Microsurgical Anatomy and Surgical Exposure of the Petrous Segment of the Internal Carotid Artery

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OBJECTIVE: The petrous segment of the internal carotid artery has been exposed in the transpetrosal, subtemporal, infratemporal, transnasal, transmaxillary, transfacial, and a variety of transcranial approaches. The objective of the current study was to examine anatomic features of the petrous carotid and its branches as related to the variety of approaches currently being used for its exposure.

METHODS: Twenty middle fossae from adult cadaveric specimens were examined using magnification of ×3 to ×40 after injection of the arteries and veins with colored silicone.

RESULTS: The petrous carotid extends from the entrance into the carotid canal of the petrous part of the temporal bone to its termination at the level of the petrolingual ligament laterally and the lateral wall of the sphenoid sinus medially. The petrous carotid from caudal to rostral was divided into 5 segments: posterior vertical, posterior genu, horizontal, anterior genu, and anterior vertical. Fourteen (70%) of the 20 petrous carotids had branches. The branch that arose from the petrous carotid was either a vidian or periosteal artery or a common trunk that gave rise to both a vidian and 1 or more periosteal arteries. The most frequent branch was a periosteal artery.

CONCLUSION: An understanding of the complex relationships of the petrous carotid provides the basis for surgically accessing any 1 or more of its 5 segments.

KEY WORDS: Internal carotid artery, Microsurgical anatomy, Periosteal artery, Petrolingual ligament, Sphenoid sinus, Surgical approaches, Temporal bone, Vidian artery

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In 1977, this laboratory presented a study focused mainly on the horizontal segment of the petrous carotid as a site for extracranial-to-intracranial anastomosis (28). Before that time, the petrous carotid was largely neglected as a focus of surgery because of the difficulty and risk associated with its exposure and manipulation. The development of microsurgical, endoscopic, cranial base, and endovascular surgical techniques for managing its manipulation and injury has led to its more frequent exposure in a variety of abnormalities and surgical approaches. Today, the various segments of the petrous carotid may be exposed in the transpetrosal, subtemporal, infratemporal, transnasal, transmaxillary, transfacial, and a variety of transcranial routes (1, 4, 33–37). There have been fewer cadaveric studies than radiological studies of the branches. The objective of this study was to examine the anatomic features and surgical relationships of the petrous carotid and its branches and to discuss the clinical implications of these findings.

ABBREVIATION: ICA, internal carotid artery

MATERIALS AND METHODS

Twenty adult middle fossae were examined using magnification of ×3 to ×40 after injection of the vessels with colored silicone. The dura covering the floor of the middle fossa was removed while taking care to preserve the greater petrosal nerve. The trigeminal nerve and ganglion were reflected anterolaterally and the temporal bone was drilled with the Midas Rex Drill (Legend; Medtronic, Minneapolis, MN) to expose the full length of the petrous carotid (Figs. 1 and 2). The initial part of the petrous internal carotid artery (ICA) was also exposed by drilling the posterior surface of the petrous apex, and the other segments plus the geniculate ganglion, cochlea, tensor tympani muscle, and eustachian tube were exposed by drilling the middle fossa floor. The parts of the artery in the carotid canal and above the foramen lacerum were also exposed from below, and the part in the lateral wall of the sphenoid sinus was exposed through the nasal cavity and maxilla with the endoscope (Fig. 3).

The periosteal layer, which enclosed the full length of the petrous ICA, was opened to expose the branches of the petrous carotid. The vidian artery was defined as a branch that entered the vidian canal, the caroticotympanic artery as a branch that entered the tympanic cavity, and the periosteal artery as a branch that coursed along or penetrated the periosteum (28). The vidian artery was followed forward into the vidian canal and pterygopalatine fossa by drilling the lateral wall of the sphenoid sinus (Figs. 1 and 2). Several measurements related to the petrous carotid and its branches were recorded.

RESULTS

ICA and Carotid Canal

We have adopted the definition of the petrous carotid as presented in the most recent editions of *Gray's Anatomy* (48, 53), which states that it has 2 curves, the most distal of which is above the foramen lacerum, and that it extends from the entrance into the petrous part of the temporal bone to the interval between the lingual process of the sphenoid bone and the petrous apex. The petrous carotid begins at the entrance into the carotid canal. It first ascends vertically, then horizontally, and vertically again in its course from posterolateral to anteromedial. The lateral aspect of its termination is in the extradural space at the level of the superior edge of the petrolingual ligament, which bridges the interval between the lingual process of the sphenoid bone and the petrous apex. The medial surface of its distal end is located in the posteroinferior part of the lateral wall of the sphenoid sinus (Figs. 1–3) (54, 55).

At the entrance into the carotid canal, the carotid sheath divides into 2 layers: 1 layer continues as the periosteum of the carotid canal, and the outer layer continues as the periosteum lining the lower surface of the cranial base (4, 54). The external orifice of the carotid canal is positioned directly anterior to the jugular foramen, and its internal orifice is located at the petrous apex and above the fibrocartilaginous tissue filling the foramen lacerum at the junction of the sphenoid, temporal, and occipital bones (Fig. 4). The artery was easily separated from the periosteum lining the carotid canal, except near the entrance, and the adjacent part of the posterior vertical segment, where dense bands related to the carotid sheath anchored the artery.

The petrous carotid ends where the superior edge of the petrolingual ligament, located parallel to and just below the level of the abducent nerve, crosses the lateral surface of the artery (Figs. 1–3). The superior edge of the petrolingual ligament is located at the junction of the petrous and cavernous carotid, where the dura lining the carotid canal is reflected onto the floor of the middle fossa (15, 55). The horizontal fibers of the petrolingual ligament connect the lingual process of the sphenoid bone and the petrous apex. The ligament is a continuation of the periosteum of the carotid canal that is reflected around the edge of the carotid canal to form the endosteal layer of the petrous apex and middle fossa. The thin bone of the middle fossa floor above the carotid canal may extend between the 2 layers even to within a few millimeters of the edge of the petrolingual ligament. The length of the petrolingual ligament measured between the sphenoidal and petrous attachments at the superior margin averaged 8.2 mm (range, 3.1–11.3 mm). The lower edge of the abducens nerve coursed an average of 2.8 mm (range, 0.9–5.9 mm) superior to the sphenoidal attachment of the petrolingual ligament and 3.3 mm (range, 1.6–6.1 mm) superior to the petrous attachment. The superior edge of the ligament is positioned adjacent to the medial surface of the trigeminal ganglion at approximately the level of a line extending backward along the upper margin of the maxillary nerve and across the ganglion.

A venous plexus coursing between the periosteum lining the carotid canal and the artery and opening above into the cavernous sinus was found in all cases. This was found to be more extensive than in our study from 1977, in which we did not inject the veins with silicone (28). In our previous study, the venous plexus could be followed only from the cavernous sinus to the distal horizontal segment, but in this study, it could be followed to the posterior vertical segments in some specimens. A fistula between this plexus and the carotid artery could produce a clinical picture mimicking a carotid-cavernous fistula.

The carotid branches of the cervical sympathetic ganglia formed a plexus on the surface of the artery. The largest bundle on the horizontal segment was located anteroinferior and gave rise to the deep petrosal nerve, a bundle of sympathetic fibers that joined the greater petrosal nerve above the lateral edge of the foramen lacerum to form the vidian nerve (Figs. 2–5). The sympathetic bundle on the anteroinferior aspect of the petrous carotid also sent fibers above the superior margin of the petrolingual ligament to the abducent nerve in all cases (Fig. 1).

Segments of the Petrous Carotid

The petrous carotid based on this study, from proximal to distal, was divided into 5 segments: posterior vertical, posterior genu, horizontal, anterior genu, and anterior vertical segments based on lines extending vertically and horizontally at the proximal and distal ends of the horizontal segment (Figs. 1–5). The posterior vertical segment and posterior genu are located in the lateral part of the petrous part of the temporal bone; the horizontal segment is directed along the long axis of the petrous part and the anterior genu; and the anterior vertical segment is located at the junction of the petrous apex with the sphenoid and occipital bones. The anterior vertical segment was the shortest and the horizontal segment the longest (Fig. 6). The classification of the segments of the petrous carotid has been discussed previously (1, 4, 25, 28, 30, 48, 52–54). Bouthillier et al. (4) have provided an excellent review of the different classifications.

The posterior vertical segment begins at the entrance into the carotid canal and ends at the posterior genu where the artery turns sharply anteromedially. The horizontal segment begins at the distal end of the posterior genu, courses anteromedially posterior to the tensor tympanic muscle, eustachian tube, foramina spinosum, and ovale and ends at the anterior genu, where

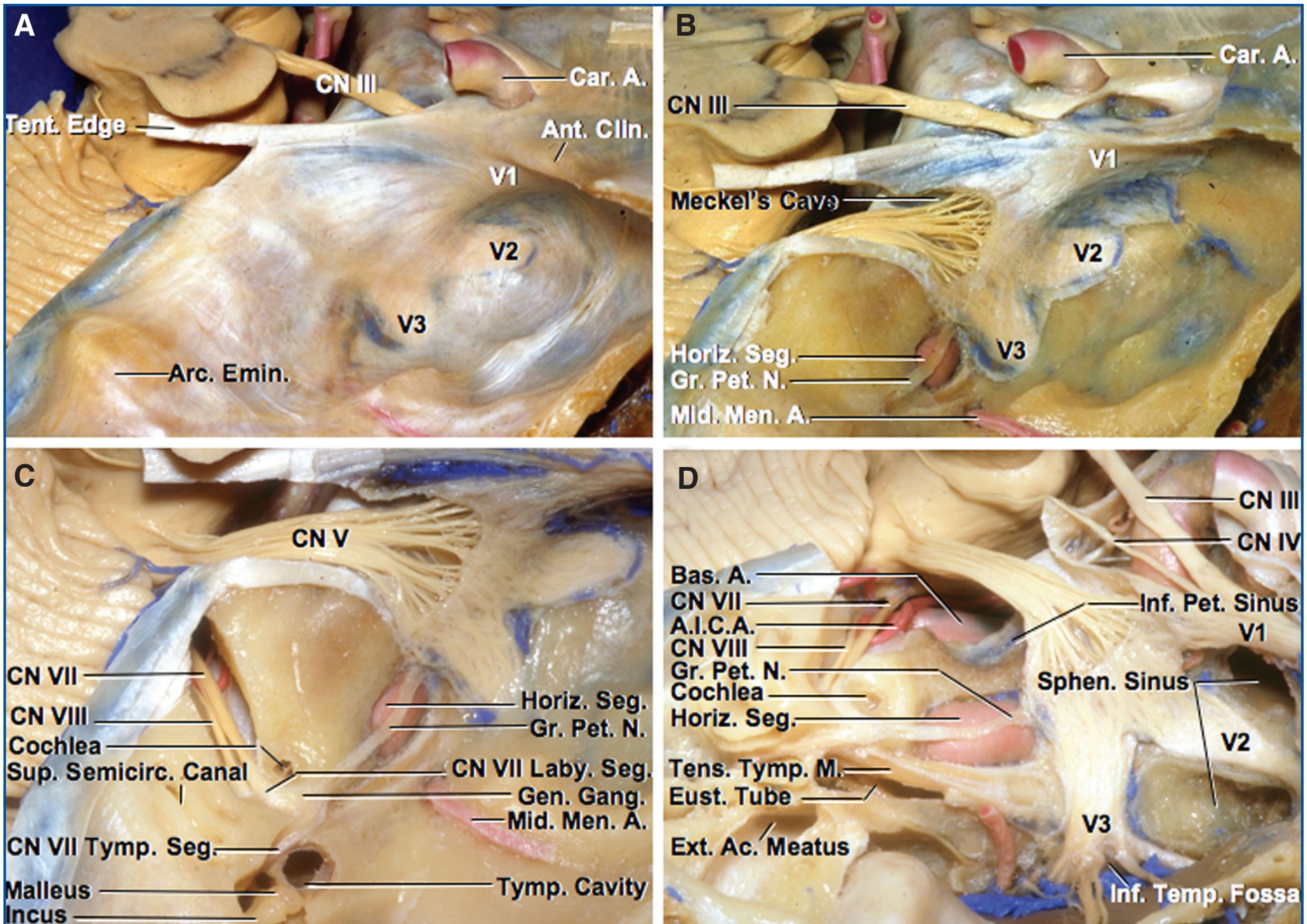

FIGURE 1. *Stepwise dissection of the right middle fossa.* **A**, *superolateral lateral view with the dura intact. The 3 divisions of the trigeminal nerve are seen through the intact dura. The cavernous carotid exits and the oculomotor nerve enters the roof of the cavernous sinus. The arcuate eminence is in the lateral margin of the exposure.* **B**, *the dura has been elevated from the floor of the middle fossa. Removal of the lateral wall of Meckel's cave exposes the posterior root of the trigeminal nerve. The petrous carotid is exposed below a dehiscence in the floor of the middle fossa lateral to the third trigeminal division as occurs in approximately 16% of middle fossae. The greater petrosal nerve passes medially along the upper surface of the petrous carotid.* **C**, *the internal acoustic meatus has been unroofed to expose the facial and vestibulocochlear nerves. The greater petrosal nerve arises from the geniculate ganglion and passes medially above the petrous carotid. The cochlea has been exposed by drilling the bone in the cochlear angle located between the labyrinthine segment of the facial nerve and the greater petrosal nerve. The posterior genu of the petrous carotid is positioned a few millimeters below, anterior, and medial to the cochlea.* **D**, *bone has been removed above and anterior to the petrous carotid to expose the tensor tympani muscle and the eustachian tube, which slope downward as they proceed medially along the anterior surface of the petrous carotid. The petrous apex and additional bone have been removed from the floor of the middle fossa to expose the external acoustic meatus, inferior petrosal sinus, and a tortuous basilar artery. The greater petrosal nerve passes medially above the petrous carotid.* **E**, *the part of the trigeminal nerve between the posterior root and the 3 divisions have been removed to expose an ossified petrolingual ligament, which extends from the petrous apex to the lingual process of the sphenoid bone. The upper edge of the petrolingual ligament is located at the junction of the petrous and cavernous carotid. The greater wing of the sphenoid bone has been drilled to expose the lateral walls of the sphenoid sinus and the vidian nerve passing forward in the vidian canal. The floor of the middle fossa has been removed to expose the infratemporal fossa and the temporalis muscle in the temporal fossa.* **F–H**, *stepwise lateral and medial exposure of the petrolingual ligament.* **F**, *another right trigeminal nerve and middle fossa. The petrolingual ligament is located at approximately the level of a line extending posteriorly along the upper surface of the second division.* **G**, *the first trigeminal division has been reflected downward to expose the upper part of the petrolingual ligament. A branch of the carotid neural plexus ascends to join the abducens nerve after the nerve has passed around the lateral margin of the cavernous carotid.* **H**, *view through the sphenoid sinus side of the dissection shown in* **F** *and* **G**. *The cavernous carotid and the anterior genu and anterior vertical segments of the petrous carotid have been exposed by removing part of the lateral wall of the sphenoid sinus. The upper edge of the petrolingual ligament, positioned on the lateral and not the medial side of the artery, is marked with a yellow interrupted line. A branch of the carotid neural plexus ascends and joins the abducens nerve (arrow). The abducens nerve passes around the lateral margin of the cavernous carotid. The vidian* *(Continues)*

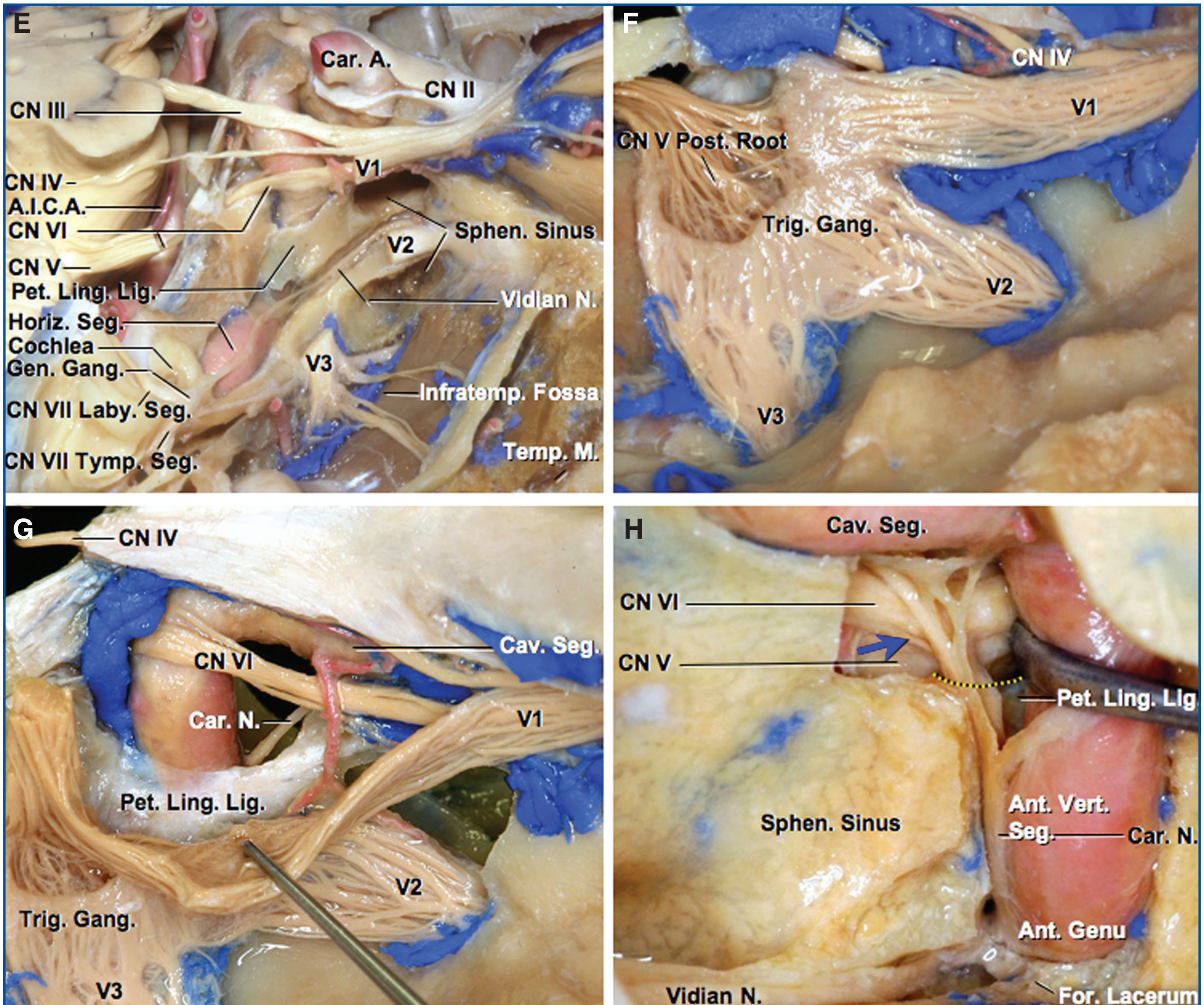

FIGURE 1. *(Continued) nerve has been exposed by removing bone along in the floor of the sphenoid sinus. A., artery; Ac., acoustic; A.I.C.A., anterior inferior cerebellar artery; Ant., anterior; Arc., arcuate; Bas., basilar; Car., carotid; Cav., cavernous; Clin., clinoid; CN, cranial nerve; Emin., eminence; Eust., eustachian; Ext., external; For., foramen; Gang., ganglion; Gen., geniculate; Gr., greater; Horiz., horizontal; Inf., inferior; Infratemp., infratemporal; Laby., labyrinthine; Lig., ligament; Ling., lingual; M., muscle; Men., meningeal; Mid., middle; N., nerve; Pet., petro, petrosal; Post., posterior; Seg., segment; Semicirc., semicircular; Sphen., sphenoid; Sup., superior; Temp., temporal; Tens., tensor; Tent., tentorial; Trig., trigeminal; Tymp., tympani, tympanic; Vert., vertical.*

the artery turns sharply upward above the foramen lacerum to continue as the anterior vertical segment. The anterior vertical segment ends at the upper edge of the petrolingual ligament, which crosses the lateral surface of the artery. Medially, this segment faces the lateral wall of the sphenoid sinus. Each segment has important relationships that provide the basis for its surgical exposure and identifying the site of its branches. The segments just proximal to the cavernous segment, the anterior genu and anterior vertical segment, have been referred to as the lacerum, trigeminal, and paraclival segments by different authors because of their relationship to the foramen lacerum, trigeminal nerve, and paraclival area, respectively (1, 4, 54, 55).

