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Surgical anatomy of the petrous apex and petroclival region

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Abstract

Surgical exposure of the clivus, the ventral or lateral aspect of the brain stem, and all the intradural structures of the petroclival area remains difficult because of the presence of the petrous apex and peripetrous complex. However, a lateral skull base approach to the petroclival area is the most suitable approach if the lesion to be resected lies medial to the fifth nerve, in front of the acousticofacial bundles, extending towards the midline. The purpose of this study is to review the topographic anatomy of the petrous apex and peripetrous structures, with emphasis on the relationships important to the lateral approaches to the petroclival area. Such anatomical knowledge allows us to study the surgical technique, exposure, and pitfalls of the main lateral transpetrosal skull base approaches used to reach the petroclival area.

Keywords: Anatomy; petroclival tumors; petrous apex; transpetrosal approach; skull base.

Introduction (Fig. 1)

The petroclival region is a surgical entity rather than an anatomical one, recognized because of specific diseases, notably petroclival tumors. It is defined as including the upper clivus and the anterior third of the petrous pyramid in front of the internal acoustic meatus. The term petroclival tumor refers to a lesion originating or inserted in the upper two-thirds of the clivus or the petrous apex, medial to the trigeminal nerve. This definition distinguishes these tumors from lesions of the cerebellopontine angle or the posterior face of the petrous portion of the temporal bone, which originate or are inserted further back and which therefore do not entail the same surgical problems. Structures close to the clival dura mater are often involved by growing tumor masses in this region and in consequence, the cavernous sinus, the Meckel's cave, the sphenoidal sinus, the sellar region, the incisure of the tentorium, the porus and the ventral edge of the foramen magnum may be encroached

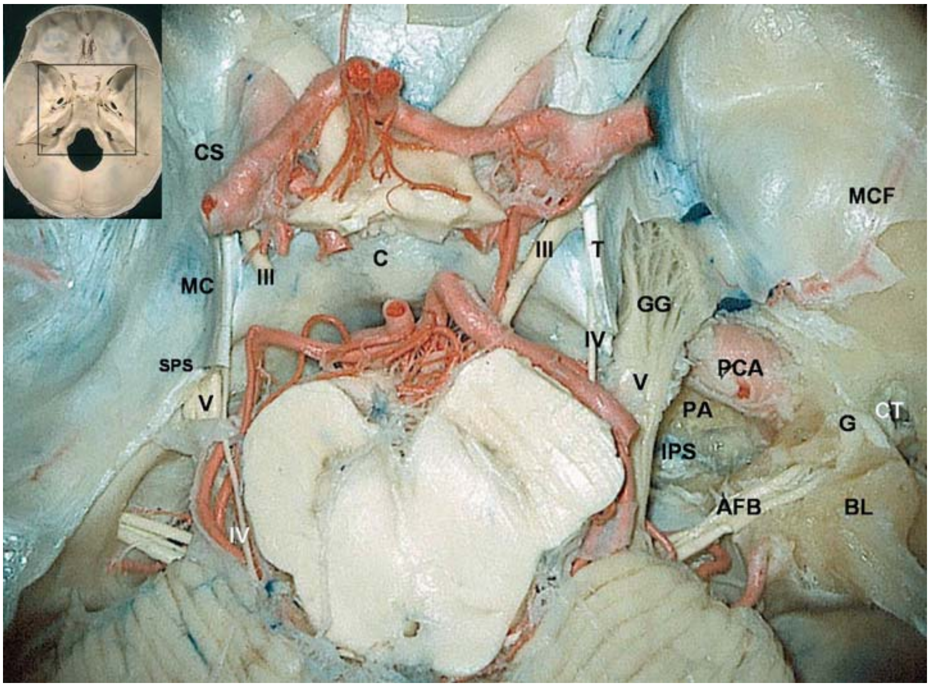


Fig. 1. Superior view of a cadaver skull base: the right middle cranial fossa has been drilled. See both petroclival areas. *CS* Cavernous sinus; *MC* Meckel's cave; *SPS* superior petrosal sinus; *C* clivus; *GG* gasserian ganglion; *T* tentorium; *PCA* petrous carotid artery; *PA* petrous apex; *IPS* inferior petrosal sinus; *MCF* middle cranial fossa; *AFB* acousticofacial bundles; *G* geniculate ganglion; *BL* bony labyrinth; *CT* cavum tympani; *III* 3rd cranial nerve; *IV* 4th cranial nerve; *V* 5th cranial nerve

upon and may need to be exposed. A lateral transpetrosal approach to this petroclival region is indicated when exposure is required beyond the lateral face of the cavernous carotid and, even more so, the petrous apex and the gasserian area. The main advantage of the lateral approach is that it creates considerably broader exposure than other approaches (e.g. a cisternal approach) at the same time as reducing cerebral retraction. Without any claim to solving all the problems of surgery of the skull base, such approaches bypass the potential pitfall represented in front by the septic craniofacial cavities and behind by the cerebellum and the brain stem itself. The problems boil down to those associated with the petrous and peripetrous barriers but these approaches probably constitute the shortest route to the clivus and the ventral surface of the brain stem.

Distinction can be made between two main types of lateral approach to the petroclival region and the ventral surface of the brain stem: antero-lateral approaches (in front of the cochlea) and posterolateral ones (which may or may not cover the labyrinthine mass). Almost every new description corresponds to a modification of an approach which is basically anterior or posterior and which constitutes one of the fundamental approaches already described.

Topographic anatomy

The petroclival region is a small cisternal space located in the most anterior part of the posterior cranial fossa (Fig. 2). It is defined by complex osteomeningeal edges but at the top, it opens onto the supratentorial sector, at the bottom onto the peribulbar area, and behind onto the area of the cerebellopontine angle. Various neurovascular structures pass through this space.

It is deeply located, below base of the brain and in front of the cerebellum. In front, it is blocked by the clivus and on the side, by the anterior third of the petrous pyramids and peripetrous elements. It is particularly difficult to expose the endocranial face of the clivus, the vertical aspect of the posterior face of the petrous portion of the temporal bone, the ventral surface of the brain stem, and all the intradural elements of the petroclival

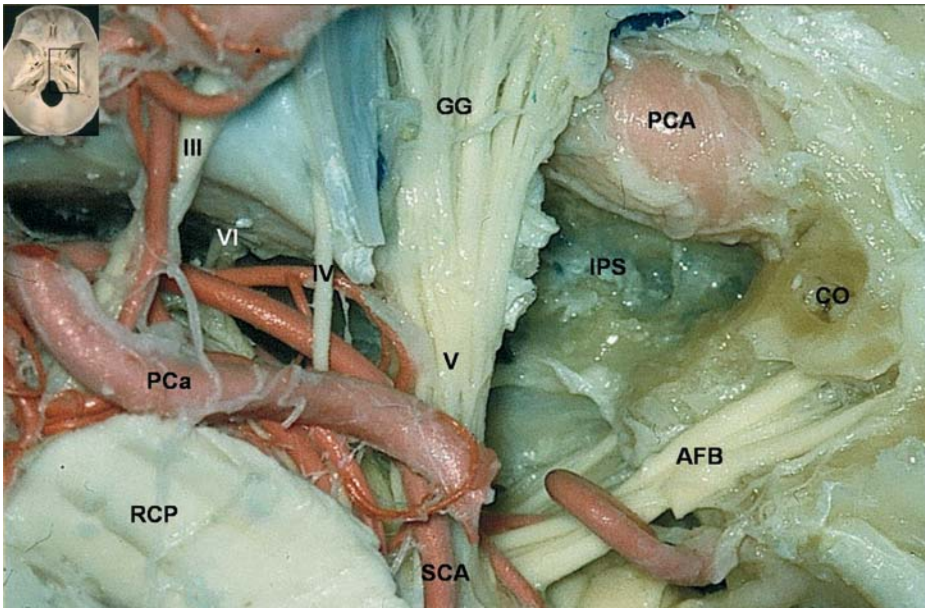


Fig. 2. Superior view of the right petroclival area: see the relationships between the petrous apex, the Vth nerve, and the petroclival area. *VI* 6th Cranial nerve; *PCa* posterior cerebral artery; *RCP* right cerebral peduncle; *SCA* superior cerebellar artery; *CO* cochlea; *GG* gasserian ganglion; *PCA* petrous carotid artery; *IPS* inferior petrosal sinus; *AFB* acousticofacial bundles

region, because of the presence of an "anatomical complex" comprising the following:

– The cavities of the petrous bone and what they contain (the middle ear, the bony labyrinth including the semicircular canals and the cochlea, the intra-petrous carotid in the carotid canal, and the facial nerve in the internal acoustic meatus and the fallopian canal).
– The dural sinuses (the superior and inferior petrosal sinuses)

To introduce the anatomical review of the surgical approaches, we will describe the complex of the petrous apex and its relationships with the main elements of the petrous pyramid. We will then focus on the region to which these approaches give access, namely the ventrolateral face of the brain stem and the cisternal petroclival region. We will also detail the cisternal configuration of the cranial nerves which are the elements that account for the morbidity associated with surgery in this region.

Petrous apex and its relationships within the petrous complex (Fig. 3)

The petrous apex or the apex of the petrous portion of the temporal bone comprises an upper surface which is part of the middle cranial fossa, and the anterior third of the posterior face of the petrous portion of the temporal bone which we are describing here. Triangular in shape with an anterior apex, both sides are clearly defined, at the top by the petrous ridge (which is the sulcus of the superior petrosal sinus [SPS]) and at the bottom by the petroclival suture (which itself forms a groove – that of the inferior petrosal sinus (IPS). Only the base of this triangle is an artificial boundary defined by a virtual line drawn vertically straight down from anterior edge of the porus acousticus. It should be specified here that the texture of the bone at the apex varies. As a rule, once the cortical is open, the bone is relatively soft, spongy and adipose – depending on the patient's age. However, in some cases, there is extensive pneumatization which helps when drilling. Moreover, it may be infiltrated by the tumor itself in which case it assumes the consistency of the tumor, be it a meningioma, a chordoma or an epidermoid cyst.

Superior aspect of the middle cranial fossa

This is formed by a forward concave face centered on the foramen spinosum, and a posterior convex face centered on the relief of the arcuate eminence. Continuous with the temporal scala, we will first address the tegmen tympani, a thin layer of bone which forms the roof of the tympanic cavity. Inside and behind the tegmen, there is the arcuate eminence, close to the petrous crest, where the external one-third and the internal two-thirds meet. This relief feature is an

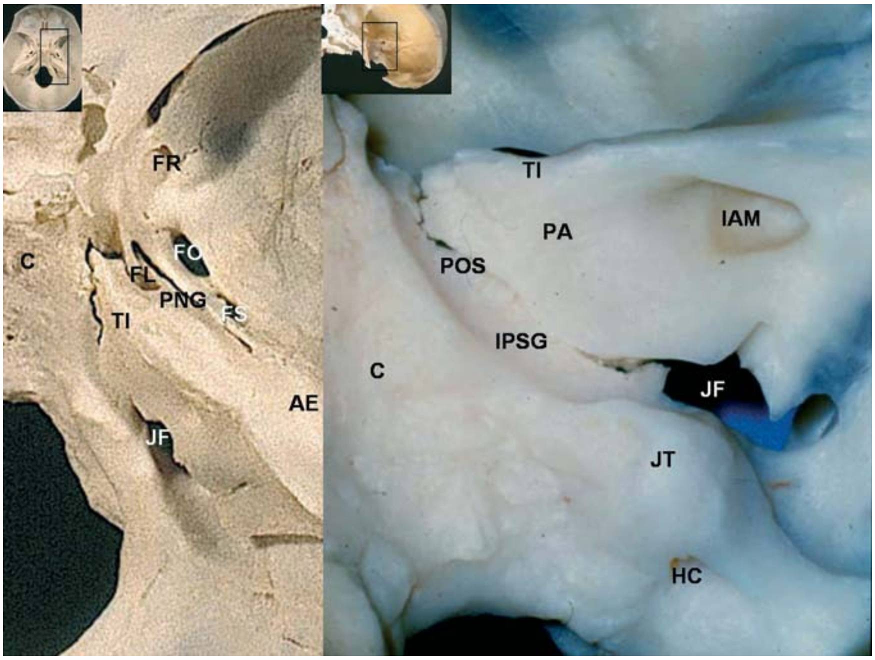


Fig. 3. Dry specimen of a right petrous bone: (A) Superior view, (B) lateral view. *C* Clivus; *FR* Foramen rotundum; *FO* foramen ovale; *FL* foramen lacerum; *TI* trigeminal incisura; *PNG* petrosal nerves groove; *FS* foramen spinosum; *JF* jugular foramen; *AE* arcuate eminence; *POS* petrooccipital suture; *PA* petrous apex; *IPSG* inferior petrosal sinus groove; *IAM* internal acoustic meatus; *JT* jugular tubercle; *HC* hypoglossal canal

important landmark since it can be used to locate the upper or anterior semicircular canal, the loop of which is found between 1 and 3.5 mm below the ventromedial face [31]. In front of the arcuate eminence, there is the meatal space which corresponds to the roof of the internal acoustic meatus. In front of the meatal space, there is a prominence out over the fossa or trigeminal pit on the petrous apex. Inside this relief is the foramen lacerum. This broad opening is oblique in front and inside and is located between the petrous apex and the dorsolateral wall of the sphenoidal sinus. Its lower half is filled with fibrocartilaginous tissue. It measures approximately one centimeter in length and is not completely traversed by the internal carotid [30]. The carotid only crosses the upper half of the foramen lacerum. It passes over and not across the lower half of the opening. The terminal part of the horizontal segment of the carotid canal opens at its upper half. The medial part of this foramen may or may not be covered in bone, exposing or hiding the horizontal segment of the intrapetrous carotid at the floor of the middle cranial fossa. Outside of the foramen lacerum, there is the sulcus of the greater petrosal nerve which comes from the hiatus of the canal for the lesser petrosal nerve which is located in front and inside the arcuate eminence. The lesser petrosal nerve, coming from the accessory hiatus, runs parallel to the former. The foramen ovale is anteromedial to the foramen spinosum. These two openings located in front of the carotid canal do not belong the petrous bone but their relationships need to be considered. The foramen spinosum is on average 4.7 mm (2.5 to 8) from the carotid canal [30]. A line joining the centers of these two foramina is parallel to the axis of the horizontal segment of the intrapetrous carotid, thus constituting an important landmark once this segment has been exposed via an extradural approach [43, 44].

Posterior aspect of the petrous pyramid

This vertical structure is defined behind by the impression of the sigmoid sinus and at the bottom by the very wide groove of the inferior petrosal sinus, deeply marking the petro-occipital suture. The internal acoustic meatus, opening behind via its porus, is located just below the petrous crest which provides a thick upper edge for this opening. The fundus of the internal acoustic meatus is divided into four parts by vertical and transverse crests [29, 33]. The antero-superior quadrant corresponds to the passage of the facial nerve, the antero-inferior one to the cochlear nerve, and the postero-superior and postero-inferior quadrants to the upper and lower vestibular nerves respectively. The endolymphatic fossa, located one centimeter behind the porus, gives passage to the endolymphatic sac, a blind bulge of the endolymphatic canal which is in contact with the dura mater and which has to be protected if hearing is to be preserved. The posterior face of the petrous portion of the temporal bone cannot be described without brief mention of the lateral mass of the occipital. In the prolongation of the sulcus of the inferior petrosal sinus, this structure represents the lower lip of the endocranial opening of the jugular foramen. The jugular tubercle projects out from the lateral mass over the hypoglossal canal which it separates from the jugular foramen. The endocranial opening of the jugular foramen is divided in two by the jugular spine of the temporal bone: laterally, the jugular indentation which gives passage to the gulf of the jugular vein, and medially, the pyramidal fossa which gives passage to the lower cranial nerves. The pyramidal fossa terminates the sulcus of the inferior petrosal sinus in front, and the jugular indentation represents the termination of the sulcus of the sigmoid sinus.

Intrapetrous cavities and their relationships

We will begin by describing these cavities on dry specimen in order to understand how they are organized in space and their various inter-relationships. Then, by means of views from above of dissections through the middle cranial fossa, we will describe the cavities in the context of the regional anatomy as a whole, treating them as inseparable from their contents.

Inner ear, carotid canal and fallopian canal on dry specimen dissection: installation (Fig. 4)

Most of the inner ear is constituted by the bony labyrinth. It comprises an anterior and a posterior segment. The former is formed by the cochlea and the latter includes the semicircular canals and the vestibule. It is about two centimeters in length and is located in the middle part of the greater axis of the pyramid. The labyrinth is particularly well described in Pellet and Cannoni [31] so we will only address those structures which are relevant to our dissections. The superior or anterior, horizontal or lateral and posterior semicircular canals form incomplete loops with a diameter of 7–8 millimeters, arranged in an orthogonal configuration with respect to one another. The upper semicircular canal forms a convex loop at the top determining the relief of the arcuate eminence, a loop more or less perpendicular to the petrous axis. The posterior semicircular canal is perpendicular to the former, in a vertical plane, close to the cortical of the posterior face of the pyramid. The horizontal or lateral semicircular canal forms a laterally convex loop in the horizontal plane. These canals are implanted on the vestibule and have a common branch for the upper and lower canals. These

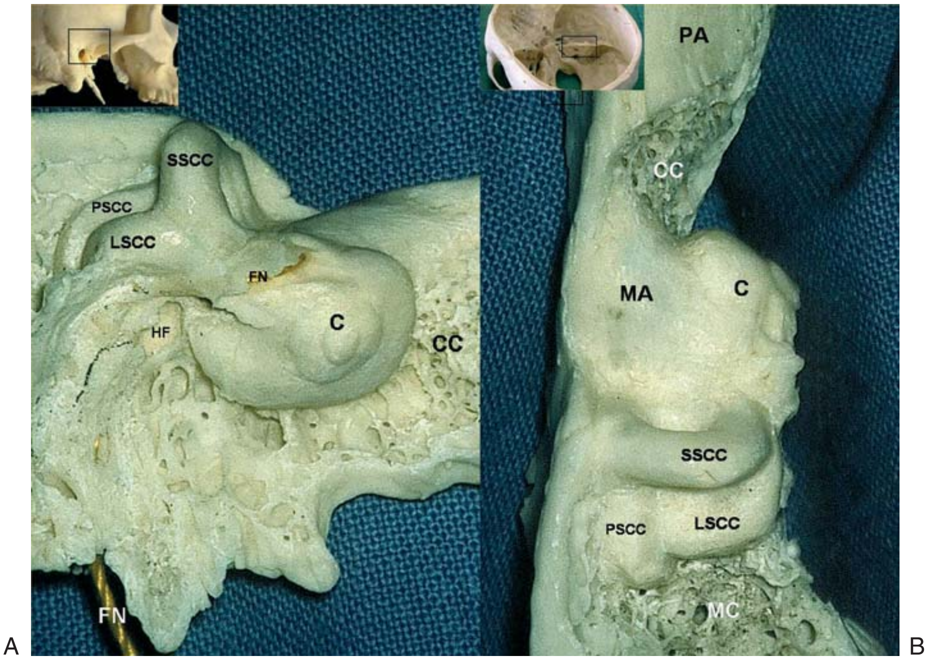


Fig. 4. Dry specimen of a right bony labyrinth: (A) Lateral view, (B) superior view. *SSCC* Superior semicircular canal; *PSCC* posterior semicircular canal; *LSCC* lateral semicircular canal; *FN* facial nerve; *HF* hemispheric fossa; *C* cochlea; *CC* carotid canal; *MA* meatal area; *PA* petrous apex; *MC* mastoidian cells

canals present ampullary dilatations. This dilatation is located on the anterior branch of the upper canal, on the lateral branch of the lateral canal, and on the posterior branch of the posterior canal. It is important to note two landmarks. The lateral branch of the lateral canal is in contact with the second portion of the facial nerve. The ampullary dilatations of the upper and lateral canals are in contact with the knee of the facial nerve. These relationships have to be borne in mind when drilling the labyrinthine mass to find the facial nerve. In our dissections, the vestibule is open. The hemispheric fossa bordered behind by the vestibular crest is exposed. Its wall separates it from the internal acoustic meatus.

