Dural relationships of Meckel cave and lateral wall of the cavernous sinus

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Object. The purpose of this study was to elucidate the anatomy of the trigeminal nerve (cranial nerve [CN] V), Meckel cave (MC), and lateral wall of the cavernous sinus (CS).

Methods. Ten fresh cadaver heads (20 sides) and 2 middle fossa embalmed specimens were removed, decalcified, sectioned, stained, and studied microscopically.

Results. In the MC, the posterior fossa meningeal dura extended into the middle fossa surrounding CN V. The average medial length of the MC was 16.7 mm and the lateral length was 13.5 mm. The dural roof of MC was thicker than its floor and was covered by a paw-shaped fibrous tissue extending from the tentorium to the ganglion (in 100% of specimens). Between the dural sleeve of the MC and venous space of the CS, a separate fibrous wall could be identified in 45% (9 of 20) extending between the tentorium and the floor of the CS. The mean length of CN V in the MC proximal to the posterior margin of the Gasserian ganglion was 11.8 mm. The mean length of CN V1 was 19.4 mm; V2, 12.3 mm; and V3, 7.4 mm distal to the anterior margin of the ganglion. The periosteal dura followed the bone of the middle fossa and was continuous with the extracranial periosteum.

The lateral dural wall of the CS consisted of a medial (membranous) and a lateral wall. The latter was separated into a thin outer layer and a thicker fibrous inner layer that became thinner as it extended posterolaterally.

Conclusions. The MC is an extension of the posterior fossa dura with intricate relationships with the surrounding dural layers. *(DOI: 10.3171/FOC.2008.25.12.E2)*

Key Words • **cavernous sinus** • **dura mater** • **Meckel cave** • **meninges** • **microsurgical anatomy**

The trigeminal nerve (CN V) is the largest CN emerging from the ventral surface of the pons near its upper border, with a large sensory and a smaller motor component. It extends anteriorly across the prepontine cistern and enters the middle cranial fossa through the porus trigeminus allowing access to the MC.[8,21,40] A sleeve of arachnoid and dura mater accompanies the nerve into the middle cranial fossa.

The sensory component (portio major) contains the afferent fibers from the facial skin and oral mucosa, and the motor root contains the efferent motor fibers (portio minor) that innervate most of the masticatory musculature (the masseter, temporalis, medial and lateral pterygoids, and the mylohyoid muscles) and the tensor tympani muscle of the middle ear.

The nerve subdivides into 3 components: the ophthalmic division, which exits the intracranial cavity through the SOF; the maxillary division, which exits through the foramen rotundum; and the mandibular division, which exits through the foramen ovale. The MC encases CN V, partially its ganglion (the GG) and is concealed by the overlying middle fossa meningeal dura.

The MC is a significant gateway into the various regions of the skull base. The sellar and parasellar regions, tentorial incisura, petrous apex, petroclival region, posterior fossa, middle fossa, and infratemporal fossa can be accessed after exploring the MC. The most common tumors in the MC are neurinomas and meningiomas.

Despite the numerous studies published on the microsurgical anatomy of the parasellar region, the meningeal architecture of the MC remains unclear. A detailed study of this anatomy will contribute to precise preoperative planning and successful realization of the surgical strategy. The purpose of the present study is to provide better understanding of the dural architecture of the middle fossa, the MC, and the relationship of the MC to its adjacent structures, specifically the lateral wall of the CS.

Abbreviations used in this paper: CN = cranial nerve; CS = cavernous sinus; GG = Gasserian ganglion; MC = Meckel cave; SOF = superior orbital fissure; SPS = superior petrosal sinus.