Posterior Vertical Segment

The posterior vertical segment of the artery passed directly upward after entering the carotid canal, before turning anteromedial at the genu to form the horizontal segment (Figs. 2, 4, and 7). The entrance into the carotid canal and origin of the posterior

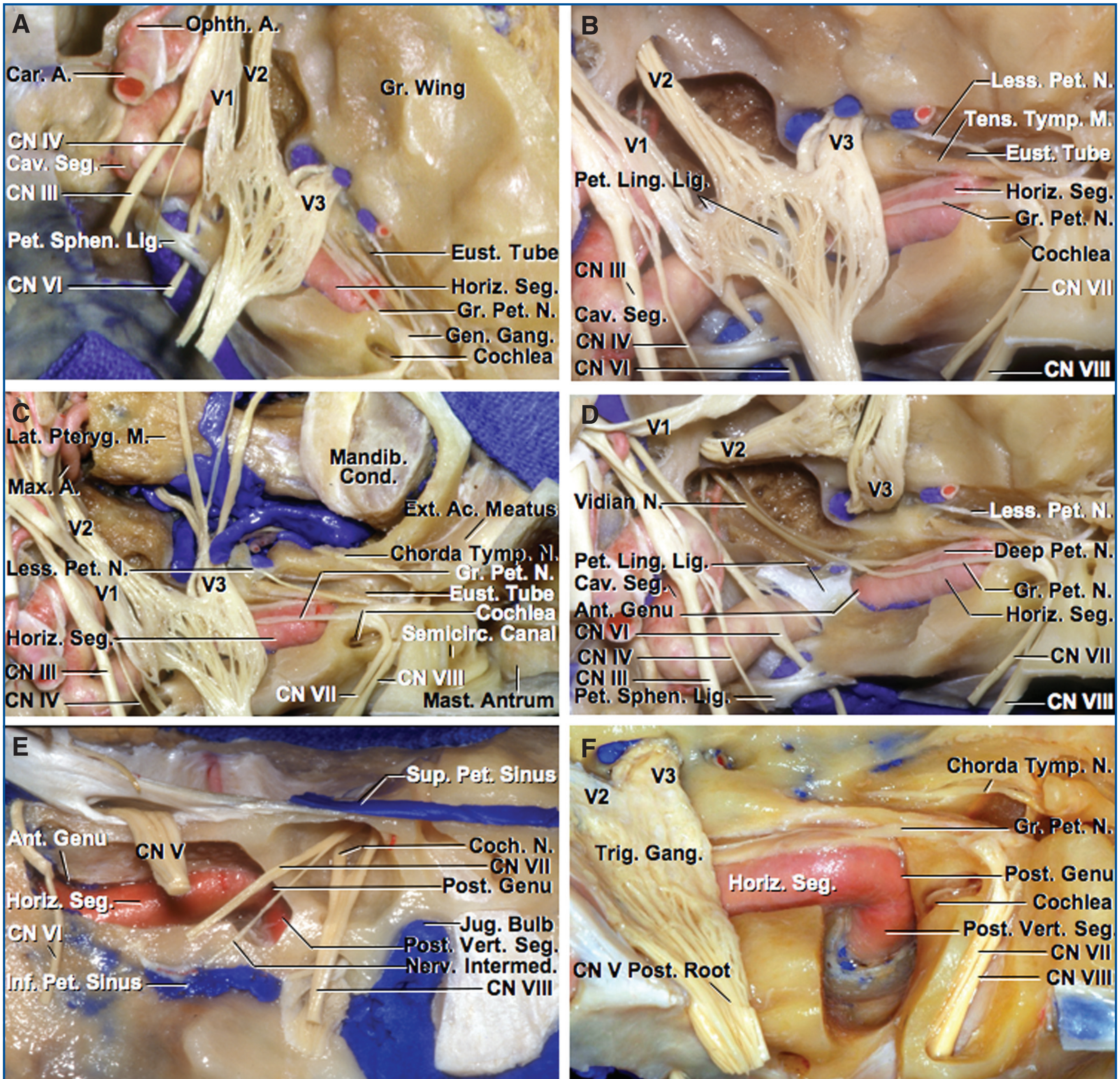

FIGURE 2. *Superior view of the middle cranial base and petrous carotid.* **A**, *the horizontal segment of the petrous carotid is exposed lateral to the trigeminal nerve. The internal acoustic meatus, eustachian tube, and cochlea have been unroofed. The anterior part of the floor of the middle fossa is formed by the greater sphenoid wing and the posterior part of the floor is formed by the upper surface of the temporal bone. The dural roof and lateral wall of the cavernous sinus have been removed.* **B**, *enlarged view. The anterior genu and anterior vertical segments of the petrous carotid are located below the trigeminal ganglion. The upper edge of the petrolingual ligament is located at the level of a line extending posteriorly along the upper edge of the second trigeminal division. The petrolingual ligament can be seen deep to the fascicles of the posterior trigeminal root.* **C**, *the floor of the middle fossa has been removed to show the relationships below the floor. The infratemporal fossa is located below the greater sphenoid wing and contains the pterygoid muscles, venous plexus, and branches of the mandibular nerve and maxillary artery. The roof of the temporal bone, which forms the posterior part of the floor of the middle fossa, has been opened to expose the mastoid antrum, eustachian tube, semicircular canals, cochlea, nerves in the internal acoustic meatus, and mandibular condyle.* **D**, *the trigeminal nerve has been reflected forward to expose the petrolingual ligament. The abducens nerve passes below the petrosphenoid ligament and through* (Continues)

vertical segment is positioned anterior to the jugular foramen fossa and bulb, posterior to the junction of the osseous and fibrocartilaginous parts of the eustachian tube and posterior to the medial edge of the tympanic portion of the temporal bone, anteromedial to the styloid process, posteromedial to the temporomandibular joint, slightly lateral to the lower edge of the petroclival fissure, and lateral to the deep apex of Rosenmüller's fossa (Fig. 4). The distance between the entrance into the carotid canal and the foramen spinosum and the stylomastoid foramen averaged 7.6 mm (range, 6.2–9.4 mm) and 11.3 mm (range, 9.2–13.9 mm), respectively. Cranial Nerves IX through XII exit the jugular foramen posteromedial to the entrance into the carotid canal (Fig. 4). The glossopharyngeal nerve courses along the posteromedial aspect of the ICA just below the entrance into the carotid canal. Jacobson's nerve, a branch of Cranial Nerve IX, enters its canaliculus on the bony prominence separating the jugular bulb and entrance into the carotid canal. The length of the posterior vertical segment along its anteromedial surface averaged 7.8 mm (range, 6.2–11.3 mm) and the angle between the long axis of it and the horizontal segment, when viewed from anteriorly, averaged 70.3 degrees (range, 35–111 degrees).

The tympanic cavity lies posterolateral to the posterior vertical segment and adjacent posterior genu of the carotid canal in 63% of specimens, lateral in 20%, and posterior in 17% (Figs. 1, 5, and 7) (28). The average thickness of bone separating the carotid canal and middle ear was 3.2 mm, and it was less than 1.0 mm in 22% (28). The petrous carotid projected posteriorly into the middle ear cavity, and was separated from it by only mucosa in 1 specimen each in this and our earlier study (28). Dehiscence of bone over the carotid canal in the middle ear has been found in 15 to 40% of the cases in previous anatomic studies (29). The aberrant ICA extending into the middle ear may cause pulsatile tinnitus and hearing loss, and may resemble a tumor on radiological examination. The close relationship between the carotid artery and the middle ear may permit middle ear infection to extend into the carotid canal.

Posterior Genu

The posterior genu is the sharp turn where the artery changes from a vertical to a horizontally directed anteromedial course (Figs. 2, 4, 7, and 8). The most important relationships of the posterior genu are to the cochlea, facial nerve, geniculate ganglion, initial segment of the greater petrosal nerve, and middle ear. The posterior genu sits directly posterior to the entrance of the eustachian tube into the middle ear.

Facial and Greater Petrosal Nerves and Cochlea. The facial nerve, origin of the greater petrosal nerves, and cochlea are considered together because the cochlea is positioned below the middle fossa floor, in the cochlear angle, located between where the long axis of the labyrinthine segment of the facial and initial segment of the greater petrosal intersect the geniculate ganglion (Figs. 1, 2, and 5). The labyrinthine segment extends from the entrance into the facial canal to the geniculate ganglion. The cochlea is positioned below the floor of the middle fossa slightly superior, posterior, and lateral to the posterior genu of the petrous carotid, where it is encased in very dense bone anteromedial to the fundus of the internal acoustic meatus. The basal turn of the cochlea, which is located posterior or posterolateral to the posterior genu of the petrous carotid, was separated from the posterior genu by a 2.2 mm (range, 0.4–4.8 mm) thickness of bone. The superior aspect of the basal turn of the cochlea may be entered during exposures directed along the posterior genu and posterior vertical segments and adjacent part of the horizontal segment as in the anterior petrosectomy approach to the clivus and brainstem or the middle fossa approach to the internal acoustic meatus. Although the cochlea may lie as deep as 4.5 mm from the floor of the middle fossa, it could be as near the floor as 3.0 mm, the average depth being 3.8 mm (28). There may be a dehiscence of the bone separating the basal turn of the cochlea from the posterior genu (23).

The greater petrosal nerve crossed above and was separated from the posterior genu by a layer of bone (Figs. 1, 2, 5, and 7). The greater petrosal nerve has been used as a landmark for orientation of the initial dissection in the middle fossa approach to the petrous carotid artery, facial nerve, and internal acoustic meatus. The greater petrosal nerve originates at the geniculate ganglion, exits through the bone at the hiatus fallopii, and runs under the dura in an anteromedial direction toward the trigeminal ganglion. The proximal part of the greater petrosal nerve is usually covered by bone; however, in 30% the nerve has no

FIGURE 2. *(Continued) Dorello's canal. The junction of the petrous and cavernous carotid is located at the upper edge of the petrolingual ligament. The greater petrosal nerve is joined by the deep petrosal branch of the carotid neural plexus to form the vidian nerve, which passes forward in the vidian canal, which has been unroofed. The lesser petrosal nerve crosses the floor of the middle fossa anterior to the greater petrosal nerve. The tensor tympani muscle and eustachian, with the former above the latter, are layered along and separated from the anterior surface of the petrous carotid by a thin layer of bone.* **E**, *posterosuperior view of another specimen. The petrous apex medial to the internal acoustic meatus has been partially removed to expose the petrous carotid. The posterior genu, located at the junction of the posterior vertical and horizontal segments, is situated below, medial, and anterior to the cochlea, which is enclosed in the bone anteromedial to the fundus of the internal acoustic meatus. The jugular bulb extends upward, toward the posterior meatal wall, vestibule, and semicircular canals. The inferior petrosal sinus courses along the petroclival fissure.* **F**, *posterosuperior view after drilling of the bone above and posterior to the petrous carotid. The cochlea, which is located above, posterior, and lateral to the posterior genu of the petrous carotid, is exposed in the angle between the greater petrosal nerve and the pregeniculate segment of the facial nerve. The chorda tympani is also in the exposure. A., artery; Ac., acoustic; Ant., anterior; Car., carotid; Cav., cavernous; CN, cranial nerve; Coch., cochlear; Cond., condyle; Eust., eustachian; Ext., external; Gang., ganglion; Gen., geniculate; Gr., greater; Horiz., horizontal; Inf., inferior; Intermed., intermedius; Jug., jugular; Lat., lateral; Less., lesser; Lig., ligament; Ling., lingual; M., muscle; Mandib., mandibular; Mast., mastoid; Max., maxillary; N., nerve; Nerv., nervus; Ophth., ophthalmic; Pet., petro, petrosal; Post., posterior; Pteryg., pterygoid; Seg., segment; Semicirc., semicircular; Sphen., sphenoid; Sup., superior; Tens., tensor; Trig., trigeminal; Tymp., tympani; Vert., vertical.*

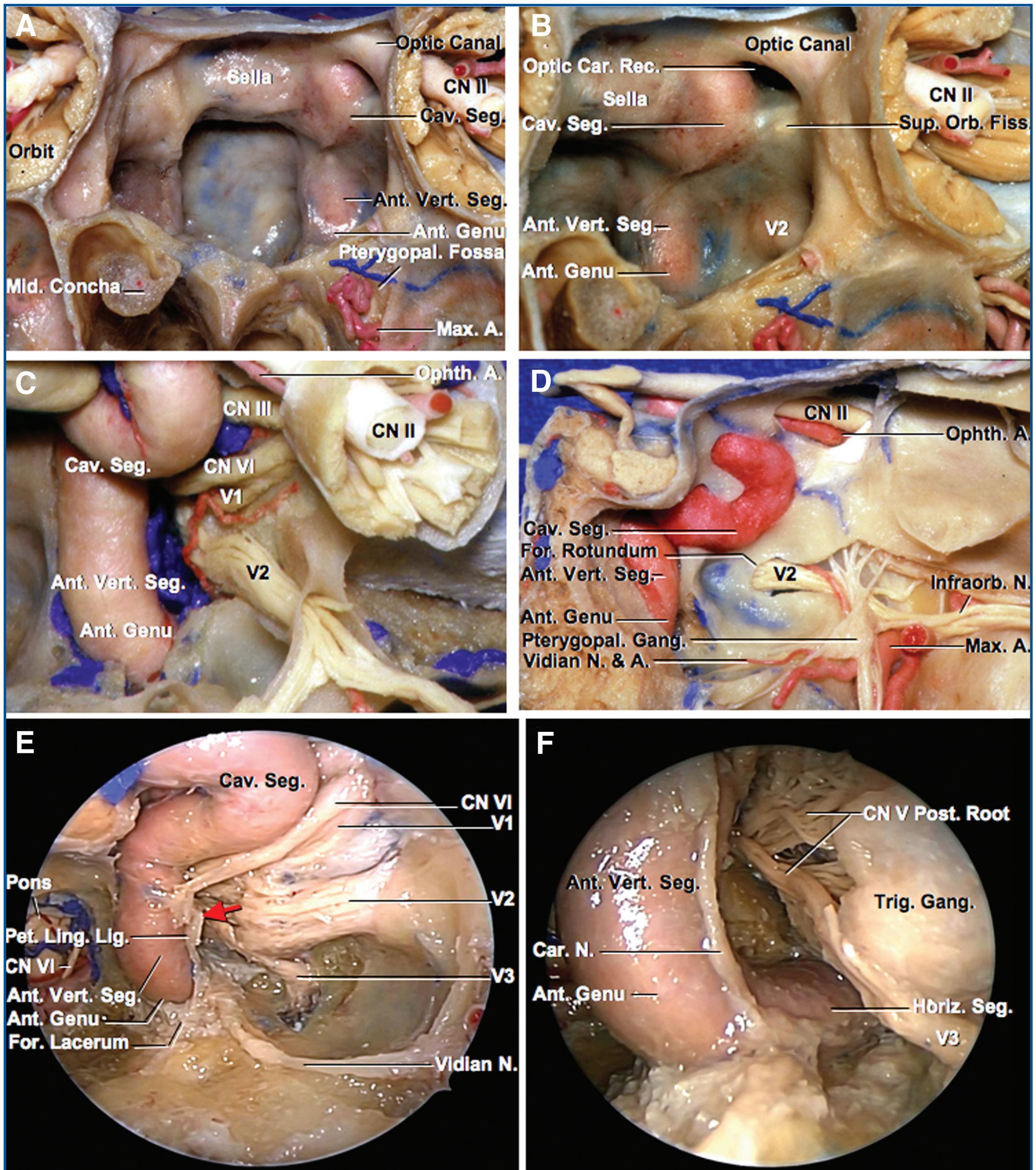

FIGURE 3. *Anterior genu and anterior vertical segment.* **A**, *anterior view of a coronal section through the sphenoid sinus, nasal cavity, and orbits. The prominences over the anterior genu and anterior vertical segment are exposed in the lateral walls of this well-pneumatized sphenoid sinus. The medial part of the posterior wall of the left maxillary sinus has been removed to expose branches of the maxillary artery in the pterygopalatine fossa.* **B**, *oblique view. The bony prominences overlying the anterior genu and anterior vertical segments, optic canal, superior orbital fissure, intracavernous carotid artery, and the V2 are exposed in the lateral wall of the sphenoid sinus. The bony depression between the carotid prominence and the optic canal, the opticocarotid recess, extends into the medial end of the optic strut. The broad round prominence below the opticocarotid recess overlies the structures passing through the superior orbital fissure.* **C**, *oblique view. The anterior genu and anterior vertical segment are exposed below the cavernous carotid. The petrolingual ligament is not seen from this side because it is located laterally at the level of a line extending posteriorly along the upper edge of the V2. The pituitary gland; ophthalmic artery; and optic, ophthalmic, maxillary, oculomotor, and abducens nerves have been exposed.* **D**, *the junction of the petrous and cavernous carotid is exposed below the sella. A line extending posteriorly along the upper edge of the V2 approximates the upper edge of the petrolingual ligament and the junction of the petrous and cavernous carotid. The maxillary nerve passes through the foramen rotundum to enter the (Continues)*

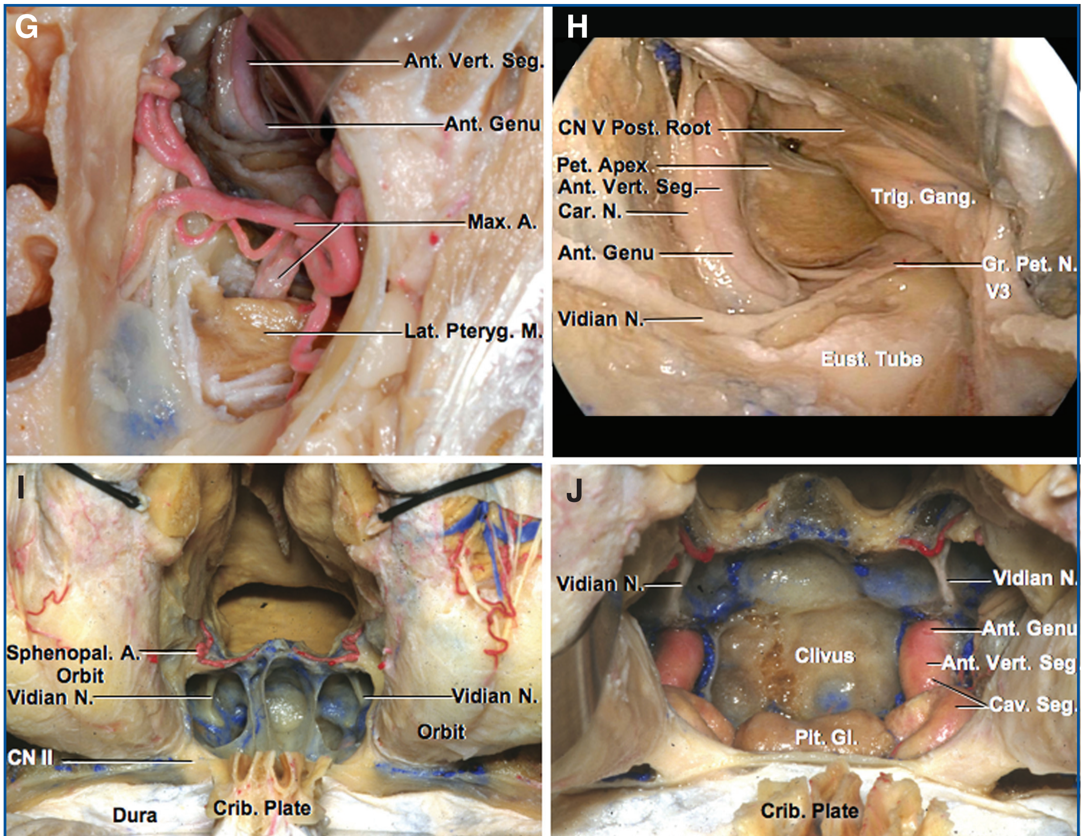

FIGURE 3. *(Continued)* *pterygopalatine fossa. The bone and dura covering the optic canal in the superolateral part of the sphenoid sinus have been opened to expose the optic nerve and ophthalmic artery in the optic canal. The terminal branches of the maxillary artery intermingle with the neural structures in the pterygopalatine fossa and exit the fossa to supply the tissues on the sphenoid face. The pterygopalatine ganglion and vidian nerve are positioned medial to the maxillary nerve.* **E** *and* **F**, *endoscopic views of the transnasal transsphenoidal exposure of the left anterior genu and anterior vertical segments.* **E**, *the clivus has been opened to expose the pons and abducens nerve. The vidian nerve has been followed backward below the floor of the sphenoid sinus to the horizontal segment. The abducens nerve and V1, V2, and V3 are exposed on the lateral side of the carotid artery. The upper edge of the petrosphenoid ligament, which attaches to the lingual process of the sphenoid, is marked with an arrow.* **F**, *enlarged view. The petrolingual ligament has been removed. The V3 and the trigeminal ganglion are in the lateral margin of the exposure. Bundles of the carotid neural plexus ascend along the petrous carotid to join the abducens nerve.* **G** *and* **H**, *transmaxillary exposure of the anterior genu and anterior vertical segment.* **G**, *the posterior wall of the maxillary sinus has been opened and the approach directed through the pterygopalatine fossa and above the vidian nerve through the lateral part of the sphenoid sinus to access the anterior genu and anterior vertical segment. Branches of the maxillary artery and second trigeminal division are exposed in the pterygopalatine fossa.* **H**, *endoscopic view. The vidian nerve has been followed back to where it joins the greater petrosal nerve, which courses on the upper surface of the horizontal segment of the petrous carotid. The posterior trigeminal root and ganglion and third division are in the lateral margin of the exposure. The petrous apex is exposed posterior to the petrous carotid. Bundles of the carotid neural plexus ascend on the petrous carotid.* **I** *and* **J**, *view of the anterior genu and anterior vertical segment through a transcranial transbasal exposure.* **I**, *a bifrontal bone flap has been elevated and the posterior part of the floor of the anterior fossa has been removed to expose the sphenoid sinus. The vidian nerves, which can be followed backward to the petrous carotid, underlie prominences in the floor of the sphenoid sinus. An osteotomy has been completed around the cribriform plate.* **J**, *the walls of the sphenoid sinus have been removed to expose the cavernous segment and the anterior vertical segment and anterior genu of the petrous carotid. The vidian canals have been unroofed to expose the vidian nerves in the floor of the sphenoid sinus. A., artery; Ant., anterior; Car., carotid; Cav., cavernous; CN, cranial nerve; Crib., cribriform; Eust., eustachian; Fiss., fissure; For., foramen; Gang., ganglion; Gl., gland; Gr., greater; Horiz., horizontal; Infraorb., infraorbital; Lat., lateral; Lig., ligament; Ling., lingual; M., muscle; Max., maxillary; Mid., middle; N., nerve; Ophth., ophthalmic; Orb., orbital; Pet., petro, petrosal, petrous; Pit., pituitary; Pteryg., pterygoid; Pterygopal., pterygopalatine; Post., posterior; Rec., recess; Seg., segment; Sphenopal., sphenopalatine; Sup., superior; Trig., trigeminal; Vert., vertical.*

