominence; Seg., segment; Sphen., sphenoid; Sup., superior; Vomerovag., vomerovaginal.

Drilling of the Lower Clivus

Retraction or resection of the rectus capitis anterior exposes the occipital condyle and the hypoglossal canal. The occipital condyle and hypoglossal canal are at the lateral limit of the lower clivus exposure with a 0° endoscope (Figure 10K and 10L). A 45° endoscope inserted above the cartilaginous part of the eustachian tube after drilling of the root of the pterygoid process provides a view of the exocranial orifice of the jugular foramen (Figure 10I and 10J). Drilling this part and exposing the jugular foramen from the medial route are technically difficult and require much attention because the cartilage of the eustachian tube blends into that

filling the lower part of the foramen lacerum. The part of the clivus below the level of the anterior edge of the pharyngeal tubercle and extending downward and laterally above the occipital condyle is drilled. The clival opening is limited laterally at the hypoglossal canal, which passes posteromedially from its extracranial opening. A wider clival opening can be achieved in the area above the hypoglossal canal, where the clival opening is limited laterally by the petroclival fissure and the jugular foramen. In this study, the mean width of the corridor averaged 38.6 mm above the hypoglossal canal and 26.6 mm at the level of the hypoglossal canal. The jugular tubercle is located on the intracranial surface in the triangular area between the petroclival fissure, the jugular foramen, and hypoglossal canal. This area consists of the hard compact bone in the thickest part of the lower clivus. Drilling here requires great care to avoid damaging the hypoglossal canal and cisternal portion of cranial nerves IX, X, and XI, which rest on the dura covering the jugular tubercle.

The apical ligament of the odontoid process extends from the tip of the dens to the anterior margin of the foramen magnum and is situated between the anterior atlanto-occipital membrane and the superior prolongation of the cruciform ligament. The upper vertical band of the cruciform ligament and the tectorial membrane attach to the upper surface of the clivus. The alar ligaments are 2 strong bands that arise on each side of the upper part of the dens and extend obliquely superolateral to attach to the medial surfaces of the occipital condyles. Whereas the apical ligaments have minimal function in maintaining stability between the head and neck,[40] the transection of the alar ligaments may cause instability at both the atlanto-occipital and atlanto-axial joints.[41,42] Drilling of the cancelous bone of the occipital condyle with preservation of the articular facet and the cortical bone at its medial surface may avoid postoperative instability.

A well-developed dural venous sinus extends around the hypoglossal canal and communicates with the marginal sinus around the foramen magnum and the hypoglossal venous plexus inside the hypoglossal canal. Dural sinuses may present a special challenge when incising the dura of the lower clivus.

Intradural Structures

Opening the lower clival dura exposes nearly all the anterior surface of the medulla (Figures 9H and 10M). The pontomedullary sulcus sits at the junction of the middle and lower clivus, and the anterior edge of the foramen magnum coincides with the level where the most inferior rootlet of the hypoglossal canal arises from the medulla. The first cervical nerve is located just below the foramen magnum. Opening of the dura between the foramen magnum and atlas exposes the upper end of the cervical cord and the C1 nerves, although this requires the transection of the apical and upper vertical ramus of the cruciform ligament. The lower clival opening accesses predominantly the premedullary cistern, which is limited above by the medial pontomedullary arachnoid membrane and laterally by the cerebellomedullary cistern, which begins at the posterior margin of the olive in front of the glossopharyngeal, vagus, and accessory nerves. The lower clival approach extends to only a small anterior part of the cerebellomedullary cistern.

The cranial nerves exposed by opening the lower clivus are the glossopharyngeal, vagus, accessory, and hypoglossal nerves, all of which arise from the medulla and are closely related to the posterior inferior cerebellar artery (PICA; Figure 10M-10O). The border between the middle and the lower clivus is located just above the level of the cisternal part of the glossopharyngeal nerve. The cisternal part of the glossopharyngeal and vagus nerves can be exposed by drilling of the jugular tubercle, which corresponds to the bony area above the hypoglossal canal in the transnasal approach. The accessory rootlets arising from the medulla are often hidden behind the hypoglossal rootlets and canal and the vertebral artery when viewed anteriorly. Drilling of the hypoglossal canal enlarges the corridor and facilitates exposure of the accessory rootlets but may lead to bleeding from the hypoglossal venous plexus and meningeal branch of the ascending pharyngeal artery and risk of injury to the hypoglossal nerve.

Opening the lower clivus exposes almost the entire intradural course of the vertebral arteries (Figures 9H and 10M). In most cases, the vertebral

artery courses in front of the hypoglossal rootlets as it ascends to join the other vertebral artery at or near the pontomedullary sulcus. The opening of the lower clivus also exposes the anterior medullary and lateral medullary segments of the PICA. The origin of the PICA could be seen in the lower clival opening in 19 of 20 PICAs in this study; 1 PICA arose from the vertebral artery at the level of the border between the middle and the lower clivus. The origin of the PICA may not be seen from the transnasal view if the artery arises from the extradural part of the vertebral artery. The anterior ventral spinal arteries and their origins were seen in the lower clival opening in all specimens.

Approach to the Middle Clivus

Exposure of the Middle Clivus

The landmarks for the middle clivus are the lower limit of the paraclival carotid artery at its upper border and the pharyngeal tubercle at its lower border. The anterior surface of the middle clivus corresponds to the area of attachment of the vomer to the floor of the sphenoid sinus and the upper part of the occipital bone. The nasopharyngeal exposure is the same as mentioned for the lower clivus. The lateral limit of the surgical corridor to the middle clivus is the upper part of the pterygoid process above and the tubal elevation below. The separation between the medial edges of the pterygoid processes averaged 24.9 mm. It is difficult to expose the foramen lacerum and petroclival fissure at the lateral border of the middle clivus without removal of the root of the pterygoid process. The procedures for removing the pterygoid process have been described previously in articles focused on the transpterygoid approach to the infratemporal fossa.[17,43-45] The uncinate process in the lateral wall of the middle nasal meatus is removed to expose the maxillary ostium (uncinectomy), which is enlarged posteriorly to the level of the anterior edge of the perpendicular plate of the palatine bone (posterior antrostomy). The sphenopalatine foramen through which the sphenopalatine artery passes and the ethmoidal crest, a horizontal crest on the perpendicular plate of the palatine bone where the middle concha articulates, are important landmarks for exposing the pterygopalatine

fossa (Figures 3 and 4). The sphenopalatine foramen is located just above the crest. Removal of the posteromedial wall of the maxillary sinus and orbital process of the palatine bone exposes the pterygopalatine fossa, vidian canal, and foramen of rotundum. Exposure of the anterior surface of the pterygoid process requires lateral retraction of the contents of the pterygopalatine, including the vidian; infraorbital, greater, and lesser palatine nerves; sphenopalatine ganglion; and terminal branches of the maxillary artery. The drilling of the pterygoid process proceeds posteriorly to expose the internal carotid artery.[19,28] The vidian canal leads to the anterior genu, or lacerum segment, of carotid when followed posteriorly.[19,28] The posterior part of the vidian nerve is hidden in the fibrocartilage at the anterolateral margin of the upper part of the foramen lacerum, where the deep petrosal and greater superficial petrosal nerves join to form the vidian nerve (Figure 11).

Drilling the Middle Clivus

The vomer is removed, and the middle clivus, the thickest part, is drilled in a medial to lateral direction to expose the dura. The trapezoid shape of the middle clivus is bordered laterally by the foramen lacerum and internal carotid artery in the upper part and by the petroclival fissure in the lower part (Figure 11). The dural opening in the middle clival approach is limited laterally by the inferior petrosal sinuses, which course along the intracranial side of the petroclival fissures. The transverse distance between the upper and lower parts of the inferior petrosal sinuses averaged 21.9 and 38.6 mm, respectively. Sacrificing an inferior petrosal sinus may allow the exposure to be widened to the medial edge of the petrous apex. Drilling the lower part of the petrous apex extends the exposure laterally to the petrous carotid.