The cochlea is joined to the cortical of the petrous apex. It is a tube rolled up on itself around a conical axis. We will look at relationships with the geniculate ganglion.

The carotid canal is located in front of the cochlea but in 33% of cases (as in this anatomical view), the knee and the vertical portion of the carotid canal are partly covered by the cochlea [30].

Intrapetrous cavities on fresh specimen dissections: description and relationships (Figs. 5–7)

Examination of the petrous portion of the temporal bone via the middle cranial fossa reveals its complex anatomy and makes it possible to define the important relationships between the intrapetrous carotid, the facial nerve, the porus, the cochlea, the geniculate ganglion, the petrosal nerves, the trigeminal ganglion, the middle ear, the eustachian tube, the tensor tympani muscle, and the middle meningeal artery.

Middle meningeal artery (Figs. 5 and 7). The first structure encountered on the floor of the middle cranial fossa, entering the skull via the foramen spinosum. It has a single trunk but in a few cases divides into two branches below the base of the skull, entering the cranium through two distinct openings [30]. If the middle meningeal artery arises from a persistent stapedial artery, a branch of the intrapetrous carotid, there will not be any foramen spinosum [23]. The petrosal artery arises from the middle meningeal artery, proximal to the foramen spinosum (58%) or distal to it (42%) [30]. It runs along with the greater petrosal nerve (or the lesser petrosal nerve in just 8% of cases) to supply the geniculate ganglion, the facial nerve and the middle ear (Fig. 5). There are also anastomotic ramifications with branches of the anterior and lower cerebellar arteries and branches of the stylomastoid artery (Fig. 7). These collaterals probably preclude peripheral facial paralysis if the petrosal artery is interrupted [24, 26].

The trigeminal ganglion (Figs. 1, 5, 6 and 8). Lying in the trigeminal fossa, the entry opening of which at the trigeminal incisure is located under the superior petrosal sinus (Figs. 1, 5 and 8). After resection of the sinus and opening of the

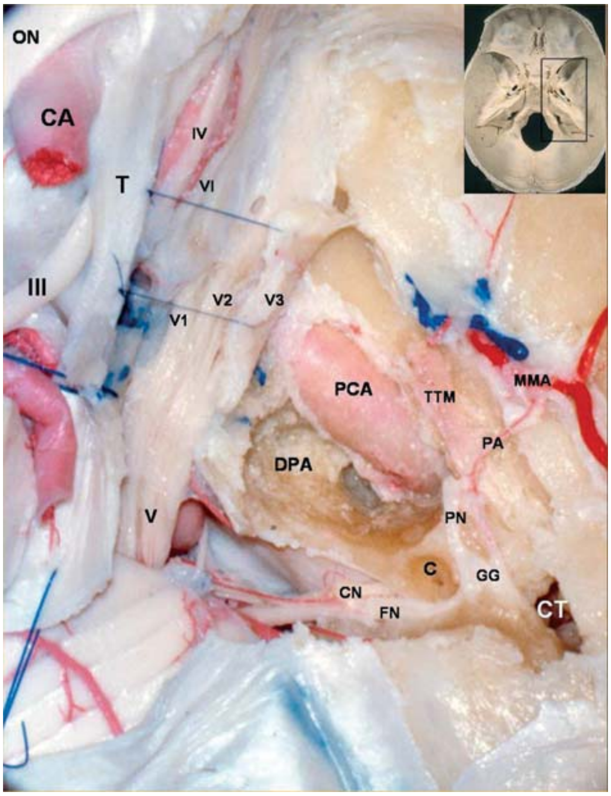


Fig. 5. Superior view of a right drilled middle cranial fossa: the third branch of the Vth nerve has been cut and displaced forwards to see the dural layer between the Vth nerve and the carotid artery. *ON* Optic nerve; *CA* carotid artery; *T* tentorium; *PCA* petrosal carotid artery; *DPA* drilled petrous apex: *TTM* tensor tympani muscle; *MMA* middle meningeal artery; *PA* petrosal artery; *PN* petrosal nerve; *C* cochlea; *CN* cochlear nerve; *FN* facial nerve; *GG* geniculate ganglion; *CT* cavum tympani; *IV* 4th cranial nerve; *VI* 6th cranial nerve; *V* 5th cranial nerve with first (*V1*) second (*V2*) and third (*V3*) divisions

dura mater covering the trigeminal ganglion and the origin of the dividing branches, it is seen that the infero-lateral angle of the ganglion is separated from the terminal portion of the horizontal carotid by only the dura mater (Fig. 6), as reported by Pait [29]. There is sometimes a thin bony sheet [30]. The supero-medial angle of the ganglion lies on the ascending portion of the intra-cavernous carotid. The ganglion usually lies on the ventral lip of the carotid canal (98% of cases according to Paullus) [30]. According to Pait, the carotid can be exposed laterally at the ganglion in 68% of cases [29].

Meckel's cave is a dural space occupying the middle fossa laterally to the cavernous sinus. It contains the trigeminal ganglion, the pars triangularis of the nerve and the origin of the branches of division that are wrapped in a cisternal

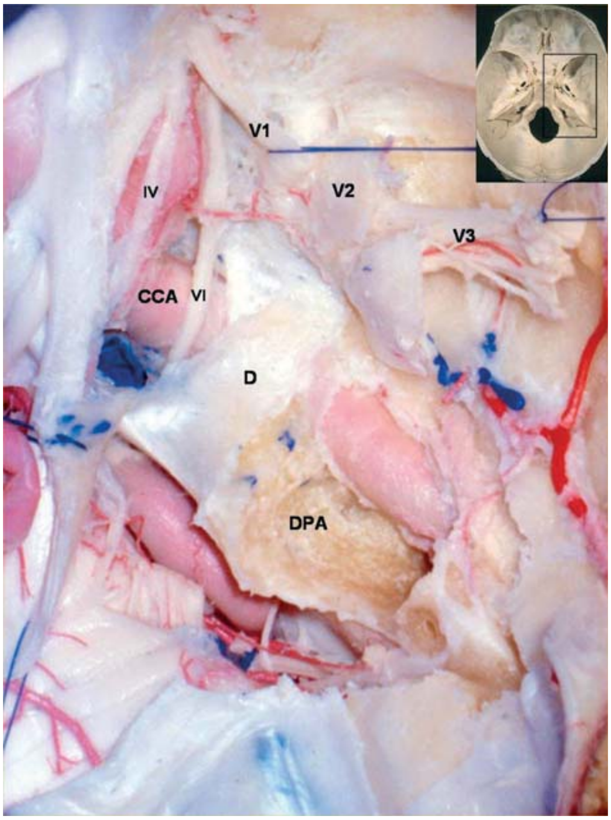


Fig. 6. Superior view of a right drilled middle cranial fossa: the Vth nerve has been removed. See the dura (*D*) and the cavernous sinus entrance. *CCA* Cavernous carotid artery; *D* dura; *V* 5th cranial nerve with first (*V1*) second (*V2*) and third (*V3*) divisions; *DPA* drilled petrous apex

space. This cistern is an extension of the cerebellopontine cistern. Communication between the posterior fossa and Meckel's cave is formed by a dural ring called the porus trigeminus through which pass the motor nerve and the sensory root of the nerve (Fig. 8) [42].

The facial nerve (intra-meatal and first portion) – petrosal nerves – the geniculate ganglion (Fig. 5). Using a diamond drill, the petrosal nerves, the geniculate ganglion, the facial nerve in the internal acoustic meatus together with its first portion are exposed, as well as the cochlear nerve and the upper vestibular nerve. The greater superficial petrosal nerve (GSPN) which is attached to the dura mater leaves the geniculate ganglion, emerges near the hiatus of the canal for the lesser petrosal nerve, and continues in an antero-medial direction towards the trigeminal ganglion. The proximal portion of the greater petrosal nerve is usually covered in bone. In 30% of cases [30], the

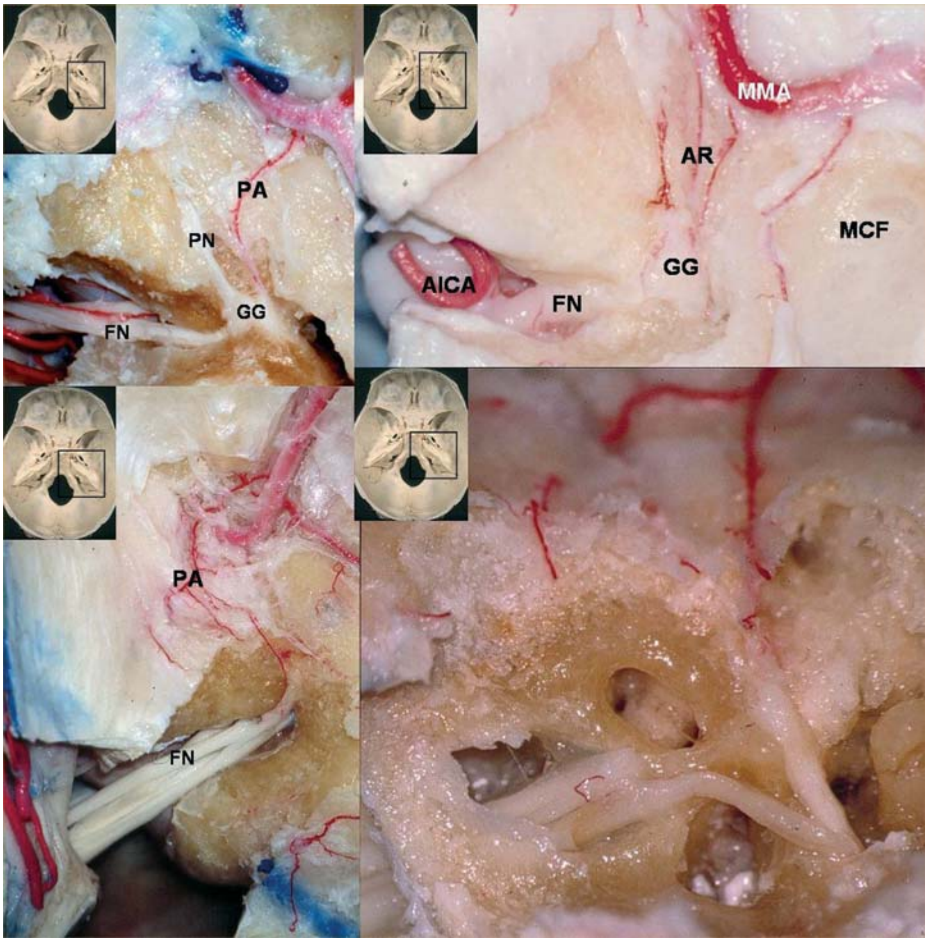


Fig. 7. Facial nerve vascular supply. Superior view of a right middle cranial fossa: *PA* petrosal artery; *PN* petrosal nerve; *FN* facial nerve; *GG* geniculate ganglion; *AICA* anterior inferior cerebellar artery; *AR* anastomotic ramifications; *MMA* middle meningeal artery

junction of this nerve with the geniculate ganglion is not covered. The average distance between the hiatus of the canal for the lesser petrosal nerve and the geniculate ganglion is 3.7 mm (range: 0.5–8 mm) [30]. The greater petrosal nerve runs parallel to the horizontal segment of the carotid, above its ventral edge in 66% of cases, and it can be located in front of it or above the anterior half of the canal [30]. The lesser petrosal nerve also arises from the geniculate ganglion and enters a sulcus located in front and outside of the canal for the tensor tympani muscle. The geniculate ganglion is postero-lateral (38%) posterior (26%) or lateral (16%) to the carotid knee [30], at an average distance of 6.5 mm (range: 3–13 mm). Usually covered with bone, the geniculate ganglion can be exposed

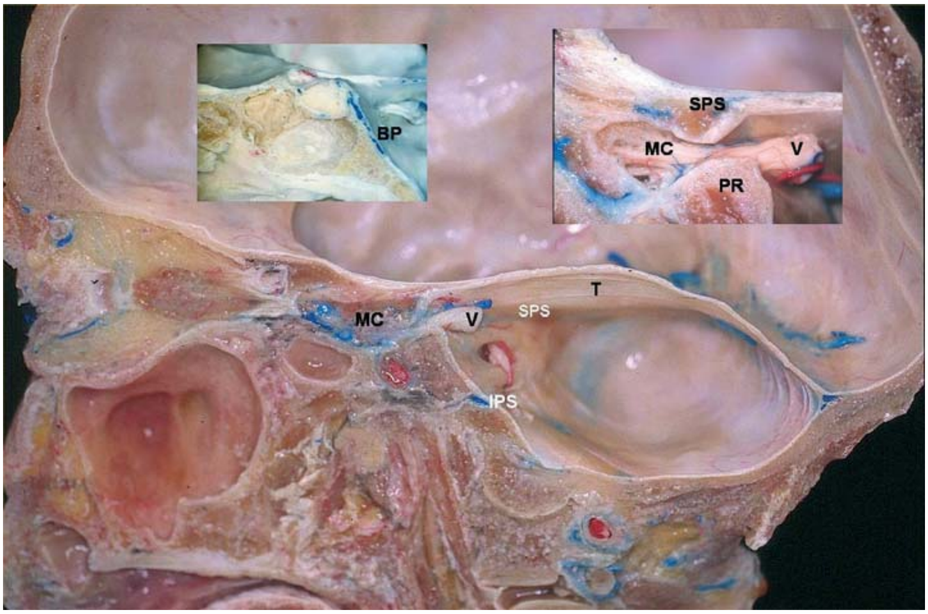


Fig. 8. Sagital section of a fresh specimen: to emphasize on Meckel's cave relationships. *MC* Meckel's cave; *V* 5^{th} nerve; *SPS* superior petrosal sinus; *IPS* inferior petrosal sinus; *T* tentorium; *BP* basilar plexus; *PR* petrous ridge

without bone coverage in 16% of cases. It is nevertheless always in a depression in the bone surface.

Cochlea (Figs. 4 and 5). By drilling inside the first portion of the facial nerve, its knee and the geniculate ganglion, in the angle between the facial nerve and the greater petrosal nerve, the dense capsule of the cochlea is exposed to an average depth of 3–4.5 mm [30]. The bone then looks darker as one drills the highly dense cortical until penetration of the membrane covering of the fluid-filled cochlea. The average distance between the cochlea and the geniculate ganglion is 0.8 mm.

Intrapetrous carotid artery and carotid canal (Figs. 5, 6 and 9). The internal carotid enters the skull via a periosteous canal. The exocranial opening of the carotid canal is located just in front of the jugular foramen, and the endocranial opening is near the petrous apex. The artery can be easily dissociated at its adhesion points in the canal, except where it enters into the vertical segment, at which point it is attached by strong fibrous tissue. The intrapetrous carotid artery has two segments, one vertical and one horizontal joined at the carotid knee. The dimension of each segment is exactly the same according to Paullus, on average 5.2 mm [30]. The average length of the vertical segment is 10.5 mm, and that of the horizontal segment 20.1 mm [30]. The horizontal segment starts at the knee and continues in the antero-medial axis of the foramen lacerum, in front of the cochlea, eventually emerging at the apex. Its roof is exposed by drilling. The medial part of the horizontal portion of the carotid canal may be covered only by the dura mater or it may be covered in bone, elements which separate the carotid from the trigeminal ganglion. The carotid knee is separated from the cochlea which is located behind and above it in most cases, the average distance between the cochlea and the knee being 2.1 mm (range: 0.6–10 mm). Nevertheless, the cochlea covers part of the knee in 33% of cases [30]. These ideas make it possible to understand why it is difficult to expose the intrapetrous carotid – especially the knee and the vertical segment – without impairing hearing function [42, 43].