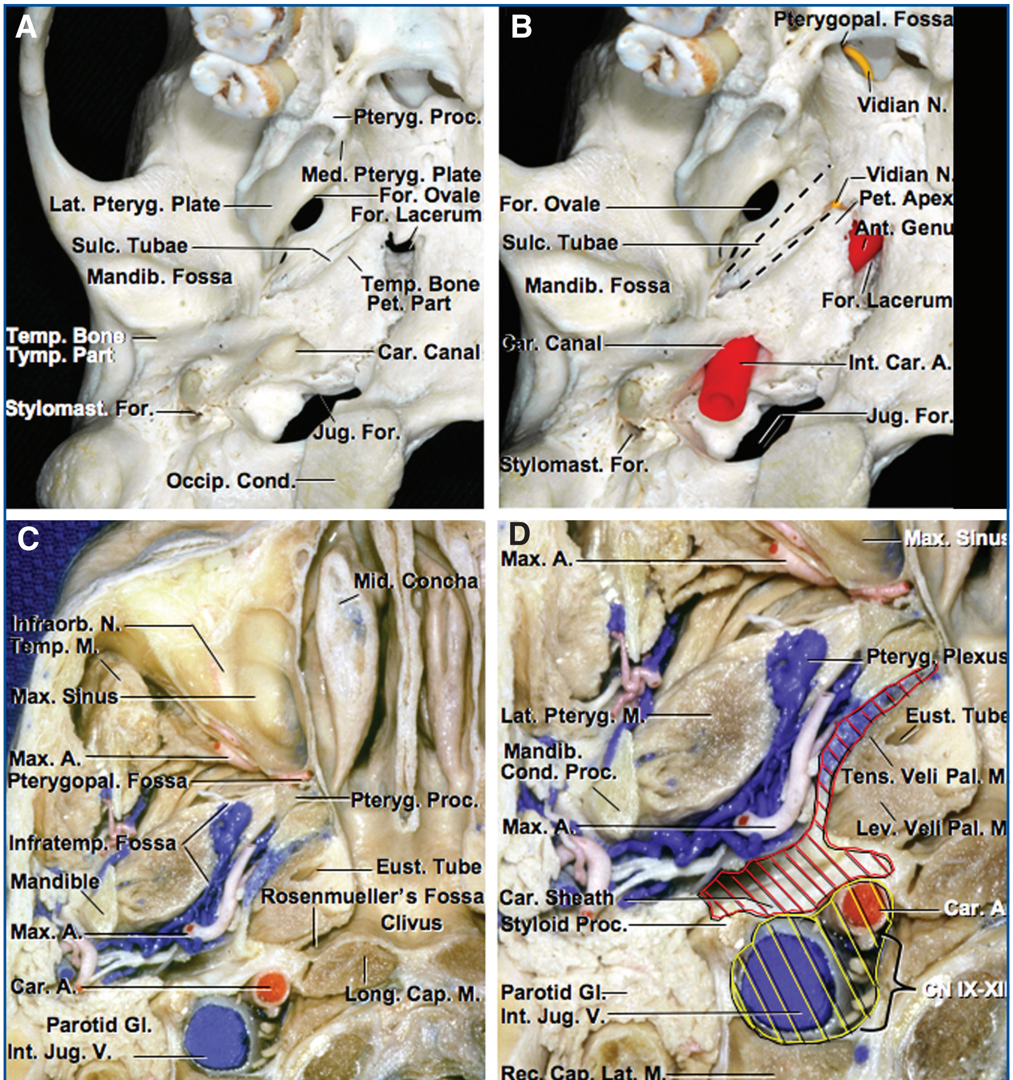

FIGURE 4. **A**, *inferior view of the carotid canal and skull base. The entrance into the carotid canal is located directly in front of the jugular foramen, posterolateral to the mandibular fossa and temporomandibular joint, and posterior to the sulcus tubae in which the eustachian tube sits. The canal extends forward and medial along the long axis of the petrous part of the temporal bone to the area above the foramen lacerum where it turns upward.* **B**, *a red tube has been placed in the carotid canal to show the course of the artery through the petrous part of the temporal bone and above the foramen lacerum. The interrupted lines show the position of the eustachian tube, which sits in the sulcus tubae below the junction of the sphenoid and temporal bones. The vidian nerve, represented by a yellow fiber, passes above the petrous apex and lateral to the foramen lacerum to reach the vidian canal and pterygopalatine fossa.* **C**, *inferior view of an axial section of the skull base. The pharyngeal recess (fossa of Rosenmüller) projects laterally from the posterolateral corner of the nasopharynx below the foramen lacerum toward the carotid artery just below where the artery enters the carotid canal. The carotid artery enters the carotid canal on the lateral side of the longus capitis muscle and posterior to the fibrous and cartilaginous part of the eustachian tube and courses anteromedial toward the petrous apex and the area above the foramen lacerum where the anterior genu is located. The lower part of the pterygoid process has been removed to expose the maxillary artery in the pterygopalatine fossa. The pterygopalatine fossa is located between the posterior maxillary wall anteriorly and the pterygoid process posteriorly. The medial part of the eustachian tube has been removed.* **D**, *enlarged view with highlighting of the pre- (red) and poststyloid (yellow) compartments of the parapharyngeal space. The styloid diaphragm, formed by the anterior part of the carotid sheath, separates the parapharyngeal space into pre- and poststyloid parts. The prestyloid compartment, a narrow fat-containing space between the medial pterygoid and tensor veli palatini muscle, separates the infratemporal fossa from the medially located lateral nasopharyngeal region containing the tensor and levator veli palatini muscles and the eustachian tube. The poststyloid compartment, located* *(Continues)*

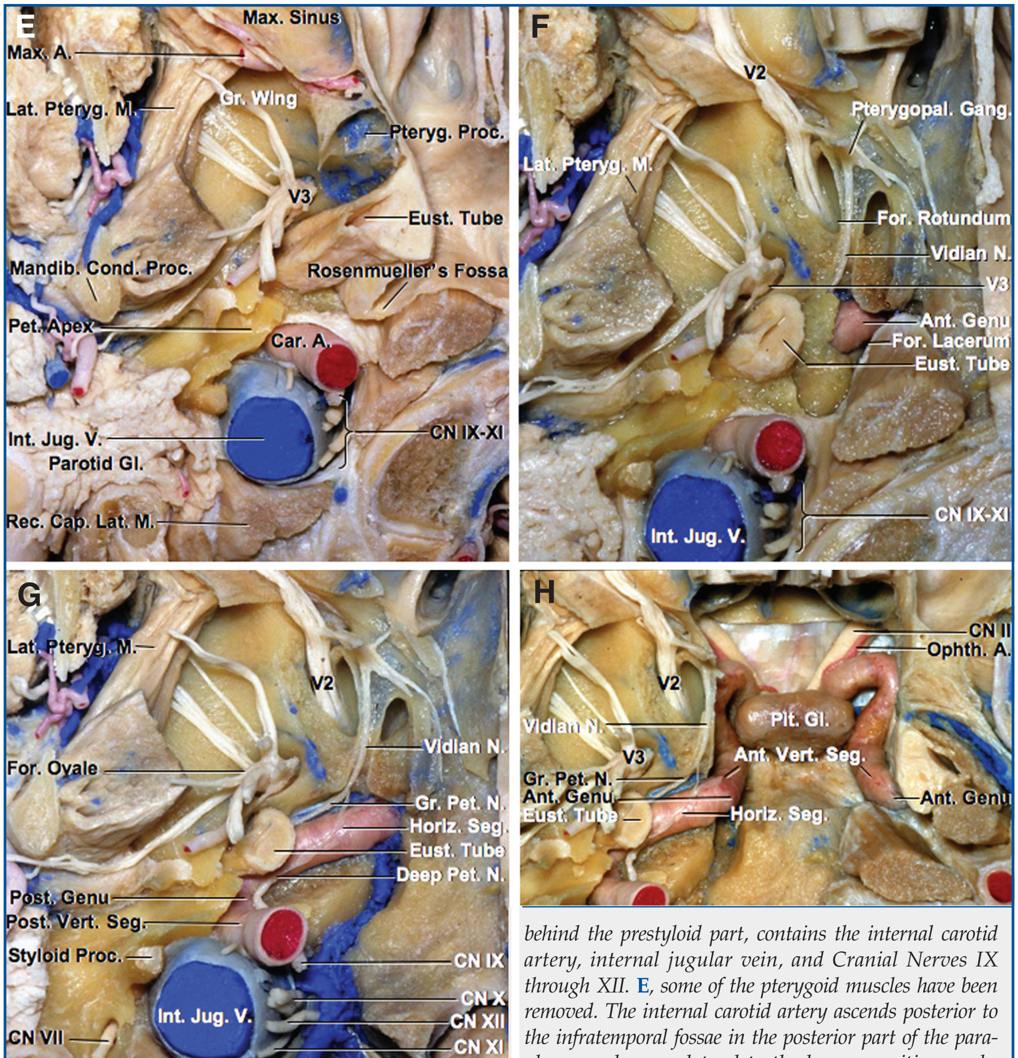

FIGURE 4. *(Continued)* *behind the prestyloid part, contains the internal carotid artery, internal jugular vein, and Cranial Nerves IX through XII.* **E**, *some of the pterygoid muscles have been removed. The internal carotid artery ascends posterior to the infratemporal fossae in the posterior part of the parapharyngeal space, lateral to the longus capitis muscle, behind the eustachian tube and posterolateral to Rosenmüller's fossa. Cranial Nerves IX through XII descend along the medial side of the internal carotid artery and internal jugular vein. The infratemporal fossa is surrounded by the maxillary sinus anteriorly, the mandible laterally, the pterygoid process anteromedially, and the parapharyngeal space posteromedially. It contains the mandibular nerve and maxillary artery and their branches, the medial and lateral pterygoid muscles, and the pterygoid venous plexus.* **F**, *the terminal part of the petrous carotid has been exposed by removing the fibrocartilaginous tissue filling the foramen lacerum. The pterygoid process has been removed to expose the maxillary nerve passing through the foramen rotundum to enter the pterygopalatine fossa, where it gives rise to the infraorbital nerve and communicating rami to the pterygopalatine ganglion. The vidian nerve exits the vidian canal and joins the pterygopalatine ganglion.* **G**, *the bone below the carotid canal has been removed to expose the posterior vertical and horizontal segments and posterior genu of the petrous carotid. The greater petrosal nerve joins the deep petrosal nerve to form the vidian nerve. The deep portion of the parotid gland has been removed to expose the facial nerve at the stylomastoid foramen. A portion of the occipital condyle has been removed to expose the hypoglossal nerve, passing above the condyle to join the nerves exiting the jugular foramen.* **H**, *the floor of the sphenoid sinus and sella has been removed to expose the pituitary gland and the anterior genu and anterior vertical segments. The anterior genu of the petrous carotid can be reached through the sphenoid sinus or by following the vidian nerve and canal backward in the paranasal area. A., artery; Ant., anterior; Cap., capitis; Car., carotid; CN, cranial nerve; Cond., condylar; Eust., eustachian; For., foramen; Gl., gland; Gr., greater; Horiz., horizontal; Infraorb., infraorbital; Infratemp., infratemporal; Int., internal; Jug., jugular; Lat., lateral, lateralis; Lev., levator; Long., longus; M., muscle; Mandib., mandible, mandibular; Max., maxillary; Med., medial; Mid., middle; N., nerve; Occip., occipital; Ophth., ophthalmic; Pal., palatini; Pet., petrosal, petrous; Pit., pituitary; Post., posterior; Proc., process; Pteryg., pterygoid; Pterygopal., pterygopalatine; Rec., rectus; Seg., segment; Stylomast., stylomastoid; Sulc., sulcus; Temp., temporal; Tens., tensor; Tymp., tympanic; V., vein; Vert., vertical.*

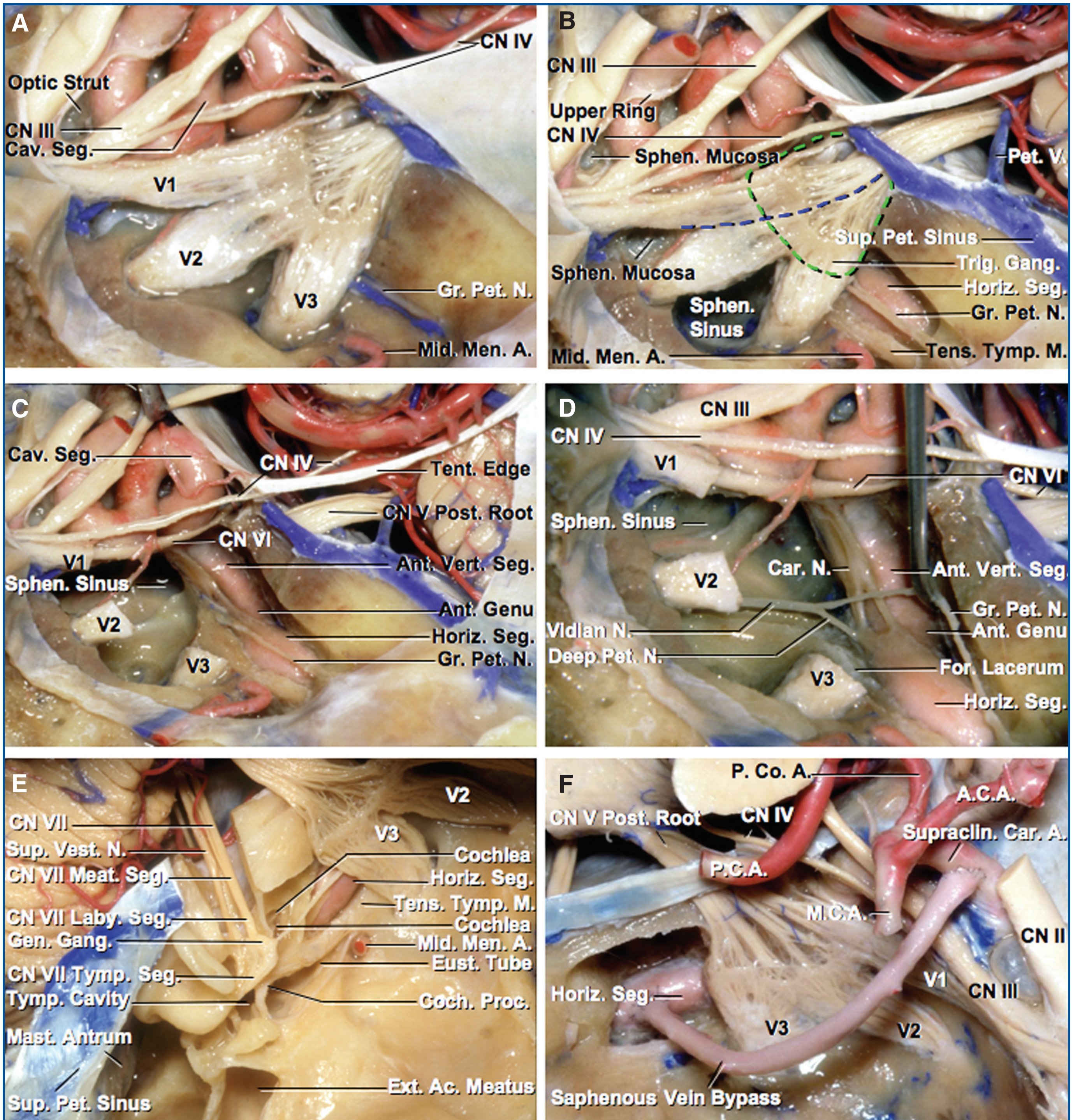

FIGURE 5. *Stepwise exposure of the petrous carotid.* **A**, *superolateral view. The dura has been elevated from the floor of the left middle fossa to expose the trigeminal ganglion (3 divisions) and the cavernous carotid.* **B**, *bone has been removed between the trigeminal divisions to expose the sphenoid sinus and mucosa. The anterior genu and anterior vertical segment, which underlie prominences in the lateral wall of the sphenoid sinus, are hidden on the medial side of the trigeminal nerve. The upper edge of the petrolingual ligament, which marks the boundary between the petrous and cavernous carotid, is positioned medial to the junction of the V1 and V2 (blue line) and the upper and middle thirds of Meckel's cave. The site of Meckel's cave, the arachnoid cistern around the trigeminal nerve, is outlined with a green line. Bone has been removed lateral to the trigeminal nerve to expose the horizontal* (Continues)

bony covering after its origin from the geniculate ganglion (28). The average length of greater petrosal nerve covered by bone before exiting at the hiatus to reach an extradural location is 3.7 mm (range, 0.5–8.0 mm) (28).

The geniculate ganglion is located above and either posterolateral (58%), posterior (26%), or lateral (16%) to the posterior genu, and is usually separated from the floor of the middle fossa by a layer of bone (Figs. 1, 2, and 5) (28). The average distance between the posterior genu and the ganglion is 6.5 mm (range, 3.0–13.0 mm) (28). In 16% of specimens, the geniculate ganglion had no bony covering and was exposed below the dura lining the floor of the middle fossa. In the 84% with a bony covering, the average thickness of bone above the ganglion was 1.2 mm (38).

The junction of the distal end of the internal acoustic meatus and the facial canal sits an average of 2.3 mm (range, 2.0–2.8 mm) below the surface of the middle fossa, and can be exposed by locating the geniculate ganglion and following the facial nerve medially toward the meatus (28). The labyrinthine portion of the facial canal sits an average of 6.6 mm (range, 4.0–10.0 mm) from the posterior genu of the carotid canal (28). The average distance between the labyrinthine segment of the facial nerve and the cochlea is 0.8 mm (28).

Horizontal Segment

The horizontal segment begins at the distal end of the posterior genu, courses anteromedially along the long axis of the petrous part of the temporal bone, largely below the greater petrosal nerve, posterior to the tensor tympanic muscle and the eustachian tube, and posterior to the foramina spinosum and ovale, and ends below the trigeminal nerve and ganglion at the anterior genu, where the artery turns upward above the fibrocartilage-filled foramen lacerum (Figs. 1, 2, and 5). The length of the horizontal segment along its superior surface averages 15.7 mm (range, 12.3–21.1 mm). The angle, measured along the floor of the middle fossa, between the long axis of the horizontal segment and the petrous ridge, averaged 9 degrees (range, 1–20 degrees), and the angle between the horizontal segment and the posterior part of the midsagittal plane averaged 58 degrees (range, 40–67 degrees). The greater petrosal nerve, the trigeminal nerve and ganglion, and the foramen spinosum and ovale are useful landmarks for locating the horizontal segment of the petrous ICA if it is not seen on elevating the dura.