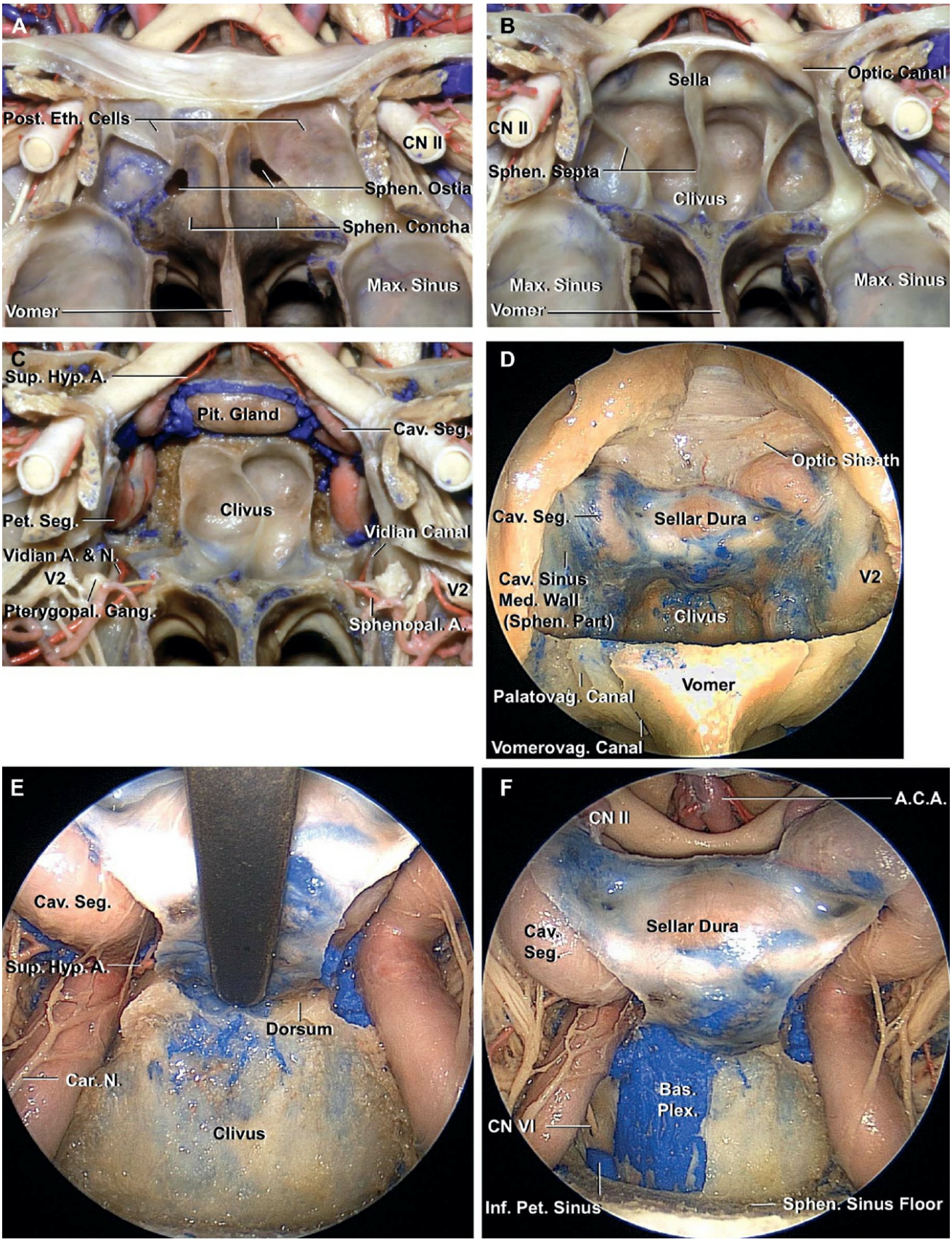

FIGURE 7. A-F. Approach to the upper clivus. The route to the upper clivus is directed through the sphenoid sinus. A through C, relationships of the sphenoid sinus and clivus. A, anterior view of the sphenoid sinus. The posterior ethmoid air cells have a common wall with the superolateral face of the sphenoid sinus and extend along the lateral edge of the sphenoid ostia. The portion of the sphenoid face below and

between the ethmoid air cells is referred to as the sphenoid concha. The sphenoid ostia are located along the narrow upper part of the sphenoid concha. The concha forms much of the thin anterior wall of the sphenoid sinus. B, the posterior ethmoid air cells and the sphenoid concha have been opened to expose the sphenoid sinus. The approach to the upper clivus is directed through the back wall of the sinus below the sella. The approach can be extended upward by elevating the gland and opening through the dorsum sellae. C, the pituitary gland and petrous and cavernous carotid have been exposed. The vidian canals are located along the lateral margin of the sinus floor. The maxillary and vidian nerves enter the posterior wall of the pterygopalatine fossa. The sphenopalatine arteries pass from the pterygopalatine fossa and through the sphenopalatine foramen to enter the nasal cavity. D, the straight endoscope has been advanced into the right nasal cavity toward the sphenoid ostium. For this exposure, the posterior part of the nasal septum has been detached from the sphenoid crest and displaced to the left, the anterior wall of the sphenoid sinus has been removed, and approximately 1 cm of the posterior edge of the nasal septum has been resected. Opening of the anterior wall of the sphenoid sinus, formed by the sphenoid conchae and the sphenoid crest, provides a triangular corridor to the sphenoid sinus. This corridor is limited laterally by the superior turbinate and the posterior ethmoid cells hidden behind the superior turbinate. The sellar dura and medial wall of the cavernous sinus have been exposed. The vomerovaginal canal is located medial to the palatovaginal canal. E, the dura covering the medial wall of the cavernous sinus has been opened. The pituitary gland and sellar dura has been retracted upward to expose the dorsum sellae. It is difficult to elevate the pituitary gland with the sellar dura intact because the dura is fixed to surrounding structures. F, the right half of the upper clivus has been drilled, and the periosteal layer of the clival dura has been opened to expose the venous confluence around the dural porus of the abducens nerve. The basilar venous plexus becomes less prominent as it descends toward the foramen magnum.

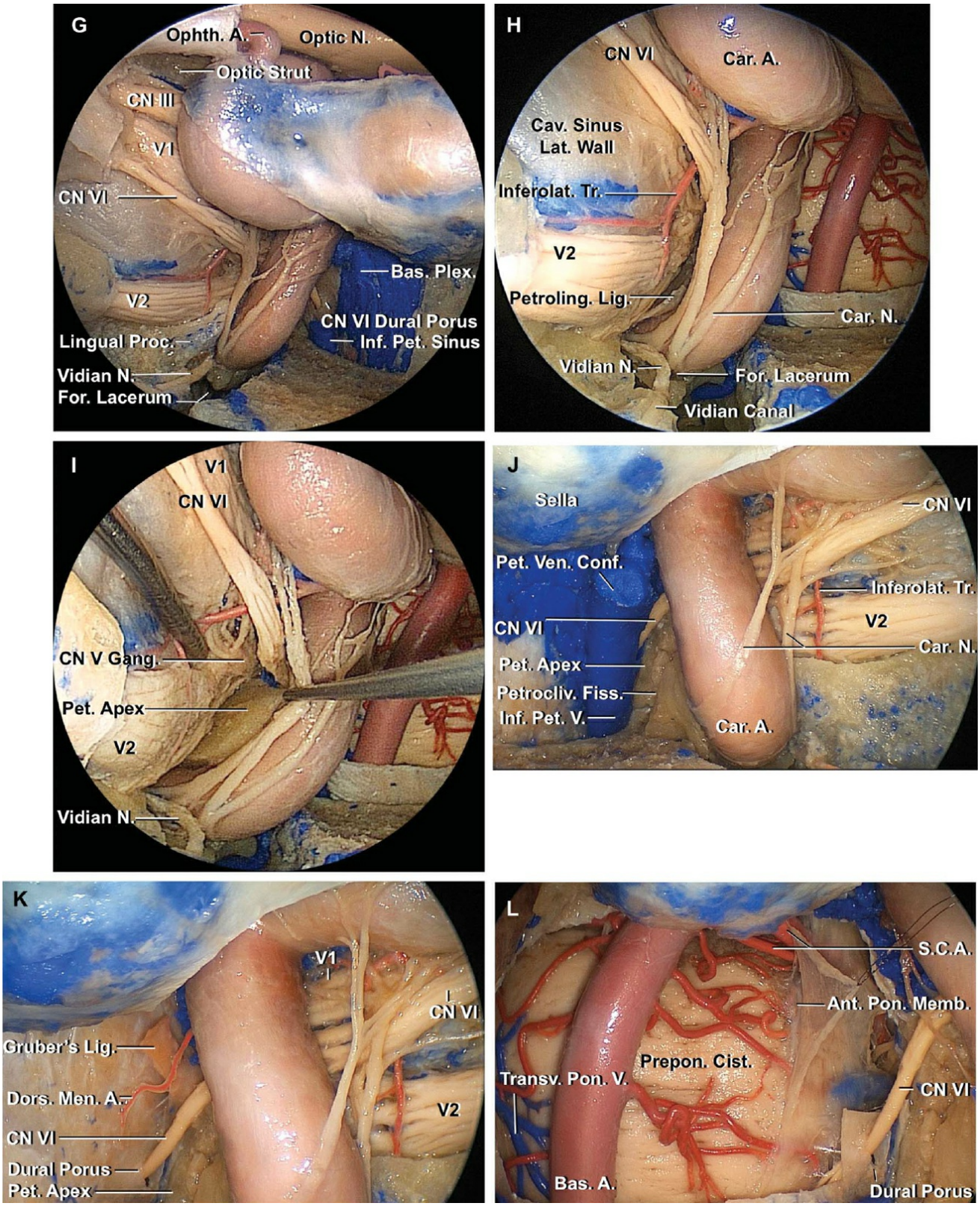

FIGURE 7. G-L. G, view of the right anteromedial cavernous sinus with a 45° endoscope directed laterally. The vidian canal opens posteriorly into the anterolateral edge to the foramen lacerum. The ophthalmic and oculomotor nerves run in the lateral wall of the cavernous sinus, and the abducens nerve passes forward in the sinus. The maxillary nerve passes forward below the cavernous sinus. The ophthalmic artery and optic nerve pass above the optic strut in the optic canal. The dural porus of the abducens nerve and basilar venous plexus have been exposed. The vidian

nerve passes below and the abducens nerve above the lingual process of the sphenoid. H, view focusing on the right paraclival internal carotid artery. The lingual process of the sphenoid bone has been removed. The petrolingual ligament bridges the interval between the lingual process and petrous apex just below the cavernous sinus. The vidian nerve courses below the petrolingual ligament. The inferolateral trunk arises from the lateral aspect of the horizontal segment of the cavernous carotid, descends lateral to the abducens nerve, and supplies the dura of the inferolateral wall of the cavernous sinus surrounding the foramina rotundum and ovale. I, the petrolingual ligament has been removed, and the petrous apex and the gasserian ganglion have been exposed by retracting the ganglion laterally and the carotid artery medially. J, view of the left anteromedial cavernous sinus with a 45° endoscope directed laterally. The upper clivus has been drilled, and the periosteal layer of the clival dura has been opened to expose the venous confluens. K, the venous confluens around the dural porus of the abducens nerve has been removed. The abducens nerve penetrates the dura and ascends lateral to the carotid artery and below the petrosphenoid (Gruber's) ligament, which extends from the lower part of the lateral edge of the dorsum sellae to the petrous apex. The dorsal meningeal branch of the meningohypophyseal trunk courses below Gruber's ligament and near the abducens nerve. L, opening the upper clival dura below the pituitary gland exposes the upper half of the anterior surface of the pons. The outer arachnoid membrane has been opened and retracted laterally. The anterior pontine membranes, located just medial to the dural pori of the abducens nerves, separate the prepontine cistern from the cerebellopontine cisterns. The upper basilar artery and its perforating branches to the pons are well visualized. The rostral limit of the upper clival approach is usually at the pontomesencephalic junction. A duplicate left superior cerebellar artery encircles the brainstem near the pontomesencephalic junction. A., artery; A.C.A., anterior cerebral artery; Ant., anterior; Bas., basilar; Car., carotid; Cav., cavernous; Cist., cistern; CN, cranial nerve; Conf., confluence; Dor., dorsal; Eth., ethmoid; Fiss., fissure; For., foramen; Gang., ganglion; Hyp., hypophyseal; Inf., inferior; Inferolat., inferolateral; Lat., lateral; Lig., ligament; Max., maxillary; Med.,

medial; Men., meningeal; Memb., membrane; N., nerve; Ophth., ophthalmic; Palatovag., palatovaginal; Pet., petro, petrosal, petrous; Petrocliv., petroclival; Petroling., petrolingual; Pit., pituitary; Plex., plexus; Pon., pontine; Post., posterior; Prepon., prepontine; Proc., process; Pterygopal., pterygopalatine; S.C.A., superior cerebellar artery; Seg., segment; Sphen., sphenoid; Sphenopal., sphenopalatine; Sup., superior; Tr., trunk; Trans., transverse; V., vein; Ven., venous; Vomerovag., vomerovaginal.