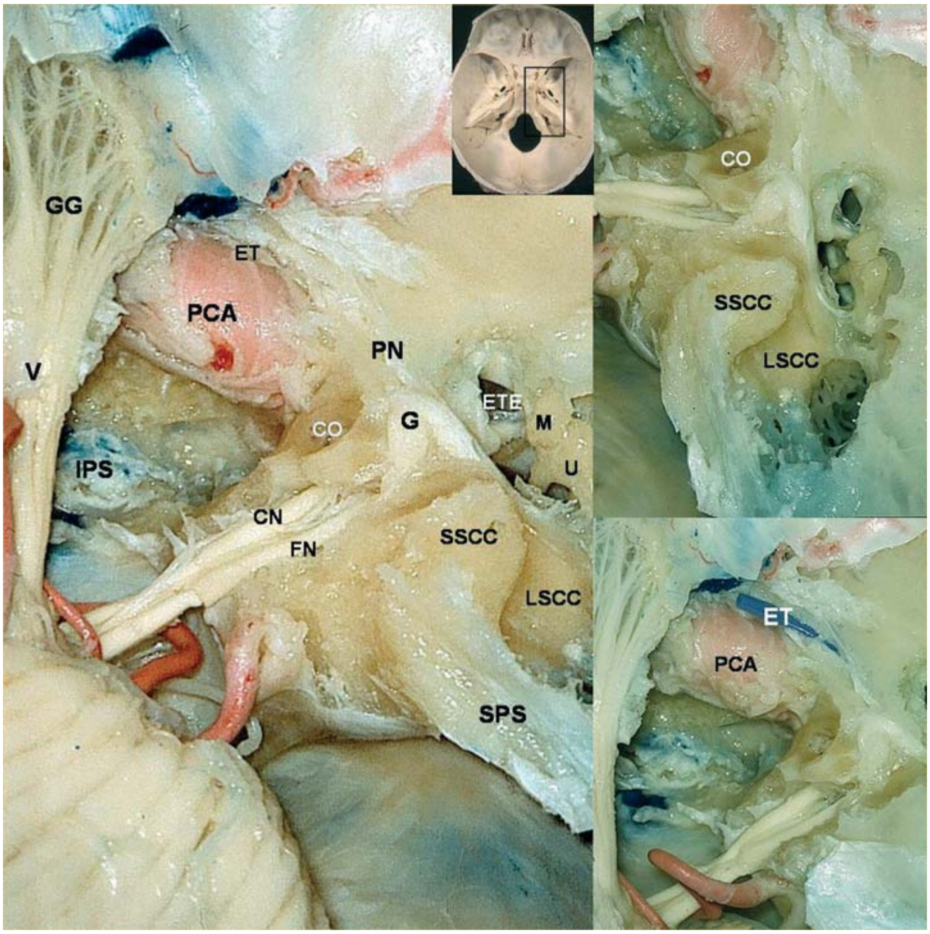


Fig. 9. Superior view of a right middle cranial fossa following drilling and dissection of the petrous bone: see the right tympanic cavity, and its relationships. *GG* Gasserian ganglion; *ET* Eustachian tube; *PCA* petrous carotid artery; *IPS* inferior petrosal sinus; *V* 5th cranial nerve; *PN* petrosal nerve; *CO* cochlea; *G* geniculate ganglion; *CN* cochlear nerve; *FN* facial nerve; *ETE* Eustachian tube entrance; *M* malleus; *U* uncus; *SSCC* superior semicircular canal; *LSCC* lateral semicircular canal; *SPS* superior petrosal sinus

Medial drilling of the horizontal segment in front of the cochlea reveals the vertical segment. Below, the drilling exposes a wide inferior petrosal sinus (Fig. 9) which goes as far as the jugular gulf between the glossopharyngeal nerve (nerve IX) and the vagus nerve (nerve X). The jugular tubercle separates this sinus from the canal of the hypoglossa and from the hypoglossal nerve. The pericarotid venous plexuses described by Paullus as sheathing the artery in its periosteous envelope are more numerous in its distal portion [30, 42, 43] although they were relatively under-developed in all our dissections.

In 50 carotid arteries, Paullus only observed collaterals of the intrapetrous carotid in 38% of cases, all of which arose in the horizontal segment [30]. He only observed one vidian artery and one periosteous artery. When present, these branches can be identified at the opening of the periosteum sheathing the carotid. They sometimes account for why the intrapetrous carotid is still supplied in a retrograde direction in some cases in which the cervical carotid is blocked.

There is major variation in the intrapetrous carotid artery which should be recognized and diagnosed before denudation of one or other of its segments. According to Lasjaunias [23], the intrapetrous segment is fenestrated in some carotid arteries, the summit of the fenestration being located at the knee. In addition, an abnormal path is known in the middle ear or abnormal flow through the ascending pharyngeal artery [14, 22, 23, 32]. This variation is rarely bilateral and is more commonly seen on the right, and may be suspected on clinical grounds (pulsating tinnitus or not, more or less constant, moderate and progressive hypoacusis). The diagnosis is made on the basis of CT scan and angiography results. TDM slices do not show the vertical segment adjacent to the cochlea and the floor of the middle ear is dehiscent. Angiography [22] uses the vertical vestibular line which should always be located outside of the carotid knee. In this type of arrangement, the flow uses the lower tympanic artery, a branch of the ascending pharyngeal artery, and the hyoid artery. In this case, the artery passes through Jacobson's canal or the tympanic canal rather than the vertical portion of the carotid canal which is atretic [23]. Other abnormalities may be associated, the most common being persistence of a stapedial artery substituting for the middle meningeal artery without any foramen spinosum present.

Middle ear, eustachian tube, tensor tympani muscle, posterior labyrinth and facial nerve (second portion) (Figs. 9 and 10). By drilling out the antero-medial side of the arcuate eminence, the upper semicircular canal can be exposed. Step-by-step drilling reveals the blue line corresponding to this canal in the surrounding compact bone at a depth of about 2 mm (between 1 and 3.5 mm according to Pellet [31]). Lateral drilling exposes the horizontal semicircular canal. By drilling the tegmen in front and outside of the horizontal semicircular canal, one penetrates the cavity of the middle ear. The opening is completed by drilling laterally through to the geniculate ganglion. The tympanic opening of the eustachian tube is easy to identify in front of the cochleariform process, and the insertion of the tensor tympani muscle. Also seen is the head of the malleus, the uncus and its short branch. Our dissections show the close relationship between the second portion of the facial nerve and the anterior branch of the horizontal semicircular canal. This is a key landmark for the second portion. It should be noted that this second portion is located on the medial or labyrinthine wall of the tympanic cavity where it projects out to the dorsal wall and penetrates into the mastoid. This projection of the canal of the facial forms the separation between the medial wall of the tympanic cavity and that of the aditus ad antrum.

The eustachian tube and the tensor tympani muscle are located in front of and parallel to the horizontal segment of the petrous carotid (Fig. 10), below the bony floor. The muscle may be above, in front of or behind the eustachian tube [28]. Both are covered in bone – in all cases according to Paullus [30]. The ostium of the eustachian tube and the tympanic cavity are located just behind the carotid knee in 63% of cases [30]. In 20% of cases according to the same

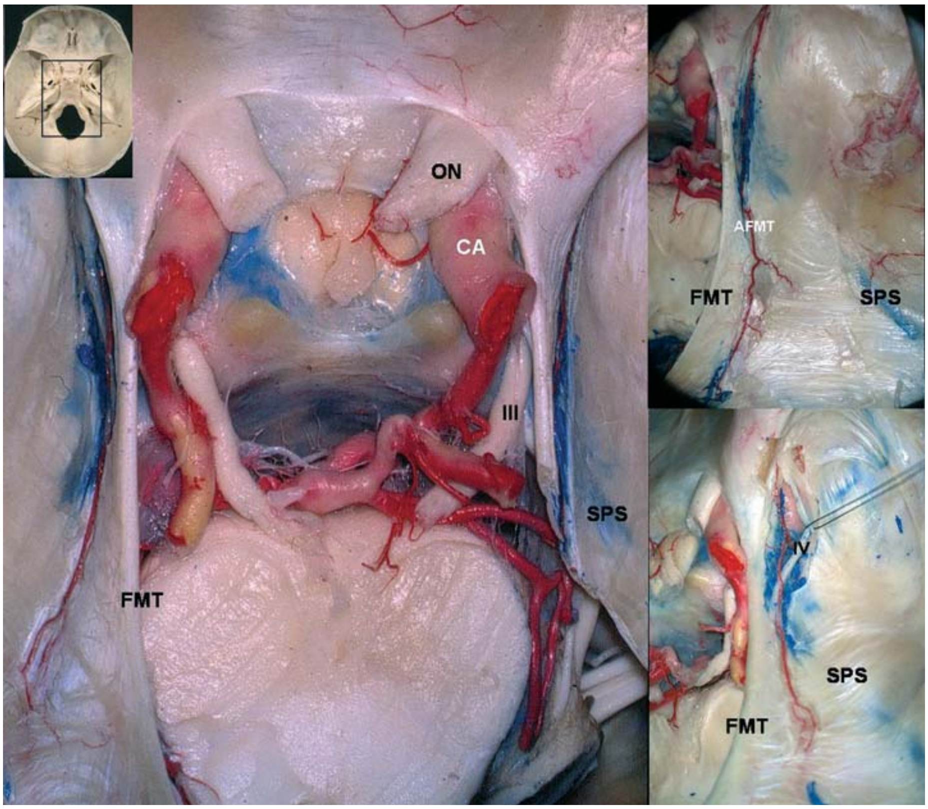


Fig. 10. Superior view of a cadaver skull base: see dural vascular supply from cavernous carotid artery. *ON* Optic nerve; *CA* carotid artery; *FMT* free margin of the tentorium; *SPS* superior petrosal sinus; *III* 3rd cranial nerve; *AFMT* artery of the free margin of the tentorium; *IV* 4th cranial nerve

expert, this ostium is located laterally to the vertical segment of the carotid and the knee. The average thickness of the bone separating the ostium from the carotid knee is 3.2 mm [30]. The eustachian tube and muscle are separated by the inter-musculo-tubar septum.

The dura mater of the middle, posterior levels (Figs. 6, 8 and 10). This lies simply on the floor of the middle cranial fossa, not posing any detachment problem apart from a few adhesion points. It covers the trigeminal nerve increasingly intimately as one moves laterally away from the apex, becoming less easy to dissociate close to where this nerve branches off, notably to form V3. It is nevertheless possible to devise a detachment plan which exposes the true lateral wall of the cavernous sinus, which will be described in the next chapter. It covers the horizontal segment of the petrous carotid, the petrosal nerves and – as we have seen in some cases – the geniculate ganglion if it is not protected by a bony covering. We have also noticed that it can form an invagination under the trigeminal ganglion to separate it from the medial portion of the horizontal carotid. It only consistently invaginates in the foramen spinosum, and sometimes in the sulcus of the petrosal nerves. At the posterior face of the pyramid, it invaginates and spreads around nerves in their respective openings.

The dura mater lines the endocranial face of the clivus, only leaving a single opening for passage of the abducent nerve under the petro-sphenoidal or petro-clinoid ligament marking the entry of the nerve's canal (Dorello's canal) (Fig. 6). We will see that there can be two distinct openings on each side for the nerve to pass through the dura. In the normal configuration, the two foramina (right and left) are separated by a distance of 20 mm (17–27 mm) [21]. The basilar venous plexuses located in the thickness of the clival dura mater can be extensively developed (Fig. 8). They are linked to the marginal sinuses of the greater foramen [25, 43].

This dura mater is prolonged by a roof which closes the petroclival region at the top in the tentorium, a thick, double sheet which is an extension of the anterior petroclinoid ligament.

This dura mater is composed of several layers which let veins and sinuses of variable dimensions through at various spots. We have mentioned the SPS, the SPI and the basilar plexus. This dura mater is vascular with meningeal branches coming from the intracavernous carotid and from the ascending pharyngeal artery (Fig. 10). These arteries take on special importance when the tumor has developed from the dura mater, notably in meningioma. The surgeon's ability to expose this dura mater as extensively as possible is one of the key features of transpetrosal approaches. About the dura of the petroclival region, V. Dolenc [6] made the following statement, "Where the layered dura at the petrous apex joins the tentorium, the lateral wall of the parasellar space, and especially, dural layers in the vicinity of Meckel's cave constitutes the richest, most complex junction of intracranial dural structures".

The superior petrosal sinus (Figs. 1, 8 and 10). This runs along the petrous crest at the junction of the upper and posterior faces of the pyramid, rejoining the cavernous sinus at the elbow of the sigmoid sinus near the sinuso-dural angle (Citelli's angle). At its origin, it is linked to the inferior petrosal sinus by the transverse sphenoidal sinus [34]. It overlies the trigeminal nerve when this crosses the petrous apex without adhering to the nerve. Its main afferent is represented by the group of upper petrosal veins [25] including the always-present upper petrosal vein which runs along the lateral edge of the nerve up till the sinus. The sinus is at least 3 mm from the porus and from the roof of the internal acoustic meatus [31]. This sinus may be prolapsed (10%), reducing the size of this space.

The inferior petrosal sinus (Figs. 8 and 10). Always very wide (and with a diameter which is often under-estimated), it runs along in a very broad sulcus cut by the petro-occipital suture, uniting the cavernous sinus at the gulf of the jugular vein. It is easy to understand that this bulky sinus could considerably hinder drilling of the petrous apex, and it has been proposed that it be embolized prior to surgery [11, 12].

Venous sinuses and the concept of petroclival venous confluence (PVC). This concept has been developed in a main paper by Destrieux *et al.* [7]. Briefly the PVC is located at the junction of the posterior part of the cavernous sinus, the SPS, the IPS and the basilar plexus. This part of the PCR includes not only the venous sinuses but also the abducens nerve and the clival arteries. Ozveren [28] have reported two types of trabecula inside the PVC. A delicate type, fragile, transparent and membranous, and a tough fibrous type forming structures that bridge the two layers of the dura.

Contents of the petroclival region (Figs. 5, 6 and 11)

The cisterns

The PCR is a cisternal space represented by the association of several arachnoid sheets which form the neighbouring cisterns. In practice, there is no petroclival cistern as such but inside and in front there is a prepontine cistern which adheres to and communicates with the cerebellopontine cistern outside and behind.

Oculomotor nerve (Fig. 11)

The third nerve is a very fragile nerve which is highly complex in functional terms, lying outside the petroclival region which forms its upper boundary. Manipulation of the nerve usually leads to severe palsy of the whole components of the nerve. Ptosis and pupillary function are usually recovered but some oculomotor function may be reduced. Exiting from the interpeduncular space, it passes intracisternally at a horizontal, slightly oblique laterally and enters the cavernous sinus at the top of the lateral wall. Its entry point in the lateral wall of the parasellar

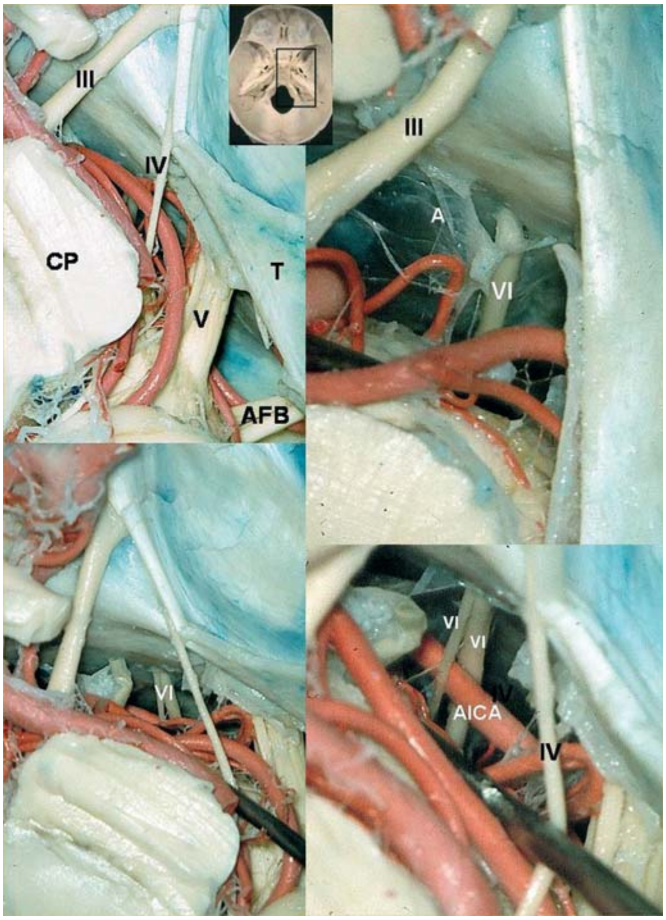


Fig. 11. Superior views of the right cisternal petroclival area and its contents: *CP* cerebral peduncle; *AFB* acousticofacial bundles; *T* tentorium; *A* arachnoid; *AICA* anterior inferior cerebellar artery; *III* 3rd cranial nerve; *IV* 4th cranial nerve; *V* 5th cranial nerve; *VI* 6th cranial nerve

space is a key surgical spot because it comes with a very limited sheath of arachnoid at the porus oculomotorius and an oblique groove at the upper surface of the nerve can always be distinguished. This oculomotorius porus gives access to a canal that can be opened far to the anterior pole of the lateral wall at the point where the trochlear nerve joins the third nerve at the entry of the superior orbital fissure. The nerve is usually safe with PC tumors but involvement of the cavernous sinus may modify the anatomy. Usually the tumor exits from the CS by the porus oculomotorius and pushes the nerve upwards.

The average cisternal course of nerve III is 20 mm in length and that of nerve IV is 32.6 mm [21].

Trochlear nerve (Fig. 11)

The forth nerve is a very small, fragile nerve, purely motor and supplying a single muscle. Localized at the upper part of the petroclival field in its cisternal course. Closely related to the inferior surface of the free edge of the tentorium. Fused to the free edge in a porus before it enters the lateral wall of the CS. The point of fusion is variable from one subject to another. In pathology, the nerve is shifted upwards and to the side making it more accessible for manipulation.

Trigeminal nerve (Figs. 5 and 6)

The PC region is centered by the root of the trigeminal nerve, the course of which is close to the horizontal and anteroposterior. This bulky root comes from Meckel's cave which lies in the gasserian cistern, a depression located on the upper surface of the petrous portion of the temporal bone. Meckel's cave is formed by a double-walled portion of the dura mater and is occupied by an arachnoid extension of the pontocerebellar cistern in which cerebrospinal fluid circulates – which is perfectly visible in MRI sequences. This root enters the PCR by passing into an oval-shaped fold of the dura mater constituted at the top by the canal of the superior petrosal sinus and at the bottom by a sheet which lines the depression formed by the porus trigeminus (Fig. 8).

On average it runs for 12.3 mm (range: 9–17 mm) within the cistern [21].

Abducens nerve (Fig. 11)

The sixth nerve arises from the ponto-medullary junction from a single trunk or two distinct trunks [1]. As emphasized by Brassier, three types of configuration of this nerve have been observed. Type I (86.5%) corresponds to a single trunk of the nerve from its origin as far as where it penetrates the dura in Dorello's canal. Type II (6%) corresponds to one origin in a single trunk which soon divides to form two branches which enter the clival dura mater separately. Type III (7.5%) corresponds to two trunks of origin with two different dural entry points. We have observed a nerve with dual origin, the two roots of which pass either side of the AICA and use the same dural entry point (Fig. 11). This type of configuration does not correspond to any of the three above-described types. Mercier reports one case of fenestration of nerve VI [26]. When the configuration is of the conventional Type I form, the nerve runs more or less vertically from the bottom up and slightly outside, flattened against the arachnoid which it crosses perpendicularly to enter Dorello's canal under the petroclinoid ligament (Fig. 6). Its average length in the cistern is 16.5 mm (12.5–21 mm) [21].