Greater Petrosal Nerve. The greater petrosal nerve usually runs anteromedial above the horizontal segment; however, it may cross the floor of the middle fossa completely anterior to the petrous carotid as found in 2 specimens (Figs. 1, 2, 4, and 5). It most commonly passes along the anterior half of the upper surface of the horizontal segment before turning downward along the anterior surface of the artery to reach the area above the foramen lacerum, where it is joined by the deep petrosal branch of the carotid neural plexus to form the vidian nerve. It is commonly separated from the artery by a thin layer of bone in the area lateral to the trigeminal nerve, and passes directly to the surface of the artery in the area below the trigeminal ganglion. The lesser petrosal nerve crosses the middle fossa anterior to the greater petrosal nerve and exits the cranium through a tiny canal in the bone separate from and anterior to the greater petrosal nerve (Fig. 2) (17).

Foramina Ovale and Spinosum. The foramen ovale is anteromedial to the foramen spinosum, and both foramina are anterior to the carotid canal (Figs. 1, 2, 4, and 9). The horizontal segment was positioned an average of 5.0 mm (range, 3.1–7.9 mm) posterior to the posterolateral margin of the foramen spinosum and 6.4 mm (range, 4.5–9.2 mm) posterior to the posterolateral margin of the foramen ovale. The distance from the posterior surface of the temporal bone at the medial edge of the porus of the internal acoustic meatus to the horizontal segment averaged 8.6 mm (range, 5.4–12.9 mm).

FIGURE 5. *(Continued) segment of the petrous carotid and the tensor tympani muscle. The greater petrosal nerve courses above the anterior half of the horizontal segment of the petrous carotid.* **C**, *the trigeminal ganglion and adjacent part of the posterior trigeminal root and divisions have been removed to expose the distal part of the horizontal segment and the anterior genu and the anterior vertical segments. The lateral wall of the sphenoid sinus has been opened. The greater petrosal nerve passes medially along the anterior surface of the anterior genu toward the vidian canal.* **D**, *bone has been removed from the floor of the sphenoid sinus to unroof the vidian canal. The vidian nerve is formed by the union of the greater petrosal and deep petrosal nerves, which join above the foramen lacerum and enter the vidian canal. The deep petrosal nerve arises from the periarterial carotid nerves. The anterior genu sits above the foramen lacerum.* **E**, *superolateral views of another right middle fossa. The bone above the internal acoustic meatus has been removed and the dura opened to expose the facial and vestibulocochlear nerves. Bone has been removed below and anterior to the greater petrosal nerve to expose the horizontal segment of the petrous carotid and the tensor tympani muscle and eustachian tube. The petrous carotid is separated from the tensor tympani and eustachian tube by a thin shell of bone. The cochlea, which is positioned slightly posterior, superior, and lateral to the posterior genu, is exposed in the cochlear angle located between the labyrinthine segment of the facial nerve and the greater petrosal nerve. The tensor tympani, which passes along the anterior margin of the petrous carotid, is innervated by the trigeminal nerve and has a sharp bend around the cochleaform process, where it gives rise to a narrow tendon, which attaches to the malleus. The tensor tympani is separated from the roof of the eustachian tube, carotid canal, and floor of the middle fossa by a thin shell of bone. The tegmen has been opened and the mastoid air cells have been removed to expose the semicircular canals.* **F**, *another specimen. Unroofing the carotid canal lateral to the trigeminal nerve exposes a sufficient length of the petrous segment to complete a bypass from the right petrous carotid to the supraclinoid carotid. The saphenous vein bypass has been anastomosed to the petrous carotid in an end-to-side fashion using 8–0 nylon interrupted sutures. The other end of the saphenous vein graft is anastomosed to the supraclinoid carotid in an end-to-side fashion between the ophthalmic and posterior communicating arteries using 8–0 suture. A., artery; Ac., acoustic; A.C.A., anterior cerebral artery; Ant., anterior; Car., carotid; Cav., cavernous; CN, cranial nerve; Coch., cochlear; Eust., eustachian; Ext., external; For., foramen; Gang., ganglion; Gen., geniculate; Gr., greater; Horiz., horizontal; Laby., labyrinthine; M., muscle; Mast., mastoid; M.C.A., middle cerebral artery; Meat., meatal; Men., meningeal; Mid., middle; N., nerve; P.C.A., posterior cerebral artery; P.Co.A., posterior communicating artery; Pet., petrosal; Post., posterior; Proc., process; Seg., segment; Sphen., sphenoid; Sup., superior; Supraclin., supraclinoid; Tens., tensor; Tent., tentorial; Trig., trigeminal; Tymp., tympani, tympanic; V., vein; Vert., vertical; Vest., vestibular.*

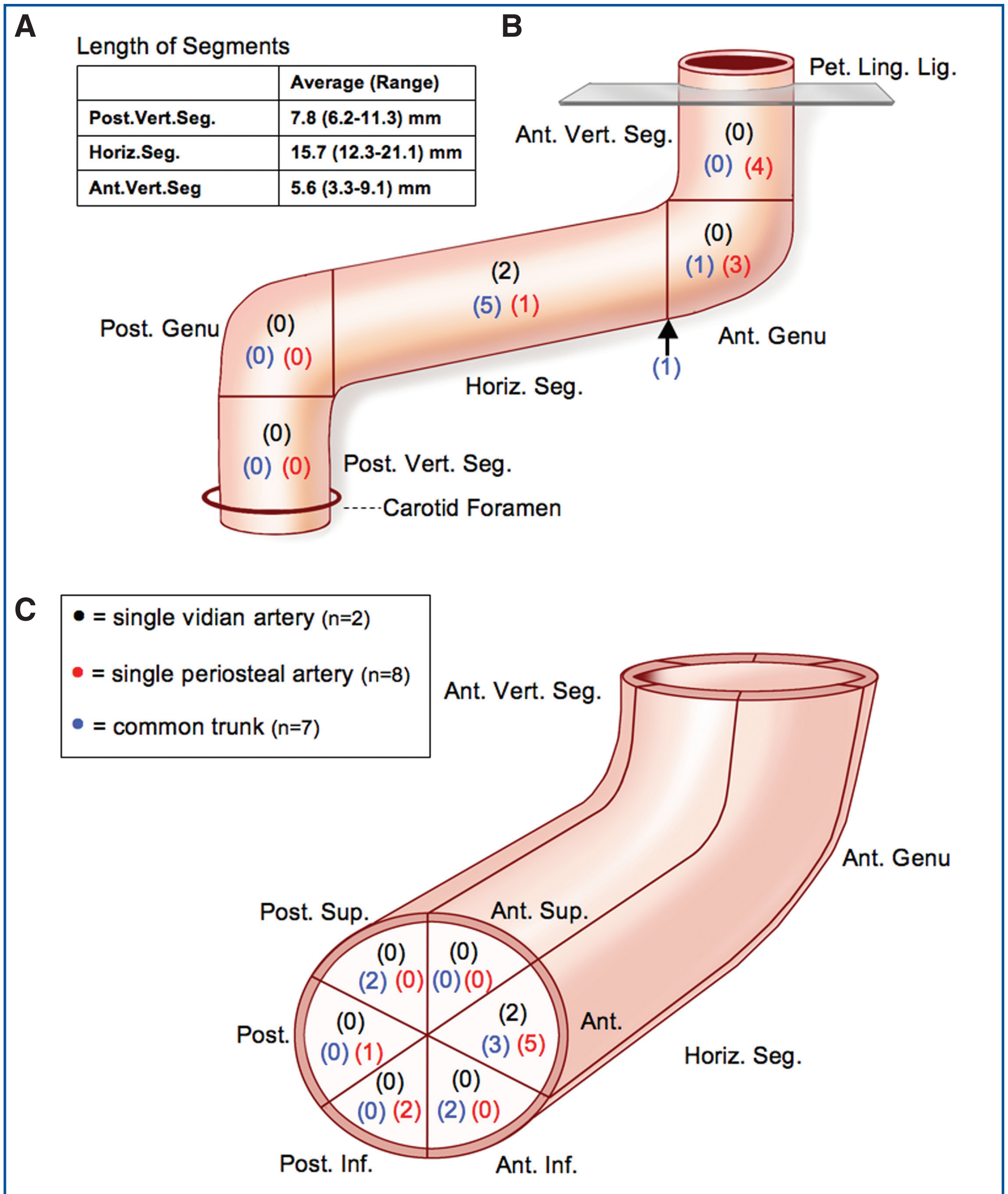

FIGURE 6. *Site of origin of petrous carotid branches.* **A**, *table showing the length of anterior and posterior vertical and horizontal segments.* **B**, *diagrammatic anterior view of the petrous carotid showing the site of origin of the vidian and periosteal arteries and common trunks. All of these branches arose from the horizontal or anterior vertical segment or the anterior genu. No branches arose from the posterior vertical segment or posterior genu. All of the single vidian arteries arose from the horizontal segment. Of 8 single periosteal arteries, 1 arose from the horizontal segment, 3 arose from the anterior genu, and 4 arose from the anterior vertical segment. Of the 7 common trunks found in this study, 5 arose from the horizontal segment, 1 arose from the anterior genu, and 1 arose at the junction of the horizontal segment and anterior genu.* **C**, *site of origin of branches on the circumference of the wall of the artery. The artery was divided vertically into anterior and posterior halves, and each half was divided into thirds. The anterior half was divided into anterosuperior, anterior, and anteroinferior thirds. The posterior half of the artery was also split into posterosuperior, posterior, and posteroinferior thirds. Both single vidian arteries arose from the anterior section. Of the 8 single periosteal arteries, 5 arose from the anterior section, 2 arose posteroinferior, and 1 arose posterior. Of the 7 common trunks, 3 arose anterior, 2 anteroinferior, and 2 arose posterosuperior. Ant., anterior; Horiz, horizontal; Inf., inferior; Lig., ligament; Ling., lingual; Pet., petro; Post., posterior; Seg., segment; Sup., superior; Vert., vertical.*

Trigeminal Nerve and Ganglion. The trigeminal ganglion and adjacent part of the posterior root rest in a shallow depression, the trigeminal impression, on the upper surface of the petrous apex. The horizontal segment passes under the lateral edge of the trigeminal nerve and ends below the trigeminal nerve and ganglion (Figs. 1, 2, and 5). The inferolateral edge of the trigeminal ganglion is positioned above the medial third of the horizontal segment, the superomedial edge rests against the ascending limb of the intracavernous segment, with the intermediate part of the ganglion resting superolateral to the anterior genu and anterior vertical segment. The portion of the ganglion, giving rise to the mandibular and maxillary divisions, lies directly above or over the anterior edge of 98% of the horizontal segments. In 2%, the ganglion was anterior to the horizontal segment (28). Kerr (20) suggested that pulsation of the carotid artery against the trigeminal ganglion might cause trigeminal neuralgia.

The bone above the horizontal segment thins progressively as the artery proceeds medially to pass below the trigeminal nerve so that the bony roof of the distal part of the segment is often absent so that only dura, and no bone, separates the carotid artery from the trigeminal ganglion. The carotid artery was found to be exposed under some portion of the trigeminal nerve with only dura, and no bone, separating the nerve from the artery in 80%. The dehiscence of bone above the distal horizontal segment extended lateral to the trigeminal impression in 3 specimens and to the lateral edge of the trigeminal impression in 1, and was located in the trigeminal impression below the nerve in 16. In the cases in which the horizontal segment lateral to the nerve was covered by bone, this covering was usually thin and could be removed easily.

In our previous study, the average length of horizontal segment that could be exposed lateral to the trigeminal nerve by removal of the bone above the horizontal segment averaged 10.2 mm (range, 5.2–14.0 mm) (28). In 1 specimen, the mastoid cells blocked exposure of the artery because pneumatization of the petrous apex was associated with a displacement of the horizontal segment 8 to 10 mm below the level of the trigeminal nerve and floor of the middle fossa. In the majority of specimens, a sufficient length of carotid artery could be exposed lateral to the trigeminal for either end-to-end or end-to-side anastomosis (Fig. 5) (28).

Eustachian Tube and Tensor Tympani. The eustachian tube and tensor tympani muscle are located below the floor of the middle fossa, anterior to the horizontal portion of the carotid canal (Figs. 1, 2, 4, and 7–10), where they may be damaged by drilling the middle fossa floor anterior to the greater petrosal nerve. The cartilaginous and fibrous part of the eustachian tube as it proceeds medially slopes gently downward across the anterior surface of the horizontal segment so that the opening into the nasopharynx is positioned below the level of the anterior end of the horizontal segment. The petrous carotid proceeds anterior and medially within the carotid canal through the petrous part of the temporal bone, but the eustachian tube rests in a sulcus, the sulcus tubae, which, although located at the lower surface of the cranial base, is positioned anterior to the horizontal segment. The eustachian tube and tensor tympani may be resected to mobilize the petrous carotid forward out of the carotid canal. The tensor tympani muscle may be superior (72%), anterior (20%), or posterior (8%) to the eustachian tube (28). The tensor tympani muscle was separated from the carotid canal by a thin shell of bone in every case; septa thickness varied from 0.1 to 5.0 mm (average, 1.3 mm) (28). Although the superior surface of the tensor tympani muscle is usually covered by bone, a small part of it may be exposed in the floor of the middle cranial fossa through a bone dehiscence between the carotid canal and the foramen spinosum. The eustachian tube was separated from the carotid artery by a thin layer of bone in 94% and by mucosa only in 6% (28). In 56%, the bone was very thin, measuring 0.1 to 0.3 mm in thickness (average, 0.8 mm). A thin lamina of bone separated the floor of the semicanal of the tensor tympani from the roof of the eustachian tube in 67% of specimens, but in 33% there was only mucosa and fibrous tissue separating them (28).

Anterior Genu

The anterior genu, the bend where the horizontal segment turns upward around the medial edge of the petrous apex to end in the anterior vertical segment, is positioned inferomedial to the trigeminal nerve and ganglion, above the foramen lacerum, and in the lateral wall of the sphenoid sinus (Figs. 3, 4, 9, and 10). The anterior genu and anterior vertical segment are referred to as the lacerum segment by Bouthillier et al. (4). The medial surface of the anterior genu and anterior vertical segment is seen in the endoscopic transsphenoidal approach in the lateral part of a well-pneumatized sphenoid sinus below the prominence overlying the cavernous carotid (Fig. 3) (1). In the transnasal endoscopic procedure, the vidian nerve can be followed backward from the pterygopalatine fossa under a prominence over the nerve in the floor of the sphenoid sinus to the area above the foramen lacerum and the lower edge of the anterior genu.

Foramen Lacerum. The foramen lacerum is an opening in the dry skull that in life is filled by fibrocartilaginous tissue (Figs. 3, 4, and 9). It has margins formed by the petrous apex, the posterolateral part of the body of the sphenoid bone, and the lateral edge of the upper part of the clival part of the occipital bone. The anterior genu sits above the anterior half and does not pass through the foramen lacerum, which in life is not the site of an opening in the cranial base because it is closed by fibrocartilaginous tissue. No structures except some tiny branches of the periosteal branches of the petrous carotid, a meningeal branch of the ascending pharyngeal artery, and some small veins pass through it (55). Its side-to-side width and anteroposterior diameter at the inferior skull base averaged 5.4 mm (range, 4.2–7.5 mm) and 5.7 mm (range, 4.3–9.1 mm), respectively.

Anterior Vertical Segment

The anterior vertical segment, the shortest of the 3 linear segments of the petrous carotid, ends where the superior edge of the petrolingual ligament crosses the lateral surface of the carotid (Figs. 1, 3, 4, and 10). The lateral surface is not covered by bone except in the cases in which the petrolingual ligament is ossified. It is difficult to visualize the ligament from the sphenoid sinus, where the anterior vertical segment underlies a prominence in the lateral wall of the sphenoid sinus. Radiological studies of the lateral wall of the sphenoid sinus have revealed a dehiscence of bone over 5.3% of arteries (50). Bony septae in the sphenoid sinus were attached to the bone covering the carotid in 26.7%. The artery may be damaged during septum detachment.

The upper edge of both the anterior vertical segment and the petrolingual ligament are located medial to the trigeminal ganglion. In the lateral view, the superior margin of the petrolingual ligament is located at approximately the level of a line extending backward along the upper edge of the maxillary nerve and across the ganglion (Fig. 5). The length of the anterior vertical segment along its posterolateral surface averaged 5.6 mm (range, 3.3–9.1 mm). The superior margin of the anterior vertical segment was located 15.8 mm (range, 10.9–21.0 mm) posterior to the superior margin of the foramen rotundum.

The trigeminal nerve sits superolateral to the anterior genu and anterior vertical segment (Figs. 1–3, 5, and 10). The carotid segment ascending medial to the anterior edge of the trigeminal ganglion and medial to the trigeminal divisions has also been referred to as the trigeminal segment of the paraclival ICA (1). That segment corresponds to the distal part of our anterior vertical segment plus the proximal part of the cavernous segment of the ICA.

Branches of the Petrous Carotid Artery

Fourteen of the 20 petrous carotid arteries had branches (70%). The branches that arose from the petrous carotid were either a vidian or periosteal artery or a common trunk that gave rise to both

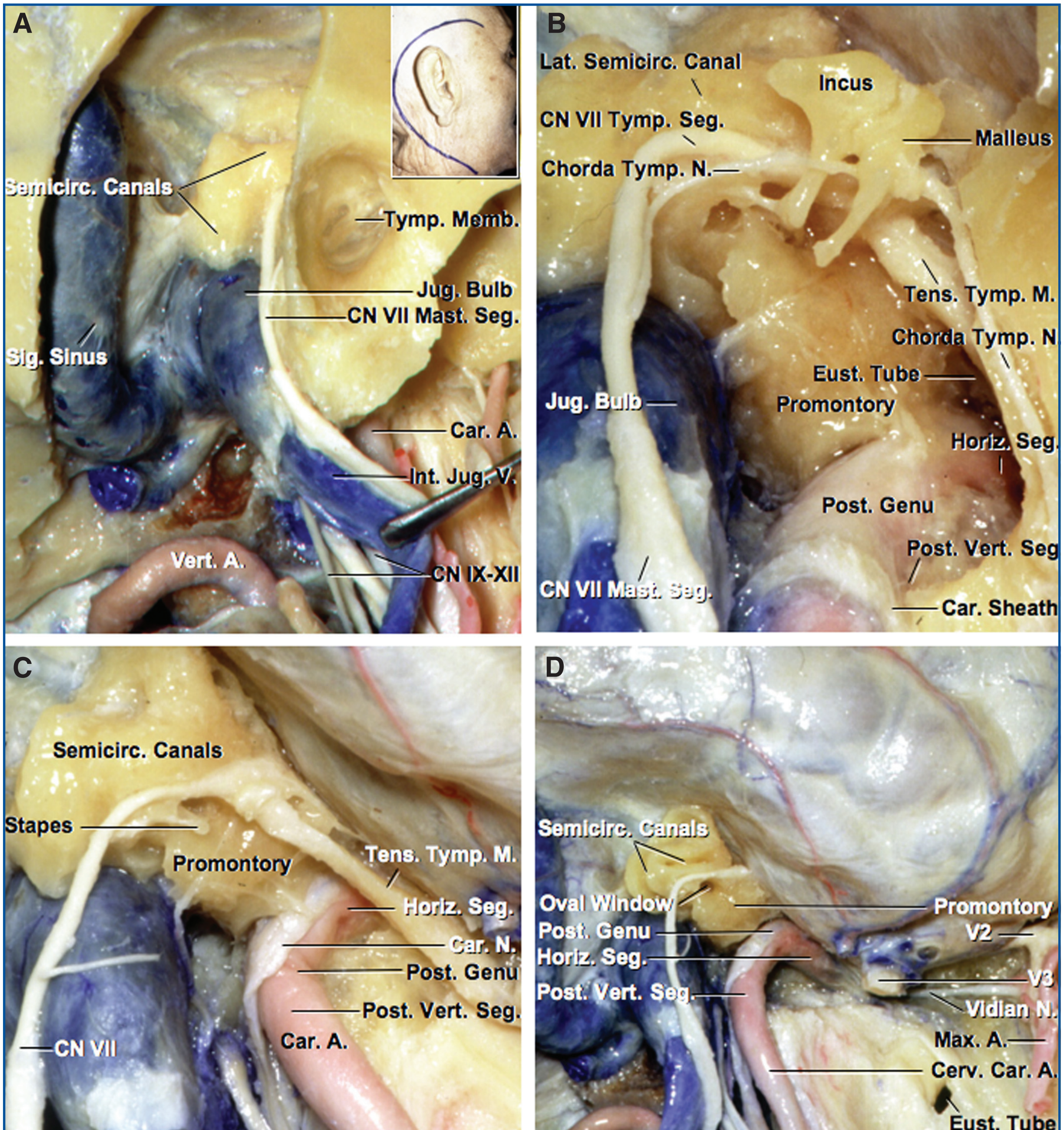

FIGURE 7. *Stepwise exposure of the petrous carotid in the postauricular transtemporal approach.* **A**, *the incision sweeps widely around the posterior margin of the ear (inset). The scalp flap has been reflected forward, the external auditory canal transected, the parotid gland removed, and a mastoidectomy completed to expose the semicircular canals and the mastoid segment of the facial nerve. The neck dissection exposes the internal jugular vein, vertebral artery, and Cranial Nerves IX to XII. The internal jugular vein exiting the jugular foramen and the cervical carotid ascending to enter the carotid canal are exposed after removal or downward displacement of the mandibular condyle.* **B**, *the external auditory canal has been resected to expose the structures in the tympanic cavity and the promontory overlying the basal turn of the cochlea. The posterior genu of the petrous carotid is located medial, anterior, and inferior to the promontory and cochlea. The tympanic segment of the facial nerve courses below the lateral semicircular canal. The chorda tympani arises from the mastoid segment of the facial nerve and passes forward along the upper part of the malleus to enter its anterior canaliculus. The tendon of the tensor tympani muscle is positioned superior to the eustachian tube, and both are positioned anterior to the petrous carotid.* **C**, *a frontotemporal craniotomy has been completed and the floor of the* (Continues)