Intradural Structures

Opening the middle clival dura exposes the lower half of the anterior surface of the pons, the lower half of the prepontine cistern, and the medial part of the cerebellopontine cistern (Figures 5, 10, and 11). The anterior pontine membranes, which separate the prepontine and cerebellopontine cisterns, become less prominent as they extend inferiorly.

The middle clival approach exposes the full length of the cisternal part of the abducens nerve. The junctions of the facial and vestibulocochlear nerves with the brainstem are seen, but most of the cisternal segment of the nerves is hidden behind the petrous apex. It is difficult to see the whole length of their cisternal segment even with a lateral-angled endoscope (Figure 11D). The root exit zone of the facial nerve can be observed in the lateral middle clival area near the border between the middle and lower clivus. It may be observed more clearly with a 45 endoscope directed superior from the level of the lower clivus (Figure 11H) because the root exit zone is located in the supraolivary fossette, a shallow depression on the lateral edge of the pontomedullary sulcus. Drilling the inferior surface of the petrous apex (inferior petrosectomy) and opening the anterior wall of the internal acoustic meatus can expose the whole length of the cisternal and part of the meatal segment of the facial and vestibulocochlear nerves (Figure 11F).

The lower basilar artery and the origin of the anterior inferior cerebellar arteries (AICAs) are usually exposed in the middle clival approach. All 20 AICA origins, in this study, branched from the basilar artery at the level of

the middle clivus. If the origin is from a tortuous basilar artery that loops laterally into the cerebellopontine angle, inferior petrosectomy may be required to expose the origin and the anterior pontine segment of the AICA. The petrosectomy may also expose the premeatal and postmeatal segments of the AICA (Figure 11F). Although the origin of the PICA is usually located at the level of the lower clivus, the cranial loop of a tortuous PICA may extend into the middle clival area.

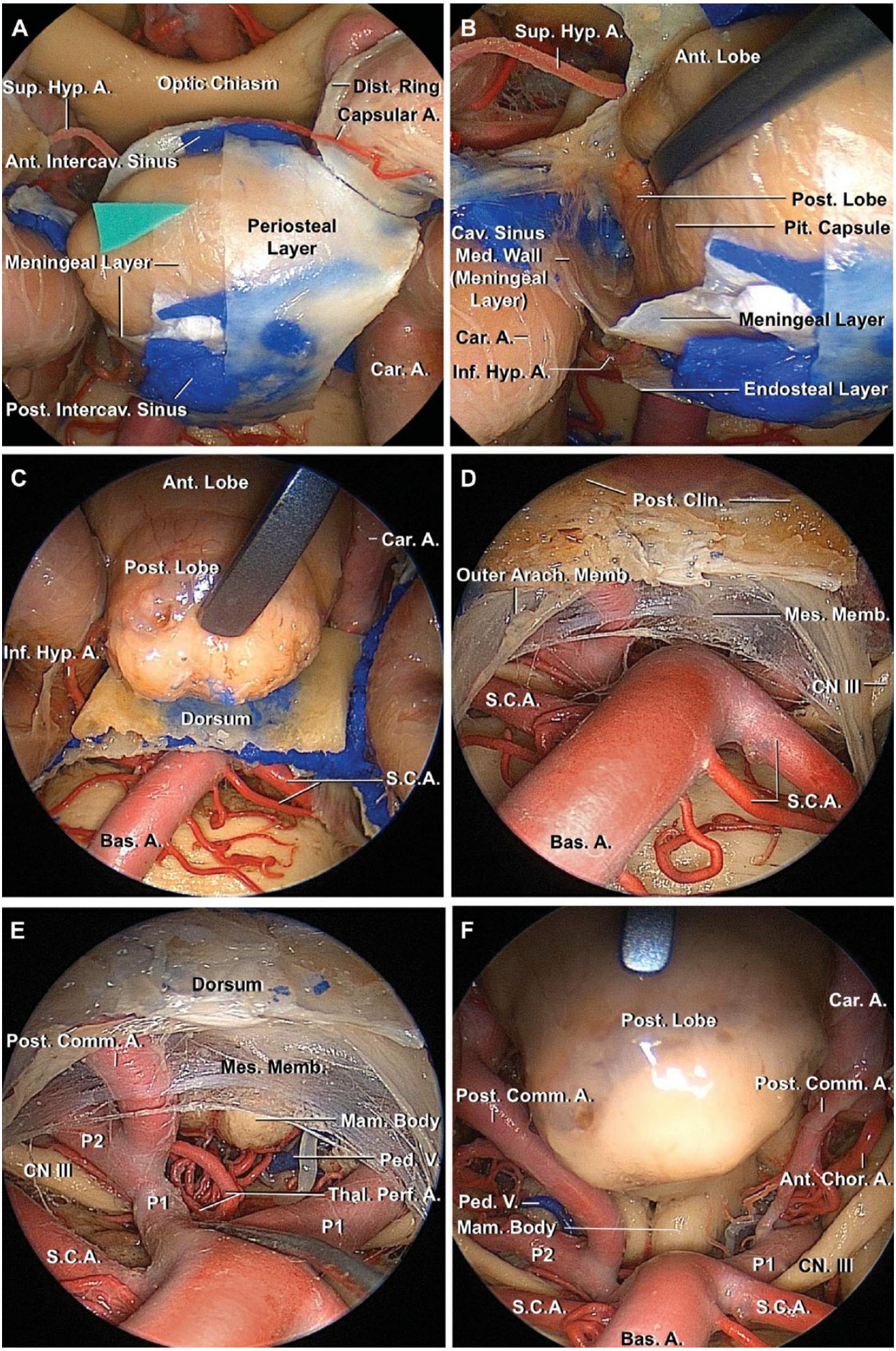

FIGURE 8. Superior extension of upper clival approach to the infrasellar

approach. A, 2 dural layers, periosteal and meningeal, line the sella below the pituitary gland. A triangular green piece has been inserted between the meningeal layer and pituitary capsule. The double-layer structure of the dura is especially apparent around the intercavernous sinuses, which course between the 2 layers. The left distal carotid dural ring has been divided. B, the sellar part of the medial wall of the cavernous sinus has been separated from the pituitary capsule, and the anterior lobe has been retracted medially to expose the posterior lobe. The medial wall of the cavernous sinus is formed by a thin layer of meningeal dura. The pituitary capsule is tightly attached to the outer surface of the gland. The sellar part of the medial wall of the cavernous sinus covers the lateral surface of the anterior lobe, but the posterior lobe is positioned behind the medial wall of the cavernous sinus in the concavity of the dorsum sellae. C, 45° endoscope directed superior. The posterior lobe of the pituitary grand has been retracted upward, and the dorsum sellae has been exposed. The posterior lobe sits in the concave anterior surface of the dorsum sellae. The inferior hypophyseal artery arises from the meningohypophyseal trunk and courses medial to supply the posterior lobe. Care is required to avoid avulsion of the inferior hypophyseal artery during transposition of the gland. D, 45° endoscope directed superior. The dorsum sellae has been drilled while preserving the posterior clinoid processes and adjacent part of the dorsum. The mesencephalic leaf of Liliequist's membrane, which spans the interval between the posterior clinoid process and the pontomesencephalic junction, has been exposed. The mesencephalic membrane is open around the upper the basilar artery. The oculomotor nerves course in the lateral wall of the interpeduncular cisterns and form the pillars to which the leaves of Liliequist's membrane attach. This specimen has a duplicate left superior cerebellar artery. E, closer view. The contents of the interpeduncular cistern and the origins of the both posterior cerebral arteries can be seen through the large opening in the mesencephalic membrane. The thalamoperforating arteries arise from the P1 and enter the brainstem by passing through the posterior perforated substance in the area behind the mamillary bodies. F, 70° endoscope directed upward showing the anatomic upper limit of the extended upper clival approach. The

diencephalic leaf of Liliequist's membrane has been opened, and the posterior lobe of the pituitary gland has been elevated. The interpeduncular and part of the chiasmatic and carotid cisterns are accessible. The right peduncular vein is exposed lateral to the mamillary bodies. A., artery; Ant., anterior; Arach., arachnoid; Bas., basilar; Car., carotid; Cav., cavernous; Chor., choroidal; Clin., clinoid; Comm., communicating; CN, cranial nerve; Dist., distal; Hyp., hypophyseal; Inf., inferior; Intercav., intercavernous; Mam., mamillary; Med., medial; Memb., membrane; Mes., mesencephalic; Ped., peduncular; Perf., perforating; Pit., pituitary; Post., posterior; S.C.A., superior cerebellar artery; Sup., superior; Thal., thalamo; V., vein.

Discussion

The definition of the upper, middle, and lower clivus described in this article, in which the clivus is divided into 3 parts by transverse lines at the level of the dural pori of the abducens and the glossopharyngeal meati, fits with our previously described concept of 3 neurovascular complexes in the posterior fossa.[46,47] The upper, middle, and lower transclival approaches provide access to the anteromedial parts of the 3 neurovascular complexes. The upper clival approach with its extensions exposes the midbrain, upper half of the pons, SCA, and oculomotor and trigeminal nerves in the upper neurovascular complex. The middle clival approach exposes the lower half of the pons, AICA, abducens, and facial and vestibulocochlear nerves in the middle neurovascular complex. The lower clival approach exposes the medulla, PICA, and glossopharyngeal, vagal, accessory, and hypoglossal nerves in the lower neurovascular complex (Figure 12).