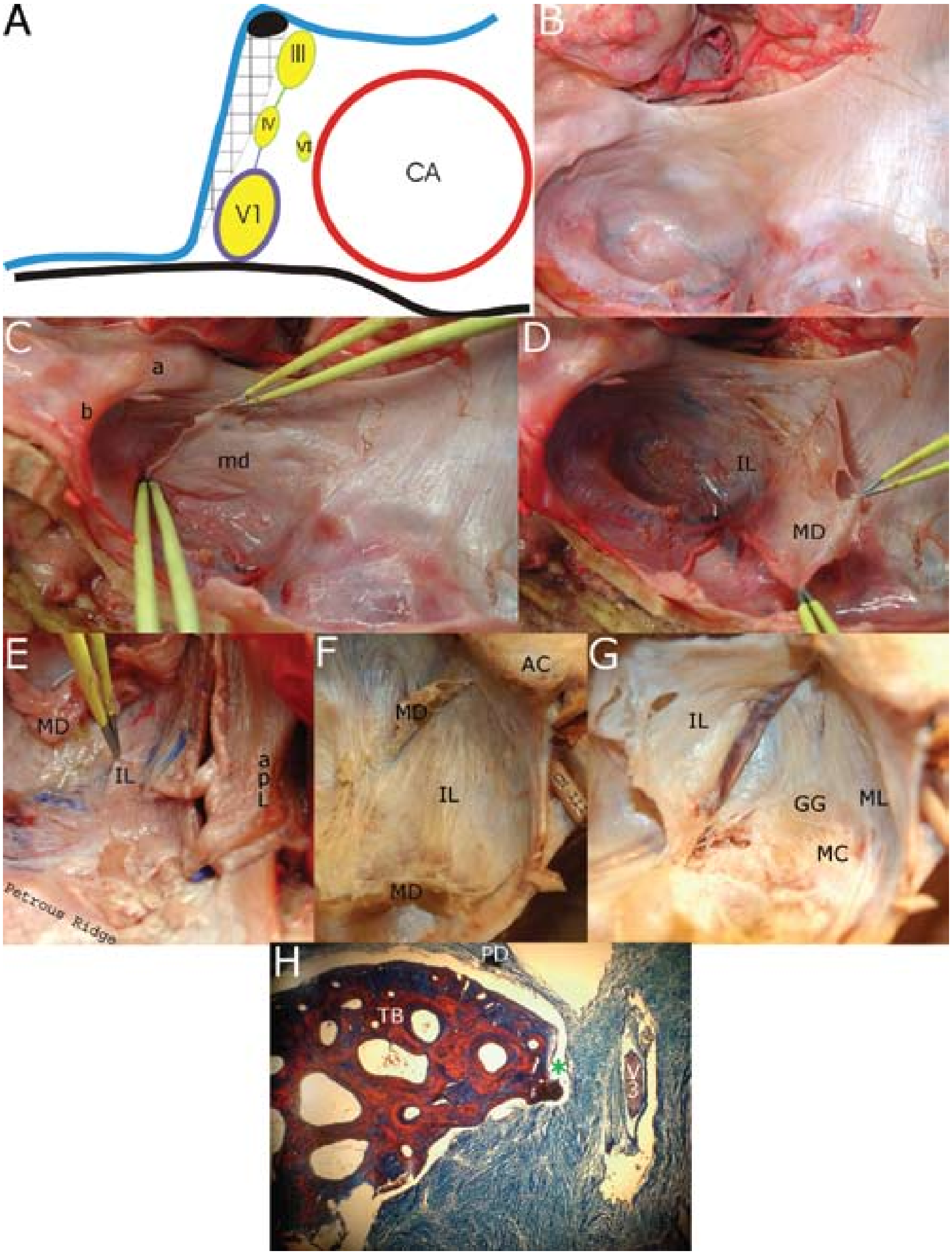

Fig. 1. Illustration (A), photographs (B–G), and photomicrograph (H). A: The meningeal and neural architecture at the level of anterior CS, posterior to the entry of the CNs into the SOF. The periosteal dura *(black line)* follows the floor of the middle fossa into the floor of the CS. The meningeal dura *(blue line)* separates from the periosteal dura at the lateral edge of the CS as it continues as the outermost layer of its lateral wall. Beyond the incisura *(black oval)*, it continues as the roof of the sinus. The intermediate layer *(hatched area)* is interspersed between the nerves and the meningeal dura. It is thickest superiorly and anteriorly and tapers inferiorly and posteriorly. The fibers are directed obliquely. The plane of dissection for the extradural approach is between this intermediate layer and the nerves. The epineurium of these nerves in the lateral wall is formed by their individual sheaths that continue from the posterior fossa. The epineurium of the ophthalmic nerve *(purple line)* is formed by the continuation of the MC that is located just anterior to the petrous edge. The MC is formed by the extension of the posterior fossa meningeal dura into the middle fossa along the trigeminal nerve. B: Serial dissection of the left middle fossa (lateral view). C: The meningeal dura (MD) is dissected off the underlying tissue. (The anterior clinoid process is designated by *a*, the lesser wing sphenoid bone by *b*.) D: The anteroposterior fiber direction of the intermediate layer (IL) can be seen. The membranous layer of the lateral wall of the CS remains unexposed. E: Posterior view (magnified) showing the intermediate layer being lifted with the forceps. F: Posterior view of a noninjected specimen. Note the anteroposterior fiber direction of the intermediate layer, which is exposed after the meningeal dura is dissected off. G: The membranous layer (ML) exposed. The nerves are visualized as the intermediate layer is reflected laterally. The MC remains intact as it is still concealed by a fibrous layer. H: The foramen ovale *(green asterisk)*. The periosteal dura (PD) can be seen lining the bone intra- and extracranially. Extracranially, the periosteum blends with collagenous tissue. AC = anterior clinoid process; aPL = anterior petroclinoid ligament/tentorial incisura; CA = carotid artery; TB = temporal bone; III = CN III; IV = CN IV; V = CN V; VI = CN VI.

