Transcranial Microsurgical and Endoscopic Endonasal Cavernous Sinus (CS) Anatomy: A Cadaveric Study

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Abstract

Aims and Objectives Even in the era of tremendous microneurosurgical and endoscopic development, the cavernous sinus (CS) is a challenging anatomical site for a neurosurgeon. Many transcranial and a few endoscopic cadaveric studies have been done to study the CS; probably none were undertaken to study its microsurgical and endoscopic anatomy side by side. In this cadaveric study we perform a side-by-side comparison of the microsurgical and endoscopic anatomy of the CS that can help neurosurgeons deal with CS lesions more efficiently.

Materials and Method Sixteen fresh cadaveric heads were studied after dissection. Six heads were dissected for transcranial study and six for endoscopic study of CS. During the transcranial study, the supratentorial brain was removed in three heads and CS and related anatomical structures were dissected. In the remaining heads, the CS was studied by keeping the brains in situ. In four heads both transcranial and endoscopic study was done simultaneously. Following dissection, microsurgical and endoscopic anatomy of CS was studied.

Result The CS and related anatomical structures were dissected sequentially in all cases (transcranially in 10 [6 + 4] heads; endoscopically in 10 [6 + 4] heads), and their relationship was studied.

Conclusion Microscopic and endoscopic exposure of the CS is relatively easy in cadavers. But endoscopic or microsurgical exposure of the CS during surgery is more difficult requiring skill. With experience of the cadaveric study , the CS may be explored via transcranial microsurgery, endonasal endoscopy, or both simultaneously, according to the nature and extension of the pathology.

Keywords
- transcranial microsurgical anatomy
- cavernous sinus
- endonasal endoscopic anatomy

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Introduction

The cavernous sinus (CS) is a challenging anatomical site for a neurosurgeon. Microscopic and endoscopic anatomical knowledge, microneurosurgical and endoscopic techniques and skill, can make surgery at this site relatively easy and safe. In the past, surgery for CS lesions was associated with a significant risk of complications, so this area was considered a "no man's land" for direct surgical intervention. Inadequate neuroanatomical knowledge and lack of microneurosurgical techniques and skill were the reasons behind this. In 1965 Parkinson[1] first described a direct surgical approach to the CS for a carotid-cavernous fistula. Subsequent microanatomical studies[2–9] and surgical series[10–27] have demonstrated that direct approaches to CS lesions can be performed safely and effectively. Recently with significant developments in neuroendoscopic techniques, endonasal endoscopic approaches to the CS are more frequently performed.

Microneurosurgically, the CS is viewed and managed from the lateral and superior sides, whereas in endoneurosurgical techniques the CS is viewed and managed from the inferior and medial sides. We undertook a side-by-side study of the microsurgical and endoscopic anatomy of the CS to help neurosurgeons more efficiently manage CS lesions using these approaches individually or in combination.

Materials and Method

After receiving ethical clearance, we dissected 16 fresh cadaveric heads in the Department of Anatomy and Forensic Medicine. Six heads were dissected for transcranial , and six heads were dissected for endoscopic study of the CS. During the transcranial study of three heads, the supratentorial brain was removed and the CS dissection was done. In the remaining heads, the CS was studied by keeping the brains in situ. In four heads, both transcranial and endoscopic study was done simultaneously. Following dissection, microsurgical and endoscopic anatomy of the CS was studied.

Transcranial Microsurgical Dissection (►Figs. 1–8)

After fixation of the head with the zygoma at the highest point and with the head turned 60 degrees to the opposite side posteriorly, extended pterional craniotomy was done. The temporal bone below the craniotomy was resected up to the root of the pterygoid process (after subperiosteal dissection of the temporalis and infratemporal muscles). The dura mater was dissected from the bone and V2 was reached at foramina rotundum (where dura was easy to peel from V2), and the dura was stripped off medially and posteriorly over the ophthalmic nerve (V1), maxillary nerve (V2), mandibular nerve (V3), and Gasserian ganglion (GG). Cutting of the middle meningeal vessels at the foramina spinosum was needed to peel dura over V3. Dural peeling was done posteriorly up to the petrous apex, medially up to cranial nerve III and free margin of the tentorial cerebelli, and anteriorly up to the superior orbital fissure (SOF), where cranial nerves III, IV, VI, the V1 nerves, and the superior ophthalmic vein were identified (►**Figs. 6–8**). Then various triangles, the walls of the CS, and the contents—and their relationships—were studied. In three cadaveric heads, after removal of the vault and supratentorial brain, the CS and related anatomical structures were studied directly from above (►**Figs. 1–5**).