An understanding of the relationship between the exoclival and endoclival structures, even when aided by neuronavigation or intraoperative imaging systems, is essential to the appropriate focal opening of the clivus. However, studies focusing on this subject have not resolved the controversy concerning partitioning the clivus. The level of the clivus has been classified arbitrarily on the basis of only the exocranial anatomic structures such as the sphenoid sinus floor. Fraser et al[12,15] reported

excellent clinical results with their focal approaches to the clivus, including a low rate of postoperative CSF leak. They defined the upper third of the clivus as the part that can be approached by opening the sphenoid sinus, whereas the lower two-thirds included the parts below the sphenoid sinus floor that can be reached without opening any sinus. Stippler et al[14] also divided the clivus into 3 parts. Our definition of the 3 transclival approaches coincides with theirs and includes an upper clival area through which the upper half of the pons and midbrain can be exposed through the sphenoid sinus. However, the sphenoid sinus floor is not always a suitable landmark for demarcation between the upper and middle clivus because of the variable extent of the pneumatization of the sinus.[48] This study adds important information to these excellent studies of anatomically reasonable focal transclival approaches.

Carefully tailored focal transclival approaches based on the location of the lesion minimize the invasiveness of a surgery. Many approaches with small or "keyhole" craniotomy have been developed in pursuing minimal invasiveness.[49,50] There are several variants of the retrosigmoid approach based on whether the pathology is located in the upper, middle, and lower neurovascular complex of the cerebellopontine angle.[46] Hitotsumatsu et al[51] also described 3 different approaches for the trigeminal neuralgia, hemifacial spasm, and glossopharyngeal neuralgia. Like these surgical innovations, the focal endoscopic transclival approach enables efficient approaches to lesions while maximizing preservation of the cranial base. The endoscope also facilitates maneuvers such as removing the tenacious attachments of the longus capitis, drilling the thick clivus, and controlling bleeding from the various venous plexuses adjoining the clivus.

Some previous reports on the transclival approach have shown wide panoramic views, but[7,21] such large exposures may increase the risk of postoperative CSF leak. Various techniques, including gasket-seal closure,[52] the use of a balloon stent,[53] an extradural (overlay) technique,[54] and a nasoseptal flap,[55-58] have been used to reconstruct the cranial base and dural defects and to avoid CSF leak. Using these novel techniques, the rate of postoperative CSF leak has been reduced to 0% to

9.5%.[52,54-56] Using carefully tailored focal transclival exposures may also further reduce the CSF leak rate.

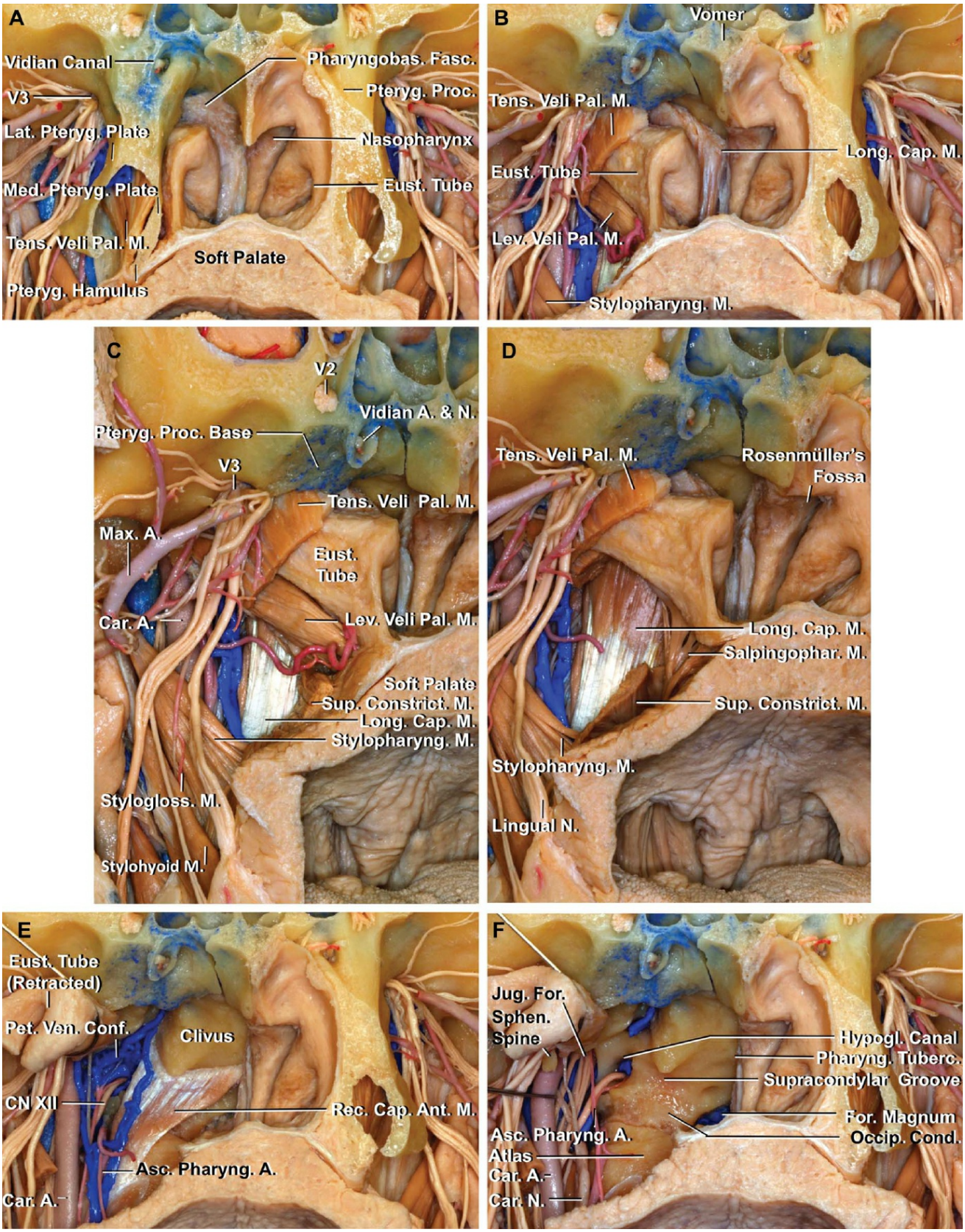

FIGURE 9. A-F. Stepwise dissection focusing on the lower clivus. A, the mucosa on the right half of the posterior nasopharyngeal wall has been removed. The pharyngobasilar fascia covering the longus capitis muscle and firmly connecting to the inferior surface of the occipital and temporal

bones is the most anterior layer encountered after opening the mucosa. The tensor veli palatini muscle descends along the anterolateral aspect of the cartilaginous part of the eustachian tube and turns medially around the pterygoid hamulus of the medial pterygoid plate to insert into the soft palate. B, the pterygoid process and the pharyngobasilar fascia have been removed, and the midportion of the tensor veli palatini has been divided. The longus capitis muscle, the second layer of the posterior nasopharyngeal wall, attaches to the clivus lateral to the pharyngeal tubercle. The levator veli palatini descends along the inferior aspect of eustachian tube before attaching to the soft palate. C, view focusing on the right side. The superior pharyngeal constrictor muscle, the upper edge of which is located at the C1 level, slightly inferior to the level of the soft palate, inserts into the pharyngeal raphe, which attaches above to the pharyngeal tubercle. The internal carotid artery ascends just lateral to the longus capitis muscle. D, the levator veli palatini has been removed to expose the salpingopharyngeus muscle, which attaches to the inferior part of the cartilaginous eustachian tube, and passes downward to blend with the posterior fasciculus of the palatopharyngeus muscle. E, the right tensor and levator veli palatini and longus capitis muscles have been removed, and the eustachian tube has been detached from the soft palate and retracted laterally. The rectus capitis anterior, located behind the longus capitis muscle, arises on the lateral mass and adjacent part of the transverse process of the atlas and attaches to the anterior surface of the occipital bone above the occipital condyle. The hypoglossal nerve and neuromeningeal branches of the ascending pharyngeal artery course along the lateral edge of the rectus capitus anterior. The petrosal venous confluence is situated lateral and deep to the rectus capitis anterior muscle around the extracranial orifice of the hypoglossal canal and petrosal part of the jugular foramen. F, the rectus capitis anterior muscle and the petrosal venous confluence have been removed. The internal carotid artery has been retracted laterally to expose the anterior edge of the extracranial orifice of the jugular foramen. The supracondylar groove, located just above the occipital condyle, is the site of attachment of the rectus capitis anterior muscle. The pharyngeal tubercle and the anterior edge of the extracranial orifice of the jugular foramen are located at

approximately the same level.