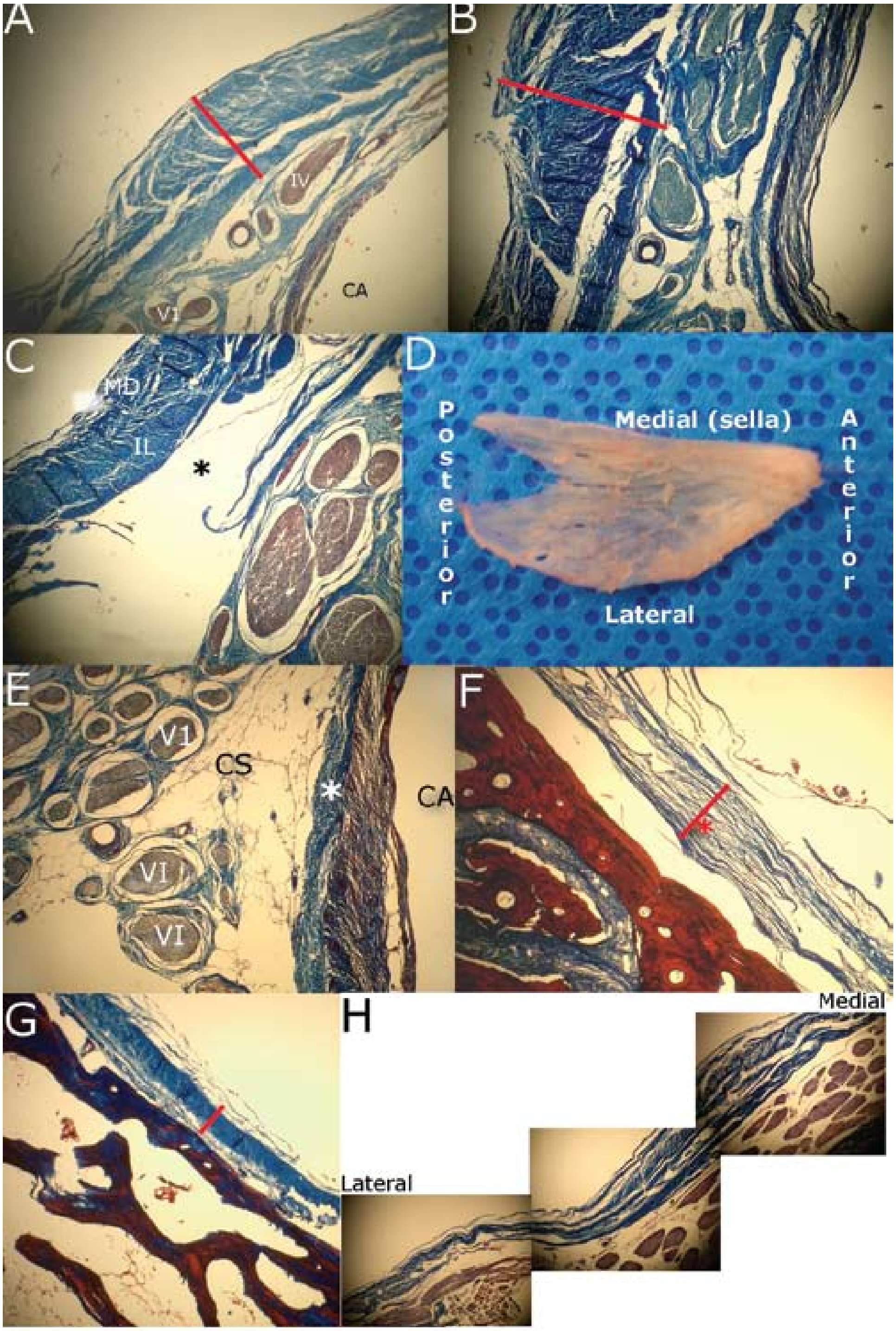

Fig. 2. Photomicrographs (A–C and E–H) and photograph (D). A: The lateral wall of the CS between the CS and the SOF. The lateral wall is thicker *(red bar)* as the intermediate layer increases in the collagen content. B: The lateral wall prior to entry of the nerves into the SOF. The intermediate layer is more prominent *(red bar)*. C: The intermediate layer with the overlying meningeal dura separate from the membranous layer as the nerves in the latter enter the SOF. The *asterisk* designates the plane between the IL and membranous layer. D: The intermediate layer dissected out. The layer is thick anteriorly as laterally and posteriorly its fibers become thinner. E: The membranous layer. The abducens nerve can be seen as 2 fascicles and their sheaths. The trabeculae of the venules of the CS are seen separated from the carotid artery by its periosteal sheath *(asterisk)*. F: The 2 layers of dura *(red asterisk)* lateral to the foramen ovale over the middle fossa floor. The dura is significantly thinner than over the lateral wall of the CS as the intermediate layer is absent. The *red bar* indicates the thickness of the dura. G: Variation in the thickness of the dura *(red bar)* lateral to the foramen ovale. The dura in this area contains more collagen but remains thinner than that over the CS. H: A composite picture of the layers covering the MC and the CS. The layers thin out from medial to lateral as the intermediate layer considerably decreases in size.

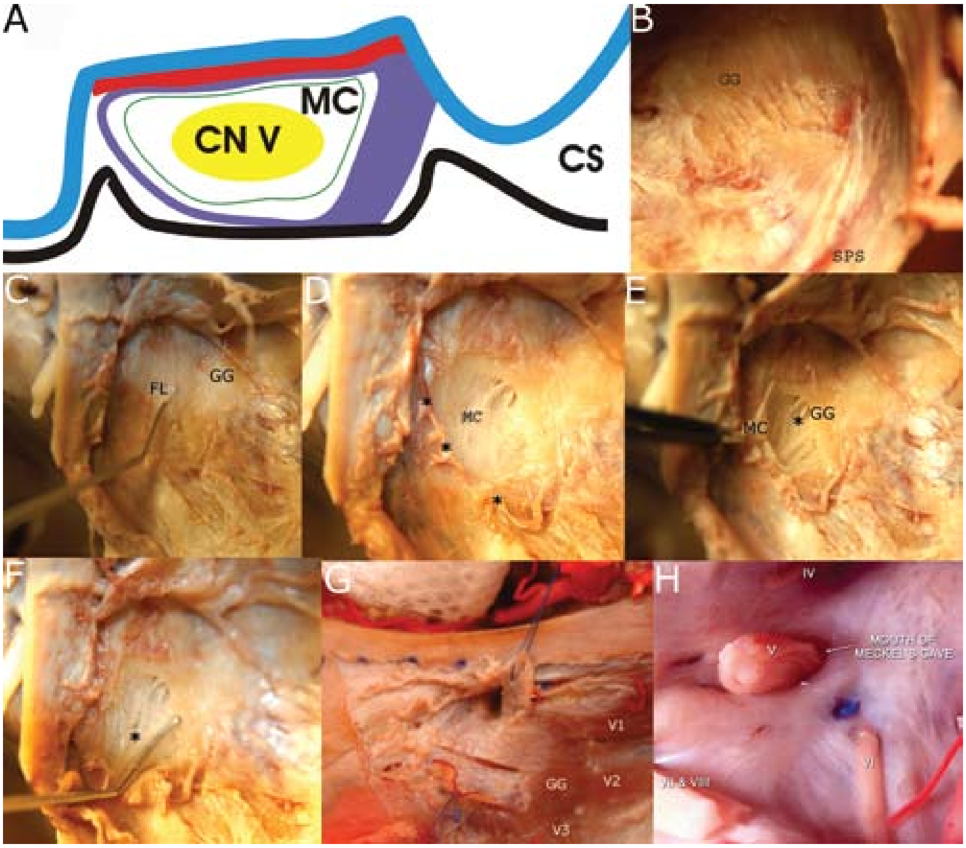

Fig. 3. Illustration (A) and photographs (B–H). A: The meningeal architecture at the level of the petrous apex, anterior to the porus trigeminus. The periosteal dura *(black)* follows the petrous apex and covers the trigeminal depression at the apex as it continues medially as the floor of the CS. The meningeal dura of the middle fossa *(blue)* covers the petrous bone and forms the outermost layer at the level of the MC. Below the meningeal layer, a characteristic opaque layer of fibrous tissue *(red)* covers the cavity of MC. This fibrous layer arises from the tentorium at the porus trigeminus and extends anteriorly parallel to the axis of the trigeminal nerve and ends along the posterior edge of the GG. It spans the entire length and breadth of the MC superiorly. The dura of the MC is reinforced with fibrous tissue medially which could be separated from the dura in 45% of the sides of the cadavers. B: Surface of the MC (magnified). The GG is visible as a semilunar body. Proximal to the GG striated fibers can be seen between the SPS posteriorly and the posterior edge of the GG anteriorly. They end abruptly at this point. Due to their caliber, they obscure the fibers of the trigeminal nerve. C: In the first step of a stepwise dissection, the probe is placed between the fibrous layer (FL) and dural sleeve of the MC. D: The fibrous layer *(asterisks)* has been dissected off. The dural sleeve of the MC is exposed. This is formed by the extension of the posterior fossa meningeal dura and is thin and translucent. E: The dural sleeve has been opened superiorly, revealing the arachnoid layer *(asterisk)*. F: The probe in the arachnoid space *(asterisk)*. G: The porus trigeminus unroofed. The MC is incised and the trigeminal nerve exposed. The dural sleeve can be followed medially as the meningeal dura over the clivus. H: Posterior view of the dorsum of the petrous bone and clivus. The trigeminal nerve (CN V) is seen entering the MC through the porus trigeminus. The adjacent CNs are individually numbered.

Methods

Ten cadavers were used—2 fresh and 8 fixed with alcohol and formalin. The brain and arachnoid were removed. One nonembalmed head was prepared with silicone injection, the technique of which is described elsewhere.[50] The heads remained attached to the body and were dissected under magnification using a floor-based Contraves microscope (Zeiss, Inc). From 2 additional fixed adult cadavers, the sella and the parasellar region, including MC and 3 divisions of the CN V, were removed (1 left side and 1 right side). The underlying osseous structure was removed along with soft tissues maintaining proper in situ anatomy. Blocks were decalcified for 8 weeks, then embedded in paraffin. Serial sections of 10-μm thickness were made and stained with H & E and Masson trichrome stains then studied under a light microscope.