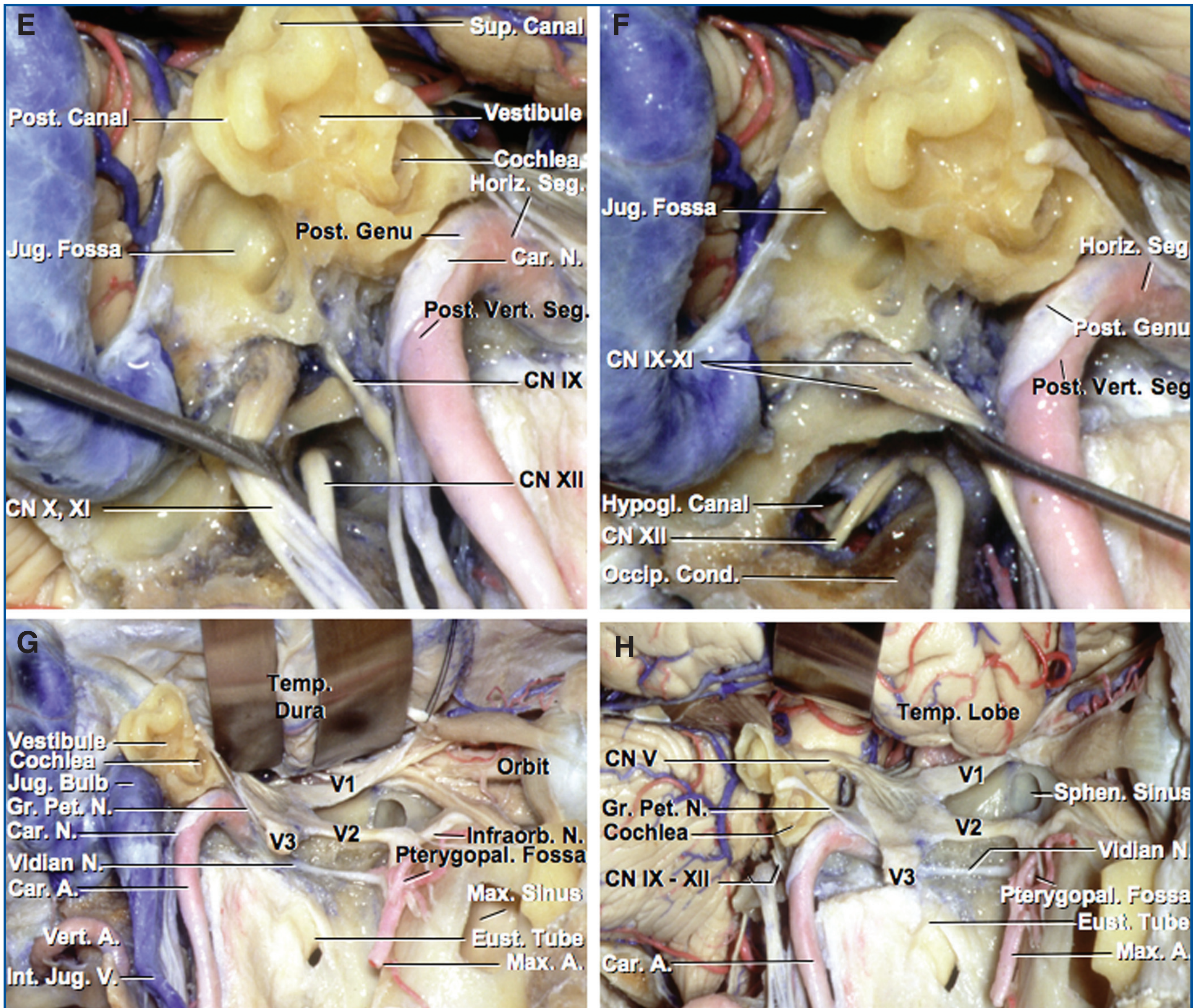

FIGURE 7. *(Continued)* *middle cranial fossa removed. The incus and malleus have been removed while preserving the stapes and the tensor tympani muscle. The posterior genu of the petrous carotid is exposed below and medial to the promontory, which overlies the basal turn of the cochlea.* **D**, *the tensor tympani has been removed. The cochlea sits deep to the promontory above the posterior genu of the petrous carotid. The semicircular canals have been exposed above the jugular bulb. The stapes has been removed from the oval window. The segment of the maxillary nerve and artery crossing the pterygopalatine fossa has been exposed. The membranous wall of the eustachian tube has been opened to expose the tube's opening into the nasopharynx. The eustachian tube descends across the anterior surface of the horizontal segment to reach the nasopharynx. The vidian nerve has been exposed.* **E**, *the facial nerve has been reflected out of view. The promontory has been drilled to expose the cochlea and the vestibule, which are positioned above, posterior, and lateral to the posterior genu. The jugular bulb has been removed to expose the jugular fossa in which the bulb resides. The nerves exiting the jugular foramen have been reflected backward to expose the hypoglossal nerve exiting the hypoglossal canal.* **F**, *the bone above the occipital condyle has been drilled to expose the hypoglossal nerve in the hypoglossal canal. The hypoglossal nerve joins the cervical carotid, internal jugular vein, and Cranial Nerves IX to XI in the carotid sheath.* **G**, *overview before opening the dura. The postauricular approach offers the potential for providing retrosigmoid and presigmoid exposure and access to the infratemporal and pterygopalatine fossae, orbit, and subtemporal area. The relationship of the petrous carotid to the cochlea, greater petrosal and trigeminal nerves, and infratemporal fossa is displayed.* **H**, *overview of exposure after opening the dura and elevating the temporal lobe. A., artery; Car., carotid; Cerv., cervical; CN, cranial nerve; Cond., condyle; Eust., eustachian; Gr., greater; Horiz., horizontal; Hypogl., hypoglossal; Infraorb., infraorbital; Int., internal; Jug., jugular; Lat., lateral; M., muscle; Mast., mastoid; Max., maxillary; Memb., membrane; N., nerve; Occip., occipital; Pet., petrosal; Post., posterior; Pterygopal., pterygopalatine; Seg., segment; Semicirc., semicircular; Sig., sigmoid; Sphen., sphenoid; Sup., superior; Temp., temporal; Tens., tensor; Tymp., tympani, tympanic; V., vein; Vert., vertebral, vertical.*

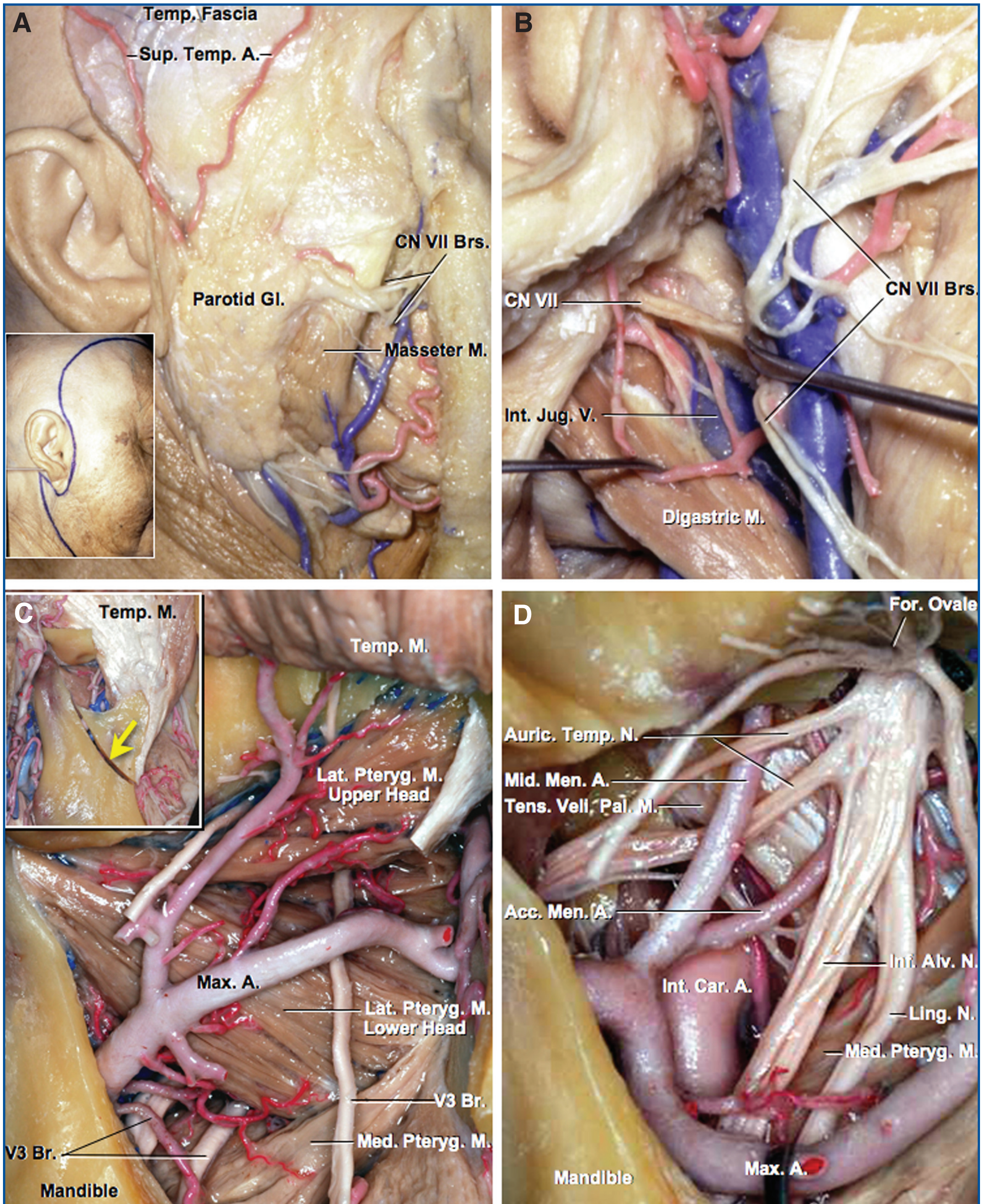

FIGURE 8. **A–D**, *preauricular subtemporal-infratemporal fossa approach to the petrous carotid.* **A**, *the skin incision (inset) and flap are positioned so that a neck dissection and a frontotemporal craniotomy can be completed. The scalp flap has been reflected forward while protecting the facial nerve and its branches. The facial nerve branches passing deep to the parotid have been preserved.* **B**, *the parotid gland has been removed and the branches of the facial nerve distal to the stylomastoid foramen have been exposed. The internal jugular vein is exposed below the facial nerve.* **C**, *an osteotomy of the zygomatic arch and across the base of the coronoid process (yellow arrow) allows the temporalis muscle to be folded upward to expose the medial and lateral pterygoid muscles, maxillary artery, and branches of the trigeminal nerve in the infratemporal fossa.* **D**, *the lateral pterygoid* (Continues)

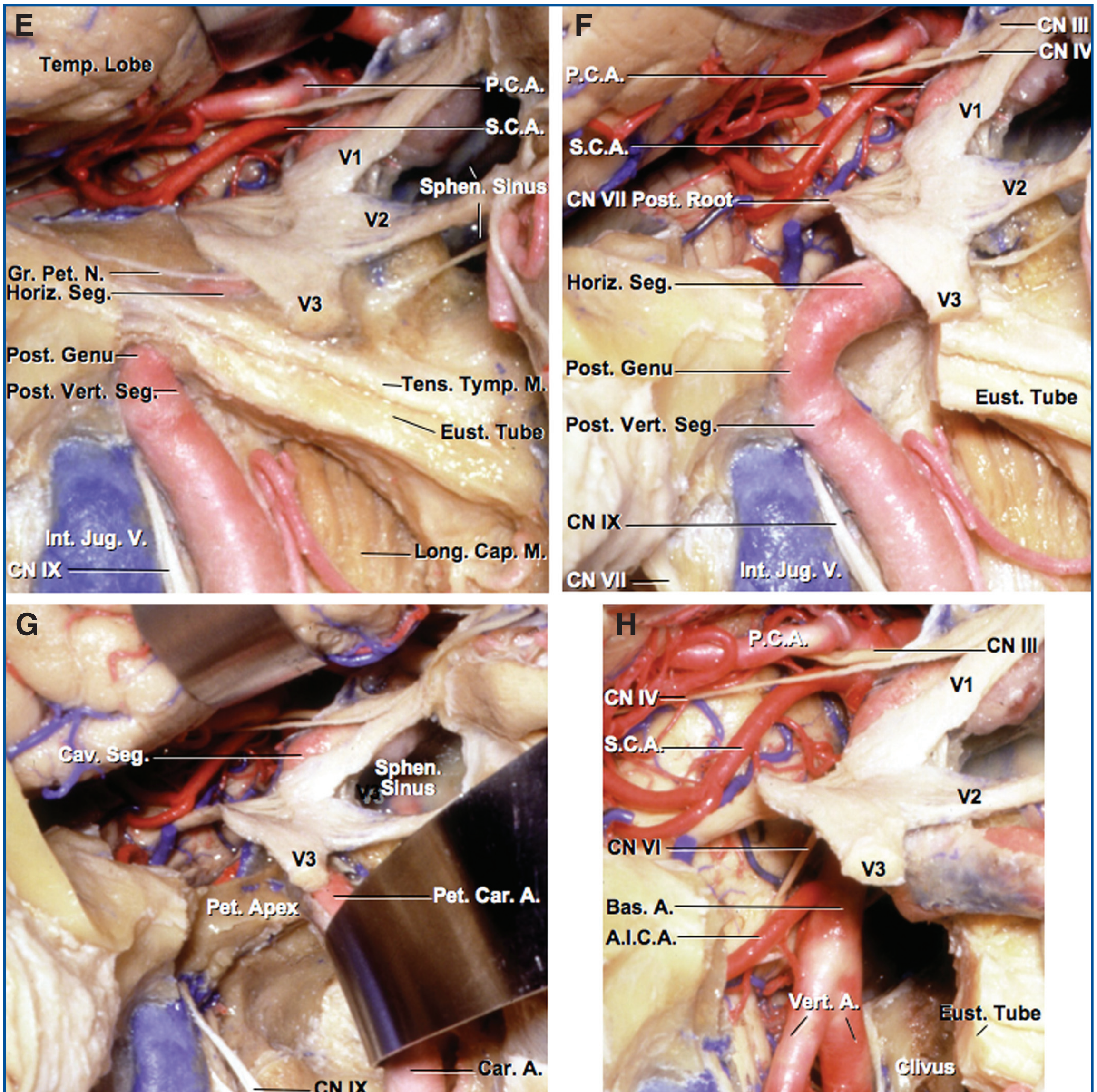

FIGURE 8. *(Continued)* *muscles have been reflected to expose the internal carotid, maxillary, and accessory meningeal arteries; the mandibular nerve and its auriculotemporal, lingual, and inferior alveolar branches; and the medial pterygoid and tensor veli palatini muscles. The accessory meningeal artery enters the foramen ovale. The middle meningeal artery passes between the 2 bundles of the auriculotemporal nerve.* **E**, *the mandibular condyle has been pushed downward and a frontotemporal craniotomy has been completed. The dura of the lateral wall of the cavernous sinus has been elevated. The floor of the middle fossa has been resected down to the level of the tensor tympani muscle and eustachian tube and the posterior vertical segment and posterior genu of the petrous carotid artery. The posterior cerebral and superior cerebellar arteries have been exposed. The lateral walls of the sphenoid sinus have been opened by removing bone between the trigeminal divisions.* **F**, *the eustachian tube and tensor tympani have been resected to expose the horizontal segment of the petrous carotid.* **G**, *the petrous carotid has been reflected forward out of the carotid canal to expose the petrous apex.* **H**, *the petrous apex and adjacent part of the clivus medial to the jugular foramen have been removed and the posterior fossa dura opened to expose the junction of the vertebral and basilar arteries and the origin of the anterior inferior cerebellar artery. A., artery; Acc., accessory; A.I.C.A., anterior inferior cerebellar artery; Alv., alveolar; Auric., auriculotemporal; Bas., basilar; Br., branch; Brs., branches; Cap., capitis; Car., carotid; Cav., cavernous; CN, cranial nerve; Eust., eustachian; Gl., gland; Gr., greater; Horiz., horizontal; Int., internal; Jug., jugular; Lat., lateral; Ling., lingual; Long., longus; M., muscle; Max., maxillary; Med., medial; Men., meningeal; Mid., middle; N., nerve; Pal., palatini; P.C.A., posterior cerebral artery; Pet., petrosal, petrous; Post., posterior; Pteryg., pterygoid; S.C.A., superior cerebellar artery; Seg., segment; Sphen., sphenoid; Sup., superior; Temp., temporal; Tens., tensor; Tymp., tympani; V., vein; Vert., vertebral, vertical.*

a vidian and a periosteal artery (Figs. 6, 11, and 12). The most frequent branch was a periosteal artery. The vidian arteries exited the petrous carotid or a common trunk and ran forward and medially along the anterior wall of the carotid canal and above and lateral to the cartilage of the foramen lacerum to enter the posterior opening of the vidian canal with the vidian nerve. The periosteal arteries supplied the periosteum of the carotid canal. Some reached the dura of the middle fossa bordering the carotid canal or terminated in or penetrated the foramen lacerum. Nine petrous carotids gave rise to a vidian or periosteal artery and 7 gave rise to a common trunk from which both arteries arose. Two vidian arteries and 1 periosteal artery gave rise to a branch that ran along the greater petrosal nerve toward, but did not reach, the geniculate ganglion. No caroticotympanic branches were found in this or our previous anatomic study. The finding of more branches in this than in our previous study, in which only 38% of our specimens had petrous carotid branches, as compared with 70% of specimens in this study, is a reflection of 2 factors (28). First, the perfusion of the vessels with colored silicone in this study aided in their identification. Second, the previous study did not examine the anterior genu and anterior vertical segment, where most of the periosteal branches arose. Branches of the petrous segment are important in occlusion of the proximal ICA because they provide a channel for the retrograde flow needed to maintain the patency of the distal part of the artery (2, 26, 28, 31, 32, 49).

There were 9 vidian and 18 periosteal arteries found in this study. Of the 9 vidian arteries, 2 arose as a single branch and 7 arose in a common trunk with a periosteal artery. In 4 of the common trunks, the vidian and periosteal branches were of equal size at the origin from the common trunk, in 2, the vidian artery was larger than the periosteal artery, and in 1, the periosteal artery was larger than the vidian artery. The distance from the origin on the petrous carotid to the posterior opening of the vidian canal ranged from 6.5 to 15.7 mm (average, 11.1 mm). The vidian canal was located in the base of the pterygoid process of the sphenoid bone just below the floor of the sphenoid sinus and inferolateral to the anterior genu of the petrous ICA. The vidian artery ran anteromedially toward the vidian canal as it diverged from the anterior surface of the horizontal segment. All the vidian arteries had an anastomosis with a branch of the maxillary artery in the vidian canal or pterygopalatine fossa: in 7, the anastomosis was in the sphenopalatine fossa, and in 2, the anastomosis was in the vidian canal. This anastomosis provides a channel for the retrograde flow needed to maintain the patency of the distal part of the artery in proximal ICA occlusion and may be involved in intractable epistaxis and supply of tumors (Fig. 4) (26, 49).