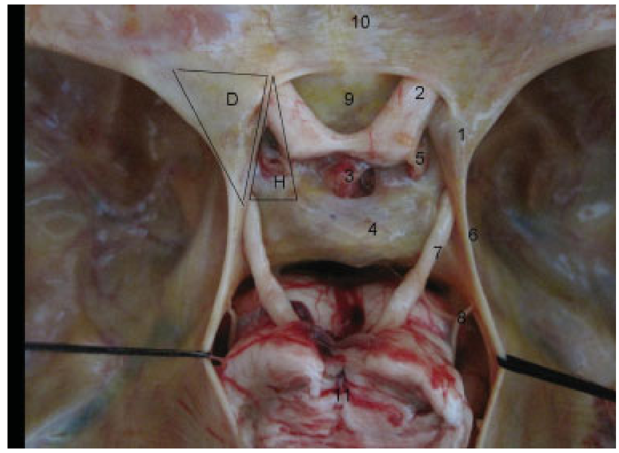

Figure 1 Sellar, parasellar, and related area after removal of supratentorial brain. (1) Anterior clinoid process. (2) Optic nerve. (3) Pituitary stalk. (4) Dorsum sella. (5) Internal carotid artery (intradural). (6) Tentorial free margin. (7) Oculomotor nerve. (8) Trochlear nerve. (9) Tuberculum sella. (10) Planum sphenoidale. (11) Midbrain. D, Dolenc's triangle; H, Hakuba's triangle.

Endoscopic Endonasal Transsphenoidal Dissection (►Figs. 9–13)

Heads were positioned in a head-high, neck-neutral, right-facing position. A 0°-endoscope was introduced in the nasal cavity, and the middle turbinate, inferior turbinate, nasal septum, and posterior nasal choana were identified. Using centripetal techniques, the nasal mucosa, ethmoidal sinuses, and middle turbinate were removed. (In centripetal techniques, the first U-shaped nasal mucosal incision was made in front of the middle turbinate and behind the uncinate

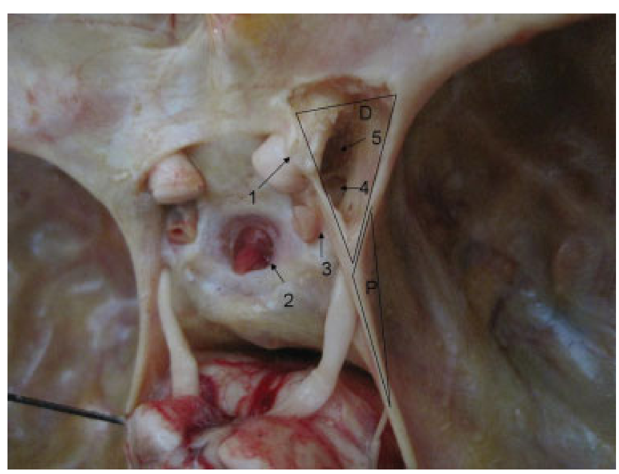

Figure 2 Sellar, parasellar, and related area after removal of supratentorial brain and drilling out of right-sided anterior clinoid process. (1) Optic nerve and sheath. (2) Pituitary stalk. (3) Distal carotid ring and internal carotid artery (intradural). (4) Internal carotid artery (clinoidal segment). (5) Ethmoidal sinus mucosa. D, Dolenc's triangle; P, Paramedian triangle.

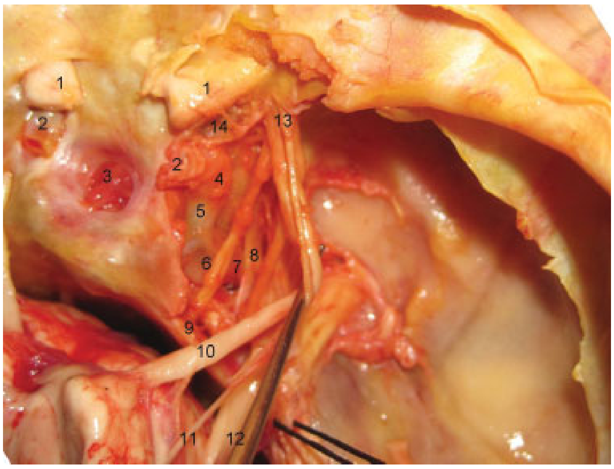

Figure 3 Cavernous sinus (CS), internal carotid artery (ICA), and related structures after removal of overlying dura and anterior clinoid process. (1) Optic nerve. (2) Intradural ICA. (3) Pituitary stalk. (4) Clinoidal ICA segment. (5) Horizontal ICA segment in CS. (6) Proximal ascending ICA segment. (7) ICA after exit from foramen lacerum. (8) Lateral carotid ring. (9) Abducent nerve and petroclival ligament (Gruber's ligament). (10) Oculomotor nerve. (11) Trochlear nerve. (12) Trigeminal nerve. (13) Nerves at superior orbital fissure. (14) Optic strut.