Results

Middle Fossa Dura

The dura mater is formed by 2 distinct layers that could be separated laterally in the middle fossa floor (Figs. 1 and 2). The outer layer, the periosteal dura, covered the inner surface of the osseous skull. The inner layer, known as the meningeal dura, lined the brain.

When the middle fossa dura was dissected off the skull, the first point of tethering was the foramen spinosum. The middle meningeal artery enters the cranial vault and could be divided. At the foramen ovale, the periosteal dura evaginated into the foramen (Fig. 1H). After the periosteal dura was incised, elevation of the dura could proceed without violation of the meningeal dura. At the foramen ovale, the periosteal and meningeal dura separated, with the former passing under the trigeminal nerve complex forming the floor of the parasellar region while the latter overlaid the entire parasellar region, including the MC.

In all specimens, the meningeal dura covered a more fibrous layer of tissue (intermediate layer); this layer could be exposed by removing the meningeal dura. Along the incisura tentorii and the petrous ridge they were inseparable. The intermediate layer varied in thickness; it was most prominent anteriorly at the anterior clinoid process and along the incisura tentorii. The fiber bundles became less prominent as they fanned out posteriorly in an oblique fashion toward the petrous bone and laterally toward the middle fossa floor covering V1 and V2 along their entire course and most of V3. The fibers were grouped in bundles and concealed the membranous part of the lateral wall. The intermediate layer could be separated from the membranous layer, exposing the oculomotor nerve (CN III), trochlear nerve (CN IV), ophthalmic nerve (V1), and along its lower border the maxillary nerve (V2). The intermediate and the membranous layers were bound by loose areolar tissue.

The intermediate layer could be followed anteriorly to the SOF but did not extend into it. This layer was separable from the membranous layer, which continued into the orbit with the nerves (Fig. 2A–C). In 13 (65%) of the sides, tiny fascicles of collagenous tissue from this intermediate layer contributed to the membranous layer at the entry of the SOF. The intermediate layer coursed along the lower surface of the sphenoid ridge laterally and was not dissected any farther.

Posteriorly, this layer fanned out and partially covered the MC, blending into the tentorium and the posterior petroclinoid ligament (the roof of the porus trigeminus, Fig. 2D). It could be easily dissected off the MC without violating it. The average anteroposterior length of the fibers was 28.7 mm (range 7.5–42 mm); the average mediolateral measurement was 33.2 mm (range 22–49 mm) (Table 1).

Meckel Cave

Removal of the meningeal dura and the intermediate layer of the middle fossa exposed the MC, which contained the CN V, and partially the GG and its 3 divisions (Fig. 3). The MC was formed by extension of the posterior fossa meningeal dura into the middle fossa. Overlying this dural sleeve of MC was an opaque fibrous sheet over its superior surface (Fig. 3B). These fibers originated from the tentorium posteriorly, and anteriorly they ended at the posterior margin of the GG. It could be dissected off the MC dural sleeve in 7 (35%) of the sides (Fig. 3C). In all other specimens, it was adherent to the dural sleeve. The fibers were directed anteroposteriorly, parallel to the

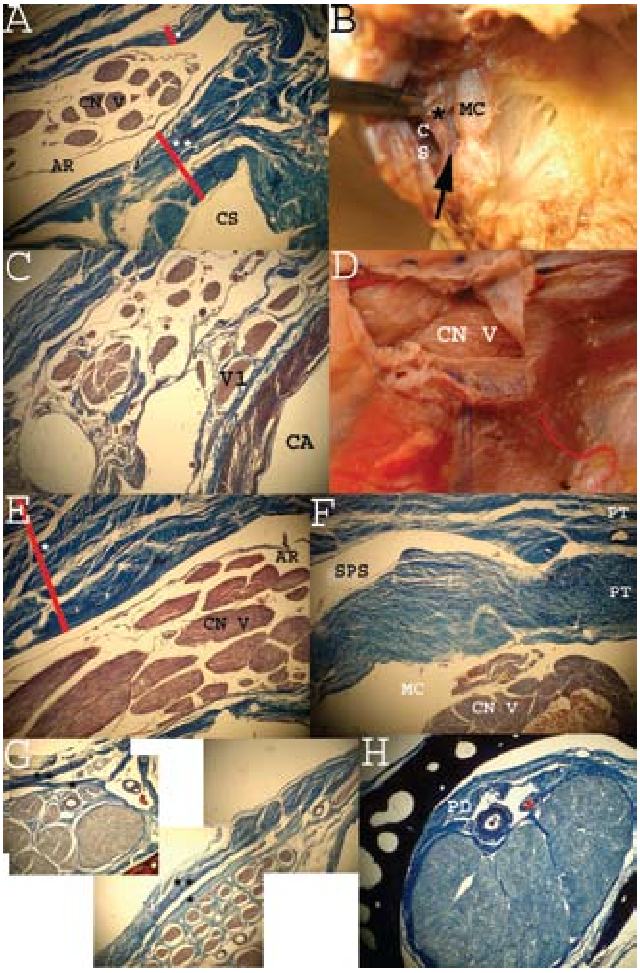

Fig. 4. Photomicrographs (A, C, and E–H) and photographs (B and D). A: The distal MC. The thin dural sleeve of the cave *(single asterisk)* can be distinguished from the overlying layers. These layers are thin proximally over the MC. The medial wall of the cave *(double asterisk)* is only partially formed by the dural sleeve. Note that additional collagen fibers in the trapezoidal layer separate it from the CS. B: The medial wall of the MC has been dissected off a separate layer (designated by an *asterisk*) between this dural sleeve and the CS as it reinforces the medial wall of the MC dura. This layer extends posteriorly from the porus to the GG anteriorly. The layers were adherent and could be separated in 45% of the specimen sides. This trapezoidal layer anchors to the floor of the CS formed by the periosteal dura *(arrow)*. C: Section distal to the CS. The membranous wall formed by the extension of the MC dura forms the only separation between the nerves (V1) and the CS. The trapezoidal wall is absent. D: Meckel cave opened. The arachnoid has been removed. The fascicles of the trigeminal nerve (CN V) are visible. The fascicles are draped over the trigeminal depression of the petrous apex, posterior to which the nerve in the posterior fossa can be seen. E: Meckel cave. The *asterisk* indicates the layers of collagen overlaying the MC just distal to the porus. The innermost of these layers is formed by the dural sleeve. The exterior-most layer is formed by the meningeal dura. Note that the arachnoid layer (AR) invests each fascicle separately. F: Cross-section through the porus trigeminus (PT). The SPS runs through the roof of the porus. The MC lies under the porus containing the trigeminal nerve (CN V). G: The *right composite* shows the fascicles of V2 accompanied by the continuation of the dura of the MC that forms its epineurium. The *left composite* shows V2 prior to its entry into the foramen rotundum. The epineurium *(single asterisks)* of the nerve is covered superiorly by the meningeal dura of the middle fossa. H: Maxillary nerve. The lining of the foramen is formed by the extension of the periosteal dura (PD).