Twelve petrous carotids gave rise to a total of 18 periosteal branches (Fig. 11). Of the 18 periosteal branches, 6 arose as a single branch from the petrous carotid, 2 arose as branches of 1 carotid, 5 arose as a single periosteal branch of a common trunk with a vidian artery, 3 arose from a petrous carotid having 1 periosteal branch from a common trunk (in addition, the vidian artery gave rise to 2 small periosteal branches), and 2 arose from a petrous carotid having 1 periosteal artery that arose from a common trunk and an additional small periosteal artery that arose from the vidian artery.

Eight periosteal arteries sent a branch through the foramen lacerum. Two periosteal arteries that arose from the superior aspect of the petrous carotid ended in the periosteum of the carotid canal and did not penetrate the foramen lacerum; however, two-thirds of the periosteal arteries arising from the inferior half of the carotid passed through the foramen lacerum. We did not follow these arteries beyond the foramen lacerum; however, they probably participate in the anastomosis in the oropharyngeal mucosa or around the eustachian tube. Enlargement of the vidian artery has been seen in tumors in the nasopharynx and pterygopalatine and infratemporal fossae and in external carotid artery occlusion or ligation. Periosteal artery enlargement has been seen in tumors extending to the lining of the carotid canal (31).

All the vidian arteries that arose directly from the petrous carotid arose from the horizontal segment (Fig. 6). Of the 8 periosteal arteries arising directly from the carotid, 4 arose from the anterior vertical segment, 3 arose from the anterior genu, and 1 arose from the horizontal segment. Of the 7 common trunks arising from the petrous carotid, 5 arose from the horizontal segment, 1 arose from the anterior genu, and 1 arose from the junction of the anterior genu and horizontal segment.

The cross section of the wall of the horizontal segment was divided into 6 areas based on whether they were anterior or posterior to a vertical line (Fig. 6). The anterior area was divided into anterior, anterosuperior, and anteroinferior sections. The posterior half of the horizontal segment was divided into posterior, posterosuperior, and posteroinferior areas. The single vidian arteries arising from the horizontal segment all arose from the anterior area. Of the 8 periosteal arteries arising from the horizontal segment, 5 arose from the anteroinferior area, 2 arose from the posterior inferior area, and 1 arose directly posterior. Of the 7 common trunks arising from the horizontal segment, 3 arose anterior and 2 arose from the anteroinferior and posterosuperior areas. The diameter of the vidian arteries having their origin from either the petrous carotid or a common trunk averaged 0.4 mm (range, 0.2–0.6 mm). The diameter of the periosteal arteries at their origin averaged 0.4 mm (range, 0.2–0.6 mm). The diameter of the common trunks at their origin averaged 0.5 mm (range, 0.4–0.7 mm). Two common trunks also arose from the superior surface of the petrous carotid, a finding not seen in the previous literature. The increased diameter of the arteries seen in angiographic studies as compared with our anatomic studies is probably a reflection of their enlargement in radiological studies in association with occlusive carotid disease, tumor, and arteriovenous fistulae (2).

The petrous ICA has been reported to have caroticotympanic branches in addition to the periosteal and vidian arteries described above. The caroticotympanic artery is a small artery reported to arise from the posterior vertical segment and posterior genu and enter the tympanic cavity through a foramen in the wall of the vertical portion of the carotid canal to supply the structures in the middle ear. The caroticotympanic artery has not been seen on any of the anatomic studies including this and our prior study (28). The arteries have been found in less than 1% of internal carotid angiographic studies (2, 25, 28, 31, 32). We suggest that some of the caroticotympanic branches seen on the angiographic studies may be branches of the ascending pharyngeal artery that arise from the internal carotid artery in the neck. The ascending pharyngeal artery, a tiny branch, often ascends directly on the wall of the ICA and is difficult to differentiate from the cervical carotid on angiograms. At the cranial base, branches of the ascending pharyngeal artery enter the carotid canal and, if enlarged with tumor, may be mistaken for a branch of the petrous carotid because they separate away from the ICA only at the level of the carotid canal where they enter the tympanic cavity. The difficulty in differentiating the ascending pharyngeal from the cervical segment of the ICA and the entrance of branches of the ascending pharyngeal into the carotid canal and tympanic cavity may explain the reported small incidence of these arteries arising as a branch of the petrous carotid.

Knowledge of the embryology of the petrous carotid provides the basis for understanding its branches and anomalies. The vidian artery usually arises from a remnant of the mandibular (first) aortic arches and later becomes a branch of the internal maxillary artery. It arose from the carotid artery in 45% of our specimens. Although most anatomists describe the artery as arising from the internal maxillary artery, *Gray's Anatomy* describes it as a small inconstant branch of the petrous carotid artery (53).

A rarely occurring branch of the vertical segment is a persistent stapedial artery not seen in this or our previous anatomic study (28). It originates as a secondary branch of the embryonic carotid. The stapedial artery takes its name from the fact that it passes through the primordium of the stapes. At 1 stage of development, it is the parent vessel for the middle meningeal and part of the external carotid artery. Later, as the stapedial involutes, the middle meningeal and external carotid branches lose their connection with the petrous carotid and are fed by the internal maxillary artery. The stapedial artery rarely persists into adult life but has on occasion been encountered during middle ear exploration (14, 28).

DISCUSSION

The petrous carotid may become involved in pathologic conditions starting in the anterior, middle, posterior, infratemporal, and pterygopalatine fossae and parapharyngeal space that extend to the temporal, occipital, and sphenoid bones. The development of a combination of microscopic, endoscopic, endovascular, and cranial base techniques has made it possible to access all parts of the petrous carotid. It has been exposed for extracranial-to-intracranial bypass, tumor removal, aneurysm obliteration, and proximal control (22, 45). Because these lesions do not strictly adhere to the anatomic subdivisions of the cranial base, variations of the transcranial, subcranial, and combined approaches must often be combined in innovative ways for lesions that extend along the various segments of the petrous carotid. Differing segments of the petrous carotid can be exposed from the lateral portion through the mastoid, middle ear, and infratemporal fossa from above through the middle and frontal fossae, and from the anterior section through the sphenoid sinus, maxilla, and nasal and oral cavities. The combination of 2 or 3 approaches may be needed either in stages or in combination in 1 operative procedure. This brief review of the operative approaches to the petrous carotid advances from proximal to distal (posterior to anterior) along the segments of the petrous carotid.

The posterior vertical segment and posterior genu may be exposed in the lateral approach directed through the mastoid and adjacent tympanic cavity (Figs. 7 and 8). All of the approaches directed from laterally through the mastoid, such as the retrolabyrinthine, translabyrinthine, and transcochlear approaches, and the various modifications of the presigmoid approaches, which combine exposure of the supratentorial and infratentorial area, and the postauricular approaches to the jugular foramen can be extended forward from the mastoid to the area along the posterior vertical segment and posterior genu and even to the infratemporal fossa.

The posterior vertical segment and posterior genu may be exposed under the mucosa in the middle ear below the promontory overlying the basal turn of the cochlea, where they may resemble an aneurysm or tumor (Fig. 7). Failure to recognize an anomalous course of the petrous carotid has led to inadvertent biopsy of the artery within the tympanic cavity (28). In this case, myringotomy or middle ear surgery may cause severe bleeding and lead to aneurysm formation (3, 7). The radiological criteria for recognition of an anomalous course of the carotid artery are failure to visualize the vertical segment below and anterior to the cochlea on lateral and coronal tomograms, and dehiscence in the floor of the middle ear and erosion along the promontory caused by grooving from the abnormally placed artery (30). This condition has been treated by creating a new protected canal using a fascial graft and bone (39). Lapayowker et al. (21) described a vertical line lateral to which the carotid artery did not project on anteroposterior tomograms except when the artery lay within the middle ear. The carotid artery, on 100 normal angiograms, was located an average of 5.38 mm medial to this line, which extends vertically through the midportion of the vestibule on anteroposterior views (21).

Tumors involving the jugular foramen and middle ear may extend along the petrous carotid to the middle fossa, downward along the eustachian tube to the infratemporal fossa or nasopharynx, or along the vidian nerve to the pterygopalatine fossa. Accessing the posterior vertical segment and posterior genu, which sit below and medial to basal turn of the cochlea, often requires that the exposure through the mastoid be widened anteriorly by sacrificing part or all of the external auditory canal and middle ear structures (Fig. 7). Drilling away the promontory or cochlea may facilitate the exposure of the petrous carotid at the cost of loss of hearing. The approaches through the transmastoid exposure may be facilitated by posterior or anterior transposition of the facial nerve, which permits better visualization of the petrous carotid and structures medial to the tympanic cavity. Displacement of the facial nerve from its bony canal seriously interferes with its vascular supply, and temporary or permanent loss of function is to be expected (42). The lateral approach directed through a mastoidectomy, used alone or in combination with other approaches, is the route most commonly selected for lesions extending through the jugular foramen (10, 16, 27).

The middle fossa approach directed through a temporal, frontotemporal, or orbitozygomatic craniotomy with or without ele-

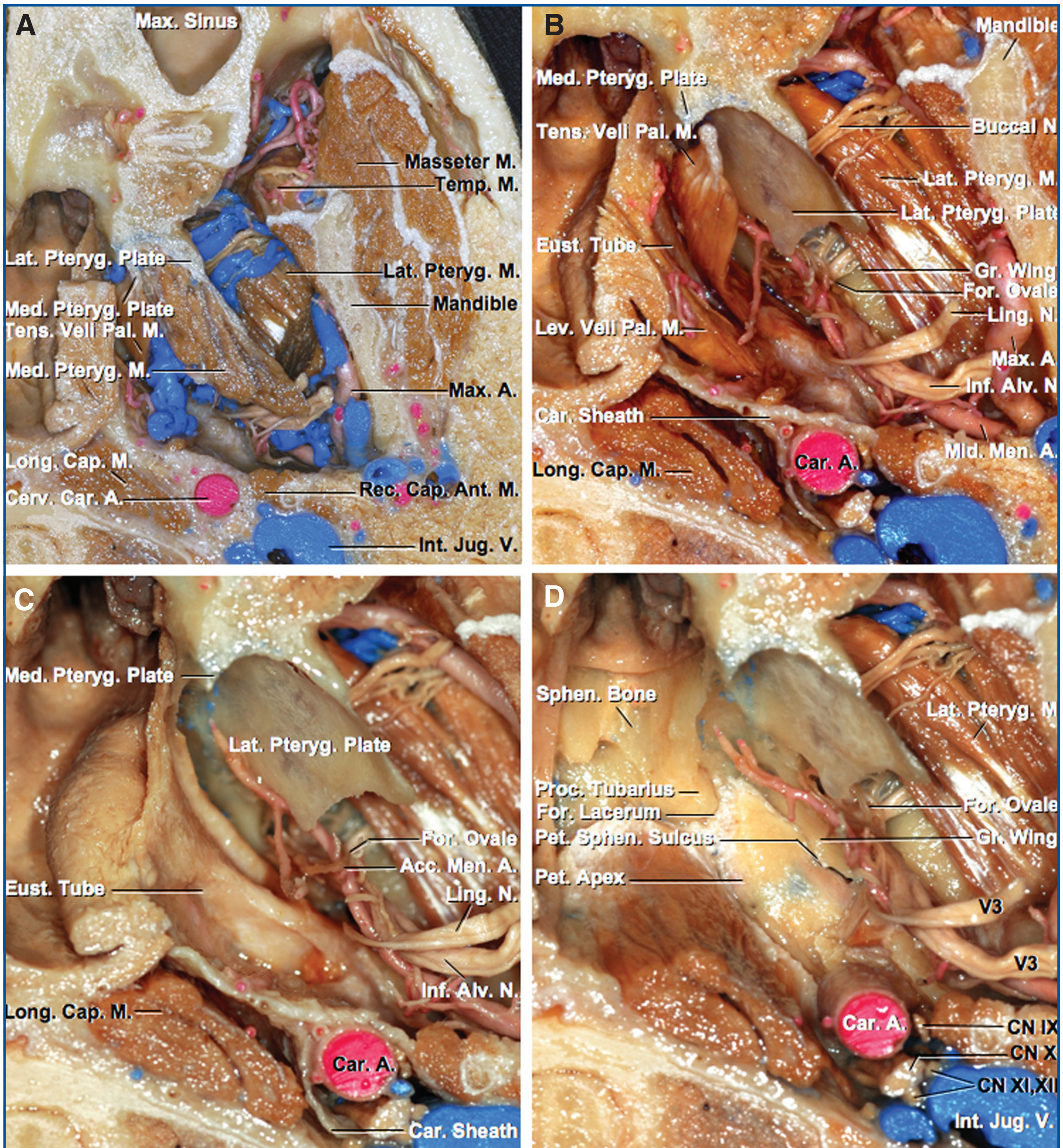

FIGURE 9. *Inferior view of a stepwise dissection of an axial section of the cranial base positioned below the sections shown in Figure 4.* **A**, *the internal carotid artery is located behind the infratemporal fossa in the posterior part of the parapharyngeal space lateral to the longus capitis muscle. The infratemporal fossa is surrounded by the maxillary sinus anteriorly, the mandible laterally, the pterygoid process anteromedially, and the parapharyngeal space posteromedially. The infratemporal fossa contains the mandibular nerve and the maxillary artery and their branches, the medial and lateral pterygoid muscles, and the pterygoid venous plexus.* **B**, *the deep head of the medial pterygoid muscle and the upper head of the lateral pterygoid muscle have been removed to expose the lateral pterygoid plate and lower surface of the greater wing of the sphenoid adjacent to the foramen ovale. The tensor and levator veli palatini have been exposed below their attachment along the margins of the eustachian tube.* **C**, *the tensor and levator palatini have been removed to expose the cartilaginous and fibrous parts of the eustachian tube. The accessory meningeal branch of the maxillary artery passes through the foramen ovale and supplies the branches of the third trigeminal division and the tensor veli palatini.* **D**, *the medial part of the fibrous and cartilaginous parts of the eustachian tube have been removed to expose the petrous apex and foramen lacerum. The mucosa has been removed from the roof of the nasal cavity to expose the processus tubarius of the body of the sphenoid bone. Fibrocartilaginous tissue fills the foramen lacerum. The petrosphenoid sulcus extends along the junction of the petrous apex and greater* (Continues)

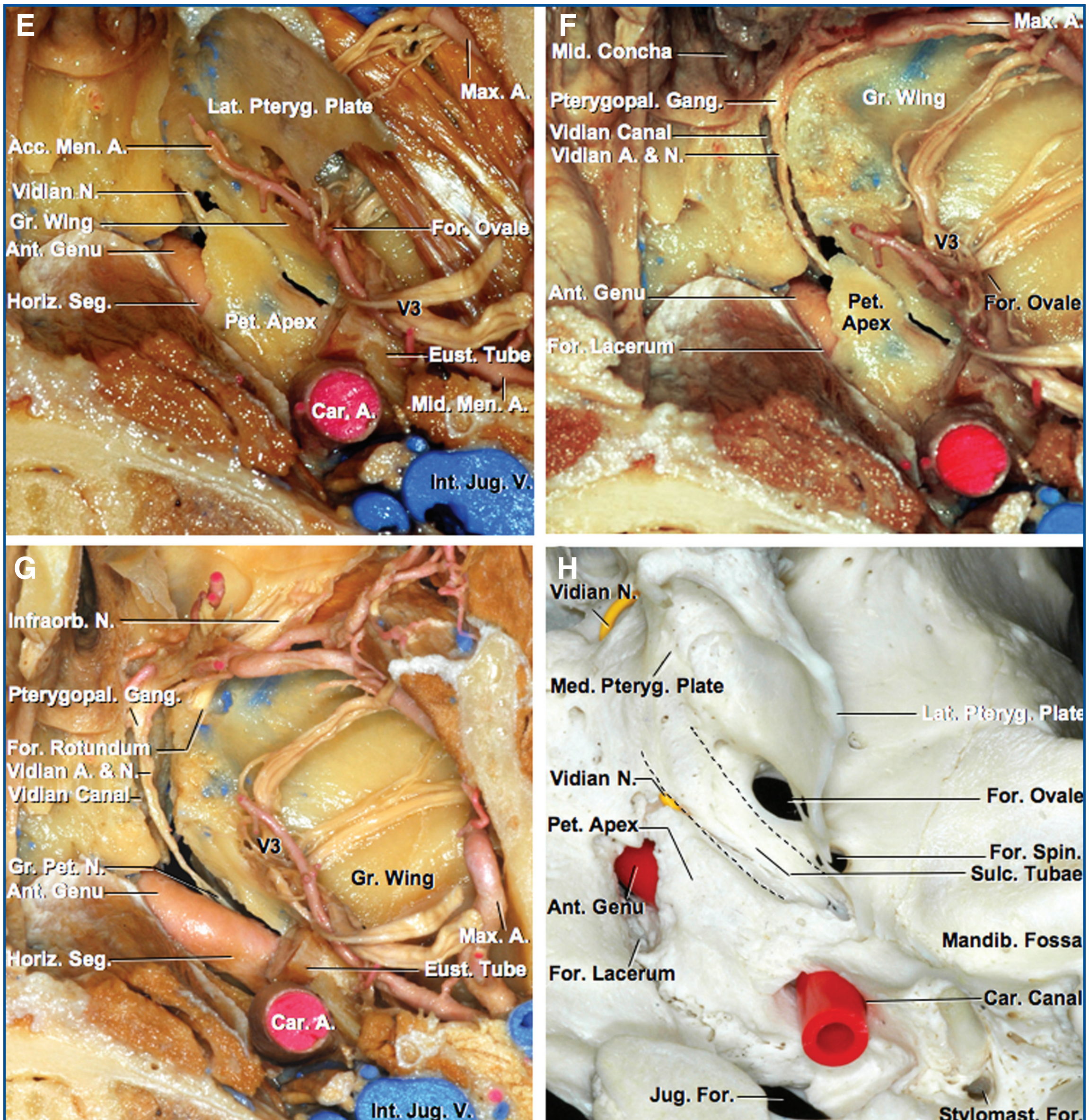

FIGURE 9. *(Continued)* *wing of the sphenoid.* **E**, *the cartilaginous tissue has been removed from the foramen lacerum to expose the anterior genu of the petrous carotid sitting above the foramen lacerum. The vidian nerve passes above the petrous apex, courses at the lateral edge of the foramen lacerum, and enters the vidian canal in the base of the pterygoid process of the sphenoid bone.* **F**, *the floor of the vidian canal, which courses in the base of the pterygoid process, has been drilled to expose the vidian nerve. The medial and lateral pterygoid plates and the pterygoid process were removed to expose the pterygopalatine fossa where the vidian nerve enters the pterygopalatine ganglion.* **G**, *the part of the petrous apex below the carotid canal has been removed to expose the horizontal segment of the petrous carotid. Some of the posterolateral portion of the eustachian tube has been preserved. The branches of the third trigeminal division are exposed below the foramen ovale in the infratemporal fossa.* **H**, *inferior view of skull base showing the course of the petrous carotid and vidian nerve. The petrous carotid enters the carotid canal and exits the skull base in the area above the foramen lacerum. The vidian nerve passes above the petrous apex to enter the vidian canal and forward to join the pterygopalatine ganglion in the pterygopalatine fossa. A., artery; Acc., accessory; Alv., alveolar; Ant., anterior; Cap., capitis; Car., carotid; Cerv., cervical; Eust., eustachian; For., foramen; Gang., ganglion; Gr., greater; Horiz., horizontal; Inf., inferior; Infraorb., infraorbital; Int., internal; Jug., jugular; Lat., lateral; Ling., lingual; Long., longus; M., muscle; Mandib., mandibular; Max., maxillary; Med., medial; Men., meningeal; Mid., middle; N., nerve; Pal., palatini; Pet., petro, petrous; Proc., processus; Pteryg., pterygoid; Pterygopal., pterygopalatine; Rec., rectus; Seg., segment; Sphen., sphenoid; Spin., spinosum; Stylomast., stylomastoid; Sulc., sulcus; Temp., temporal; Tens., tensor; V., vein.*