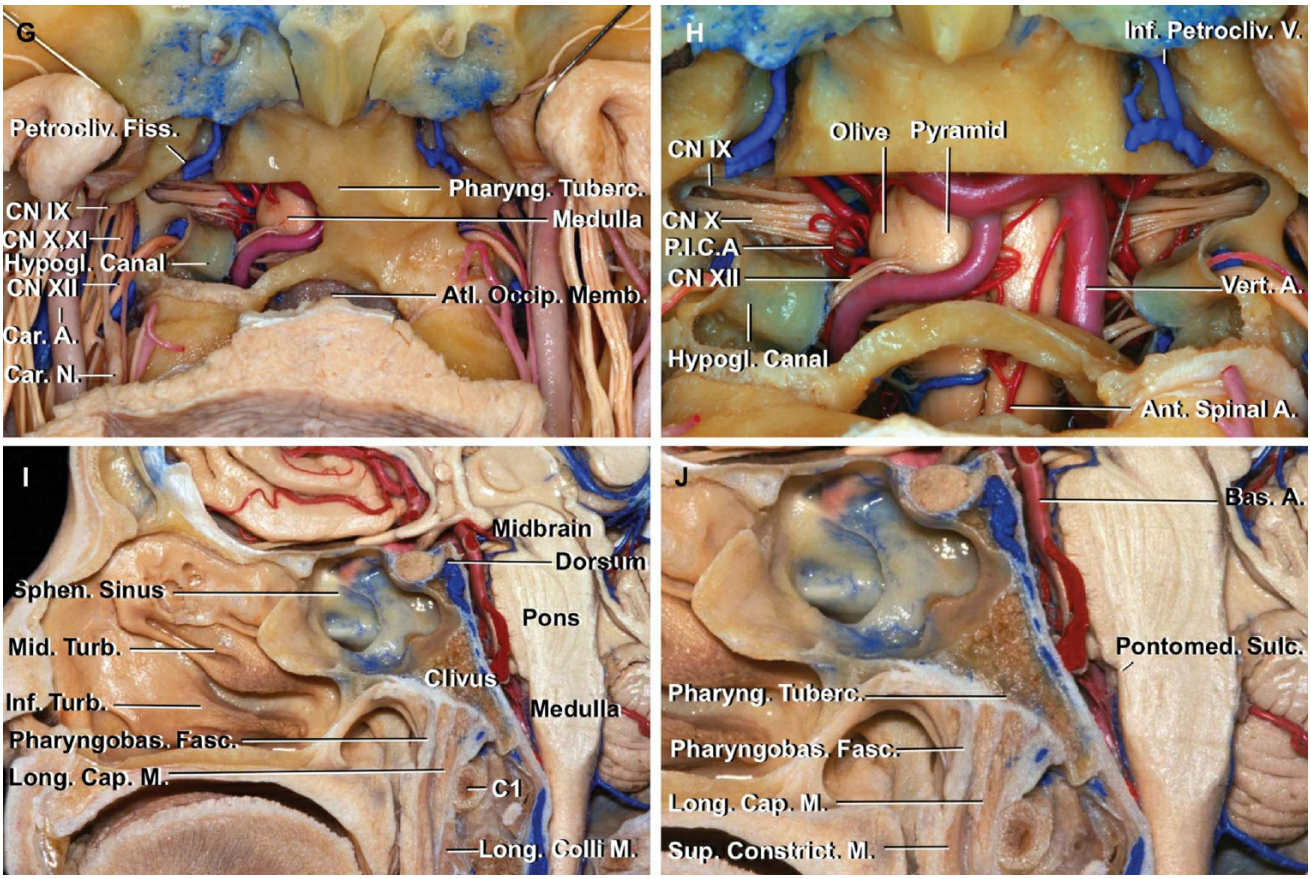

FIGURE 9. G-L. G, the right lower clivus has been drilled while preserving the vidian canal, articular facet of the occipital condyle, and anterior edge of the foramen magnum. The triangular area surrounded by the petroclival fissure, jugular foramen, and hypoglossal canal corresponds to the site of the jugular tubercle on the intracranial surface. Cranial nerves IX, X, and XI course just behind the jugular tubercle. H, enlarged view. The lower clivus has been drilled bilaterally. Opening the lower clival dura exposes the anterior surface of the medulla and the vertebral, posterior inferior cerebellar, and anterior spinal arteries. The glossopharyngeal and vagus nerves arise from the retro-olivary sulcus rostral to and behind the level of origin of the hypoglossal rootlets. The whole cisternal segment of these nerves can be exposed by drilling of the jugular tubercle. The accessory rootlets are hidden by the hypoglossal canals and the vertebral arteries. I, midsagittal section of another specimen showing the relationship between the posterior nasopharynx and lower clivus. The anterior surface of the clivus leans approximately 45° anterior in the view through the nasal cavity. The posterior nasopharyngeal wall has 3 layers: mucosal, fascial, and muscular. The

pharyngobasilar fascia and longus capitis muscles are attached to the clivus; the longus colli muscles are attached to the atlas. The rectus capitis anterior muscle is not shown because the muscle is situated lateral to the midline. J, enlarged view. The pharyngobasilar fascia diminishes in thickness as it descends and gradually blends into the superior pharyngeal constrictor at the level of soft palate. The anterior edge of the pharyngeal tubercle is located at almost the same level as the pontomedullary sulcus. A., artery; Ant., anterior; Asc., ascending; Atl., atlanto; Bas., basilar; Cap., capitis; Car., carotid; CN, cranial nerve; Cond., condyle; Conf., confluence; Constrict., constrictor; Eust., eustachian; Fasc., fascia; Fiss., fissure; For., foramen; Hypogl., hypoglossal; Inf., inferior; Jug., jugular; Lat., lateral; Lev., levator; Long., longus; M., muscle; Max., maxillary; Med., medial; Memb., membrane; Mid., middle; N., nerve; Occip., occipital; Pal., palatini; Pet., petro, petrosal; Petrocliv., petroclival; Pharyng., pharyngeal; Pharyngobas., pharyngobasilar; P.I.C.A., posterior inferior cerebellar artery; Pontomed., pontomedullary; Proc., process; Pteryg., pterygoid; Rec., rectus; Salpingophar., salpingopharyngeus; Sphen., sphenoid; Stylopharyng., stylopharyngeal; Stylogloss., styloglossus; Sulc., sulcus; Sup., superior; Tens., tensor; Tuberc., tubercle; Turb., turbinate; V., vein; Ven., venous; Vert., vertebral.

As important as focal opening of the clivus is in preventing CSF leak, this should not be at the expense of vascular control and tumor removal. Many clival lesions such as chordoma require the removal of any and all involved tissue, including bone and dura. In general, the wider the margin is around these tumors, the lower the chance for recurrence is. This principle should not be compromised for ease of reconstruction. However, for relatively large lesions, this concept may be optimized by opening the “upper two-thirds” or “lower two-thirds” of the clivus, which may enable both sufficient exposure and minimal invasiveness. The true value in understanding the anatomy of the clivus and paraclival regions is in providing safe wide exposure and access. Even when wide opening of the clivus is required, the anatomic findings shown in this study may aid in safe and efficient exposure.

Chordomas and chondrosarcomas involving the clivus are commonly

approached via the transnasal route.[10,12,14] It seems reasonable to apply the focal transclival approach to these lesions because they may arise at the various clival levels unless the lesion involves the whole clivus. Hong Jiang et al[59] reported varying the endoscopic approach for clival chordomas on the basis of the level of the clival involvement. Furthermore, chordomas can also extend to involve the intradural neurovascular complexes of the posterior fossa. Al-Mefty et al[60] found at surgery that 53% of chordomas had intradural extension. In this situation, an accurate understanding of the relationship between the level of clival involvement and the intradural neurovascular complexes is essential.

Other intradural pathologies in the anterior midline region such as epidermoid cysts,[11] neuroenteric cysts,[8,13] meningiomas[15,61] and intra-axial lesions like cavernous malformations are potentially suitable for the focal transclival approach. The focal transclival approach may be applied to midline posterior fossa aneurysms if the aneurysm is contraindicated for the endovascular treatment and flow control can be affected in the clival exposure or by supplemental endovascular techniques.[62,63] Carefully selected aneurysms arising at the origin of the SCA, AICA, and PICA might also be approached through the upper, middle, and lower clival approach, respectively.

Cranial base approaches to the midline posterior cranial fossa are classified into 4 groups according to the direction of the approach: anterior, anterolateral, lateral, and posterior.[2] The anterolateral approaches include the transcavernous approach, in which anterior and posterior clinoidectomies and removal of the dorsum sellae are combined with an orbitozygomatic craniotomy for reaching low-lying basilar apex or basilar-SCA aneurysms. This approach may also expose lesions in the interpeduncular cistern and superior margin of the prepontine cistern, predominantly on the ipsilateral side,[64,65] which corresponds to part of the upper clival area.

The lateral approaches include the subtemporal anterior transpetrosal, translabyrinthine, transcochlear, and combined supratentorial and

infratentorial presigmoid approaches. The anterior transpetrosal or Kawase approach reaches the ipsilateral half of the upper clival area, with limited exposure below the level of the ipsilateral trigeminal nerve that includes part of but not all the ipsilateral half of the middle clival area.[3,66] The translabyrinthine and transcochlear approaches are modifications of the presigmoid approach that extend the surgical view further toward the midline. The transcochlear approach permits visualization of the abducens nerve medial to the internal acoustic meatus, the lower margin of the trigeminal nerve, the nerves entering the jugular foramen, a segment of the basilar artery, and the origin and initial segment of the AICA,[3] which approximates the entire ipsilateral middle clivus area. The combined supratentorial and infratentorial presigmoid approach provides exposure of the petroclival region from the middle fossa and tentorial incisura to the jugular bulb.[3] The exposure thus covers not only the ipsilateral upper and middle clival area but also the upper half of the lower clival area, but approaching the midline is difficult without the addition of the transcochlear exposure, which improves access to the front of the brainstem, clivus, and basilar artery but is done at the cost of a temporary or permanent facial paralysis and loss of hearing.