TABLE 1: Measurements of the trigeminal nerve, its branches, and associated structures*

Cadaver No. & Side	Measurement (mm)																
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1 rt	8	19	21	16	8	4	12	5	8	9	6	6	32	35	12	8	2
1 lt	8	17	19	14	9	5	8	4	7	10	7	5	30	34	14	5	1
2 rt	7	15	17	14	7	4	6	3	6.5	6	5	4	25	30	10	3	1
2 lt	6	16	16	13	7	3.5	5	3.5	6	6	5	4	24	29	9	2	0.5
3 rt	12	16	16	10	8	4	8	4	7	10	7	6.5	30	22	9	3	2
3 lt	14	17	20	11	7	4	8	5.5	10	13	8	8	40	27	10	4	2
4 rt	12	16	22	18	11	5	9	5	9	12	7	8	32	30	11	6	2
4 lt	15	20	21	15	9	6	9	5	8	7	6	7	7.5	32	25	5	3
5 rt	15	13	21	11	11	4	8	5.5	9.5	12.5	6.5	8.5	19	39	11	5	1
5 lt	14	15	21	11	6	4	10	4	7	11	5	7	27	36	14	5	1
6 rt	15	16	24	9	8	3	9	6	10	14	6	8.5	25	45	14	5	2.5
6 lt	16	18	18	12	5	4	10	5	7.5	5	5	6.5	23	40	14	5	1
7 rt	12	15	21	10	6	5	8	5	8	11	6	7	25	35	13	7	1
7 lt	13	15	21	10	5	5	10	6	7.5	11.5	6	7	28	39	16	7	2
8 rt	13	15	19	9	5	4	8	5	6	4	6	5	30	31	11	5	2
8 lt	13	14	19	9	4.5	4	8	6	6	5	6	7	31	29	10	5	2
9 rt	9	12	17	8	3	3	9	5	7	11	10	10	32	27	11	4	1
9 lt	10	11	17	9	5	4	9	5.5	9	13.5	10	10	33.5	28	12	4	2.5
10 rt	12	16.5	20	19	12	5	9	7	12	17	11	12	42	49	14	6	3
10 lt	12	16	18	18	13	5	9.5	7	11	15	8	7	38	27	12	4	1
mean	11.8	15.625	19.4	12.3	7.475	4.275	8.625	5.1	8.1	10.3	6.825	7.2	28.7	33.2	12.6	4.9	1.675
min	6	11	16	8	3	3	5	3	6	4	5	4	7.5	22	9	2	0.5
max	16	20	24	19	13	6	12	7	12	17	11	12	42	49	25	8	3

* A = length of the trigeminal nerve in the MC; B = width of the GG; C = length of intracranial V1; D = length of intracranial V2; E = length of intracranial V3; F = height of the porus trigeminus; G = width of the porus trigeminus; H = distance between the foramen ovale and the foramen spinosum; I = distance between the foramen ovale and the foramen rotundum; J = distance between the foramen rotundum and the superior orbital fissure; K = distance between the foramen spinosum and the petrous internal carotid artery (ICA); L = distance between the ICA and the foramen ovale; M = anteroposterior length of fibers of the intermediate layer; N = mediolateral length of fibers of the intermediate layer; O = length of anteroposterior interface of the CS and the MC; P = length the MC medially; Q = length of the MC laterally. See also Fig. 5.

axis of the MC. Close to the GG, the fibers fanned out but did not extend beyond the ganglion.

The exposed dural sleeve could be dissected circumferentially and extended proximally to the porus trigeminus. Medially and inferiorly it extended over the clivus and laterally over the posterior surface of the petrous bone as meningeal dura (Fig. 3G). The posterior fossa periosteal dura did not contribute to this dural pocket per se as it followed the bony surfaces. The sleeve was translucent (Fig. 3D) and surrounded the GG as it adhered to its medial and lateral surfaces.

The dural sleeve could then be opened to expose the arachnoid layer of the MC (Figs. 3E and 4E). The subarachnoid space extended an average of 4.9 mm (range 2–8 mm) medially and 1.7 mm (range 0.5–3 mm) laterally beyond the posterior edge of the GG (Fig. 3F). There was minimal extension of the arachnoid space over the divisions of CN V, with the arachnoid space being most prominent over the medial surface of the ophthalmic division of the trigeminal nerve. The arachnoid mater covered the CN V circumferentially but was not distinguishable as a separate layer beyond termination of the dural sleeve. The mean length of the MC was 11.8 mm (range 6–16 mm) and the mediolateral dimension of the GG averaged 15.6 mm (range 11–20 mm). After the termination of the subarachnoid space, the dura of the MC continued distally over the divisions, adherent to them although separable.

The 3 divisions of CN V could be followed into their respective foramina. The V1 and V2 were located in the membranous part of the lateral wall. The mean lengths of the ophthalmic, maxillary, and mandibular nerves from the distal aspect of the GG to their foramina were 19.4, 12.4, and 7.3 mm, respectively.

The MC was concave in its inferior and medial surfaces but more flat superiorly.

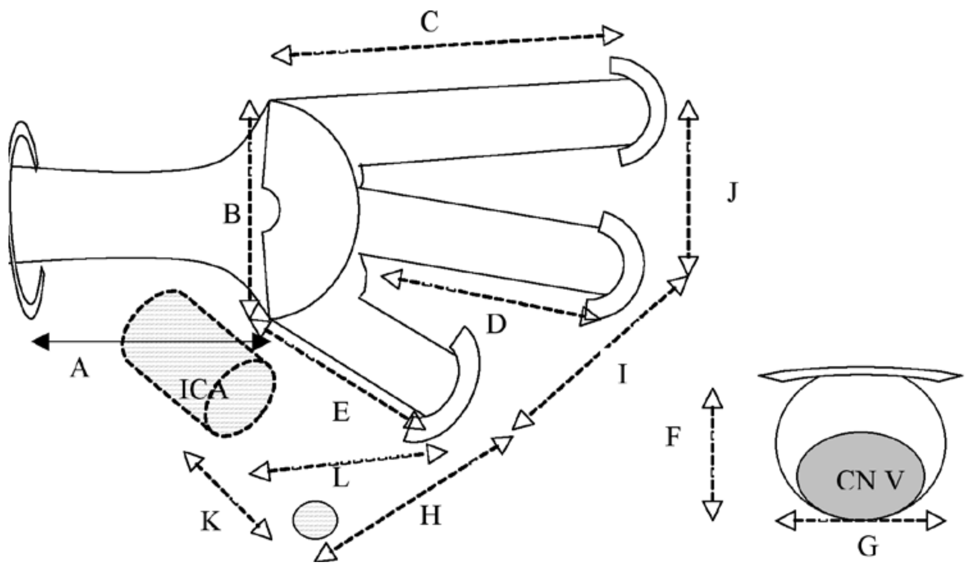

Fig. 5. Diagram illustrating the anatomical locations used for the measurements (A–Q) presented in Table 1