The nerve leaves the posterior fossa by piercing the meningeal dura over the clivus approximately 1 cm below and medial to the trigeminal root. The relationships between Dorello's canal and inferior petrosal sinus are very closed.

For the first few millimeters of its intradural course, this nerve is sheathed by the arachnoid and bathed in CSF [28]. It can be deduced that the petroclival portion of the abducens nerve does not belong to the extradural space. This is an important observation because, at the level of the petrous apex, it twists round horizontally under the petroclival ligament (Gruber's ligament) to pass over the dorsal and lateral surface of the internal carotid artery as it enters the posterior cavernous sinus.

Ozveren [28] described two anatomic variations (lateral or medial) in the course of the abducens nerve in the petroclival region, depending on the nerve's angles and attachment points. The proximity of the abducens nerve to the petrous ridge in the lateral type (57% in the study from Tokyo) might have surgical importance in the anterior transpetrosal approach. The abducens is a small nerve which supplies a single muscle. Usually shifted downward and distorted between two fixed points. Sometimes involved and encased by the tumor if the lesion is an external one like a chordoma.

Acousticofacial bundles (Figs. 5 and 6)

The cochleo-vestibulo-facial bundle has been studied in detail by Mercier [26] and Rhoton [33]. It runs in an almost frontal plane as it crosses the cistern of the pontocerebellar angle (*cisterna cerebellopontis*). The relationships it has with the loop of the AICA are variable and have been reviewed by Lang [21]. In our preparation, the AICA crosses the nervous bundle by its dorsal face, the loop being fixed by the dura mater above the porus (6% according to Lang) [21]. The average cistern length of nerve VII is 16 mm (10–26 mm), and that of nerve VIII 15 mm (8.5–22 mm) [21].

This neurovascular structure transversally crosses the cerebellopontine angle and is protected by the arachnoid sheath of its individual cistern. Even though it is outside the petroclival region, it is exposed in the surgical field laid open by a number of common approaches to the PCR. Tumors originating from the PCR usually push the cerebellopontine cistern and its contents backwards.

The brain stem

The petroclival region is defined medially by the lateral aspect of the brain stem in its middle protuberant part. In practice, the lower boundary is the bulbopontine sulcus and the upper boundary is the ponto-mesencephalic sulcus.

Surgical anatomy

The surgical anatomy of the petroclival region is detailed in each of the approaches we describe below. Here, we consider two complementary concepts dealing with the systematization of the lateral skull base.

Skull base anatomy and triangles (Fig. 12)

When detailing the anatomy of the base of the skull, it is possible to find reliable permanent landmarks that are helpful to delineate operative corridors. Since these corridors are broadly speaking triangular in shape, several authors have systematized the triangulation of skull base landmarks as follow [4, 8, 9, 13, 42].

The triangles from the parasellar subregion

– Anteromedial triangle (Dolenc): the limits are the lateral border of the optic canal, medial surface of the third nerve within the sheath of the dura entering the superior orbital fissure, and the distal dural ring.
– Medial triangle (Fukushima): the limits are the lateral wall of the intradural carotid artery, posterior clinoid process and porus oculomotorius. An intradural intracisternal space.
– Superior or paramedial triangle: the limits are located in the lateral wall of the cavernous sinus between the third and the fourth nerve. The anterior apex is formed by the point at which nerve IV crosses over nerve III.

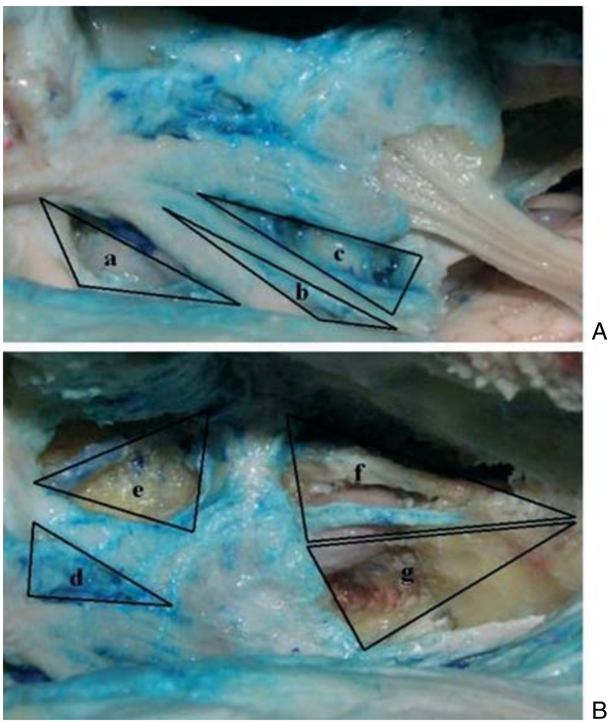


Fig. 12. Systematization of the main skull base triangles: (A) Triangles of the parasellar subregion: *a* anteromedial triangle, *b* paramedial triangle, *c* lateral triangle. (B) Triangles of the middle cranial fossa subregion: *d* anterolateral triangle, *e* far lateral triangle, *f* posterolateral triangle, *g* posteromedial triangle

- Oculomotor trigone (Dolenc): the three summits of the triangle are the ACP, the PCP, the petrous apex.
- Lateral triangle (Parkinson): the limits are the lateral wall of the cavernous sinus between the trochlear nerve and the ophthalmic division of the trigeminal nerve, and the dura between and behind these two nerves. Provides direct access to the intracavernous carotid artery.

The limits of the triangles from the middle cranial fossa subregion

- Anterolateral triangle (Mullan): between the ophthalmic and the maxillary branches of the trigeminal nerve.
- Far lateral triangle (Dolenc): between the foramen rotundum and the foramen ovale (or between the second and third division of the trigeminal nerve).
- Posterolateral triangle (Glasscock): posterior rim of foramen ovale and third branch of the trigeminal nerve (anterior border), the line from the arcuate eminence to the posteromedial corner of gasserian ganglion, and the line between the foramen spinosum and arcuate eminence. Through this triangle, the following important structures may be accessed: the great superficial petrosal nerve, the intrapetrous carotid artery (C6), the tensor tympani muscle and the eustachian tube.
- Posteromedial triangle (Kawase): the line connecting the arcuate eminence and the postero-medial corner of the geniculate ganglion – nerve V – the line connecting the arcuate eminence and posterior aspect of nerve V where it crosses the crest of the petrous apex.

The triangles from the petroclival subregion

- Inferomedial triangle (Dolenc): this triangle is formed by the apex of the Posterior clinoid process, the dural entry point of nerve IV into the tentorium, and the dural entry point of nerve VI [8].
- Inferolateral (trigeminal) triangle: this triangle is defined by the dural entry point of nerve IV into the tentorium (upper point), the entry point of nerve VI into the dura of the clivus (medial point), and the entry point of the petrosal vein into the SPS (lateral point).

The petrous bone segmentation

Pellet *et al.* [31] formulated the concept of petrous bone segmentation. The surface of the petrous pyramid carries several landmarks and is covered in critical neurovascular structures that can be easily identified during surgery. The internal carotid artery, the internal auditory canal, the fallopian canal and the semicircular canals are used as the boundaries in this concept. This segmentation is

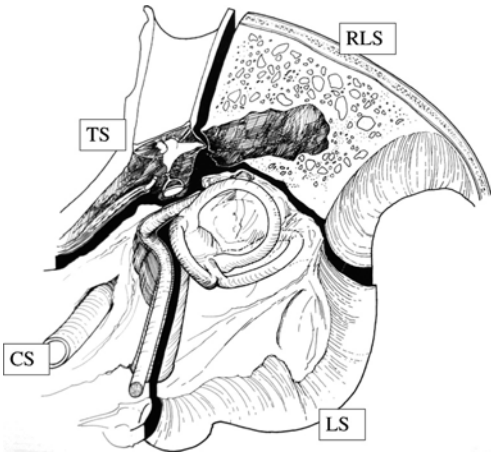


Fig. 13. Petrous bone segmentation (from Pellet *et al.*): *CS* carotid segment, *LS* labyrynthine segment, *RLS* retrolabyrynthine segment, *TS* tympanic segment

particularly applicable when it comes to the posterolateral approach to the petrous bone. This concept is illustrated in Fig. 13.

– The posterolateral segment is also named the retrolabyrinthine or mastoid segment. Superficially, it is limited by the posterior margin of the external auditory canal in front and by the sigmoid sinus behind. This segment contains mastoid air cells particularly the antrum. Horizontal removal of this area gives access to the third portion of the intrapetrous facial nerve and the semicircular canal.
– The postero-medial segment is also named the labyrinthine segment. The anterior limit is the posterior margin of the internal auditory canal and the medial limit is the dura of the posterior fossa. This segment is a logical progression from the mastoid segment, accessed by drilling the semicircular canals and the vestibule.
– The anterolateral segment also called the tympanic segment corresponds to the middle ear and is rarely exposed in current approaches to the petroclival region.
– The anteromedial segment or carotid segment corresponds to the petrous apex. It is limited medially by the petrous ridge, laterally by the intrapetrous carotid, in front by the porus trigeminus and behind by the anterior border of the internal auditory canal.

Classification of the approaches

Many different approaches have been described for the removal of petroclival tumors. There is no single ideal approach and which is the most suitable will depend on several parameters. Ongoing progress in neuroimaging techniques are making it easier to identify the origin and spread of the lesion which are important parameters when it comes to choosing the approach route. Extradural tumor masses are mainly represented by chordomas, chondrosarcomas, epidermoid cysts and cholesterol granulomas. Tumors originating from the dura are mainly meningiomas while intracisternal lesions are schwannomas of the trigeminal nerve or epidermoid cysts. For all these lesions it is also necessary to consider relationships with the cranial nerves and the brain stem. Ideally, surgeons who operate at the base of the skull should be familiar with all the relevant approaches but in practice, most have more experience with a limited number of routes: this will also influence their surgical decision.

Briefly we can describe three kinds of approaches to the PCR: anterior transmaxillary or transfacial approaches; intradural cisternal approaches; and approaches via the base of the skull. In this paper we will focus on lateral skull base approaches because we consider that these facilitate resection with very moderate invasiveness and are associated with relatively low level post-operative morbidity. However, here are a few comments about the other two types of approach:

Anterior transmaxillary or transfacial approaches need two-team expertise and are recommended for midline clival tumors (preferably extradural). The operative field that is created is deep and narrow, laterally limited by both carotids and the cavernous sinus [18]. The angle of approach is thus reduced, vascular control is hazardous, and closure is compromised (particularly when the dura is opened).

Intradural cisternal approaches were historically the way to gain access to the PCR. These routes use the natural spaces afforded by the cistern to advance towards the target. Their main advantages are short exposure time and rapid identification of neurovascular structures. However, in many respects they are not specific to the PCR because they do not give direct, close access to this region and require intradural retraction of the parenchyma.

The pterional-trans-sylvian approach was first popularized by Yasargil. The sylvian fissure opening gives access to the pericarotid and optochiasmatic cisterns. Working corridors are between the optic pathway and carotid artery, and between carotid artery and the third nerve. The posterior clinoid process has to be drilled and then opening of the Liliequist membrane gives access to the upper pole of the petroclival tumor, particularly when the tumor is inserted close to the posterior clinoid process. Although the usefulness of this approach is limited, it can offer many advantages when included in a more complex strategy involving an epidural transcavernous approach to the parasellar and suprasellar extensions of some petroclival tumors.

The subtemporal transtentorial approach was developed by Drake for basilar trunk aneurysms, particularly for basilar tip vascular lesions. In this approach, the third and fourth temporal gyri are directly retracted upwards to gain access to the free edge of the tentorium. This approach can be convenient for resection of tentorial and falcotentorial meningiomas but affords poor PCR exposure. Direct temporal lobe retraction and venous problems constitute serious limitations.

The retrosigmoid – lateral suboccipital approach is still routinely used by many experienced surgeons to reach the PCR. The disadvantages are that the acousticofacial bundle is always in the way and that the working corridor is narrow and deep. Moreover, it is difficult to control lesions that are located close to the basilar trunk and in front of it [35]. Control is compromised if the tumor has a supratentorial portion, in which case the trochlear nerve is at risk when the tentorium is encroached upon. Possibilities for resection of the dura and underlying bone tissue are very limited.

Lateral skull base approaches (Fig. 15)

These approaches offer the shortest distance to the PCR. Coming from an extradural route means less brain retraction and better preservation of veins. It also means earlier interruption of the tumor vascular supply, earlier tumor detachment and more radical resection. However it should be kept in mind that extra time is needed to perform this approach and a collaborative team is often required. Moreover, a good knowledge of the anatomy of the lateral skull base

Fig. 14. Axial CT scan of a left petrous bone (bone window) showing several individual variations: the bold white arrow shows the high degree of the pneumatization. The black small arrow shows a high jugular bulb positioned close to the posterior lim of the internal auditory meatus. The empty white arrow shows the widening of the internal auditory canal

is required as well as sustained training and practice if these approaches are to be successfully exploited. As mentioned above, careful analysis of neuroradiologic images will provide a satisfactory estimate of the origin, insertion and development of the lesion and will show individual anatomical variations that may influence the operation (Fig. 14). From a technical point and regardless of the approach that is selected, the following general principles should always be applied: use constant anatomical landmarks for the drilling step, optimize dura exposure and opening, take care with the retractors to preserve veins, induce clotting meticulously one step at a time, protect and preserve critical neurovascular structures, perform reconstruction with care, and hermetically close the dura.

Epidural subtemporal approaches (from above). *Anterior & lateral skull base approaches* (1 & 2 from Fig. 15)

Middle fossa anterior transpetrosal approach (anterior petrosectomy)

Background

This approach was developed by Kawase in 1985 to treat two aneurysms at the vertebro-basilar junction [20]. It was adapted by House in 1986 to treat advanced or extensive lesions in the ventro-superior part of the cerebellopontine angle [16], and then by Velut in 1988 to excise a petroclival meningioma [44]. In 1991, Kawase reported using this approach to excise a series of ten spheno-

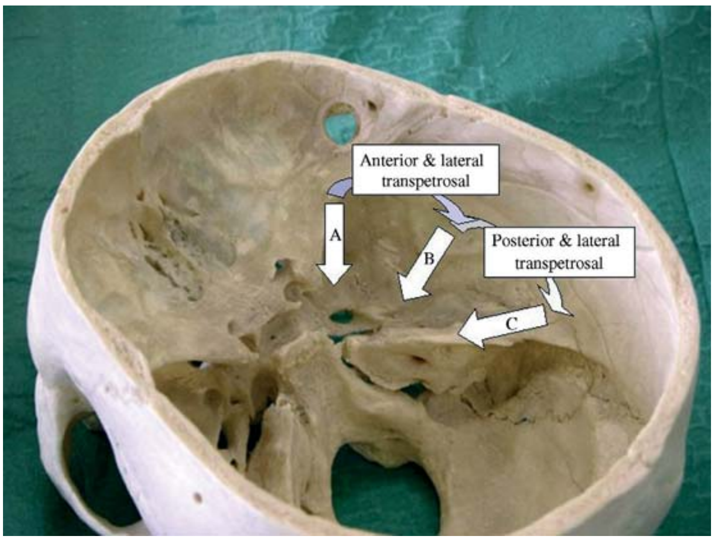


Fig. 15. Lateral skull base approaches: *A* Operative trajectory when the petroclival area is approached from the epidural temporopolar transcavernous route. *B* The arrow indicates the operative trajectory using an anterior petrosectomy. *C* The arrow simulates the surgical trajectory when using a retrolabyrinthine route

petroclival meningiomas [19]. Fournier proposed using this approach to gain access to prepontile lesions (after preliminary embolization of the IPS) [11, 12].

The principle of this approach is to perform, via a sub-temporal extradural route, petrectomy of the petrous apex, in front and medial to the horizontal segment of the intrapetrous carotid, preserving the cochlea and therefore hearing. This approach affords access to the brain stem in front of the cranial nerve plane.