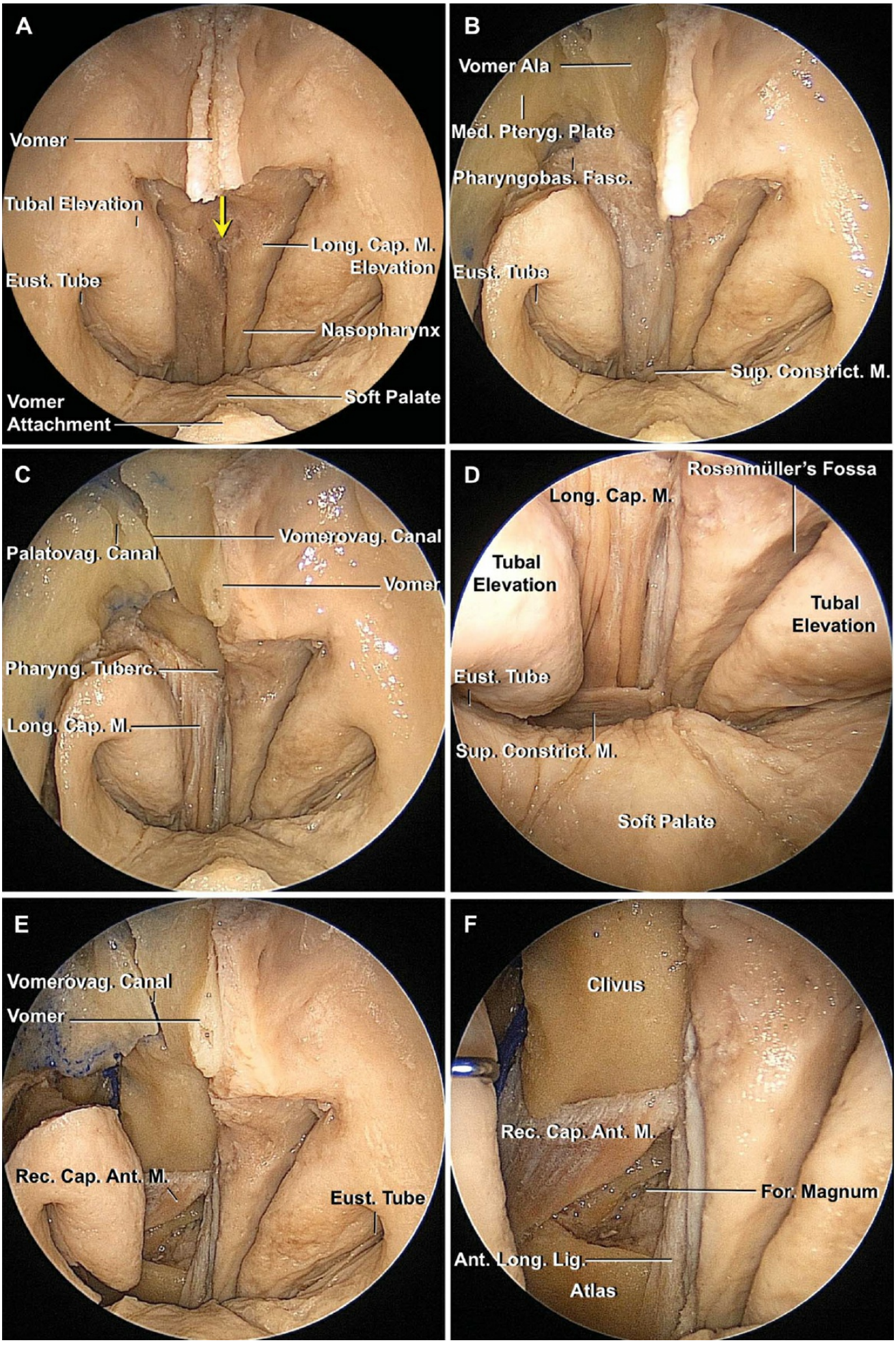

FIGURE 10. A-F. Endoscopic approach to the lower clivus. A, an endoscope has been introduced through the inferior nasal meatus to

view the posterior nasopharyngeal wall. The posterior part of the nasal septum has been detached from the sphenoid crest and removed. The mucosa on the right half of the posterior nasopharyngeal wall has been removed. The eustachian tubes open onto the lateral walls of the nasopharynx just anterior to the prominent and firm tubal elevations. The insertion of the longus capitis muscle to the clivus can usually be seen on the mucosal surface as a V-shaped elevation. The pharyngeal tubercle is located at this lower edge of the V (yellow arrow). There is a shallow, inverted-triangleshaped depression on the mucosa above the insertion of the longus capitis muscle that corresponds to the site of the pharyngeal tonsil or adenoid in childhood. B, the nasopharyngeal mucosa on the right side has been removed. The pharyngobasilar fascia covers the longus capitis muscle and attaches firmly to the inferior surface of the occipital and temporal bones. As the fascia descends, it diminishes in thickness and gradually blends into the superior pharyngeal constrictor at the level of soft palate. At its upper edge, the pharyngobasilar fascia blends with the fibrocartilage around the border between the sphenoid and occipital bones and foramen lacerum. C, the pharyngobasilar fascia on the right side has been removed to expose the longus capitis attachment to the clivus lateral to the pharyngeal tubercle. This specimen has a vomerovaginal canal that shares its anterior end with the palatovaginal canal. The vomerovaginal canal is positioned between the vaginal process of the sphenoid and the ala of the vomer. D, 45° endoscope directed inferior. The upper edge of the superior constrictor is located at the C1 level at the border between the oropharynx and nasopharynx and is not usually opened for exposure of the lower clivus. The fossa of Rosenmüller projects laterally from the posterolateral corner of the nasopharynx behind the tubal elevation. The parapharyngeal segment of the internal carotid artery courses just deep to the lateral limit of the fossa of Rosenmüller. E, the longus capitis muscle and pterygoid process on the right side have been removed to expose the rectus capitis anterior muscle. F, closer view. The rectus capitis anterior is a short, flat muscle that extends across the atlanto-occipital joint and connects to the lateral mass of the atlas and the basal part of the occipital bone.

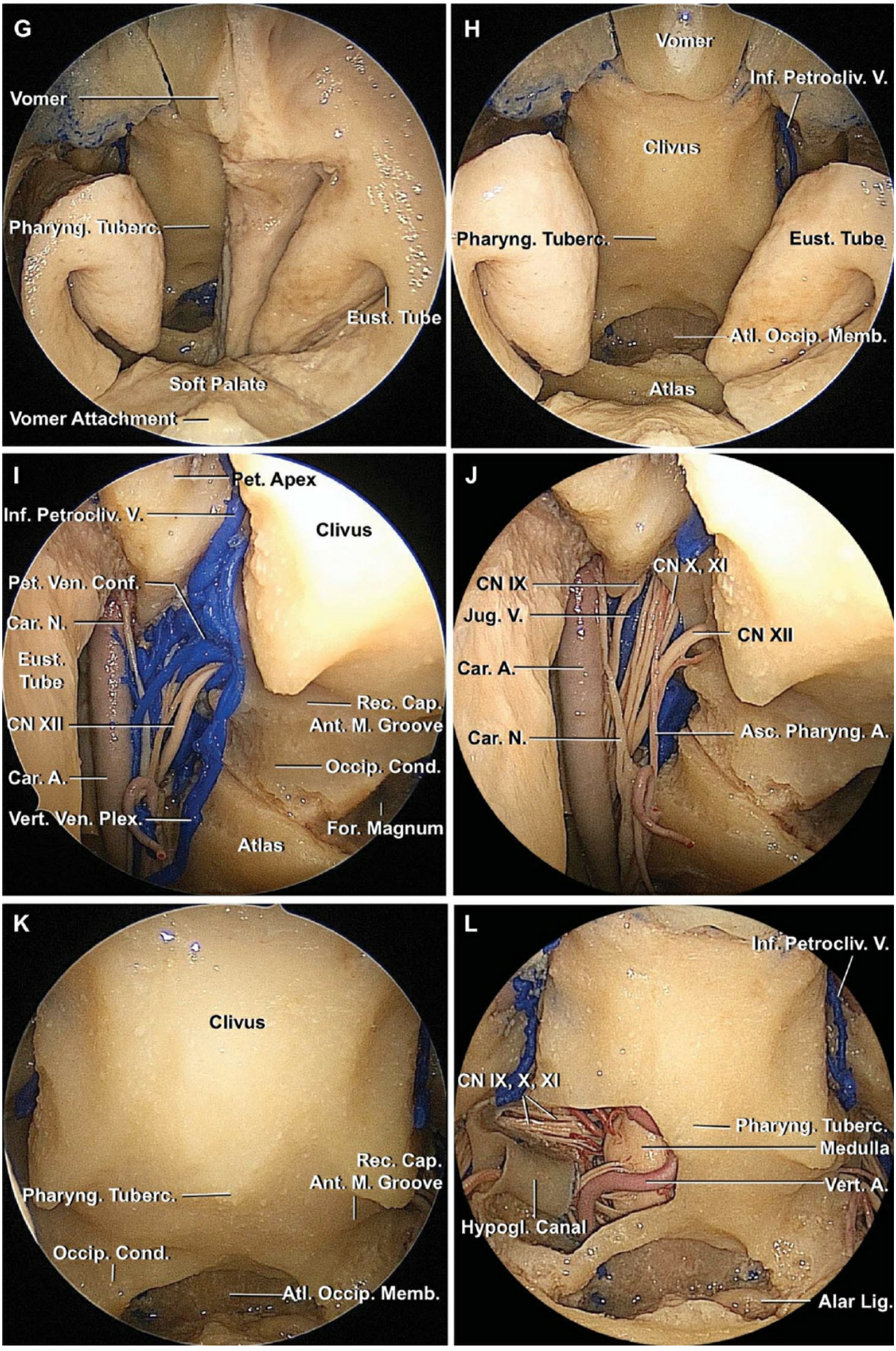

FIGURE 10. G-L. G, The right rectus capitis anterior has been removed.

The relationship between the posterior nasopharyngeal mucosa and the pharyngeal tubercle is shown. H, the remainder of the posterior nasopharyngeal wall and pterygoid process has been removed. The inferior petroclival vein courses along the extracranial surface of the petroclival fissure. I, 45° endoscope has been inserted above the cartilaginous part of eustachian tube and directed laterally to view the jugular foramen and the adjacent area. The petrosal venous confluence at the lower end of the inferior petrosal sinus connects to the venous plexus of the hypoglossal canal and prevertebral venous plexus. In this specimen, the venous confluence empties below the extracranial orifice of the jugular foramen into the medial aspect of the internal jugular vein through openings in the venous walls between the glossopharyngeal and vagus nerves. The inferior petroclival vein also empties into the petrosal venous confluence. J, some of the petrosal venous confluence has been removed to expose the jugular foramen. The glossopharyngeal nerve exits the jugular foramen along the anterior wall of the internal jugular vein, whereas the vagus and accessory nerve exit along the medial venous wall. The neuromeningeal branch of the ascending pharyngeal artery gives rise to the hypoglossal and jugular branches just below the jugular foramen. Both branches penetrate the petrosal confluence and enter the hypoglossal canal and the jugular foramen to supply the surrounding dura. K, anterior view of the clivus.