Wall Between the MC and the CS

The medial side of the MC was thick in all cadavers. In 9 (45%) of the sides, the dural sleeve could be separated from a vertical layer of fibrous tissue that spanned the incisura tentorii superiorly and the periosteal dura of the middle fossa inferiorly (Fig. 4B), separating the MC dura from the CS (Fig. 4A). This created a trapezoidal shape, with the medial porus of the MC as the posterior limb and the medial edge of the GG as the anterior margin where it adhered to the dural sleeve of the MC. Anterior to the GG this reinforcement was absent (Fig. 4C). In 2 instances, this wall was not patent, which may not entirely have been the result of the dissection technique. The medial wall of the MC extended on average for 12.6 mm (range 9–25 mm) along the CS.

Porus Trigeminus

At the trigeminal depression of the petrous apex, the foramen through which CN V enters into the MC is termed the porus trigeminus (Figs. 3H and 4D and E). Superiorly it was formed by the posterior petroclinoid ligament, which contained the SPS, which could be traced into the CS (Fig. 4F). The medial wall of the porus trigeminus was formed by the base of the posterior clinoid process. Its average vertical height was 4.3 mm (range 3–6 mm), and its horizontal width was 8.6 mm (range 5–12 mm). In 7 specimens (35%) ossification centers were observed along the SPS in the roof of the porus. See Table 1 and Fig. 5 for the anatomical locations and measurements for all parameters studied.

Discussion

Dura Mater

The meninges consist of an outer, tough, tightly woven pachymeninx (dura mater) and an inner delicate leptomeninx (pia-arachnoid complex), which together cover the entire surface of the brain.[16] The dura mater consists of 2 layers, the outer periosteal layer and the inner meningeal layer. Different terms have been used to describe these layers: outer/inner layer, periosteum/dura propria, and periosteal/meningeal dura. In this manuscript the periosteal/meningeal nomenclature will be used to describe the 2 dural leaves.

Over the inner cranial convexity these 2 layers are fused in most regions and separate only to enclose major sinuses and around the sella.[25] The meningeal dura forms the diaphragma sellae and the periosteal dura the sellar floor.[60,61] The MC is similarly confined between these 2 layers but also consists of its own separate sleeve of posterior fossa meningeal dura from the petrous apex onward.

The meninges develop from the mesenchyme,[58] which subdivides into endo- and ectomeninx. This process begins at the skull base at 6 weeks' gestation.[3] The ectomeninx becomes dura mater at 3 months' gestation.[25,33] The outer dural layer then becomes the periosteal dura, which adheres to the cranium, while the inner layer becomes the meningeal dura. This differentiation begins at the base of the skull and extends laterally. Weed[58] performed serial injections of dye in pig and human embryos and observed development of the subarachnoid space by invasion of the primitive meninx by CSF, which caused it to divide, in the third gestational month. As the cranial nerves develop, the arachnoid mater follows their tract.

The dural fibers are oriented in the direction of maximum tension forces.[22,25] The fiber orientation in the lateral wall of the CS (the intermediate layer) is directed obliquely in a mediolateral direction. Tension vectors in the parasellar region are, however, unlikely to have influenced dural fiber orientation.

Haines et al.[23] reviewed the structure of the dural layers related to subdural hematomas and hygromas. The meningeal dura had less collagen and more fibroblasts than the periosteal dura. Separation of the arachnoid mater from the meningeal dura (dura propria) occurred at the dural border cell layer that contains no collagen.[18,23] The meningeal dura was depicted as thinner than the periosteal dura. Allen and Didio[1] observed that, upon separation of the arachnoid from the meningeal dura, the dural border cells layer seldom remains intact as it forms the plane of separation.

In the present study, the outermost layer of the lateral wall was considerably thinner than the intermediate layer. As the removal of brain included the arachnoid mater, separation likely occurred at this dural border layer, implying that the outer layer of the CS was formed by the meningeal dura. In our specimens, however, the meningeal dura did not reveal many fibroblasts.

Foramina

At the craniovertebral junction, the meningeal dura continues caudally as the outer lining of the dural tube, and the periosteal dura becomes the extracranial periosteum, posterior atlantooccipital membrane, tectorial membrane, articular capsules, ligamentum flavum, posterior longitudinal ligament, and vertebral periosteum.[5,25] Similarly, the periosteal dura is continuous with extracranial periosteum through the foramen ovale. These fibers contribute to the soft tissue on the external surface of the foramen ovale and with V3 epineurium. The dural layers are similarly merged at the foramen spinosum. Fusion of the intracranial and extracranial periosteum impedes the extradural approach to the parasellar region. Sharp release of this dural tether allows elevation of the periosteal dura along the lateral border of V3 posteriorly toward the tentorium and anteriorly to V2 at foramen rotundum (Fig. 4G and H), leaving the meningeal dura intact. A venous plexus (from the primitive prootic sinus)[32] could be identified prominently at the foramen ovale, continuous with the venous pool in the tentorium and enclosed within the 2 dural leaves. This forms a part of the so-called laterotrigeminal system,[35,51] and Pacchionian granulations can be found in this venous pool predominantly lateral to V3.

Lateral Wall of the Cavernous Sinus

Following the description of this venous channel as a venous plexus by Parkinson,[44,45] the number of anatomical studies of the parasellar region has exploded. The anatomy of the lateral wall of the CS was summarized by Umansky and Nathan,[57] and a 2-layer concept is now uniformly accepted anatomically and surgically.[2,12,24,29,30,46]

In this concept, the lateral wall consists of an outer layer that is formed by the meningeal dura and an inner layer that is formed by the dural sleeves of CN III, V1, and to a lesser degree CN IV and is commonly referred to as the membranous layer (Fig. 2C). A cleavage plane between these layers allows a surgical plane to the CS without violating the subarachnoid space, a so-called extradural approach.

We suggest the existence of a separate layer between the meningeal dura and the membranous layer. This intermediate layer has high collagen content with few cells. Collagen bundles were directed obliquely as they fanned over CN V posteriorly and laterally. This layer could be dissected from the meningeal dura. These 2 layers were closely adherent at the incisura tentorii and SOF. The intermediate layer could be easily separated from the membranous layer at all locations.