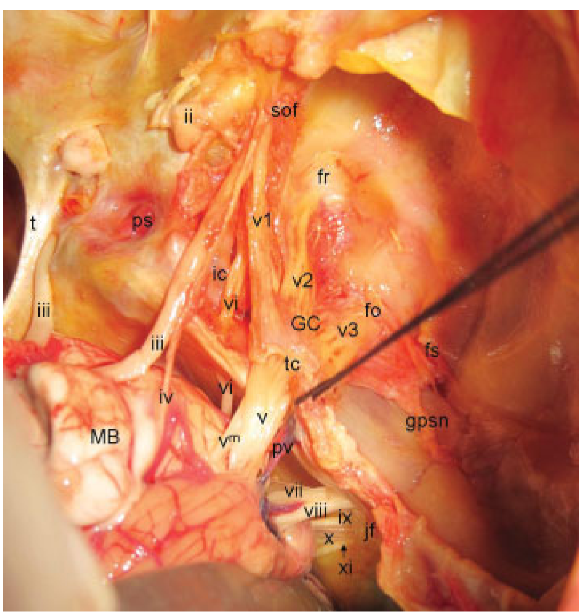

Figure 4 Cranial nerves after cavernous sinus dissection. fo, foramen ovale; fr, foramen rotundum; fs, foramen spinosum; GC, Gasserian ganglion; gpsn, greater petrosal superficial nerve; ic, internal carotid artery; ii, optic nerve; iii, oculomotor nerve; iv, trochlear nerve; ix, glossopharyngeal nerve; jf, jugular foramen; MB, midbrain; ps, pituitary stalk; pv, petrosal vein; t, free margin of tentorium cerebelli; tc, trigeminal cave; v, trigeminal nerve; v1, ophthalmic nerve; v2, maxillary nerve; v3, mandibular nerve; vii, facial nerve; viii, vestibulocochlear nerve; vm, trigeminal motor root; x, vagus nerve; xi, accessory nerve.

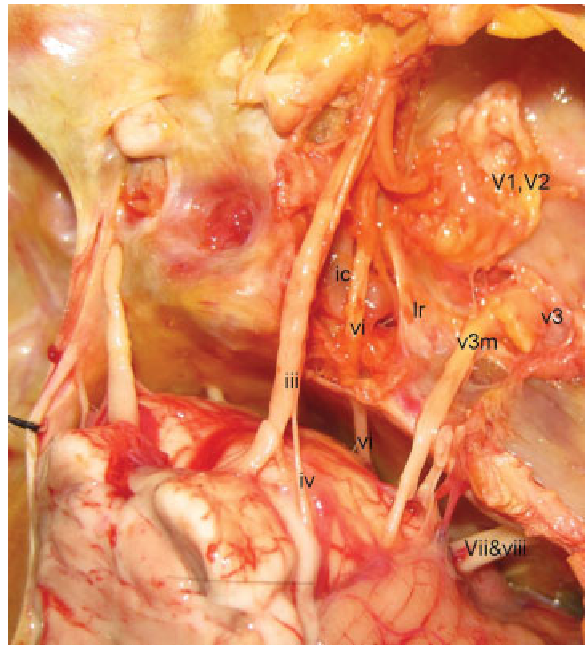

Figure 5 Cavernous sinus and related structures after cutting and mobilization of the sensory divisions of the trigeminal nerve. ic, internal carotid artery; lr, lateral carotid ring; iii, oculomotor nerve; iv, trochlear nerve; v1, ophthalmic nerve; v2, maxillary nerve; v3, mandibular nerve; v3m, trigeminal motor root; vii, facial nerve; viii, vestibulocochlear nerve.