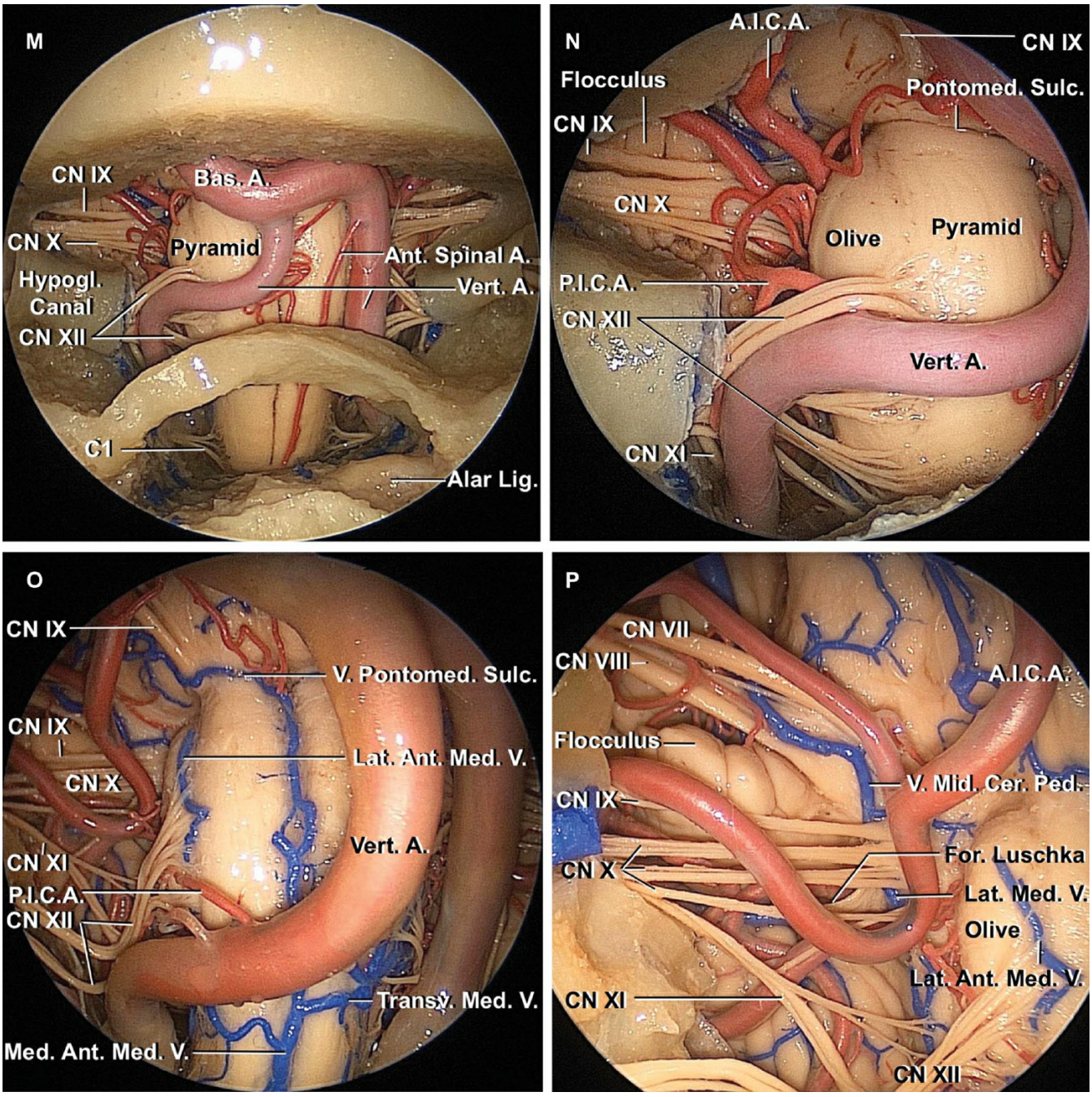

FIGURE 10. M-P. L, the lower clivus has been drilled on the right side to expose the medulla. The upper edge of the lower clivus is located approximately 4 mm above the top of the pharyngeal tubercle. M, the remainder of the lower clivus has been drilled while preserving the hypoglossal canals. The exposure includes the anterior aspect of the medulla; the glossopharyngeal, vagus, accessory, hypoglossal, and C1 nerves; and the vertebral, posterior inferior cerebellar, and anterior spinal arteries. N, closer view of the right side. The hypoglossal rootlets, which arise along the preolivary sulcus, usually pass posterior to the vertebral artery. The posterior inferior cerebellar artery arises near the junction of the hypoglossal rootlets with the medulla. The glossopharyngeal, vagus, and accessory nerves arise behind the hypoglossal rootlets, as a line of rootlets originating from the retro-olivary sulcus, a shallow groove

between the olive and the posterolateral surface of the medulla. The rostral part of the accessory nerve is hidden by the hypoglossal canal and vertebral artery. O and P, another lower clival region. O, the lower clivus and hypoglossal canals have been drilled. P, closer view of the right side. A., artery; A.I.C.A., anterior inferior cerebellar artery; Ant., anterior; Asc., ascending; Atl., atlanto; Bas., basilar; Cap., capitis; Car., carotid; Constrict., constrictor; Cer., cerebellar, cerebello; CN., cranial nerve; Cond., condyle; Conf., confluence; Eust., eustachian; For., foramen; Hypogl., hypoglossal; Inf., inferior; Jug., jugular; Lat., lateral; Lig., ligament; Long., longus; M., muscle; Med., medial, medullary; Mid., middle; N., nerve; Occip., occipital; Palatovag., palatovaginal; Ped., peduncle; Pet., petro, petrosal, or petrous; Petrocliv., petroclival; Phayrng., pharyngeal; Pharyngobas., pharyngobasilar; P.I.C.A., posterior inferior cerebellar artery; Pontomed., pontomedullary; Pteryg., pterygoid; Rec., rectus; Sulc., sulcus; Sup., superior; Trans., transverse; Tuber., tubercle; V., vein, Ven., venous; Vert., vertebral; Vomerovag., vomerovaginal.

The posterior approaches include the retrosigmoid and far lateral approaches. The retrosigmoid provides access from the level of the trochlear and trigeminal nerves above to the accessory and hypoglossal nerves below. The center of the retrosigmoid exposure, however, is the cerebellopontine angle, and the exposure of the structures medial to the internal acoustic meatus is as limited as in the retrolabyrinthine or translabyrinthine variants of the presigmoid approach.[3] The basic far lateral approach is characterized by dissection of the muscles along the posterolateral aspect of the craniocervical junction, early identification of the extracranial vertebral artery, and a suboccipital craniectomy or craniotomy extending into the foramen magnum to the posterior edge of the ipsilateral occipital condyle. This approach may be expanded by use of the transcondylar, supracondylar, and paracondylar extensions, which expand access to the lower clivus and premedullary area.[4,6]

The anterior microsurgical approaches include the transcranial-transbasal, extended frontal, and transoral approaches. The transcranial-transbasal approach, involving a bifrontal craniotomy with preservation of the

supraorbital rim, accesses the brainstem through the ethmoid and sphenoid sinuses, sella, and clivus.[67] The extended frontal approach is similar to the transcranial-transbasal approach, except that it includes an orbitofrontoethmoidal osteotomy. The foramen magnum can be accessed through both the transcranial-transbasal and extended frontal approaches. Although both approaches may access nearly the entire clivus, the subsellar area is hidden by the bulging subsellar dura in the transcranial-transbasal approach.[2] The microscopic or endoscopic transoral approach may provide access from the lower clivus to the body of C3 inferiorly.[21]