Technique

The patient is placed in a supine position with the head turned to an angle of 50° on the opposite side to where the approach is to be made, with the cervical spine in slight extension. The sagittal plane is then horizontalized by rotating the operating table (Figs. 16–20). The authors recommend a crossbow incision with a fronto-temporal line in the hairline together with a dorsal incision over the auricle to reach the retro-mastoid line behind. The fronto-pterional scalp is lifted leaving the superficial temporal fascia and the galea in the same plane. The temporal scalp releases the roof of the external acoustic meatus. A stalked temporal flap is created in its lower ventral part on the temporal muscle and trimmed flush to the base. With microscopic guidance, extradural basi-temporal detachment is begun, extending from the sinuso-dural angle behind to the foramen spinosum in front

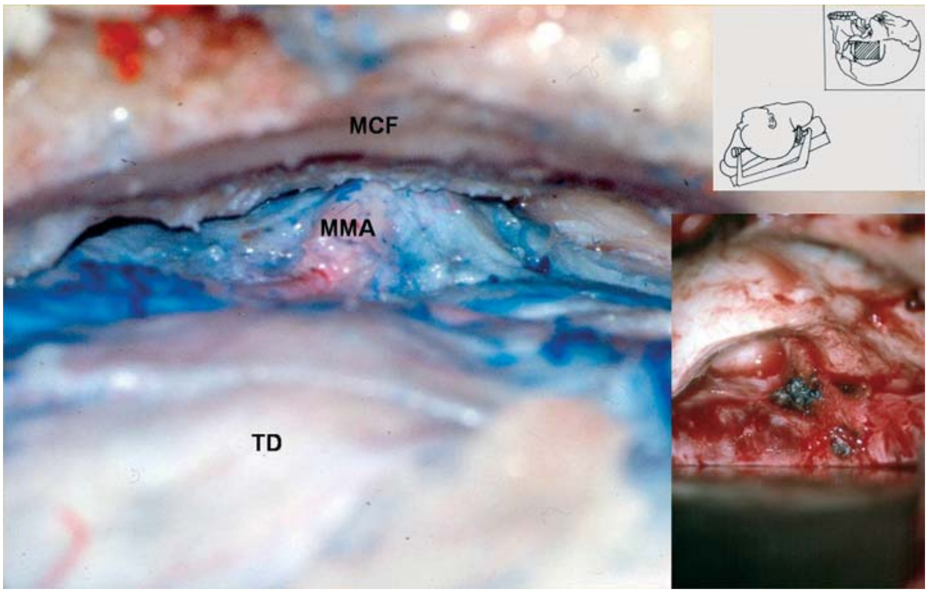


Fig. 16. Right sided anterior petrosectomy on a cadaver dissection: identification of the main anatomical landmarks. *MCF* Middle cranial fossa; *MMA* middle meningeal artery; *TD* temporal dura. See on the right lower corner of the figure the correlation with a clinical case

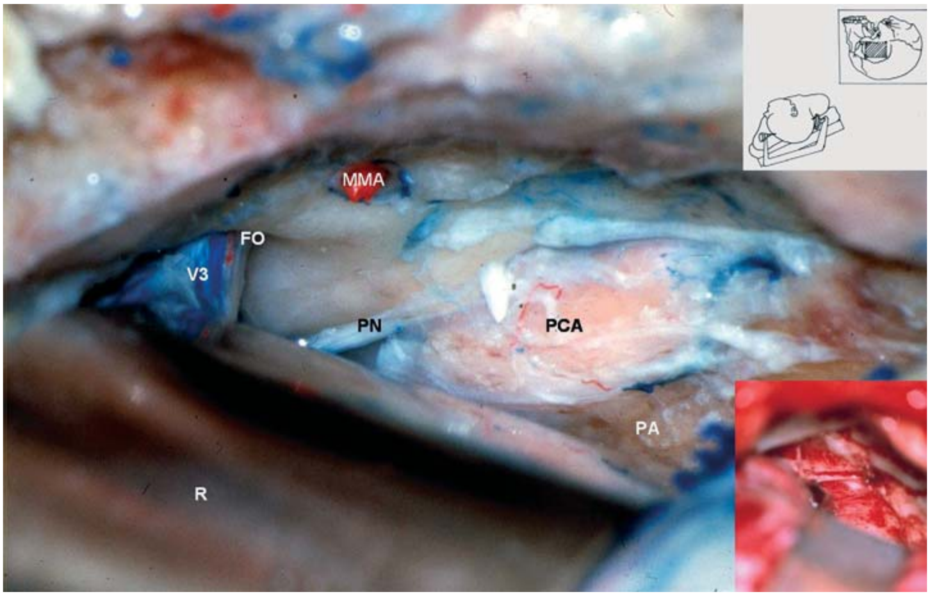


Fig. 17. Right sided anterior petrosectomy on a cadaver dissection: exposure of the horizontal segment of the petrous carotid artery (*PCA*). *MMA* Middle meningeal artery; *FO* foramen ovale; *V3* 3rd branch of the Vth nerve; *PN* petrosal nerve; *R* retractor; *PA* petrous apex

(Fig. 16). Coagulation is performed and the middle meningeal artery is sectioned, as well as the petrosal nerves in order to prevent traction on the geniculate ganglion [43, 44] (Fig. 17), although Kawase recommends preserving these nerves in order to prevent inhibiting homolateral tears secretion [19]. Identify the foramen ovale. If the foramen lacerum is covering it, the horizontal carotid can be localized by means of two landmarks as we have previously seen (Fig. 17): the axis of the petrosal nerves and the axis joining the middle points of the foramen ovale and the foramen spinosum which are parallel to the horizontal segment. When the roof of the horizontal carotid is denuded by a long or relatively non-covering foramen lacerum, the dura mater which separates it from the temporal lobe can be detached fairly easily. As we have pointed out, there may be inconvenient venous bleeding which will be all the more abundant as one comes closer to the distal part of the horizontal segment. Drilling of the portion covering the foramen lacerum may also be hindered by this venous bleeding. Lifting of the dura is restricted in front by the mandibular nerve. An attempt must be made to detach the superior petrosal sinus from its sulcus before drilling is begun. This is performed medially over the entire exposable length of the horizontal carotid without going further back than the plane passing through the hiatus of the petrosal nerves in order to avoid the cochlea and the first portion of the facial nerve (Fig. 18). Despite the obstacle

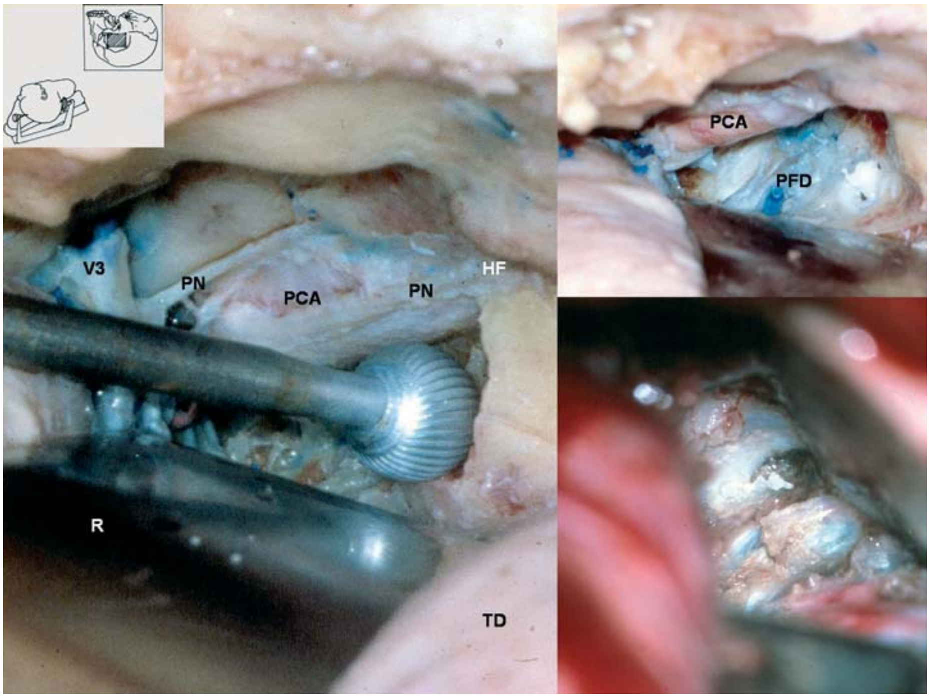


Fig. 18. Right sided anterior petrosectomy on a cadaver dissection: drilling of the petrous apex following carotid artery identification. *V3* 3rd branch of the Vth nerve; *PN* petrosal nerve; *R* retractor; *PCA* petrous carotid artery; *HF* hiatus Falopi; *TD* temporal dura; *PFD* posterior fossa dura

of the dural lifting and as long as embolization is performed beforehand, we propose extending the drilling beyond the inferior petrosal sinus [10–12].

This releases a triangle of the dura mater located between the upper and inferior petrosal sinuses, respectively at the top and at the bottom, going behind as far as to denude the ventral dural wall of the internal acoustic meatus (Fig. 18). The dura mater of the posterior fossa is open behind from the top down.

Exposure (Fig. 19) [10]

The photograph shows the operative field.

- The ventral side of the pons is exposed from nerve V as far as the origin of nerve VI.
- Also exposed: the homolateral V, the entire path of the homolateral VI, and the origin of the homolateral acoustico-facial bundle in its cisternal passage. Only the contralateral VI will be seen in the distal portion of its cisternal passage.
- The basilar artery is exposed over a little more than one centimeter as well as the AICA from its origin as far as the ventral part of its loop.

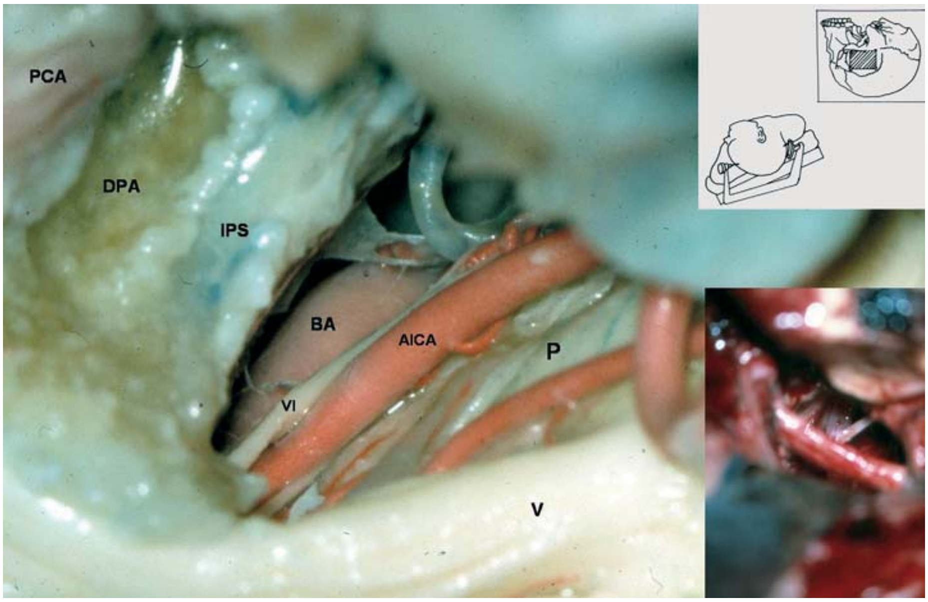


Fig. 19. Right sided anterior petrosectomy on a cadaver dissection: intradural exposure and operative field. *PCA* Petrous carotid artery; *DPA* drilled petrous apex; *IPS* inferior petrosal sinus; *BA* basilar artery; *VI* 6th cranial nerve; *AICA* anterior inferior cerebellar artery; *P* pons; *V* 5th cranial nerve

A clinical example is proposed (Fig. 20), namely a right petroclival meningioma operated upon via this approach.

Reconstruction

Limited. If petrosal cells have been opened, they should be filled with powdered bone or muscle. The surgical cavity can be filled with fat, being aware of the risks of septic necrosis. Kawase proposes lining the floor of the temporal fossa by rotation of the temporal muscle, the edges of the dural defect being sutured on the muscular fascia [19].

Pros and cons

Pros:

- Principally access to the ventral side of the pons, in front of the plane of VII and the lower cranial nerves.
- With preserved hearing function.
- Extradural access, protecting the temporal lobe, is considered as an advantage by all experts.

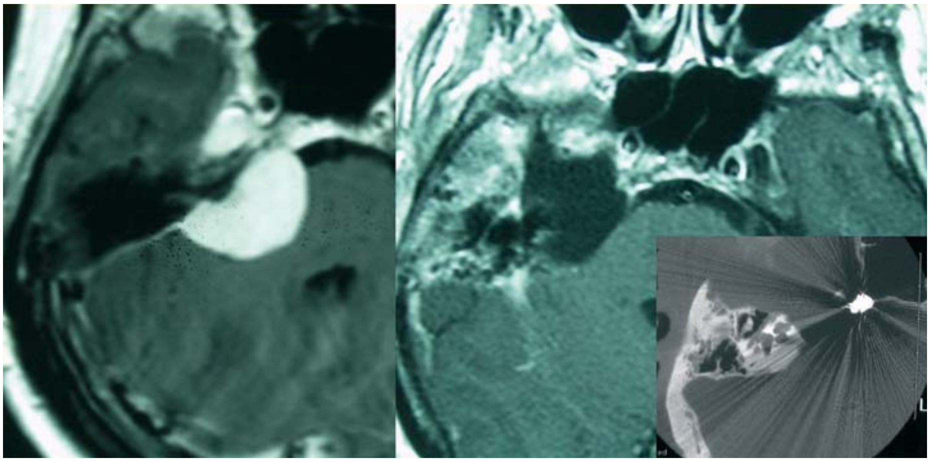


Fig. 20. Case illustration: a 30-year-old woman presenting with headaches and mild hearing loss. See the left sided petroclival meningioma, with postoperative MR scan, and postoperative bone window CT scan showing preservation of the cochlea

– Access can be gained to the contralateral apex if the lesion is pushing all the axial structures back.
– Finally, as will be described further on, transtentorial extension as needed can afford access beyond V and the upper pontile sulcus.

Cons:

– Some temporal retraction is unavoidable.
– The mandibular nerve restricts retraction of the dura, drilling down and drilling under the lower dorsal angle of the trigeminal ganglion and thus hinders access to the cavernous sinus.
– The "useful" access to the foramen magnum is practically impossible via this approach. Drilling of the carotid knee via this approach almost always means sacrificing the cochlea with very little gain.
– This approach permits no real control of the petrous carotid and does not afford either the repair or the bypassing that might be necessary.
– Access to the pontocerebellar angle is limited.
– No access is afforded to either the cerebello-medullary angle or the lower cranial nerves.

Transtentorial extension

The dural opening can be extended, if desired. The dura mater is cut into on either side of the superior petrosal sinus which is interrupted (e.g. using clips) in front of the point where it joins the upper petrosal vein and behind where nerve IV enters the dura (at least one centimeter behind the posterior clinoid process). These landmarks are difficult to discern without the intradural control image of the free edge of the tentorium. The dura mater of the middle cranial fossa is open in parallel to the superior petrosal sinus. The tentorium is cut. This extension makes it possible to control the pons above nerve V at the top at the expense of more extensive temporal retraction.

Anterior petrosectomy as an extension of the epidural temporopolar transcavernous approach (Fig. 21)

This anterior petrectomy can represent the second stage of a broader approach described in the next chapter. It may be further extended by drilling outside the cavernous carotid. This stage will make it possible to go lower, mobilizing the cavernous carotid but virtually always entails opening the cochlea. This type of drilling is very useful in the context of surgery to treat chordoma.

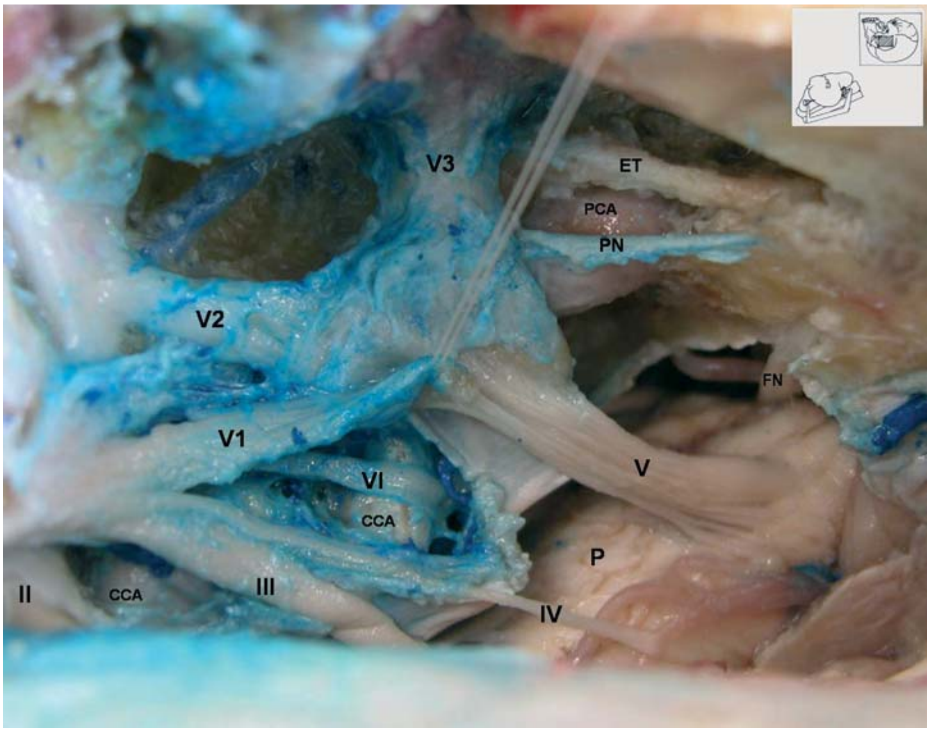


Fig. 21. Extension of an anterior petrosectomy with achievement of an epidural temporopolar transcavernous approach in a cadaver dissection: *V* 5th cranial nerve with first (*V1*) second (*V2*) and third (*V3*) divisions; *II* Optic nerve; *III* 3rd cranial nerve; *IV* 4th cranial nerve; *VI* 6th cranial nerve; *CCA* cavernous carotid artery; *P* pons; *ET* Eustachian tube; *PCA* petrous carotid artery; *PN* petrosal nerve; *FN* facial nerve

Epidural temporopolar transcavernous middle fossa approach

We detail here a widened lateral skull base approach that combines an epidural temporopolar transcavernous (Dolenc, Fukushima, Hakuba, Day) approach with a middle fossa anterior transpetrosal approach (Kawase) [2, 5, 9, 13, 15, 16, 19, 20]. Of course, this extended option is not always necessary to remove tumors from the PCA but is very useful for tumors which occupy the posterior fossa at the level of the petrous apex and clivus and reach the middle fossa (Meckel cave, posterior cavernous sinus, superior orbital fissure, optic canal, suprasellar region).

Installation (patient lying in the supine position)

The head is rotated to a 45° lateral position and maintained in a 3 pin Mayfield frame. Care should be taken to avoid compression of the contralateral jugular vein. Neuromonitoring of the cranial nerves and a CSF closed drainage system are prepared.

Skin incision (Fig. 22)

Is performed in the shape of a question mark starting anterior to the tragus at the level of the zygomatic arch, passing over the external ear and coming into the frontal region. This incision can be modified according to the extent of the planned drilling. The frontotemporal pericranial flap is dissected and the temporal muscle is turned back in a posteroinferior direction. Identification of the root of the zygoma is an important step for the future drilling of the middle fossa but usually, orbitozygomatic deposit does not give additional exposure to petroclival tumors.

Bone flap (Fig. 22)

A frontotemporal craniotomy is performed as far as the floor of the middle fossa below. The pterional region is drilled to flatten both the orbital roof and the lateral wall of the orbit. Opening of the frontal sinus and of the periorbital fascia should be avoided during this step. The pterion (lateral portion of the great sphenoid wing and lesser sphenoid wing) is drilled with a cutting drill until the meningo-orbital band is seen. There is no need for an orbitozygomatic osteotomy as seen in literature [17].