process. Starting above the inferior turbinate, the incision extended up and medially to a point on the septal mucosa opposite the staring point. From the starting point, the mucosal incision was extended posteriorly over the inferior turbinate and, passing above the posterior choana, it was extended horizontally on the septum and ended at the lower point of the first incision on the septum). The superior turbinate and sphenoidal ostium were then seen ~1.5 to 2.0 cm above the choana (►**Fig. 9A**). Superior turbinate mucosa of the sphenoethmoidal recess and posterior nasal septum was removed. Then the septum was broken at the junction of the rostrum and the vomer. Submucoperiosteal dissection and mucosal removal were done on the opposite side to clear the rostrum and the opposite face of the sphenoid up to the ostium on the opposite side. Using binostril techniques, the posterior part of the nasal septum was removed with a "back bite" punch. The sphenoidal sinus was exposed by removing the bone between the ostia with the Karrison up-cut or down-cut rongeur. The floor of the sphenoidal sinus was cut as lateral as possible (up to the root of the pterygoid process). The septum in the sinus was removed. The sellar floor, opticocarotid recess (OCR), carotid and optic protuberance, and dorsum sella were identified (►**Fig. 9B**), and identification of these structures guided us to locate the exact site of the CS. The sphenoidal mucosa was dissected and removed. Bone over the sella and CS (carotid protuberance) was removed with a punch or microdrill, and the floor of the CS was exposed (►**Fig. 9C**). Bone was removed anterior to the superior intercavernous sinus, anterolaterally to the opticocarotid recess , posteriorly to the inferior intercavernous sinus, posterolaterally to the posterior clinoid process, and

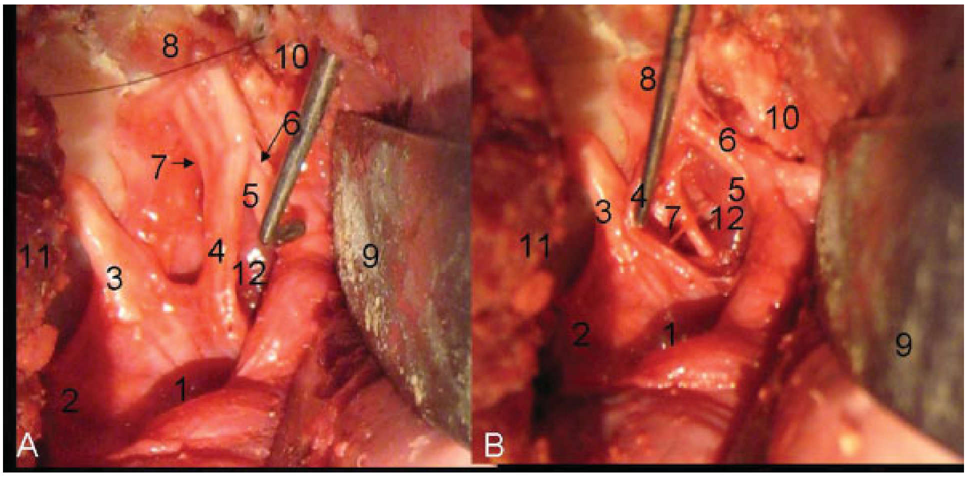

Figure 6 Extradural subtemporal exposure of cavernous sinus. (1) Gasserian ganglion. (2) Mandibular nerve. (3) Maxillary nerve. (4) Ophthalmic nerve. (5) Oculomotor nerve. (6) Trochlear nerve. (7) Abducent nerve. (8) Superior orbital fissure. (9) Retractor retracting dura and temporal lobe. (10) Anterior clinoid process. (11) Temporalis muscle. (12) Internal carotid artery.

laterally to the root of the pterygoid process. Through the floor, the CS was entered and studied.

Result

A. Transcranial Study

CS Anatomy

The CS was a hexahedral compartment. The margins of the CS were limited by the medial aspect and the lesser and greaters wing of the sphenoid bone, the anterior and posterior clinoids, and the tip of the petrous bone. The average dimensions of the CS were 19.5 mm (18.5 to 22.5 mm) long by 10 mm (8 to 12.5 mm) wide. It was bound on all sides by dura mater, which was continuous from the base of the middle and posterior cranial fossa and the diverging aspects of the tentorium. The floor and medial wall of the CS were formed by a periosteal layer of dura. As it continued upward along the lateral surface of the pituitary gland and clinoid processes, this thin layer was joined by another layer of dura that covered the floor of the sella turcica. The double-layered dura of the clivus extended anteriorly to form part of the