Tobenas-Dujardin[56] studied the embryological development of the lateral sellar compartment and observed that "successive layers of conjunctive cells formed the superficial layer" and compared it to the pachymeningeal layer on the cortical bone. They suggested that it accompanied the nerves into the SOF.

Umansky and Nathan[57] described the composition of the membranous wall and referred to the outer layer as dura mater. The 2 layers were difficult to separate ("a uniformly thick single wall") anteriorly where the nerves entered the SOF.[57,64] However, we also dissected these layers to the SOF, which was minimally impeded distally by fibers connecting the intermediate layer with the membranous layer. As the nerves extended into the SOF their separation from the outer layers was observed on the microscopic sections as the cleavage plane became more prominent. Dolenc[12] used the SOF to gain access to the interdural plane in his frontotemporal epidural approach by cutting into the periosteal dura (the dural tent of the SOF), thereby avoiding damage to the nerves.[13] He further developed this plane followed by an intradural exposure of the lateral wall and MC for access to the region.

Hakuba et al.[24] exposed the lateral wall extradurally in patients with vascular or tumor involvement of the CS by releasing the dura around the trigeminal divisions in this plane via an orbitozygomatic approach, thus providing an anterolateral view. This was followed by an intradural exposure as well, which allowed for better reconstruction of the lateral wall. Kawase et al.[29] used similar steps in a pure lateral approach without an intradural component.

In contrast to the Dolenc approach, the Hakuba et al.[24] and Kawase et al.[29] approaches define the cleavage plane laterally in the middle fossa. We observed that the intermediate layer is thin around the V3, and so the cleavage plane could be developed either between the meningeal dura and intermediate layer or between the intermediate layer and membranous layer. At the SOF, the meningeal dura and intermediate layer are inseparable, which allows for the plane to be directed over the membranous layer.

The application of the anatomical knowledge of the intermediate layer is determined by the location of the pathological condition being treated. Choosing the dissection plane between the meningeal dura and the intermediate layer for an extradural exposure may yield additional protection of the nerves in the membranous layer, perhaps lowering postoperative morbidity.

Goel[20] acknowledged the possibility of separating the outer dural wall in 2 or more layers and indicated that the outer dural layer was thicker posteriorly, contrary to our findings.

The intermediate layer may be considered to be a dissection artifact. In other dural sites, however, multiple layers have been identified. Around the superior sagittal sinus, up to 8 layers have been described, as well as separate fiber layers contributing from the crista Galli and petrous bone to the falx and tentorium,[25] suggesting that multiple layers may develop around venous spaces. Similarly, loop-shaped collagenous fiber bands have been described at venous entry points into dural sinuses.[59] Furthermore, the thickness of the meningeal dura of the MC is similar to that of the meningeal dura of the lateral wall of the CS, which is thin. Thus, the intermediate layer may be a reinforcement of the meningeal dura as a fiber contribution from the incisura. Also, the meningeal dura of the lateral wall of the CS retains its thickness from medial to lateral (Fig. 2F and G) compared with the intermediate layer, which shows a decrease in thickness posteriorly and laterally (Fig. 2H). Finally, the fiber direction in the intermediate layer is nearly perpendicular to that in the meningeal dura.

Thus, this intermediate layer is best seen as a distinct fiber system contribution to the meningeal dura.

Meckel Cave

The GG originates from 2 sites: the cranial neural crest (between the 7-somite and 13-somite stages) and the overlying thickened ectoderm.[4] By the end of the 4th embryonic week, the GG is a well-defined structure with borders that are distinguishable from the surrounding mesoderm. At 6 weeks' gestation, 3 processes of the ganglion can be identified, and a week later fibers emerge from the ganglion and enter the marginal zone of the neural tube immediately cephalad to the apex of the pontine angle.[17,32] The ophthalmic division develops first, followed by the maxillary and mandibular divisions. At 12 weeks' gestation, the dural pouch of the MC attains its final shape and the arachnoid ends at the GG.[32]

The GG is situated in the middle fossa medially elevated 45° from its floor.[52] It is semilunar, with its greatest breadth at the origin of the maxillary division. In our study, the GG measured 15.6 mm (range 11–20 mm) mediolaterally, findings comparable to the 14–22 mm reported by Lang[36] and the 17 mm reported by Soeira et al.[52] On its concave side, the junction of the CN V with the GG lies in a trough that runs from side to side, the sinus ganglii.[15]

The CN V in the MC consists of the pars compacta, which enters the porus and splays into separate fascicles as the pars triangularis to merge with the GG. Its intracaval length was 11.8 mm (range 6–16 mm), comparable to the measurement of Inoue et al. (11.1 mm).[27] As the cave extended 4.9 mm medially and 1.7 mm laterally beyond this point, the length of the MC medially was 16.7 mm and the length laterally was 13.5 mm.

Since its original description by Johann Friedrich Meckel the Elder (1724–1774) in 1748,[42] most descriptions of this region have dealt either with the trigeminal nerve or the CS. After descriptions by Henle (1871) and Krause (1896), Hovelaque[26] was the first to properly designate a dural and an arachnoidal component to the MC, which Lockhart[40] later clarified to be a posterior fossa dura evagination into the middle fossa. Burr and Robinson[7] used carbon particles to examine the extent of the MC and demonstrated the cave to extend "much farther distally on the posterior surface of the ganglion … when it was lifted from its bed." Dandy (1938) described complications of alcohol spillage into the MC and subsequently the posterior fossa following injections into the GG for trigeminal neuralgia. Ferner[14,15] investigated the anatomy of the trigeminal nerve and outlined the MC in microscopic detail. He observed the dural pouch as 1 layer of dura and arachnoid. He believed the periosteal dura to contribute to the pouch as well.

In all our specimens, the dural sleeve circumferentially invested the trigeminal root. This dura was continued into the posterior fossa medially over the clivus, laterally over the posterior surface of the petrous bone, and superolaterally as the undersurface of the tentorium. This dura was particularly thin but was easily dissected from the periosteal dura on its undersurface. Superiorly, a characteristic layer of fibrous tissue (a fibrous slip of tissue) covered the superior surface of the cave in all specimens. This slip was continuous with the tentorium and the posterior petroclinoid ligament. It was a distinctly different fiber system from the intermediate layer fibers, which were nearly absent over this region. Furthermore, the fiber direction of this fibrous slip was along the axis of the MC, whereas the intermediate layer fibers were obliquely oriented. This landmark may serve as a visual guide for the cave as it ends along the posterior edge of the GG. The dural sleeve could be dissected farther beyond the GG medially than laterally.