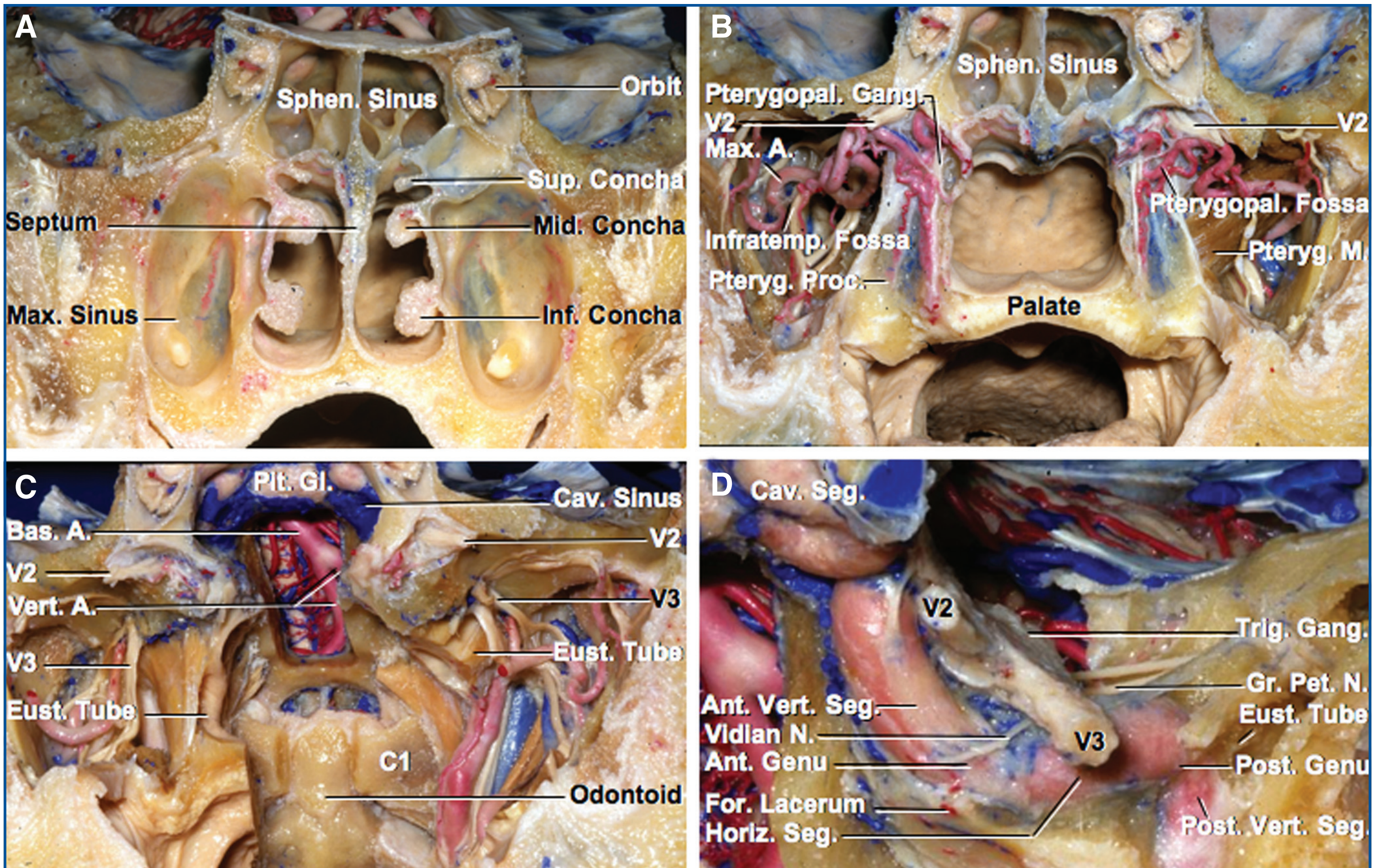

FIGURE 10. *Stepwise exposure of the petrous carotid from anterior section.* **A**, *anterior view of a coronal section through the sphenoid and maxillary sinuses, nasal cavity, orbits, and infratemporal fossa. The inferior, middle, and superior concha project medially from the lateral nasal wall.* **B**, *the posterior and lateral wall of the maxillary sinus has been removed to expose the pterygopalatine and infratemporal fossae. The pterygoid process of the sphenoid bone forms the posterior wall of the pterygopalatine fossa. The pterygopalatine ganglion is positioned at the anterior end of the vidian canal in the medial part of the pterygopalatine fossa. The maxillary nerve exits the foramen rotundum to enter the pterygopalatine fossa. The maxillary artery passes through the infratemporal fossa and enters the pterygopalatine fossa, where it gives rise to branches that follow the branches of the maxillary nerve. The infratemporal fossa, located below the greater wing of the sphenoid bone, contains the pterygoid muscles and venous plexus, branches of the third trigeminal division, and the maxillary artery.* **C**, *the wall of the sphenoid sinus has been removed to expose the cavernous sinus and pituitary gland. The pterygoid processes have been removed to expose the eustachian tube, which opens into the nasopharynx just behind the medial pterygoid plate. The anterior arch of C1 has been removed to expose the odontoid. The clivus has been opened to expose the vertebral and basilar arteries.* **D**, *the eustachian tube and floor of the left middle fossa have been removed to expose the upper cervical, petrous, and cavernous carotid. The petrous carotid is positioned behind the fibrous and cartilaginous parts of the eustachian tube, which has been removed. The anterior genu and anterior vertical segment are exposed below and medial to the trigeminal nerve. The greater petrosal nerve passes forward above the horizontal segment and joins the vidian nerve in the area above the foramen lacerum. The trigeminal ganglion and second and third divisions are exposed in the lateral wall of the cavernous sinus. The osseous portion of the eustachian tube is exposed lateral to the posterior genu of the cavernous carotid. A., artery; Ant., anterior; Bas., basilar; Cav., cavernous; Eust., eustachian; For., foramen; Gang., ganglion; Gl., gland; Gr., greater; Horiz., horizontal; Inf., inferior; Infratemp., infratemporal; M., muscle; Max., maxillary; Mid., middle; N., nerve; Pet., petrosal; Pit., pituitary; Post., posterior; Proc., process; Pteryg., pterygoid; Pterygopal., pterygopalatine; Seg., segment; Sphen., sphenoid; Sup., superior; Trig., trigeminal; Vert., vertebral, vertical.*

vation of the zygomatic arch, combined with extradural exposure and drilling the middle fossa floor to expose the petrous carotid and infratemporal fossa, can access the posterior vertical and horizontal segments and the posterior and anterior genua (Figs. 1, 2, and 13). Structures at risk of being damaged in these exposures include the tensor tympani muscle, eustachian tube, geniculate ganglion, cochlea, and facial and trigeminal nerves. The absence of bone covering the geniculate ganglion, as found in 16% of middle fossae in this study, places the nerve at risk in elevating that dura from the floor of the middle fossa. There are several reasons why the absence of bone over the geniculate ganglion is not readily noted during middle fossa surgical approaches. When exposed by the absence of bone, the ganglion does not protrude from the bone defect but remains flush with or slightly depressed from the surrounding bone surface. When such a bone defect is viewed from the side, as in the usual extradural subtemporal approach, the irregularities of the floor of the middle fossa may hide it or make it barely perceptible.

Because bleeding may result from elevation of the dura above the entrance into the facial canal, electrocoagulation should be avoided in such close proximity to the exposed facial nerve.

Another route across the middle fossa is the anterior petrosectomy approach, which uses resection of the anterior petrous pyramid via a temporal or frontotemporal exposure (Fig. 1). The degree of temporal lobe retraction required may be reduced by using an orbitozygomatic craniotomy or zygomatic arch resection. The area of the petrous apex removal extends from just posterior to the petrous carotid, medial to the internal auditory canal and behind the cochlea, to the petrous apex and petroclival junction. The petrous carotid may limit the surgeon's line of vision and restrict access to the inferior part of the petroclival region, but this restriction may be overcome with anterior mobilization of the artery (44, 46). The trigeminal nerve can be elevated to improve the exposure, although this may result in facial hypesthesia (18, 19). Although only a small window in the petrous bone is provided, exposure can be expanded by dividing the adjacent part of the tentorium. The lateral and anterior surfaces of the pons and the upper clivus and adjacent part of the cavernous sinus can be approached through this route directed behind the petrous carotid. The middle fossa approach can also be directed through the floor lateral to the internal acoustic meatus with exposure or removal of the semicircular canals, thus completing a middle fossa translabyrinthine approach to provide an extended middle fossa exposure of the posterior genu and horizontal segment (Fig. 5E).

A preauricular infratemporal fossa approach can also be used to access the upper cervical carotid and the posterior vertical segment, posterior genu, and horizontal segment (Fig. 8). This approach reaches the cranial base from an anterolateral direction. It uses the pathway anterior to the external auditory canal and the tympanic part of the temporal bone, which are exposed by division of the zygomatic arch, resection or downward displacement of the mandibular condyle, and extensive resection of the lateral part of the middle fossa floor. The approach exposes the infratemporal fossa and provides access to the upper cervical and petrous carotid and may access the para- and retropharyngeal areas, the nasopharynx, and the ethmoid, sphenoid, and maxillary sinuses and the lateral and basal aspects of the cavernous sinus. The approach allows the petrous carotid to be reflected forward out of the carotid canal after resection of the eustachian tube and tensor tympani. After reflecting the carotid artery forward out of the carotid canal, the petrous apex on the medial side of the carotid canal can be removed for exposure of the upper medial part of the posterior fossa. The approach alone can access the anterior part of the jugular foramen after reflecting the petrous portion anteriorly. Further extensive drilling will expose the middle to upper clivus.

The postauricular transtemporal approach, which allows a transmastoid exposure to be combined with exposure of the infratemporal fossa, may be used as an alternative to the preauricular infratemporal approach when the abnormality involves the mastoid and the infratemporal fossa and extends to the hypotympanic area and jugular bulb (Fig. 7) (8, 9, 43). The facial nerve is displaced anterosuperiorly and the sigmoid sinus may be ligated and divided. When this approach is combined with an infratemporal fossa exposure and anterior displacement of the petrous carotid, the petrous part of the temporal bone can be removed completely.

Lesions involving the anterior segments of the petrous carotid can be accessed through an intracranial or subcranial route or a combination of the 2 (Figs. 3 and 10). From above and anteriorly, the transcranial-transbasal approaches directed through the sphenoid sinuses can access the anterior vertical segment and anterior genu. These segments can also be accessed from anteriorly and below through the approaches directed through the sphenoid, the most localized of which is the transnasal transsphenoidal approach. Access to the petrous carotid is facilitated by the use of an endoscope to visualize the lateral walls of the sphenoid sinus, where the anterior genu and anterior vertical segments can often be seen under the mucosa and a thin shell of bone. The vidian nerve and canal can be followed along the floor of the sphenoid to the anterior genu (Fig. 3).

The distal horizontal segment, anterior genu, and anterior vertical segment can also be exposed in a wide variety of anterior subcranial approaches that access the sphenoid sinus, infratemporal fossa, or petrous apex (24, 33, 35–38). These include the transoral approach, with division of the soft palate or removal of a part of the hard palate; a medial maxillotomy, often combined with a lateral rhinotomy; and a bilateral maxillotomy, as with a Le Fort osteotomy or the unilateral upper or lower subtotal maxillotomy, all of which may provide access to the sphenoid sinus, petrous apex, and infratemporal and pterygopalatine fossae (12, 13). The lateral and posterolateral approaches may provide better access to the temporal bone, jugular foramen, and posterior segments of the petrous carotid than these anterior approaches.

Bypass from the cervical to the petrous segment or from the petrous segment to the supraclinoid carotid have provided an alternative to other bypass procedures (22, 51). There is a 10 mm length of petrous carotid, a length suitable for bypass grafting, lateral to the trigeminal ganglion that can be exposed by drilling the roof of the horizontal segment (Fig. 5) (28). It has been assumed that there is antegrade thrombosis at least to the level of the origin of the ophthalmic artery after occlusion of the ICA in the neck. However, there is evidence to suggest that antegrade thrombosis does not extend into the petrous canal, thus making it a suitable site for the distal end of a graft from the cervical carotid in selected cases. Angiographic patency of the cavernous and petrous carotid arteries has been demonstrated in ICA occlusions. It is postulated that the petrous and cavernous branches allow the retrograde flow needed to maintain the patency of these segments (6, 47).

Petrous carotid aneurysms may be of congenital (60%), traumatic (22%), postinfectious (9%), or atherosclerotic (9%) origin (11, 24, 40, 41, 47). One-half arise near the posterior genu and project posterior and lateral. The horizontal segment is a more frequent site than the posterior vertical segment. The diagnosis of petrous carotid aneurysm has occasionally been made only after a biopsy specimen was taken for a presumed tumor. Approximately one-third of the cases present with epistaxis or aural hemorrhage after trauma or myringotomy. Epistaxis was more common than aural hemorrhage (24, 28). The bleeding

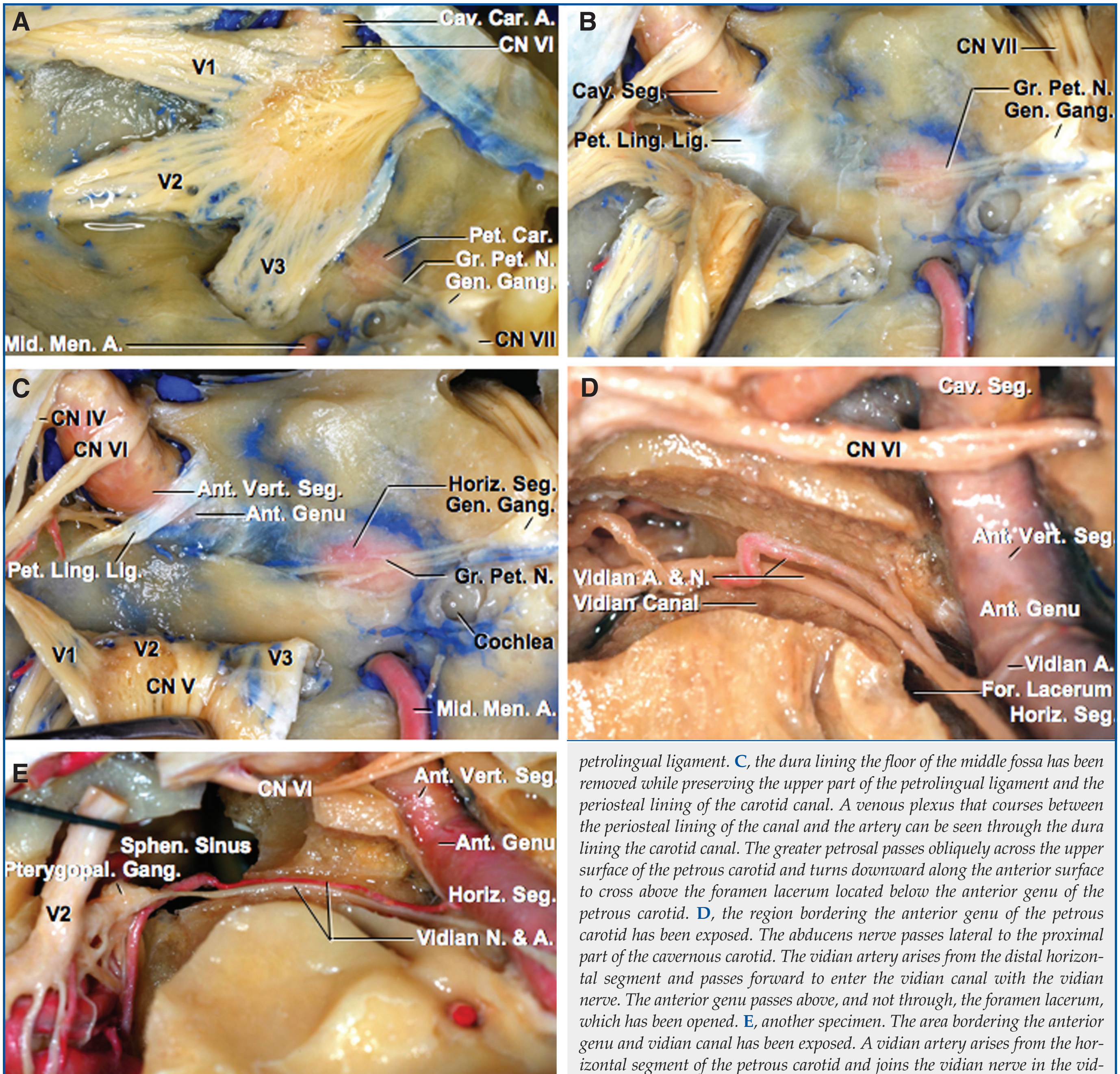

FIGURE 11. *Branches of the petrous carotid artery.* **A–D**, *stepwise dissection of a left middle fossa.* **A**, *lateral view. A short segment of the petrous carotid artery is exposed under the dura at the lateral margin of the V3. The geniculate ganglion and facial nerve have been exposed. The greater petrosal nerve exits the geniculate ganglion and passes anteromedial above the petrous carotid.* **B**, *the trigeminal nerve has been reflected forward to expose the petrolingual ligament. This petrolingual ligament is formed at the point where the dura lining the carotid canal is reflected laterally to cover the middle fossa floor. Reflecting the trigeminal nerve forward exposes the abducens nerve coursing around the lateral margin of the cavernous carotid above the petrolingual ligament.* **C**, *the dura lining the floor of the middle fossa has been removed while preserving the upper part of the petrolingual ligament and the periosteal lining of the carotid canal. A venous plexus that courses between the periosteal lining of the canal and the artery can be seen through the dura lining the carotid canal. The greater petrosal passes obliquely across the upper surface of the petrous carotid and turns downward along the anterior surface to cross above the foramen lacerum located below the anterior genu of the petrous carotid.* **D**, *the region bordering the anterior genu of the petrous carotid has been exposed. The abducens nerve passes lateral to the proximal part of the cavernous carotid. The vidian artery arises from the distal horizontal segment and passes forward to enter the vidian canal with the vidian nerve. The anterior genu passes above, and not through, the foramen lacerum, which has been opened.* **E**, *another specimen. The area bordering the anterior genu and vidian canal has been exposed. A vidian artery arises from the horizontal segment of the petrous carotid and joins the vidian nerve in the vidian canal. The vidian artery anastomoses with the maxillary artery in the pterygopalatine fossa. The vidian nerve ends in the pterygopalatine ganglion. The V2 also passes through the pterygopalatine fossa and has multiple anastomoses with the pterygopalatine ganglion.* **F**, *another petrous carotid. The petrolingual ligament and abducens nerve cross the lateral surface of the cavernous carotid. The greater petrosal nerve passes, not above, but anterior to the petrous carotid and turns downward along the anterior wall of the carotid canal, where it is joined above the foramen lacerum by a vidian artery. The vidian artery and nerve pass forward inside the sheath lining the vidian canal. A bundle of the carotid nerve plexus ascends on the surface of the petrous carotid and joins the abducens nerve (green arrow).* (Continues)