Exposure of the epidural temporopolar space (Fig. 23)

The external border of the superior orbital fissure (SOF) is exposed by shaving the lateral wall of the orbit anteriorly and by gently retracting the temporopolar dura back after the meningo-orbital band has been cut. At this point, it is necessary to shave the anterolateral (Mullan) triangle between V1 and V2 and then

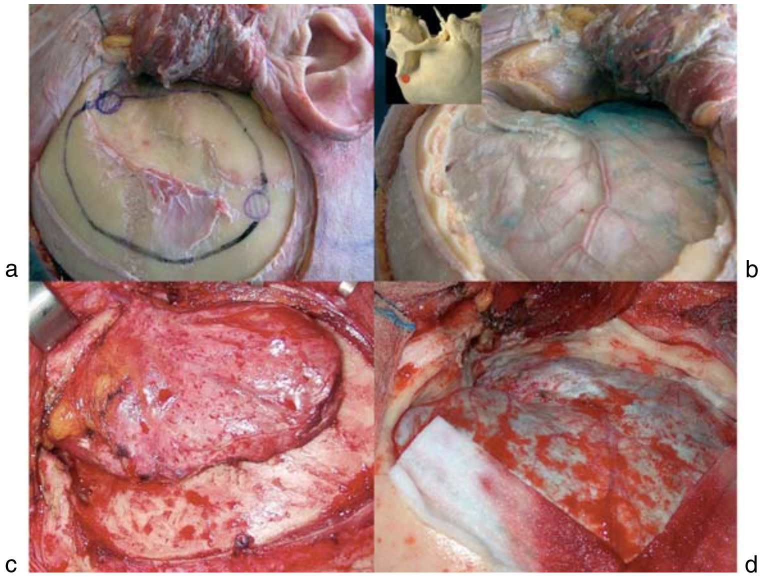


Fig. 22. Superficial steps of the anterolateral skull base approaches: head cadaver, right side. (a) Design of the skin incision & delineation of the bone flap. (b) The bone flap is achieved and the frontotemporal dura mater is exposed. Operative case, right side. (c) Incision of the temporal muscle. Note that a muscle cuff is kept on the bone in order to improve the stitching at the end of the procedure. Just under the retractor, the zygomatic arch is shown (d) Exposure of the dura that is elevated from the middle fossa. Note the red point as the key hole

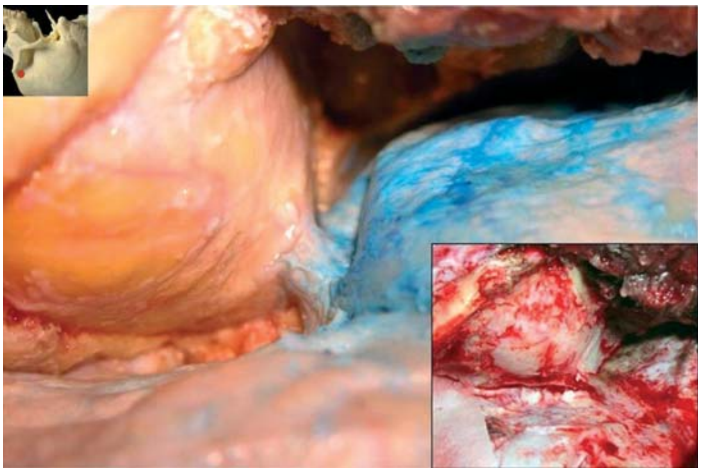


Fig. 23. Exposure of the epidural temporopolar space (Head cadaver dissection, right side): the meningoorbital band is the thick fibrous band that connect the periorbital fascia to the temporopolar dura. At the right bottom corner, the same view is shown in an operative case

the far lateral triangle between V2 and V3. This step is facilitated by drilling the foramen rotundum and foramen ovale. In order to generate more room for the drilling of the far lateral triangle, the dura from the floor of the great sphenoid wing. This entails identification, cutting and coagulation of the middle meningeal artery at the foramen spinosum. Some venous bleeding from the posterior margin of the ovale foramen is normal because the dura at that point is filled by bridging veins that connect the lateral cavernous sinus with the pterygoid venous plexus. Such bleeding is easily stopped by gentle packing with small pieces of oxidized cellulose. These steps are necessary for exposure of the true lateral wall of the cavernous sinus but also make it possible to work backwards to the anterior petrosectomy.

Extradural Anterior clinoid process (ACP) removal and optic canal exposure (Fig. 24)

Whether or not this step is undertaken will depend on the extent of the tumor. If the tumor has spread to the suprasellar space and optic canal, this step is indicated.

In order to generate space in the direction of the anterior clinoid process, it is helpful to cut the meningo-orbital band in first, to release CSF from the lumbar drain, and then to install a rigid, extradural self-retaining retractor. The unroofing of the optic canal provides a good landmark to avoid injuring the nerve intradurally while drilling the ACP. This roof is exposed after lifting the dura away from the orbital roof and pushing it in a medial direction towards the planum sphenoidale. Once it has been clearly identified, the ACP is removed

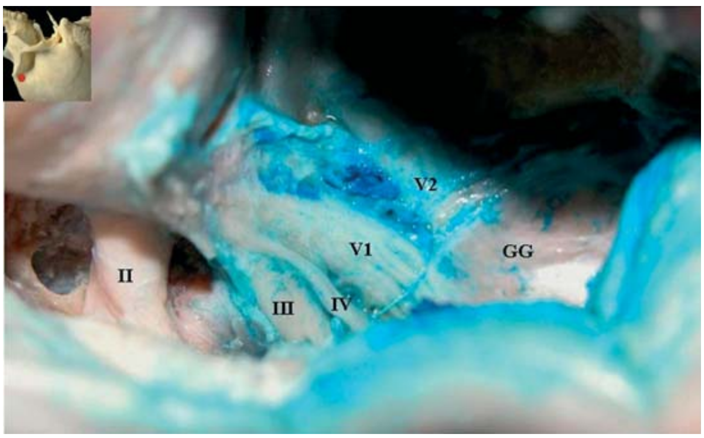


Fig. 24. Extradural removal of the anterior clinoid process and exposure of the optic canal. *II* Optic canal, *III* third nerve in the lateral wall of the cavernous sinus, *IV* fourth nerve, *V1* ophtalmic division of the trigeminal nerve, *V2* maxillary division of the trigeminal nerve, *GG* Gasserian ganglion

using the eggshell technique (hollowing out the inside by drilling) and peripheral dissection outside using a thin, sharp, rigid dissector (Fukushima's instrumentation). The final step is one-piece removal of the "tooth-like" skeleton of the ACP. It is now possible to expose the optic canal through 270° of its circumference by drilling the floor of the optic canal also named the optic strut.

Anterior petrosectomy

The dura is now retracted from the subtemporal middle fossa below V3. It is necessary to identify the thin bone of the tegmen tympani, the eminencia arcuata, and the fibers from the GSPN. It is always possible to preserve these fibers. The GSPN actually adheres to the middle fossa dura but sharp dissection using a 15 blade knife or a thin dura elevator will separate it, from the Fallopian Hiatus and geniculate ganglion on the lower side of the Meckel's cave. It is important to mobilize V3 and to lift the dura of the Meckel's cave in order to proceed medially toward the petrous apex. The GSPN overlies the horizontal portion of the intrapetrous carotid artery (C6). These two structures are important landmarks when it comes to defining the boundaries of Glasscock's triangle. One should keep in mind that the medial segment of the bony roof of C6 is usually dehiscent which is why we recommend first flattening the middle fossa using a diamond drill until the carotid has been clearly identified. Glasscock's triangle should be drilled if the surgeon wishes to mobilize the C6 carotid segment laterally. Such a step requires identification of the tensor tympani muscle and the Eustachian tube underneath. Both structures lie at the lateral surface of C6 and may be sacrificed during this procedure. When lifting the dura, the surgeon will reach the petrous ridge and the groove of the superior petrosal sinus. The limits of Kawase triangle are delineated as follow: C6 laterally, petrous ridge medially, Meckel cave and V3 anteriorly. At this point, some authors recommend unroofing the internal auditory canal that defines the posterior limit of the petrous apex. Whatever the technique used to locate the IAC, it is necessary to expose the dura of the anterior border of the porus. Attempting to unroof the whole canal, particularly the fundus, may damage the geniculate ganglion and the deeper cochlea.

Once the landmarks of the posteromedial triangle have been identified, the petrous apex is drilled. Drilling is facilitated by a high pneumatization in some cases but if this is not possible, the fatty aspect of the bone is usually helpful. In cases of petrous apex meningiomas, the osteoma needs to be resected using a cutting drill. Approaching the cortical bone of the inner surface, close to the dura, needs more cautious drilling to avoid opening the dura at too early a stage. The operator should drill downwards until the blue color of the inferior petrosal sinus is seen. If the IPS is torn, bleeding is always abundant and the sinus lumen should be gently packed with small pieces of oxidized cellulose. This type of problem can be prevented by pre-operative embolization of the

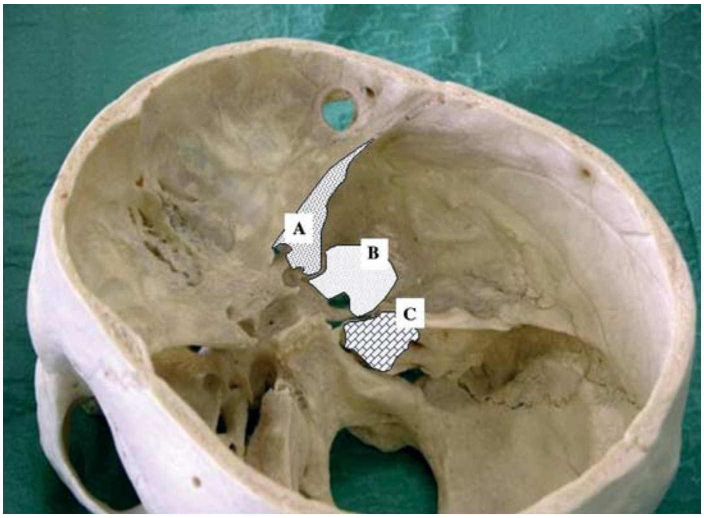


Fig. 25. Extent of the skull base resection during the anterolateral skull base approach: *A* Resection of the lesser sphenoid wing and anterior clinoid process, *B* drilling of the anterolateral and far lateral triangles, *C* resection of the posteromedial triangle

sinus, as recommended by Fournier *et al.* [11, 12] but the proximity of the abducens means that this technique entails a risk of nerve palsy. It is sometimes quite difficult to reach the extreme tip of the petrous apex and upward retraction of the Meckel cave is then needed. Usually the apex can be removed in the same way followed by the anterior clinoid process. Once drilling is finished, careful hemostasis of the dura and epidural space is important before the dura is opened. At the end of the procedure and before opening the dura, the extent of the skull base resections is shown on Fig. 25.

Opening the dura (Fig. 26)

As we have previously seen, the anatomy of the petroclival dura is particularly complex. Optimal opening of the dura should be systematically matched to pre-existing bone exposure. Insufficient dura opening may narrow the operative corridor and entail unnecessary retraction. Care should be taken to proceed in a methodical, meticulous way to avoid damaging the underlying cranial nerves, prevent excessive bleeding from the venous sinuses, and preclude closure problems.

Step 1. Lifting of the dura propria from the lateral wall of the cavernous sinus (Fig. 24): A cleavage plane exists at the junction of the temporal dura and the periorbital fascia, at the apex of the superior orbital fissure. Gradual lifting of the dura propira will allow identification of the true cavernous membrane of the lateral wall – a loose tissue sheathing the oculomotor nerves and V1.

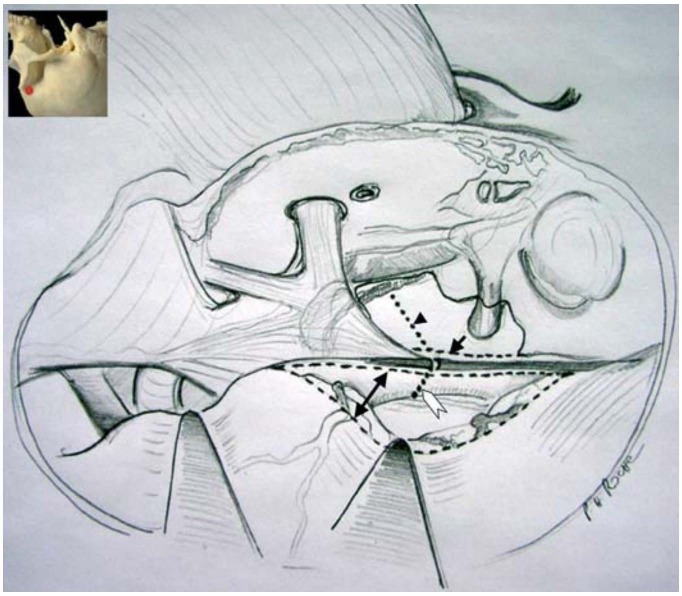


Fig. 26. Artistic drawing showing the process of dura opening (right side): the double arrow shows the horizontal incision of the temporal dura above the superior petrosal sinus. The black arrow indicates the horizontal section of the posterior fossa dura under the superior petrosal sinus. The arrow head shows the vertical incision of the posterior fossa dura between the superior and inferior petrosal sinuses. The chevron arrow shows the transversal section of the tentorium until the free edge is reached

Extradural lifting of the temporal lobe preserves the veins. Lifting behind exposes the trigeminal ganglion and is blocked in the medial direction by the edge of the tentorium.

Step 2. Opening the dura over the sylvian fissure and as far as the optic canal – using a T-shaped configuration. Following these two steps (1 and 2), the dura can be removed from the lateral wall of the cavernous sinus when necessary, e.g. if there is a meningioma encroaching upon the lateral wall. Here the temporal veins draining into the sphenoparietal sinus may be sacrificed.

Step 3. Opening the dura of the posterior fossa (Fig. 26). Clear identification of the SPS. Horizontal section of the basitemporal dura parallel and just above the SPS from the Meckel cave to the suprameatal area behind. Horizontal section of the posterior fossa dura just under the SPS, from the porus trigeminus to the suprameatal area behind. Coagulation and transverse section of the SPS. It is usually necessary to push oxidized cellulose into the SPS to induce hemostasis. Suture of both edges of the cutting section and traction lifting of the threads to broaden the surgical field. Progression medially to the free edge of the tentorium but not too close to the posterior wall of the cavernous sinus (to avoid damaging nerve IV). If the tentorium is involved by

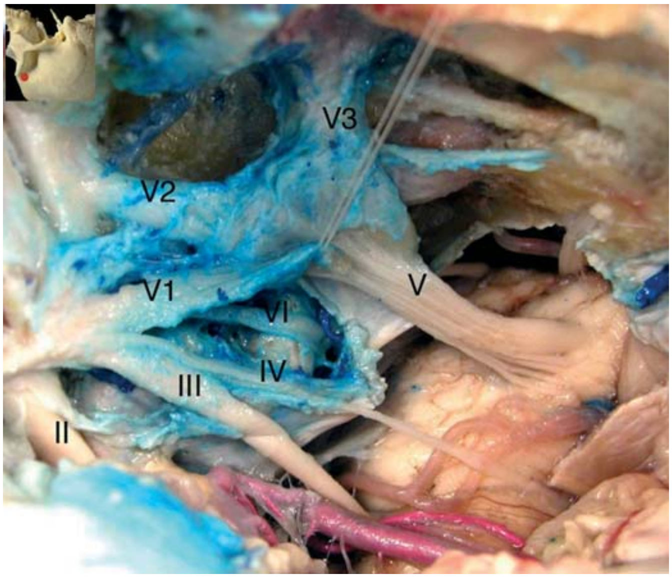


Fig. 27. Exposure of the cranial nerves from the optic nerve to the acousticofacial bundle after achievement of the epidural temporopolar transcavernous approach: *II* The optic nerve is shown in its intracranial compartment and coursing in the optic canal. *III* The third nerve is shown in its intracisternal portion and in the lateral wall of the cavernous sinus. The same aspect is shown for the fourth nerve (*IV*). *VI* The sixth nerve is shown while its cross the carotid artery inside the cavernous sinus. *V3* Mandibular division of the trigeminal nerve. *V* Sensitive root of the trigeminal nerve

the tumor, it is easily removed providing a direct communication between the supra and infratentorial spaces and exposing the cranial nerves from the optic nerve to the acousticofacial bundles (Fig. 27).

Tumor removal

This approach offers various operative corridors from the middle to the posterior fossa. Usually, the tumor is removed not in its entirety but in fragments. The microsurgical technique used will of course depend on the origin and nature of the tumor. During the removal of chordomas or chondrosarcomas, the extradural step is essential because most of the tumor is resected before opening of the dura; usually the tumor consists of soft tissue which can be removed using ring curettes and forceps under controlled suction. For meningiomas, the surgeon alternates extracapsular devascularization and detachment maneuvers with intracapsular debulking.

The surgical problems will of course depend on the lesion being resected.

– Vessels. The middle and upper cerebellar arteries and, inside, the basilar trunk are often in contact with bulky tumors. Particular difficulties are linked to meningiomas in which vessels are sometimes totally surrounded by the tumor (which can be predicted from the pre-operative images). The veins at risk are at the interface between the tumor and the trunk. Usually the petrous veins can be preserved but it is much more difficult to save the integrality of the pontine subpial veins in cases of large tumors because of adhesion.

- Nerves. The fourth nerve is at the external pole of the tumor, flattened up against the free edge of the tentorium. The sixth nerve is below and is visible at the end of the procedure at the bottom and in front. Sometimes, it is not identified in the course of resection and remains at a distance. The trigeminal is in the middle of the field and is usually easily dissected being strong and large-caliber.
- Brain stem. The lateral side of the pons is exposed over its entire height during the approach, centered by the entry point of the trigeminal nerve.