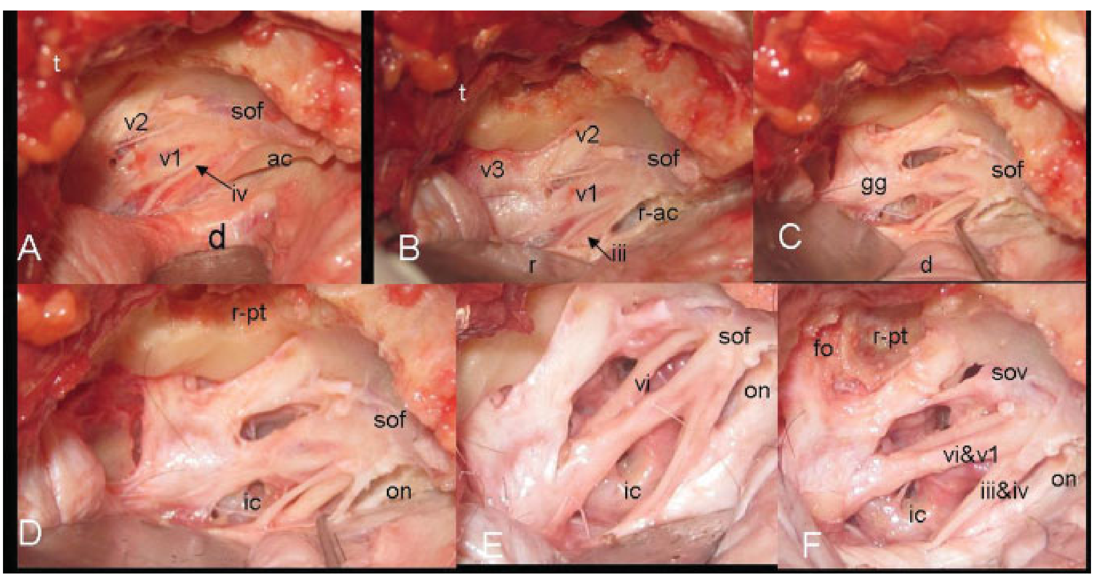

Figure 7 Stepwise dissection of the cavernous sinus after peeling of temporal dura through posteriorly extended pterional craniotomy with removal of temporal bone (up to lateral pterygoid plate) and anterior clinoidectomy (extradural). (A) ac, anterior clinoid process; d, temporal dura; iv, trochlear nerve; sof, superior orbital fissure; t, temporalis muscle; V1, ophthalmic nerve; V2, maxillary nerve. (B) iii, oculomotor nerve; r, retractor retracting temporal lobe; r-ac, removed anterior clinoid process; sof, superior orbital fissure; t, temporalis muscle; V1, ophthalmic nerve; V2, maxillary nerve; v3, mandibular nerve. (C) d, dura; gg, trigeminal ganglion; sof, superior orbital fissure. (D) ic, internal carotid artery; on, optic nerve; r-pt, partially removed root of pterygoid process; sof, superior orbital fissure. (E) ic, internal carotid artery; on, optic nerve; sof, superior orbital fissure; vi, abducent nerve. (F) fo, foramen ovale; ic, internal carotid artery; iii&iv, third and fourth cranial nerve; on, optic nerve; r-pt, partially removed root of pterygoid process; sof, superior orbital fissure; vi&v1, sixth and ophthalmic nerve.

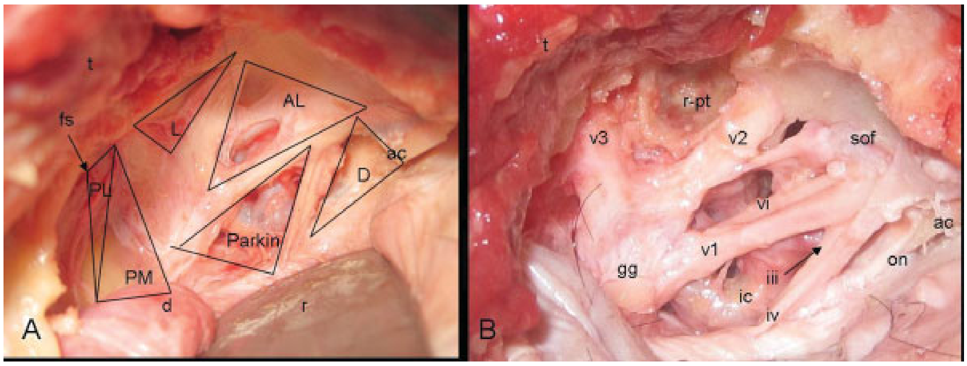

Figure 8 Dissection of the cavernous sinus after peeling of temporal dura through posteriorly extended pterional craniotomy with removal temporal bone (up to foramen ovale with partial removal of root of pterygoid process) and anterior clinoidectomy (extradural) showing different triangles and different structures. (A) ac, anterior clinoid (drilled); AL, anterolateral triangle; d, dura; D, Dolenc triangle; fs, foramen spinosum; L, lateral triangle; Parkin, Parkinson's triangle; PM, posteromedial triangle; PL, posterolateral triangle; r, retractor; t, temporal muscle. (B) ac, drilled anterior clinoid; gg, trigeminal ganglion; ic, internal carotid artery; iii, third nerve; iv, fourth nerve; on, optic nerve; r-pt, partially removed root of pterygoid process; sof, superior orbital fissure; t, temporalis muscle; v1, ophthalmic nerve; v2, maxillary nerve; v3, mandibular nerve; vi, abducent nerve.

posterior wall. The double-layered dura of the floor of the middle fossa extended medially at the superior border of the second division of the fifth cranial nerve to become the lateral wall of the CS.