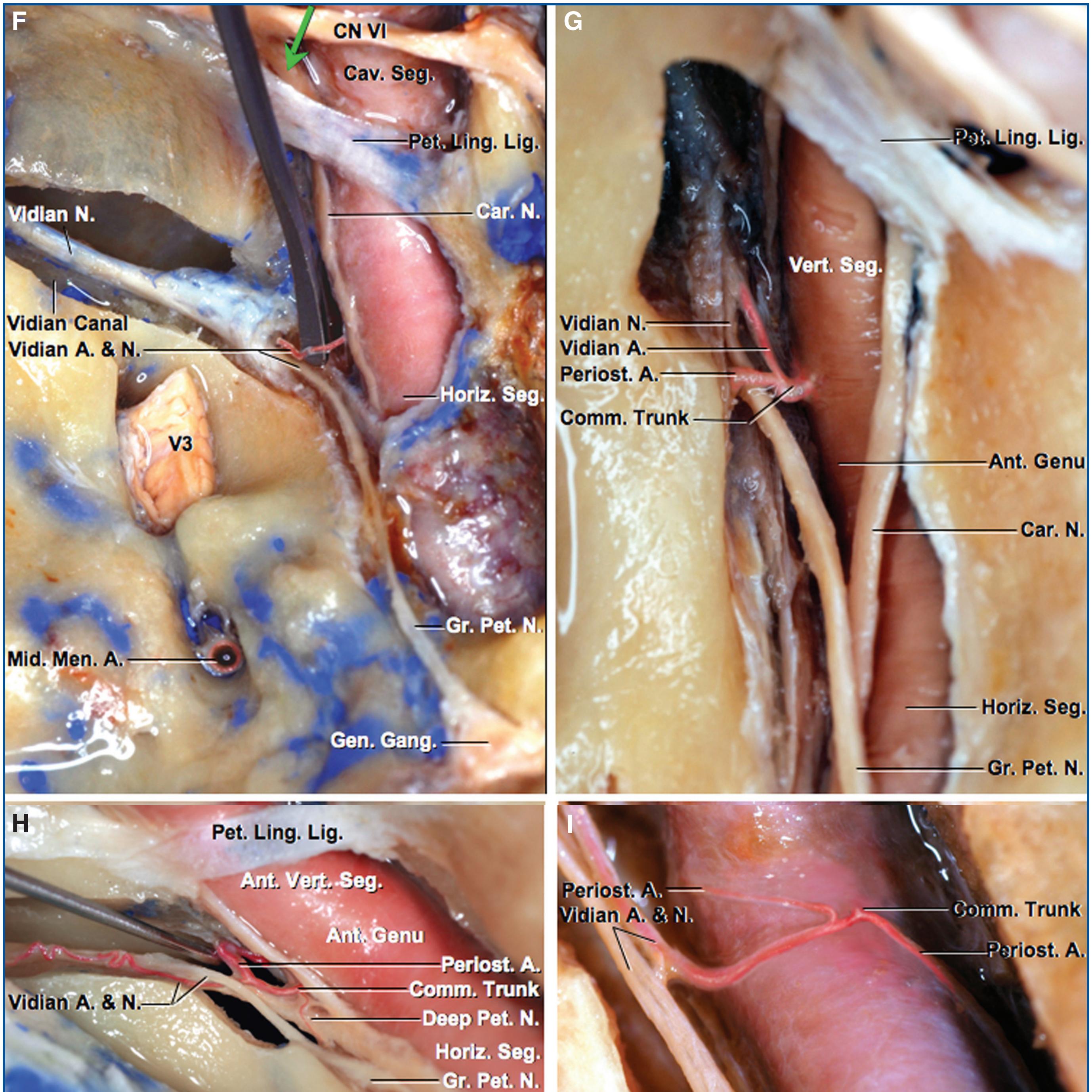

FIGURE 11. (Continued) **G**, *the distal horizontal segment, anterior genu, and anterior vertical segment of another petrous carotid have been exposed. The greater petrosal nerve passes above and anterior to the petrous carotid and above the foramen lacerum, where it is joined by a vidian artery that arises in a common trunk with a periosteal branch. The vidian artery enters the vidian canal with the vidian nerve.* **H**, *a common trunk arises from the anterior genu of the petrous carotid and gives rise to a vidian and periosteal artery. The deep petrosal nerve, a branch of the carotid neural plexus, joins the greater petrosal nerve to form the vidian nerve.* **I**, *a common trunk that arises from the distal horizontal segment gives rise to both a vidian and a periosteal artery. The vidian artery also gives rise to a small periosteal artery near its origin. A., artery; Ant., anterior; Car., carotid; Cav., cavernous; CN, cranial nerve; Comm., common; For., foramen; Gang., ganglion; Gen., geniculate; Gr., greater; Horiz., horizontal; Lig., ligament; Ling., lingual; Men., meningeal; Mid., middle; N., nerve; Periost., periosteal; Pet., petro, petrosal, petrous; Peterygopal., pterygopalatine; Seg., segment; Sphen., sphenoid; Vert., vertical.*

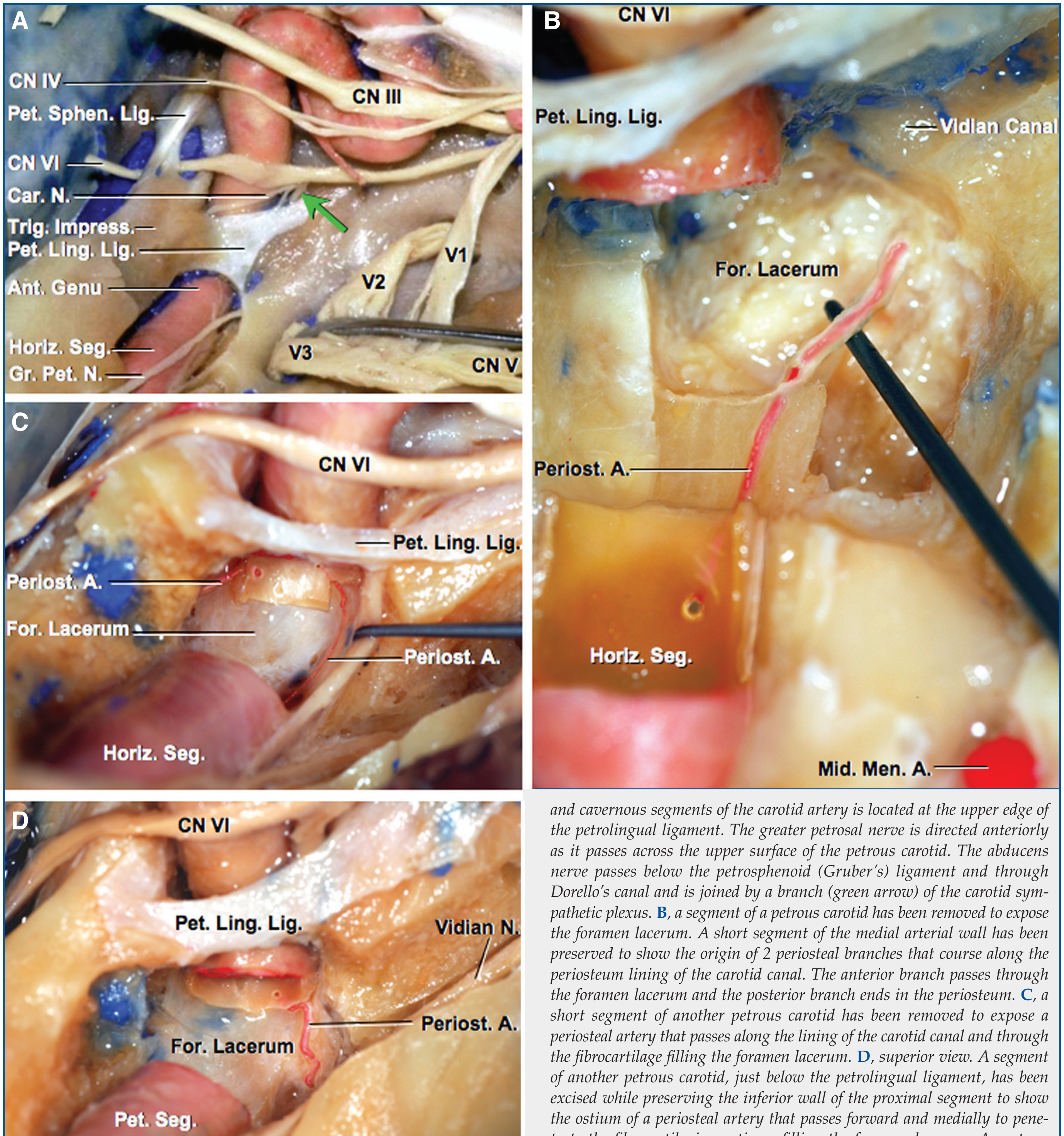

FIGURE 12. *Periosteal branches of the petrous carotid.* **A**, *right middle fossa and cavernous sinus.* **B–D** *are oriented as shown in* **A**. *The dura has been elevated from the middle fossa floor and the trigeminal nerve has been reflected forward to expose the petrolingual ligament, the terminal part of the petrous carotid, and the trigeminal impression. The junction of the petrous and cavernous segments of the carotid artery is located at the upper edge of the petrolingual ligament. The greater petrosal nerve is directed anteriorly as it passes across the upper surface of the petrous carotid. The abducens nerve passes below the petrosphenoid (Gruber's) ligament and through Dorello's canal and is joined by a branch (green arrow) of the carotid sympathetic plexus.* **B**, *a segment of a petrous carotid has been removed to expose the foramen lacerum. A short segment of the medial arterial wall has been preserved to show the origin of 2 periosteal branches that course along the periosteum lining of the carotid canal. The anterior branch passes through the foramen lacerum and the posterior branch ends in the periosteum.* **C**, *a short segment of another petrous carotid has been removed to expose a periosteal artery that passes along the lining of the carotid canal and through the fibrocartilage filling the foramen lacerum.* **D**, *superior view. A segment of another petrous carotid, just below the petrolingual ligament, has been excised while preserving the inferior wall of the proximal segment to show the ostium of a periosteal artery that passes forward and medially to penetrate the fibrocartilaginous tissue filling the foramen lacerum. A., artery; Ant., anterior; Car., carotid; CN, cranial nerve; For., foramen; Gr., greater; Horiz., horizontal; Impress., impression; Lig., ligament; Ling., lingual; Men., meningeal; Mid., middle; N., nerve; Periost., periosteal; Pet., petro, petrosal, petrous; Seg., segment; Sphen., sphenoid; Trig., trigeminal.*

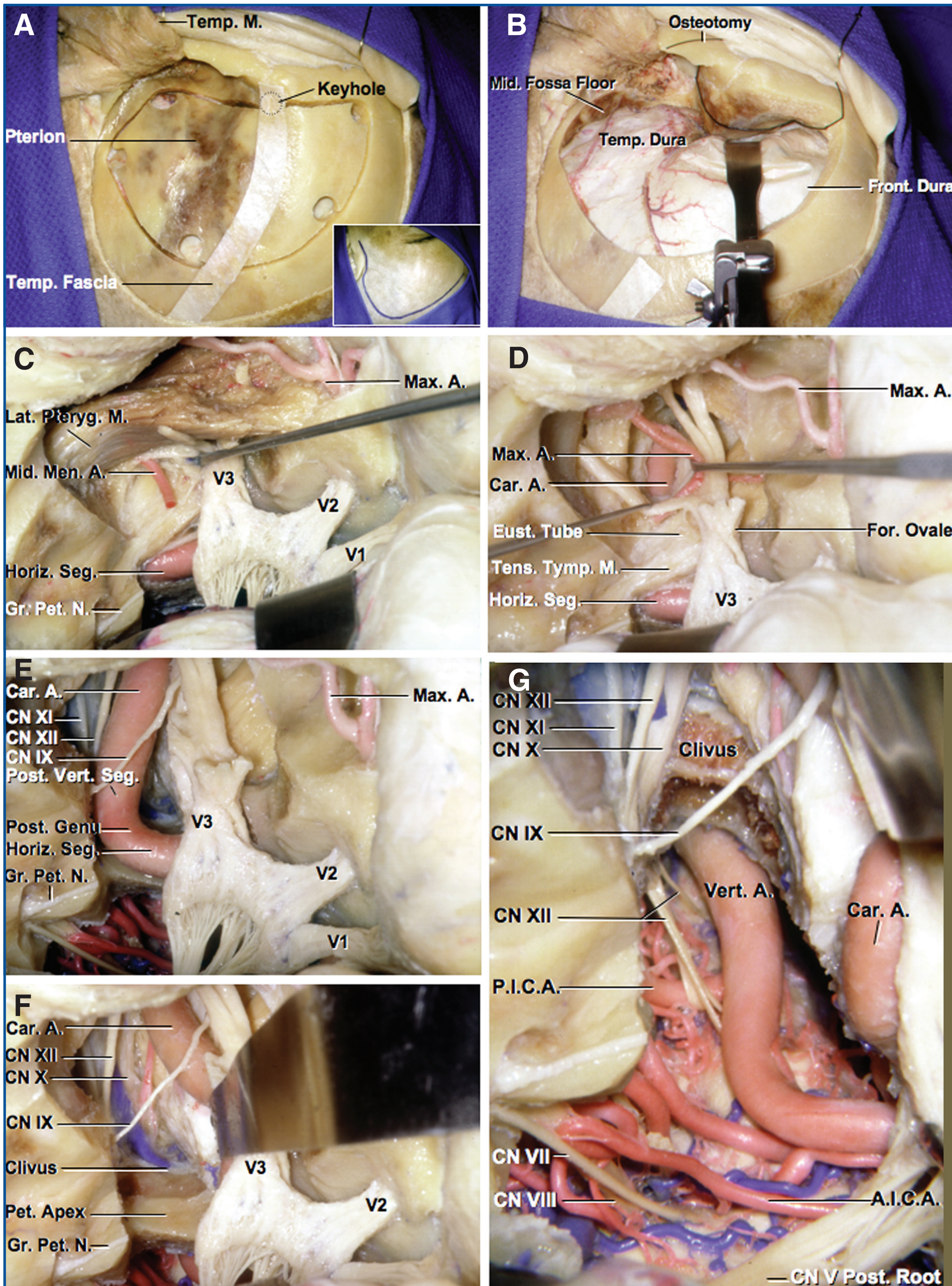

FIGURE 13. *Three-piece orbitozygomatic craniotomy with exposure and transposition of the petrous carotid.* **A**, *inset shows the site of the skin incision. The first osteotomy divides the anterior and posterior end of the zygomatic arch so that the arch and temporalis muscle can be folded downward to increase the exposure of the middle fossa. The second bone cut is around the pterional bone flap, which has been completed, and the third cut is the orbitozygomatic osteotomy.* **B**, *the dura has been elevated from the roof and lateral wall of the orbit and the sphenoid ridge has been removed. The third piece, the orbitozygomatic osteotomy, includes the roof and the portion of the lateral wall of the orbit as outlined.* **C**, *the floor of the middle fossa has been removed to expose the mandibular nerve, lateral pterygoid muscle, and terminal part of the maxillary artery in the infratemporal fossa. The bone lateral to the trigeminal nerve has been removed to expose the horizontal segment.* **D**, *the cervical carotid and the branches of the mandibular nerve have been exposed in the infratemporal area. The eustachian tube and tensor tympani muscle are layered along the anterior margin of the horizontal segment.* **E**, *the tensor tympani and eustachian tube have been resected to expose the posterior genu and posterior vertical and horizontal segments.* **F**, *the petrous carotid has been reflected forward to expose the petrous apex and clivus on the medial side of the carotid canal.* **G**, *the petrous apex and lateral part of the clivus have been removed and the dura opened to expose the pons, medulla, anterior and posterior inferior cerebellar and vertebral arteries, and hypoglossal nerve. The opening through the petrous apex and clivus is located anterior to where Cranial Nerves IX to XII exit the jugular foramen. A., artery; A.I.C.A., anterior inferior cerebellar artery; Car., carotid; CN, cranial nerve; Eust., eustachian; For., foramen; Front., frontal; Gr., greater; Horiz., horizontal; Lat., lateral; M., muscle; Max., maxillary; Men., meningeal; Mid., middle; N., nerve; Pet., petrosal, petrous; P.I.C.A., posterior inferior cerebellar artery; Post., posterior; Pteryg., pterygoid; Seg., segment; Temp., temporal; Tens., tensor; Tymp., tympani; Vert., vertebral.*

has been controlled by packing the artery or carotid occlusion (5, 24). Other presenting symptoms included hearing loss and tinnitus, diplopia caused by extraocular nerve involvement, and trigeminal dysfunction.

CONCLUSION

An understanding of the complex relationships of the petrous carotid provides the basis for exposing any 1 or more of its 5 segments. The branches of the petrous carotid play an important role in maintaining its patency and making it a suitable site for bypass after proximal internal carotid occlusion.

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COMMENTS

In this anatomic study 20 middle fossae from adult cadaveric specimens injected with colored silicone were examined under ×3 to ×40 microscopic magnification. The title of the article is somewhat misleading, as the study is not focused purely on the petrous carotid artery. Osawa et al. described the various segments of artery as well as the microanatomy of adjacent structures that might be involved by various pathological lesions and/or might be exposed in the transpetrosal, subtemporal, infratemporal, transnasal, transmaxillary, transfacial, and a variety of transcranial routes.

The article comes from the renowned microanatomic laboratory of the senior author. In the tradition of all his previous works, it incorporates a precise and accurate dissection technique, detailed description and brilliant color illustrations of the corresponding anatomy at each stage, and emphasis on the surgical significance of both the normal anatomy and of its variations. Perfect knowledge of anatomical structures guides the surgical strategy and is a prerequisite for avoidance of complications. Interestingly, Osawa et al. found that 70% of the petrous carotid arteries had branches, either a vidian, a periosteal artery, or a common trunk that gave rise to both a vidian and one or more periosteal arteries. A periosteal artery was the most frequent branch.

Although one should always be aware that the normal microanatomy does not correspond completely to the anatomy that we see intraoperatively, this article would be of great value both for those applying microsurgical or endoscopic techniques.

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Hannover, Germany

Osawa et al. presented a detailed analysis of the anatomy of the petrous ICA, building on the senior author's seminal work published more than 30 years ago in 1977 (1). The surgical exposure of the petrous carotid artery is not simplistic, and the data presented in this article will help readers understand, identify, and avoid, the potential pitfalls that may be encountered during this endeavor.

The postauricular transtemporal approach illustrated in Figure 7 in the article typically results in at least a conductive hearing loss owing to removal of the external auditory canal and middle ear structures. If further exposure is desired the cochlea must be removed with resultant complete loss of hearing. Facial nerve transposition can further enhance the exposure of the petrous ICA from this approach, but some degree of permanent facial paralysis will certainly ensue. The advantage of the preauricular infratemporal fossa approach is the anterior trajectory that avoids the need for sacrifice of the external auditory canal, tympanic bone, or cochlea, with subsequent preservation of hearing. Disruption of the temporomandibular joint and of the muscles of the infratemporal fossa can, however, result in pain, malocclusion, and trismus. One other point about both of these routes of exposure relates to the difficulty of separation of the petrous ICA from the periosteum of the carotid canal at its entrance and adjacent posterior vertical segment where, as described by the authors, it is bound down by dense fibrous bands that are extensions of the carotid sheath. To safely expose this area the bone of the canal needs to be carefully removed with a high-speed drill and the dense bands need to be sharply divided. One should not attempt to advance surgical instruments into the canal as arterial laceration may occur.

The detailed anatomic description of the vidian artery and canal and their relationship to the horizontal and anterior vertical segments of the petrous carotid are particularly welcome and timely. During extended endoscopic approaches to the cranial base, the vidian neurovascular bundle is identified and used as a vital anatomic landmark, which leads the surgeon to the petrous internal carotid artery.

This article represents a great deal of work and a commitment to excellence that we have come to expect from this group. We in the field of neurosurgery collectively benefit from their efforts.

Franco DeMonte
Houston, Texas

Osawa et al. have provided an outstanding anatomic study of the petrous internal carotid artery (ICA), which, of course, has been described by other authors. One controversial issue here is where the petrous segment ends and the cavernous segment starts. We have thus described a transitional "trigeminal segment" (2) and Bouthillier et al. (1) have described a "lacerum segment." The practical application of this classification is that this is the most difficult segment to expose surgically from any approach.

The branches of the petrous ICA are mostly important for endovascular surgery, because they may be collateral channels connecting to branches of the external carotid artery and, therefore, could be a route through which the ICA could be inadvertently embolized during external carotid artery embolization procedures. The aberrant courses of the petrous ICA are very important, as that course may result in injury by ear, nose, and throat surgeons. The horizontal segment of the petrous ICA is well exposed by a middle fossa approach (in practice, a temporal craniotomy, combined with a zygomatic osterotomy) and the entire artery via a preauricular subtemporal-infratemporal approach. The latter approach can be now performed without resection of the mandibular condyle by using a zygomatic osteotomy incorporating the condylar fossa. Resection of the Eustachian tube is not required for the exposure of the artery but is necessary for its translocation to allow resection of tumors that lie medial to it. Such tumors usually are chondrosarcomas, chordomas, extensive paragangliomas, or lower cranial nerve schwannomas. Aneurysms of the petrous ICA can usually be treated by an endovascular approach, however, if the collateral vessels are inadequate, then a bypass may be performed into the horizontal segment (if it is not diseased) or into the supraclinoid ICA or the middle cerebral artery.

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1. Bouthillier A, van Loveren HR, Keller JT: Segments of the internal carotid artery: A new classification. **Neurosurgery** 38:425–433, 1996.
2. Ziyal IM, Ozgen T, Sekhar LN, Ozcan OE, Cekirge S: Proposed classification of segments of the internal carotid artery: anatomic study with angiographical interpretation. **Neurol Med Chir (Tokyo)** 45:184–190, 2005.

Osawa et al. have provided an elegant and thorough description of the anatomy and surgical exposures of the petrous segment of the internal carotid artery. A thorough understanding of the middle fossa cranial base and its relation to the petrous segment are important for both cerebrovascular and cranial base surgeons alike. Although not used commonly, access to the horizontal segment in an atraumatic fashion is useful for proximal control of the internal carotid artery and for a proximal anastomosis site for a short bypass graft to the supraclinoid carotid. They have provided an important contribution to the neurosurgical and anatomic literature.

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Daniel L. Barrow
Atlanta, Georgia