Variable descriptions of the dura beyond the GG exist in the literature, including continuation of the arachnoid and dura over the 3 divisions of the CN V to the foramen,[47] cessation of arachnoid on the posterior part of the GG and continuation of the dura,[37] and cessation of arachnoid and dura at the GG and continuation of dura as epineurium.[15,25,36,57] On the lateral side of the GG, the subarachnoid space extended for 1.6 mm anteriorly from the posterior edge of the GG (range 0.5–3 mm) as arachnoid and dura fused with the surface of the GG. Medially this distance was greater, as the subarachnoid space continued over 4.9 mm (range 2–8 mm) beyond the posterior edge of the GG. This space was most frequently dissected over the posterior surface of the ophthalmic nerve. The dura of the MC continued as the epineurium over the 3 trigeminal divisions. On the microscopic sections a space was observed between this epineurial extension and the nerve. During operative dissections, a probe can be passed into this space as far distally as the respective foramina of the trigeminal divisions. Although the MC dura continues as epineurium over the divisions, it not likely that it is accompanied by an arachnoid layer. This may be supported by the absence of colored ink over these nerves in studies reported by Burr and Robinson.[7]

The average length of the ophthalmic division was 19.4 mm (range 16–24 mm) compared with 15.2 mm reported by Strobel[53] and 27.4 mm reported by Soeira et al.[52] Lang[36] measured the intracranial length of the maxillary branch as 10.3 mm and Soeira et al. as 12.5 mm, which corresponds to our measurement of 12.3 mm (range 8–19 mm). The intracranial length of the mandibular division is important for percutaneous rhizotomies and correct needle placement into the MC. Strobel[53] found this length to be 6.6 mm, similar to Soeira et al.'s 6.0 mm[52]. In our specimens, the length of this nerve was 7.4 mm (range

3–13 mm). A variation of 10 mm can be crucial in the correct placement of the percutaneous probe as damage to the GG is to be avoided.

Separation of the periosteal dura and the epineurium of the mandibular branch was less distinct on its exit at the foramen ovale. Collagen bundles are dispersed between the two as the intracranial periosteum continues as the external cranial periosteum. A similar pattern is present at the foramen magnum as the meningeal dura continues as spinal dura. The periosteal dura is continuous with the external cranial periosteum and the atlantooccipital membrane, tectorial membrane, articular capsules, ligamentum flavum, posterior longitudinal ligament, and vertebral periosteum.[5,34]

Youssef et al.[63] eloquently described the meningeal architecture of the MC as it relates to surgical interventions for tumors. The findings of our study are mostly in agreement with theirs. However, our study shows the medial wall of the MC to consist of more than just the dural sleeve of the trigeminal root. Furthermore, Youssef et al. did not find any contribution of the intermediate layer in their dissections.

Tumors in the MC

Tumors affecting the MC were classified according to their morphological configuration: Type A tumors were located mainly in the middle fossa; Type B were located predominantly in the posterior fossa; and Type C had components in the middle and posterior fossae and were thus dumbbell- or hourglass-shaped.[28] Modifications of this classification have been proposed by other authors.[12,39,49,55,62] Almost half of schwannomas are located within the MC.[9]

In a review of 25 cases,[2] an expanded MC was reported to provide access to the middle as well as the posterior fossa component. The dural sleeve component of the MC can hardly provide much resistance to expanding tumors. The fibrous slip, however, is thicker and provides more resistance. The intermediate layer of the lateral wall of the CS at the level of the MC is considerably thinned out.

Of surgical importance is the medial wall of the MC. Tumor expansion into the CS may be impeded by the trapezoidal wall separating the MC from the CS. Samii et al.[49] found no invasion of the CS in 3 patients, 1 with a Type A tumor (size 48 cm^3), 1 with Type B, and 1 with Type C. Taha et al.[54] found tumors in the CS in 13 (87%) of 15 patients with trigeminal neuromas. Pollack et al.[48] found no extension into the CS in 7 of their patients with MC involvement. In Delfini and coworker's[11] experience with MC meningiomas, 50% were confined to the MC.

This trapezoidal wall could only be dissected as a separate entity in 45% of our specimens. In the remainder, the medial wall of the MC was significantly thicker than the dural sleeve alone. This may play a factor in physically inhibiting the tumor growth from the MC into the CS. This reinforcement of the medial wall of the MC can be seen as a reinforcing fiber system arising from the tentorium similar to the intermediate layer in the lateral wall of the CS and the fibrous slip on the superior surface of the MC.

Tumor extension can also occur along the divisions of the trigeminal nerve[43,48] and into the membranous wall of the CS where additional barriers are absent. This may explain why certain tumors only invade the CS along the divisions of the trigeminal nerve as opposed to from within the MC.

The porus trigeminus containing the SPS forms an additional barrier for expansion of tumors out of the MC. The bundles of collagen extend from the tentorium to adhere to the posterior sphenoid bone. The ossification centers (which we found in 35% of the specimens) can be considered a nodular form of petroclinoid ligament calcification, different from the os supra petrosum, which lies at the tip of the petrous bone under the dura. Both are detectable by means of plain skull radiographs.[10,31]

Percutaneous Procedures in the MC

Percutaneous procedures rely upon proper placement of the needle in the MC. For glycerol rhizotomy, a radiopaque agent is injected to ensure placement in the MC. Often a characteristic view of the cave is obtained, possibly with minimal extension of the arachnoid space over the divisions.[19,41] In balloon rhizotomy procedures performed for trigeminal neuralgia, a balloon is introduced into the MC and inflated to straddle the porus trigeminus for compression of the trigeminal nerve at the porus.[6] The pressures within the MC are raised to supraphysiologic levels by the balloon inflation. Lee and Chen[38] measured these pressures and calculated a mean pressure of 2956 ± 185 mm Hg the MC. It is remarkable that no major hemorrhage is caused by this massive expansion of the MC and likely compression of the CS and the adjacent abducens nerve tethered at the Gruber ligament. Reinforcement of the MC may resist these forces upon the CS as pressure alone may not be as harmful to the sinusoids of the CS, and sparing of the abducens nerve may be indicative of protection provided by the medial wall of the MC.

Conclusions

The MC is a dural sleeve accompanying the CN V into the middle cranial fossa and ends over the GG. It is reinforced superiorly by a fibrous slip from the tentorium and medially from the CS by a trapezoidal fibrous wall from the incisura tentorii. The lateral wall of the CS was found to consist of an inner membranous and an outer meningeal dural layer separated by a fibrous intermediate layer, arising from the incisura tentorii fanning out from the anterior clinoid process posteriorly and medially.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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