The roof of the CS was formed by the upward extension of the lateral wall as it joined with the thickened tentorial edge attached to both the posterior and the anterior clinoid processes. Medially, the roof was continuous with the sellar diaphragm. Anteriorly, the CS tapered and twisted to terminate at the SOF (►**Figs. 1–5, 7, 8**). Posterosuperiorly, it ended at the tentorium. Posteromedially, the CS was continuous with the lateral edge of the clivus, and inferolaterally it extended into a funnel-shaped space around the internal carotid artery (ICA) through the foramen lacerum.

The structures lying within the CS were the ICA and its branches, the abducent nerve, sympathetic nerve fibers, and fat. The oculomotor and trochlear nerves and the first and second divisions of the trigeminal nerve coursed within the lateral wall of the sinus (►**Figs. 3–8, 14A, 15A, B, C**). The morphological structure of the CS was found trabeculated with intradural venous channel.

Internal Carotid Artery (►Figs. 3–8, 14, 15)

From the point of its entry at the foramen lacerum to its exit into the intradural space, the ICA traveled laterally to medially in the coronal plane, posteriorly to anteriorly in the sagittal plane, and inferiorly to superiorly in the axial plane. Among the four segments of the ICA, the intracavernous portion of the ICA had five parts: (1) the posterior vertical segment, (2) the posterior bend, (3) the horizontal segment, (4) the anterior bend, and (5) the anterior vertical segment. The junction of the intrapetrous horizontal and intracavernous vertical portions of the ICA forms a (lateral) loop that overlies the foramen lacerum and runs below the lower aspect of the mandibular (V3) nerve. At its exit from the petrous bone, the artery was fixed by a thick fibrous band of dura known as the lateral ring. Passing through the lateral ring, the artery ran under the trigeminal nerve. The intracavernous vertical segment was the initial ascending portion of the ICA immediately distal to the foramen lacerum. The medial loop was formed at the junction of the intracavernous vertical and horizontal segments of the ICA. The medial loop was situated adjacent to the lateral aspect of the posterior clinoid process.

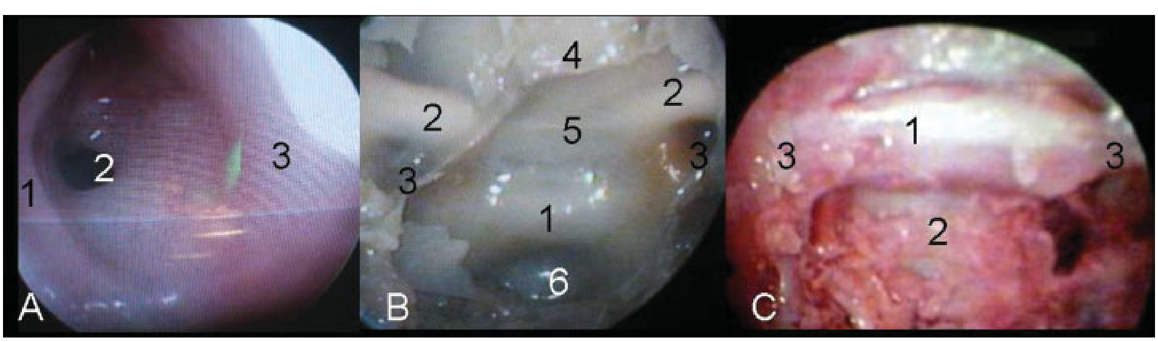

Figure 9 (A) Endoscopic view of sphenoethmoid recess. (1) Superior turbinate. (2) Sphenoidal ostium. (3) Nasal septum. (B) Endoscopic view of sellar parasellar floor after exposure of sphenoidal sinuses. (1) Sellar floor. (2) Optic protuberance. (3) Opticocarotid recess. (4) Plannum sphenoidale. (5) Tuberculum sella. (6) Dorsum sella. (C) Endoscopic view after removal of sellar and parasellar bone. (1) Sellar dura. (2) Dorsum sellae area. (3) Dura over cavernous sinus.