Closure

The closure procedure should be meticulous, hermetic, helped by abundant use of grafting material (particularly fat or temporal muscle). In some cases, when

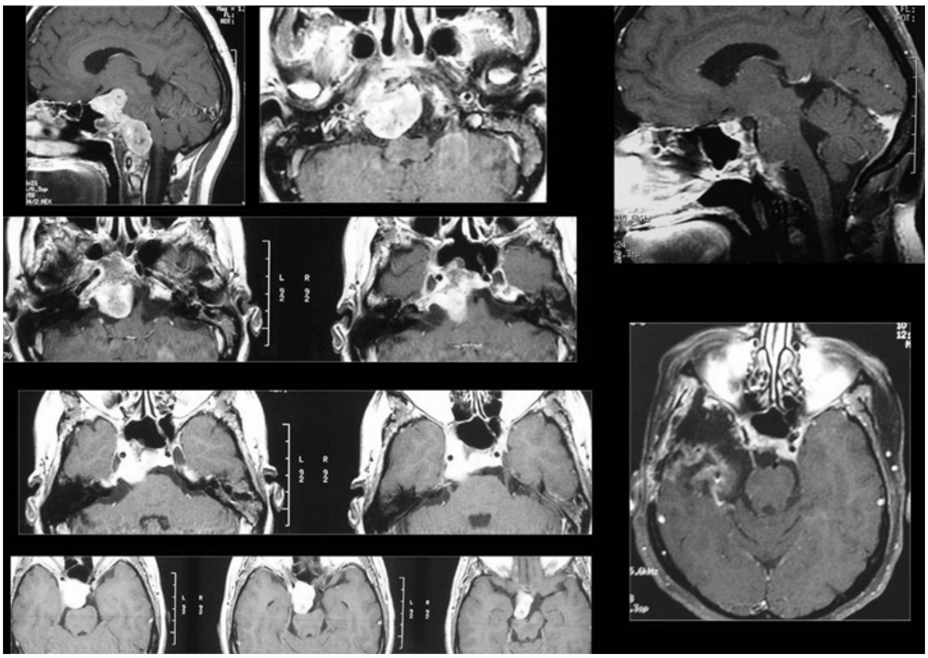


Fig. 28. Case illustration: a 40-year-old woman presenting with a recurrent clival chordoma, chordoma which was operated on 2 years ago elsewhere and treated subsequently by proton beam therapy. She complained of headaches, gait disturbances, and diplopia. Pre and post operative (using an epidural temporopolar transcavernous middle fossa approach) MR scan are presented

the sinuses have been extensively opened up or if there is parapharyngeal exposure, reconstruction with a vascularized muscle flap will be necessary: in this case, it is useful to ask a plastic surgeon to help with reconstruction. If special tissues are used, the patient should be warned and derails should be given in the operative chart because post-operative MR control results may be misinterpreted if this information had not been communicated beforehand. Extradural drainage should be avoided so that no CSF channel is created. If drainage is unavoidable, install superficial layers with low-pressure aspiration. There is a need for an extensive peripheral holding of the dura. Meticulous reapplication and stitching of the temporal muscle is required and the skin is stitched in two layers.

A clinical case is presented on Fig. 28. A 40-year-old woman was referred to us with a recurrent clival chordoma. The patient was operated on 2 years ago and underwent proton beam therapy before recurrence.

Subtemporal preauricular infratemporal fossa approach (inferolateral)

Principle

Technically more difficult than anterior petrectomy, this fully mobilizes the petrous carotid.

This approach was first described by Sekhar to expose and control the upper cervical carotid and the entire intrapetrous carotid, in the course of surgery to address bulky lesions at the base of the skull [40]. It is used for the excision of extradural, originally exocranial lesions of the skull base (possibly extending into the cranium on the median line) [27, 36–39]. It was then adapted to approach intradural structures in the petroclival region located in front of the brain stem [41]. The principle underlying this approach is to expose the ventral side of the pons and the prolonged medulla from nerve V to the petrous apex at the top as far as nerve XII at the greater foramen below, by completely drilling out the anterior part of the petrous pyramid, preserving the cochlea and remaining outside the pharynx in front. The infra-temporal approach makes it possible to work underneath the temporal lobe without any retraction, as a result of total ablation of the floor of the middle cranial fossa; it also means that the bone can be drilled as far as the hypoglossal canal. Most importantly, it affords access to the brain stem in front of the plane of nerve VII and the mixed nerves.

Technique

The patient in installed in a supine position, with the head in a bone-gripping frame turned to an angle of 45° away from the side of the incision, in slight extension. An arc-shaped, fronto-temporal incision is made at the hairline, extending in front of the tragus, running around the lobule of auricle and terminating at the anterior edge of the sternocleidomastoid muscle. To preserve the frontal, temporal and zygomatic branches, the incision should be made flush with the tragus and should allow sub-periosteal detachment of the posterior root.

The trunk of the facial nerve is identified directly above the ventral edge of the cartilage of the external acoustic meatus, and is followed up until its entry into the parotid. Then superficial parotidectomy is performed allowing identification of the nerve's branches.

The zygomatic arch is sectioned using an oscillating saw in front at the root of the temporal process of the zygomatic bone and behind just in front of the mandibular fossa in front of the transverse root. It is displaced downwards.

The temporal muscle is taken out of the temporal fossa and also displaced downwards.

One exposes at the neck the internal jugular vein with nerve XI running along its lateral face. It is then followed at the top as it passes medially to the diagastric to cross the facial nerve. The muscle is sectioned and the occipital

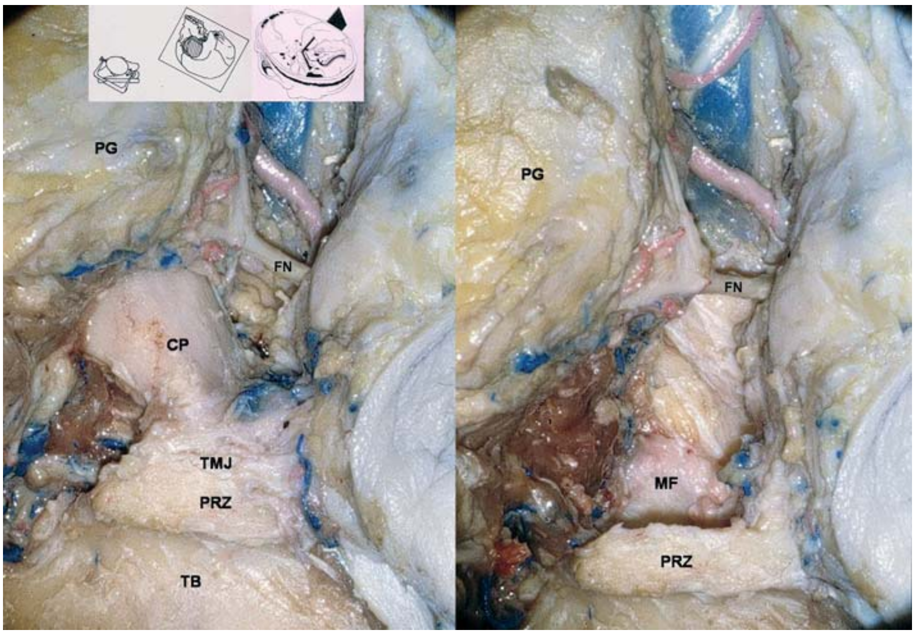


Fig. 29. Right sided inferolateral approach on a cadaver dissection: see exposure of the condylar process (*CP*) and temporomandibular joint (*TMJ*) on the right part of the figure, and resection of the condylar process with exposure of the mandibular fossa (*MF*) on the left. *PG* Parotid gland; *FN* facial nerve; *PRZ* proximal root of zygoma, *TB* temporal bone

artery is interrupted where it crosses the internal carotid which allows dissection of nerve XII from where it emerges from the base to pass between the internal carotid and the jugular vein (Fig. 29).

Then the styloid process is exposed which is ablated together with the vaginal process after removal of the elements of the stylian diaphragm. The internal carotid is then exposed up till about one centimeter from where it enters the carotid canal.

The capsule of the temporomandibular joint is opened. The condyle process is luxated. Better exposure is obtained by resection of the condyle process and from the upper third of the mandibular ramus, the only option for formaldehyde-fixed preparations. This resection can be extended down to the mandibular incisure without any risk of damaging the lower alveolar nerve which penetrates the mandible at the mandibular foramen located about one centimeter under the incisure. This exposes the mandibular fossa (Fig. 29).

Temporal craniotomy extended in front flush with the pterion and behind to the top of the roof of the external acoustic meatus. The posterior root of the zygoma is ablated from the mandibular fossa and the floor of the temporal fossa as far as the foramen spinosum and the foramen ovale to expose nerve V3 (Fig. 30).

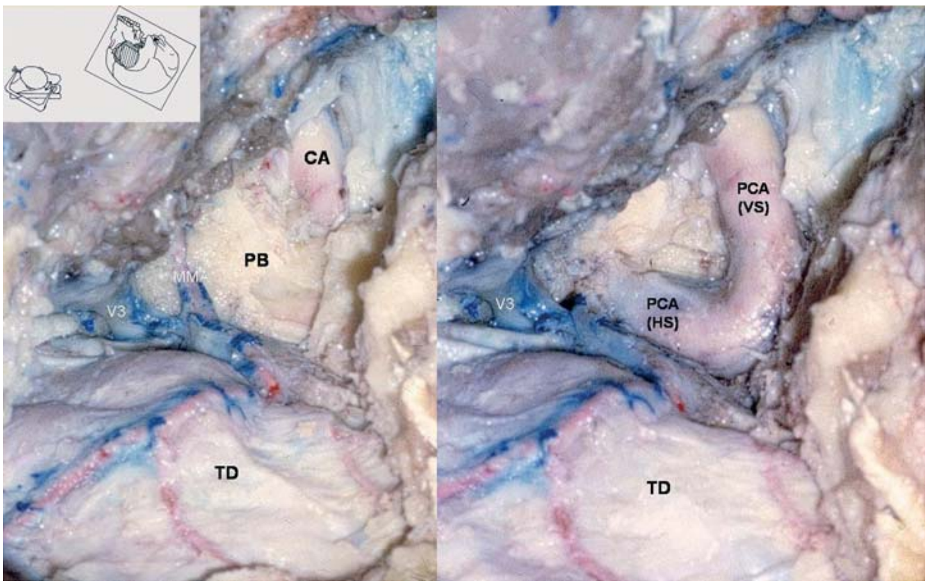


Fig. 30. Right sided inferolateral approach on a cadaver dissection: progressive exposure of the entire petrous carotid artery: *CA* cervical carotid artery; *PB* petrous bone; *TD* temporal dura; *MMA* middle meningeal artery; *V3* 3rd branch of Vth nerve; *PCA (VS)* petrous carotid (vertical segment); *PCA (HS)* petrous carotid (horizontal segment)

The dura is detached from behind forwards and from the outside inwards. The middle meningeal artery and the petrosal nerves are interrupted.

The eustachian tube and the tensor tympani muscle are exposed and resected. The eustachian tube will be filled in subsequently.

Then the lateral covering of the intrapetrous carotid is drilled without going beyond the knee located inside the section of the eustachian tube. The pericarotid venous plexuses are found developed mainly at the distal portion of the horizontal segment. The periosteum of the carotid canal adheres to a fibroa-cartilaginous annulus which encircles the carotid at the point at which it enters the canal. This annulus must be opened in order to be able to mobilize the artery. This is dissected in its high cervical portion above nerve VII in the downward direction. The petrous carotid is then released with its periosteal envelope and displaced forwards and laterally (Fig. 31).

Then the petrous bone is drilled medially to the carotid and the cochlea as far as the anterior edge of the internal acoustic meatus (Fig. 31). In front and without interrupting nerve V3 by virtue of its approach from below up, the drilling can expose the medial carotid at the lower dorsal angle of the trigeminal ganglion. The drilling field retracts down because of the canal of the hypoglossa and the jugular foramen. This exposes a triangle of the dura mater at the sub-temporal base. The drilling will go below the inferior petrosal sinus which should be first embolized.

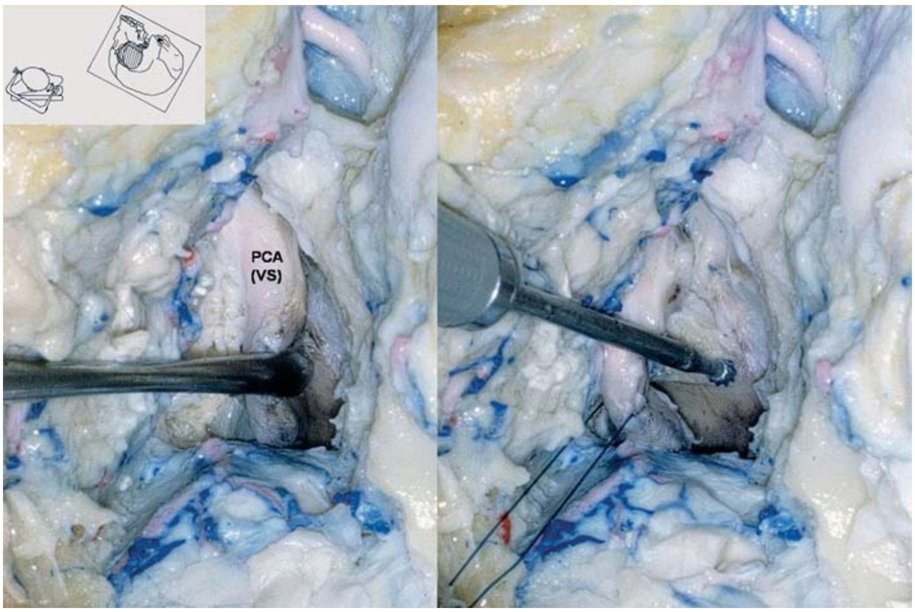


Fig. 31. Right sided inferolateral approach on a cadaver dissection: Mobilization of the petrous carotid artery and drilling of the petrous apex: *PCA (VS)* petrous carotid (vertical segment)

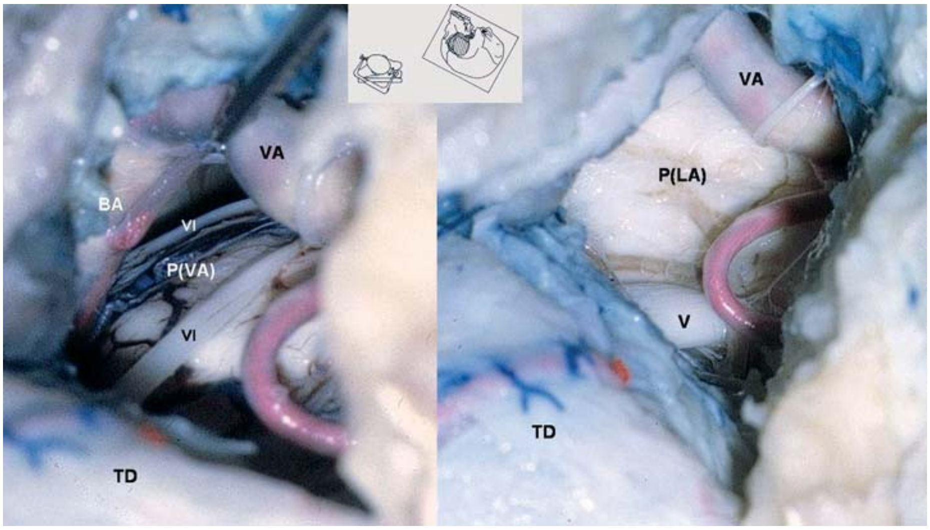


Fig. 32. Right sided inferolateral approach on a cadaver dissection: intradural exposure and operative field. See both VIth nerves (VI) and ventral aspect of the pons (PVA). *BA* Basilar artery; *VA* vertebral artery; *TD* temporal dura; *V* 5th nerve

Exposure

The following structures are exposed: (Fig. 32) [10]

- The brain stem – more specifically the ventro-lateral side of the pons below nerve V, the lower pontile sulcus, the oliva and the upper part of the pyramid.
- The cranial nerves from nerve V at the top to nerve XII at the bottom without visualizing the lower cranial nerves (the homolateral nerve V from the pons to the petrous apex, the homolateral nerve VI from its origin to its dural entry point, the contralateral nerve VI over one-third of its cisternal passage, the homolateral cochleo-vestibulo-facial bundle from its origin as far as the open porus in front, and the rootlets of the homolateral nerve XII.
- The basilar artery, the vertebro-basilar junction if it is ipsilateral or median, the homolateral AICA from its origin to the anterior part of the pontocerebellar angle.

Reconstruction

All the dural incisions must be scrupulously closed by direct suturing or by interposition of a pericranial flap. The cavity is then filled using fat (e.g. taken from the abdomen). If the approach has created communication channels between the intradural space and air-filled cavities (the nasopharynx, the paranasal sinuses, etc.), a vascular flap must be used to protect the dura mater and the major vessels. If dehiscence is limited and the vascularization of the temporal muscle has been preserved, the latter can be used in rotation (knowing the angle is limited). Some experts recommend using a fragment of rectus abdominis muscle stalked on deep epigastric vessels. Other flaps may be used.

Pros and cons

Pros:

- The whole carotid (intra-petrous and high cervical) is controlled meaning grafting and reconstruction, if necessary.
- The contralateral petroclival region can be accessed if the lesion is involving axial structures behind.
- The approach can be extended in front or up at the same time. Notably, it will be seen that access up to nerve V is obtained by combination with an intradural, sub-temporal approach. In this way, exposure of the posterior clinoid processes from nerve II to nerve IV can be added.

Cons:

- Interruption of the eustachian tube will entail permanent tympanostomy.
- Apart from reconstruction, the loss of a condyle process in the event of resection is responsible for trismus, malocclusion and contralateral pain, at least temporarily.

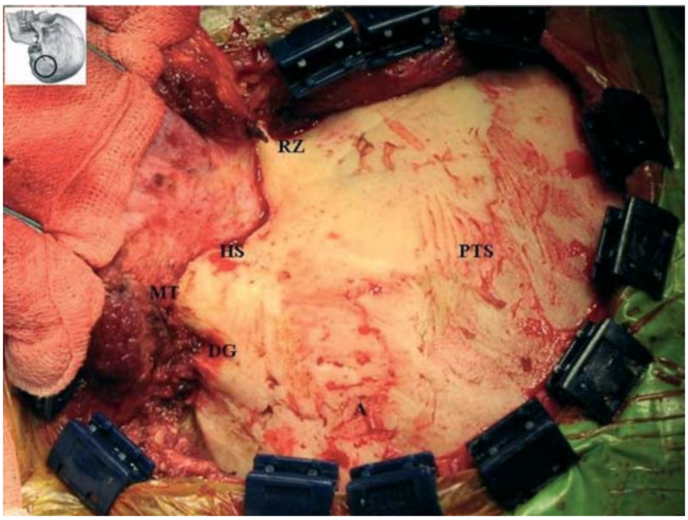


Fig. 33. Combined petrosal approach (left side). The skin and muscle have been elevated and the main bony landmarks are identified. *A* Asterion, *MT* Mastoid tip, *PTS* parietotemporal suture, *RZ* root of zygoma, *SH* spine of Henle

Combined petrosal approaches

For large tumors growing from the petroclival region and extending behind into the cerebellopontine angle, pure lateral or anterolateral approaches are insufficient to provide total resection. A few skull base teams have developed combined approaches that reach the petroclival by temporal craniotomy combined with a varied degree of removal of the petrous bone. These approaches provide the surgeon a multifocal extensive operative corridor extending from the posterior to the middle fossa. We have chosen to detail the least invasive of these approaches, one that allows the preservation of neuro-otologic structures.