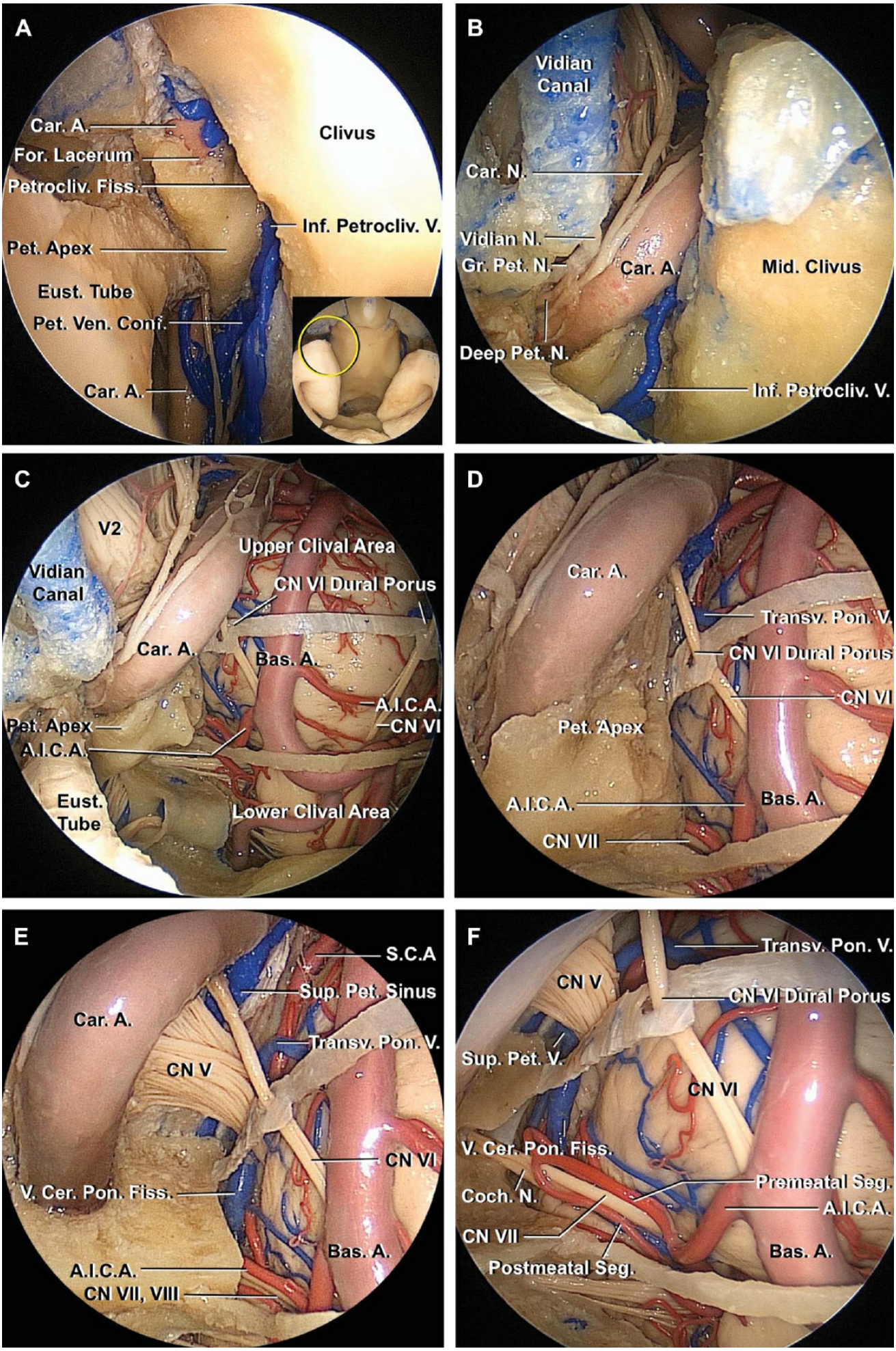

FIGURE 11. A-F. Endoscopic approach to the middle clivus. A, view

focusing on the middle clivus and foramen lacerum with a 45° endoscope directed laterally. The yellow circle in the inset shows the endoscopic field. The pterygoid processes have been removed. Some of the fibrocartilage filling the lower part of the foramen lacerum has been removed to expose the anterior genu of the petrous carotid. The vidian nerve is hidden in the fibrocartilage at the anterolateral margin of the foramen lacerum. B, the vidian canal has been skeletonized. The vidian canal, which conveys the vidian artery and nerve, opens posteriorly into the upper part of the anterolateral edge to the foramen lacerum. The deep petrosal branch of the carotid sympathetic plexus joins the greater petrosal nerve at the foramen lacerum near the posterior opening of the vidian canal to form the vidian nerve. The upper end of the inferior petroclival vein connects through the foramen lacerum with the venous plexus around the carotid artery or with the cavernous sinus. The trapezoid-shaped middle clivus is bordered laterally by the foramen lacerum and internal carotid artery in the upper part and by the petroclival fissure in the lower part. C, right lateral part of the middle clival area. The right inferior petrosal sinus and adjacent dura have been removed. A thin dural bridge sits at the junction of the upper and middle clivus, and a thin bony bridge separates the middle and lower clivus. The lower part of the pons, basilar and anterior inferior cerebellar arteries, and cisternal part of the abducens nerves are exposed. D, closer view with the 45° endoscope directed laterally. All the cisternal segment of the facial nerve, except the origin, is hidden by the petrous part of the temporal bone. It is difficult to see the whole cisternal segment even with the angled endoscope directed laterally. E, the petrous apex and bone below the distal carotid canal have been removed to expose more of the cisternal segment of the facial and vestibulocochlear nerves. The posterior root of the trigeminal nerve passes forward below the superior petrosal sinus. F, more of the temporal bone below the carotid canal and trigeminal nerve has been drilled. The anterior wall of the internal acoustic meatus has been opened to expose the cisternal and meatal segments of the facial and vestibulocochlear nerves, as well as the premeatal and postmeatal segment of the anterior inferior cerebellar artery.

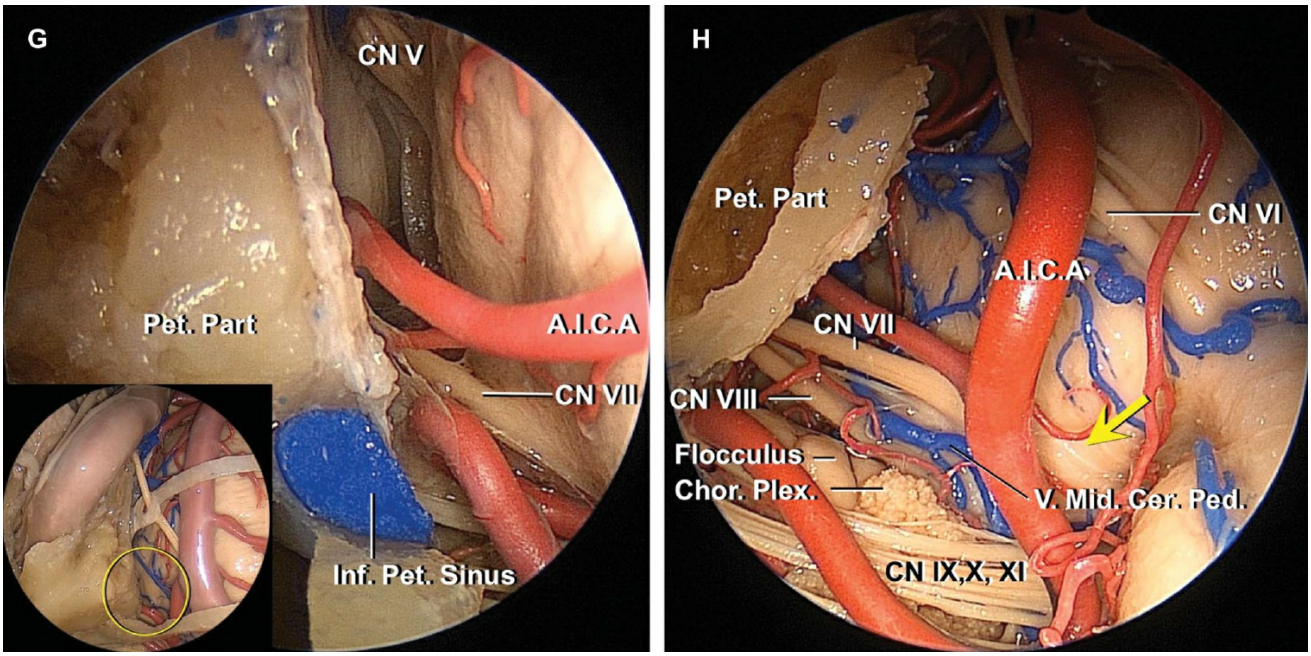

FIGURE 11. G-H. G, 45° endoscope directed laterally to view the proximal part of the facial nerve in the cerebellopontine angle. The yellow circle in the inset shows the endoscopic visual field. The facial nerve courses in the lower lateral part of the middle clival area. H, closer view with the 45° endoscope. The endoscope has been introduced at the level of the lower clivus and directed superior. The root exit zone of the facial nerve can be observed more clearly (arrow) than in G because the root exit zone is located in the supraolivary fossette, a shallow depression at the lateral edge of the pontomedullary sulcus. A., artery; A.I.C.A., anterior inferior cerebellar artery; Bas., basilar; Car., carotid; Cer., cerebello; Chor., choroid; CN, cranial nerve; Coch., cochlear; Conf., confluence; Eust., eustachian; Fiss., fissure; For., foramen; Gr., greater; Inf., inferior; Mid., middle., N., nerve; Ped., peduncle; Pet., petro, petrous, petrosal; Petrocliv., petroclival; Plex., plexus; Pon., pontine; S.C.A., superior cerebellar artery; Seg., segment; Sup., superior; Transv., transverse; V., vein; Ven., venous.

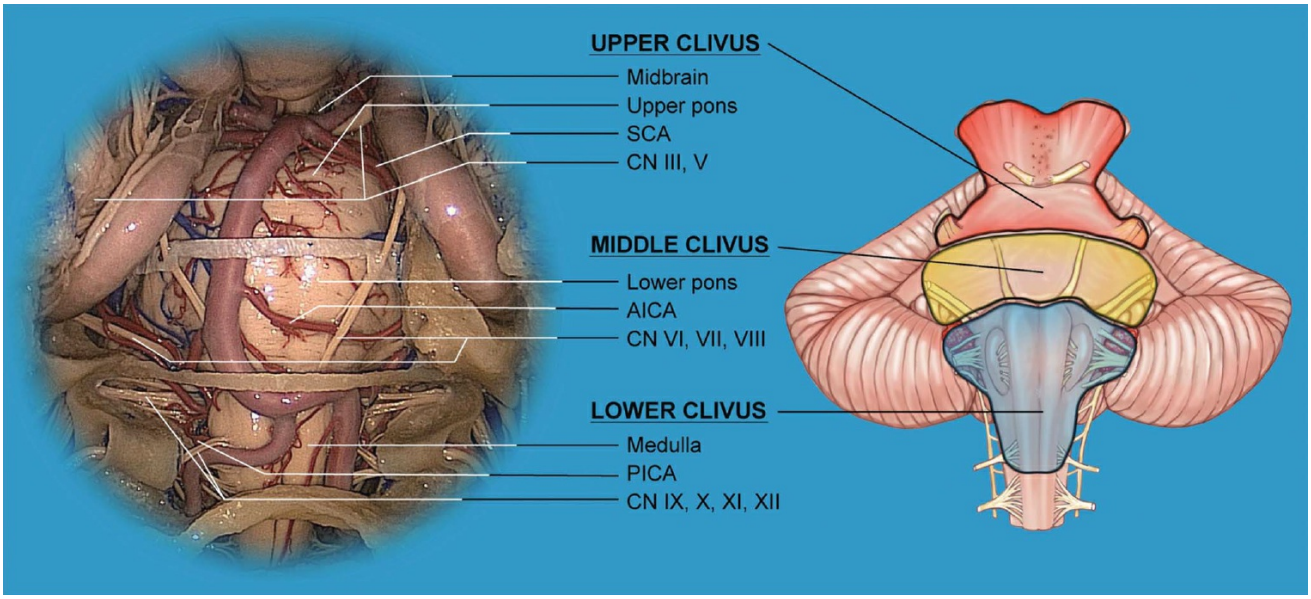

FIGURE 12. Relationship between each division of the clivus and the neurovascular complexes in the posterior fossa as defined by Rhoton.46 The upper clival approach exposes the anterior part of the upper neurovascular complex, including the midbrain and adjacent part of the pons, superior cerebellar artery, oculomotor, and trigeminal nerves. The middle clival approach exposes the anterior part of the middle neurovascular complex, including the lower half of the pons, anterior inferior cerebellar artery, abducens, facial, and vestibulocochlear nerves. The lower clival approach exposes the anterior part of the lower neurovascular complex, including the medulla, posterior inferior cerebellar artery, glossopharyngeal, vagal, accessory, and hypoglossal nerves. AICA, anterior inferior cerebellar artery; CN, cranial nerve; PICA, posterior inferior cerebellar artery; SCA, superior cerebellar artery.

The lateral and posterior approaches to the cisterns medial to cranial nerves V, VII, VIII, and IX are limited compared with the transnasal approach. There is also the added risk of approaching the midline structures from laterally and posteriorly by working between and medial to the bundles of cranial nerves arising from the brainstem. The transclival approach has the advantage of providing better exposure and a direct front view of midline structures, as shown in this study. In contrast, the transnasal approach may face a similar risk if used to reach lesions on the lateral side of the cranial nerves by working from medial to lateral through the nerve bundles. The focal endoscopic transnasal transclival approach should be viewed as a complementary route to the other cranial-base surgeries, and the selection of the approach should be

based on the location (especially in reference to the cranial nerves), extension, and nature of the lesions.

Conclusion

The clivus is divided into upper, middle, and lower parts by 2 endocranial landmarks: the dural pori of the abducens nerve and glossopharyngeal meatuses. The pharyngeal tubercle and the lower limit of the paraclival carotid artery, which is located 4.9 mm above the posterior opening of the vidian canal, are important exocranial surgical landmarks for accessing each division of the clivus through the endoscopic transnasal approach. The transnasal transclival approach can be carefully tailored to deal with focal pathologies involving the clivus and adjacent part of the posterior fossa.

Disclosures

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The Neurosurgical Atlas is honored to maintain the legacy of Albert L. Rhoton, Jr, MD.

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