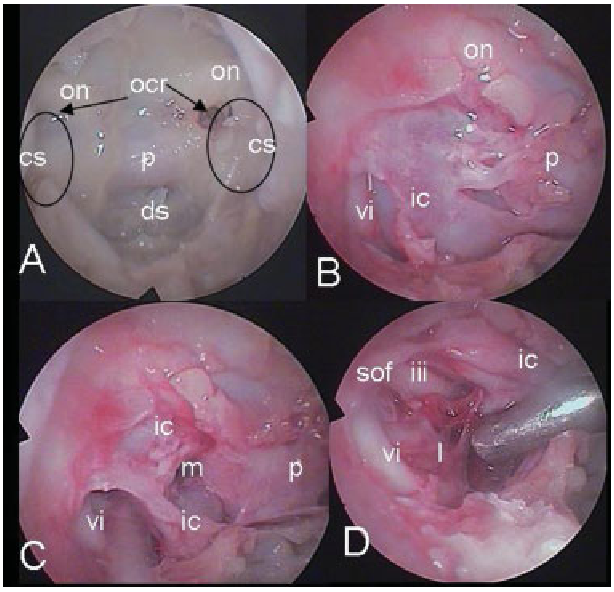

Figure 10 Endoscopic transnasal transsphenoidal exposure of sella, parasellar areas (cavernous sinus). (A) cs, cavernous sinus; ds, dorsum sellae; ocr, opticocarotid recess; on, optic protuberance; p, sellar floor. (B) ic, internal carotid artery; on, optic nerve;p, pituitary gland; vi, sixth nerve. (C) ic, internal carotid artery; m, medial compartment of right cavernous sinus; p, pituitary gland; vi, sixth nerve. (D) iii, third nerve; l, lateral compartment of right cavernous sinus; sof, superior orbital fissure; vi, sixth nerve.

The intracavernous horizontal segment of the ICA passed anteriorly toward the anterior portion of the CS, where it curved upward (anterior loop) before exiting from the CS. This portion of the ICA (clinoidal segment) was medial and inferior to the anterior clinoid process (►**Fig. 9**). The average length of the cavernous segment of the ICA was 22.5 mm (18.5 to 25 mm). The length of the posterior vertical segment averaged 4.8 mm (4.5 to 6.5 mm), the length of the horizontal segment 14 mm (12 to 15 mm), and the anterior vertical segment length 4.2 mm (3 to 5.5 mm). Among the branches of the intracavernous ICA, the meningohypophyseal trunk was found in all dissections (100%), the inferolateral trunk (ILT) was found in all but one dissection (94%). The capsular artery, the intracavernous origin of the ophthalmic artery, and the persistent trigeminal artery were not found in any dissection of the CS.

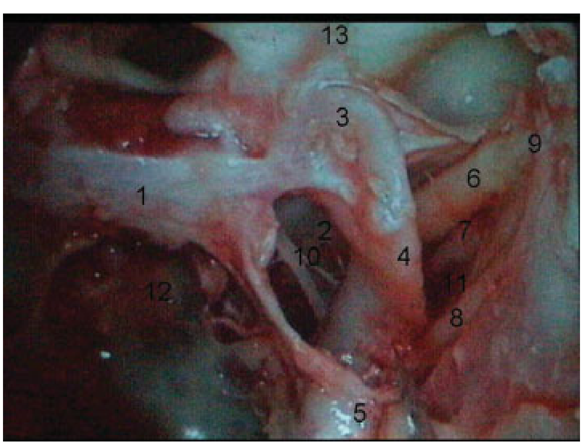

Figure 11 Endoscopic view of cavernous sinus and sella. (1) Pituitary gland. (2) Medial compartment of cavernous sinus. (3) Clinoidal segment of internal carotid artery (ICA). (4) Horizontal portion of ICA. (5) Proximal ascending segment of intracavernous ICA. (6) Oculomotor nerve. (7) Trochlear nerve. (8) Abducent nerve. (9) Superior orbital fissure. (10) Meningohypophyseal trunk. (11) Lateral compartment of cavernous sinus. (12) Dorsum sellae. (13) Optic protuberance.

Oculomotor Nerve

The oculomotor nerve, after entering the roof of the CS lateral to the posterior clinoid process, ran in the lateral wall and lay immediately under the lower margin of the anterior clinoid process before it exited the sinus to enter the SOF. In this region, the third cranial nerve was separated from the anterior clinoid process by a thin layer of dura and could easily be injured during removal of the anterior clinoid process (ACP) (►**Figs. 1–8, 14A, 15A, B, C**).

Trochlear Nerve

The trochlear nerve entered the roof of the CS posterolateral to the third cranial nerve and under the free edge of the tentorium. Within the lateral wall, it passed over the oculomotor nerve to exit through the SOF. The average distance between the entry point of the third and fourth nerve into the CS wall was 9 mm (8 to 11 mm) (►**Figs. 1–8, 14A, 15A, B, C**).