The combined retrolabyrinthine (Anterior Sigmoid)-middle fossa approach [2, 3, 11, 13]

Head positioning and the skin incision

The head is secured with three-point pin fixation and placed in the lateral position facing away from the surgeon. A periauricular skin incision in the

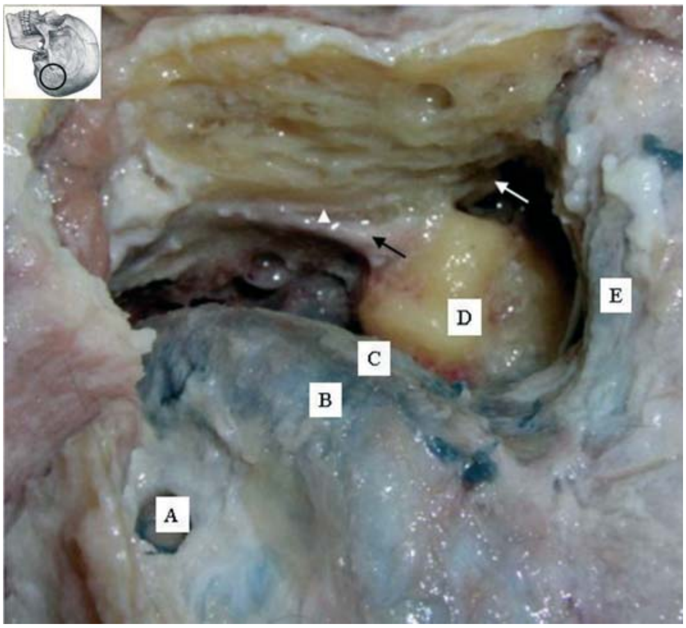


Fig. 34. Head cadaver dissection (left side) showing the final exposure of the retrolabyrinthine step of the approach: *A* Retrosigmoid dura, *B* sigmoid sinus, *C* presigmoid dura at the level of the endolymphatic sac, *D* semicircular canals at the level of the common crus, *E* temporobasal dura. The black arrow indicates the facial nerve in the Fallopian canal at the junction between the second and the third portion. The arrow head shows the corda tympani. The white arrow indicates the ossicles in the tympanic cavity

shape of a question mark or an L is made. Continue as far as possible in the anterior direction in order to retract the temporal muscle down and forwards. The following bony landmarks are now exposed (Fig. 33): Mastoid tip, spine of Henle, asterion, parietotemporal suture, root of zygoma.

Bone drilling and bone flap

A retrolabyrinthine mastoidectomy is then performed. This will superficially expose the sigmoid sinus and the jugular bulb, the presigmoid dura and the dura under the temporal lobe. In the depth, after removal of the mastoid air cells, the shape of the semicircular canals can be identified. The yellowish compact bone of the lateral semicircular canal is first identified at the medial surface of the mastoid antrum, once this air cell has been broadly drilled out using a diamond drill. The loop of the lateral semicircular canal is a constant landmark for the fallopian canal because the second portion of the facial nerve passes just underneath. It is necessary to expose the relief of the posterior labyrinth properly in order to improve the angle of vision (Fig. 34). A large temporo-occipital bone flap is then created, exposing the retrosigmoid and temporobasal dura (Fig. 35). This step allows lifting of the dura from the middle fossa, proceeding

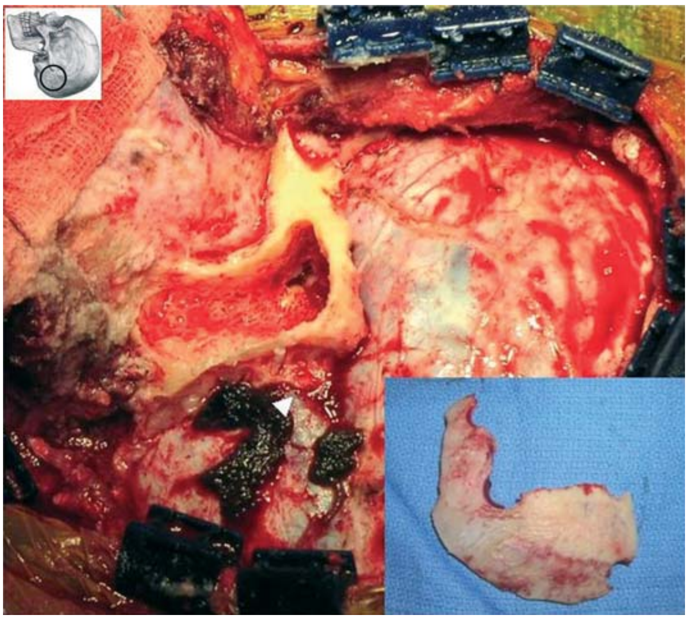


Fig. 35. Combined petrosal approach (left side): the temporo-occipital bone flap has been elevated (small window), exposing the dura and the transverse sinus. The junction between transverse and sigmoid sinus is shown by the small white arrowhead. The early step of the mastoidectomy has been undertaken. Note that in this case, the bone flap has been performed before the mastoidectomy

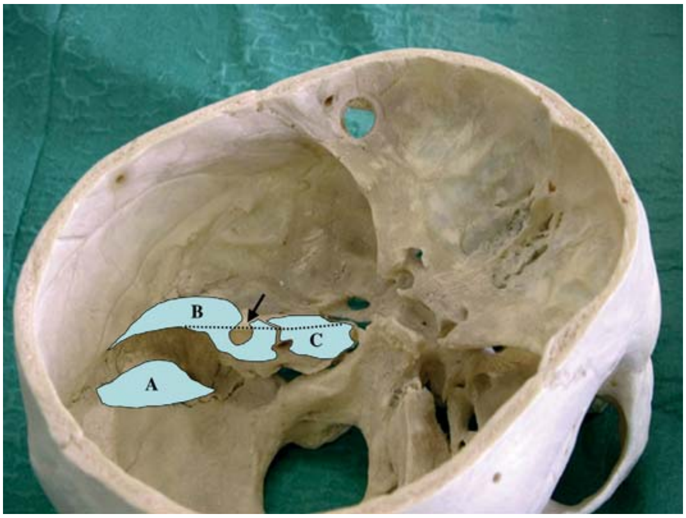


Fig. 36. Combined petrosal approach (left side): on the dry skull, the skull base is viewed from inside and the A letter indicates the retrosigmoid part of the resection, the B shows the retrolabyrinthine part and the C the anterior part of the bony resection. The black arrow indicates the position of semicircular canal that has not been drilled. The dotted line represents the junction between the superior and posterior surfaces of the petrous bone (petrous crest)

gradually from the arcuate eminence to the Meckel cave forward and medially. The retromeatal triangle (between the superior semicircular canal and internal auditory canal) and the posteromedial (Kawase) triangle are then drilled and the internal auditory canal is unroofed. Care should be taken to follow and resect the petrous ridge, proceeding forwards in the direction of the porus trigeminus after lifting of the dura out of the superior petrosal sinus. The extent of bony resection from the skull base is illustrated by the Fig. 36.

Opening of the dura (Fig. 37)

As mentioned above, opening and management of the dura is a key step of skull base approaches particularly in the present approach. Opening of the presigmoid dura from the sinodural angle to the jugular bulb. Cutting of the basitemporal dura just above the sinodural angle toward the geniculate ganglion, parallel to the superior petrosal sinus. It is important not to cut the dura too far back in order to preserve the posterior temporal vein of Labbe. Then the superior petrosal sinus is cut and coagulated, the dura of the tentorium is incised proceeding toward the free edge medially and anteriorly, avoiding damage to the trochlear nerve. It becomes possible to resect a large portion of the tentorium if this dural structure is involved by the tumor. This approach offers multiple angles of vision of the petroclival region and related structures (depending

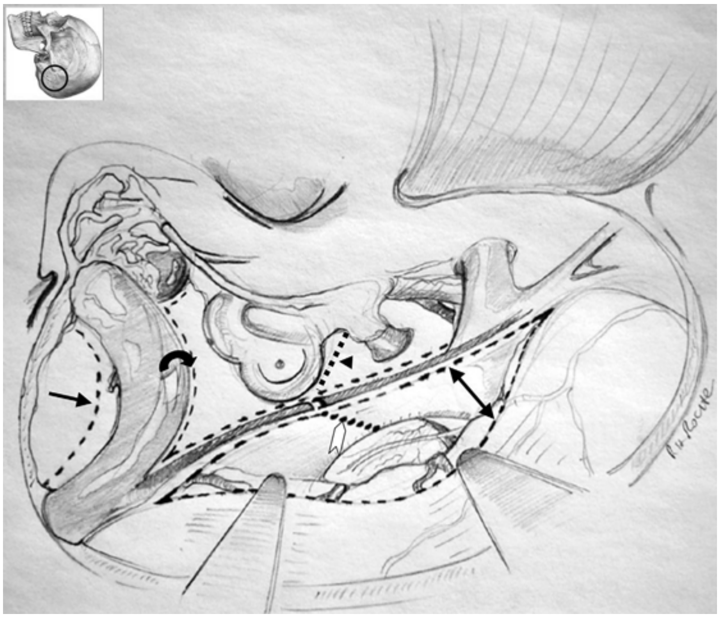


Fig. 37. Artistic drawing showing the process of dura opening during the combined petrosal approach (left side): the double arrow shows the horizontal section of the temporal dura. The arrow head indicates the vertical section of the posterior fossa dura. Note that the location of this section can be modified anteroposteriorly. The chevron arrow shows the transversal section of the tentorium. The black arrow shows the opening of the retrosigmoid dura while the circular arrow shows the incision of the presigmoid dura

on the positioning of the extradural triangular retractors) (Fig. 38). It is particularly easy to control the cerebellopontine angle and also the lower cranial nerves behind and below. Now, the ipsilateral cranial nerves can be identified from nerves III to XII. Tumor removal proceeds in the same way as described above, and the principles of closure are also the same. The dura is to be stitched and immobilized in a meticulous way. The bone flap is positioned and fixed. A clinical case is presented on Fig. 39.

This approach offers quite similar exposure to the wider transcochlear approaches but it remains conservative because intrapetrosal neuro-otologic structures (i.e. labyrinth and facial nerve) are unopened or unmobilized. The main disadvantage is indisputably the extra time entailed by this approach.

Other combined approaches

Instead of a retrolabyrinthine approach, a translabyrinthine approach can be combined with anterior petrosectomy. In this procedure, quasi-total petrosectomy is achieved and the operative corridor is widened. This technique is of particular interest when there is already deafness in the ipsilateral

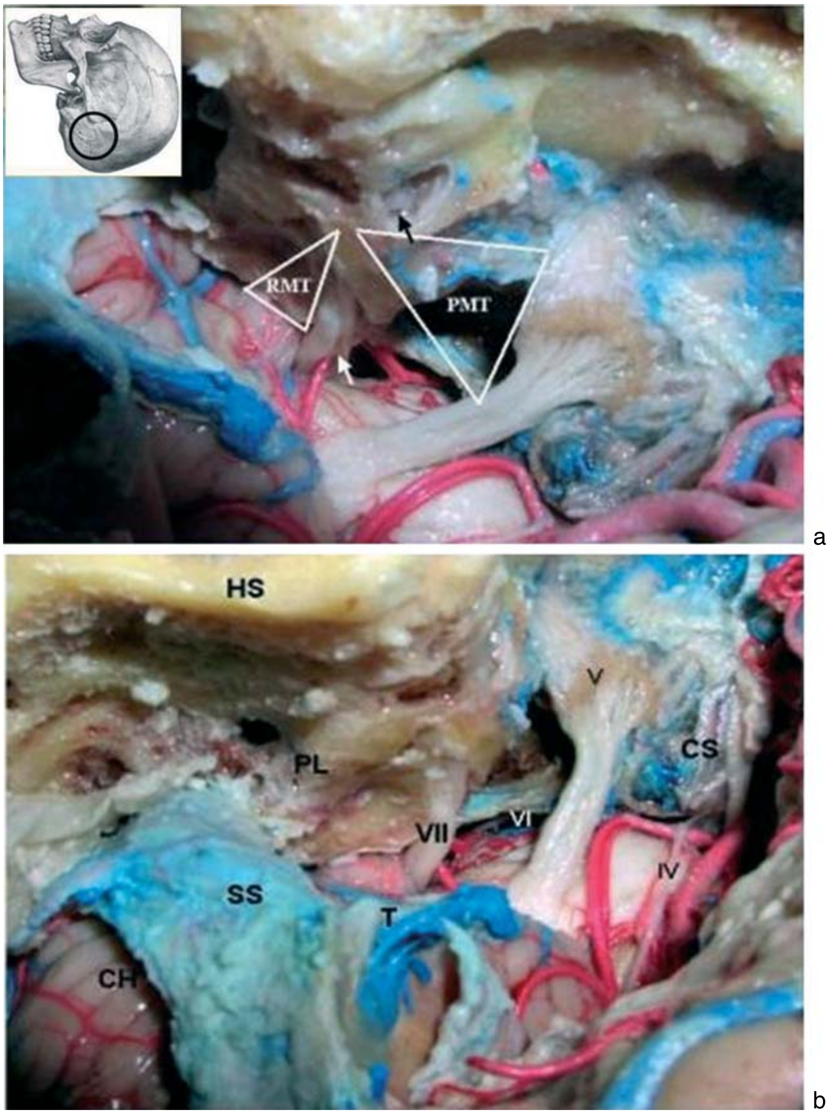
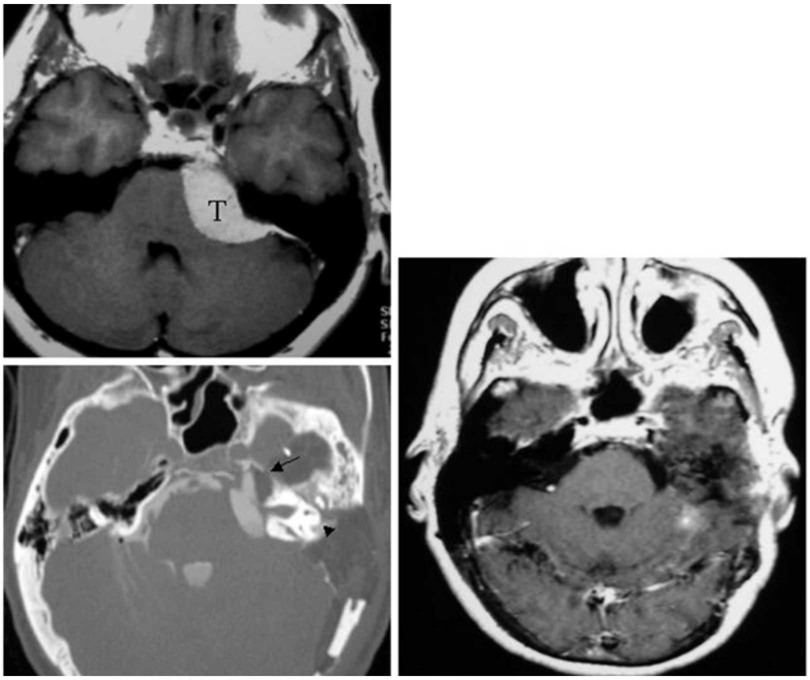


Fig. 38. Injected head cadaver dissection (left side). The combined petrosal approach has been achieved and the dura has been removed in order to show the main intradural structures. (a) The petroclival region is approached from above. The white arrow shows the acousticofacial bundle and the black arrow indicates the middle ear ossicles after opening the tegmen tympani. The RMT triangle is the retromeatal triangle and the PMT triangle is the premeatal triangle. (b) The petroclival region is approached from the back. *CH* Cerebellum hemisphere, *CS* cavernous sinus, *HS* henle spike, *PL* posterior labyrinthe, *SS* sigmoid sinus, *T* tentorium



a b c

Fig. 39. Case illustration: a 49-year-old woman presenting with headaches, moderate gait ataxia and hypoacousia on the left side. (a) Preoperative MR imaging shows a left petroclival tumor (*T*) that is homogeneously enhanced after gadolinium administration. This feature is in favour of a petroclival meningioma. (b) The combined petrosal approach is visualized by this CT scan cisternography using bony window. Black arrow indicates the anterior petrosectomy while the black arrowhead shows the lateral semicircular canal that has been skeletonized during the retrolabyrinthine step of the approach. (c) Axial postcontrast MRimaging at 3 years following the surgery. The petroclival area is devoid of any residual or recurrent meningioma

ear. Dura opening, tumor removal and closure are conducted following the same principles. Another solution is to associate a partial labyrynthectomy to the apicectomy. In this approach, a large segment of the SCC and of the PCC is resected at the level of the common crus. This canalicular defect is immediately obtured by bone wax, thereby theoretically preventing the deafness.

Indications

The purpose of this paper is not to give a flow chart of surgical strategies for the removal of petroclival tumors. Moreover, given the complexity of the parameters to betaken into account, each situation is different. Many variables are related to the patient: age, general condition, neurological status (peripheral nerve, axial structures, hydrocephalus), prior treatments, factors that may influence treatment. Tumor-dependent variables include histology and anatomical origin of the lesion (from the bone, the dura, the cranial nerves, etc.), growth potential, insertion, volume, extension, relationship to critical structures. Of course, the experience of the surgical team and the availability of effective adjunctive techniques (e.g. radiosurgery or conformational radiation therapy) may influence the therapeutic strategy and the approach.

Conclusions

Despite considerable progress in non-invasive therapeutic modalities, many lesions that involve the petroclival region still require surgical treatment. This treatment remains challenging due to many characteristics: the depth of the PCR, the propensity for many tumors to engulf nerves and blood vessels, the invasion of neighbouring areas and extension to multiple cranial fossae and foramina.

The goals of this chapter are to provide the basics of the comprehensive surgical anatomy that is required to treat the lesions occupying the PCR, and to illustrate our purpose by detailing the most important approaches via the lateral skull base. These approaches are conservative insofar as they preserve intrapetrosal neuro-otologic structures. However, in many cases, attempts at total resection may risk impaired function. That is the reason why the trend these days is towards selective, tailored surgery rather than radical resection. Surgery is one component in a global multimodal management strategy in which less invasive techniques have their place. In this field, outcomes of combined microsurgical and radiosurgical techniques should be promising for petroclival tumors.

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