Trigeminal Nerve

The ophthalmic division (V1) of the trigeminal nerve ran within the lateral wall of the CS in its lower part and coursed obliquely and superiorly to exit the CS through the SOF. The maxillary division (V2) was situated at the most posteroinferior aspect of the lateral wall and left the cranial cavity through the foramen rotundum. The mandibular division (V3) did not enter the CS and left the cranium through the foramen ovale. The Gasserian ganglion was located outside the CS (►**Figs. 3–8, 14A, 15A, B, C**).

Abducent Nerve

The abducent nerve entered the sinus through Dorello's canal, which was bounded by the petroclival ligament (Gruber's ligament) superiorly and by the petrous apex inferiorly. It crossed above the vertical segment of the intracavernous ICA medially to laterally and ran parallel to the horizontal segment of the ICA underneath the V1 nerve to reach the SOF. The average length of the intracavernous segment of the sixth nerve was 19.5 mm (18 to 22 mm) (►**Figs. 3–8, 14A, 15A, B, C**).

In the transcranial dissection, the following triangles were studied:

Anteromedial (Dolenc's) Triangle

This triangle was defined by the lateral aspect of the optic nerve, the medial aspect of the third cranial nerve, and the tentorial edge from the entry point of the third cranial nerve to the entry point of the optic nerve into the optic canal (►**Fig. 4**). It contained the clinoid segment of the ICA and was exposed by removing the anterior clinoid process either extradurally or intradurally. Complete drilling out of the anterior clinoid process was needed to get access to Dolenc's triangle (►**Fig. 1, 2, 8A**).

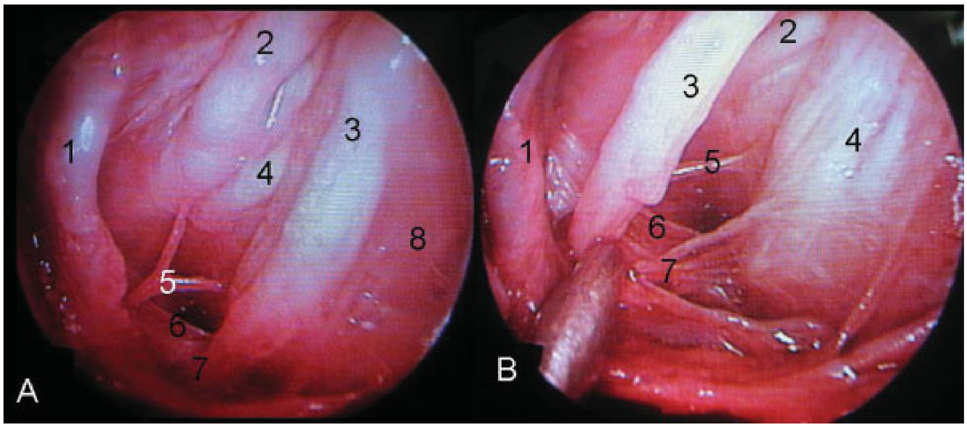

Figure 12 (A) Endoscopic view of cavernous sinus showing cranial nerves. (1) Internal carotid artery (ICA). (2) Oculomotor nerve. (3) Abducent nerve. (4) Trochlear nerve. (5) Inferolateral trunk. (6) Superior boundary of Dorello's canal (Gruber's ligament). (7) Exit of sixth nerve from canal of Dorello's. (8) Ophthalmic nerve. (B) Close endoscopic view of cavernous sinus after dissection and mobilization of sixth nerve. (1) ICA. (2) Trochlear nerve. (3) Abducent nerve. (4) Ophthalmic nerve. (5) Inferolateral trunk. (6) Superior boundary of Dorello's canal (Gruber's ligament). (7) Exit of sixth nerve from canal of Dorello's.

Medial (Hakuba's) Triangle

This triangle was formed by connecting three points in the superior wall of the CS: the lateral margin of the supraclinoid ICA, the dural entrance of the oculomotor nerve, and the anterolateral margin of the posterior clinoid process, which could be used for exploration of the horizontal portion of the cavernous ICA (►**Fig. 1**).

Paramedian Triangle

It is defined by the lateral aspect of the third cranial nerve and by the medial aspect of the fourth cranial nerve, respectively. The posterior margin is the portion of the tentorial edge between the entry points of the third and fourth cranial nerves and can be used surgically to explore the medial loop of the intracavernous ICA and the meningohypophyseal trunk (►**Fig. 2**).

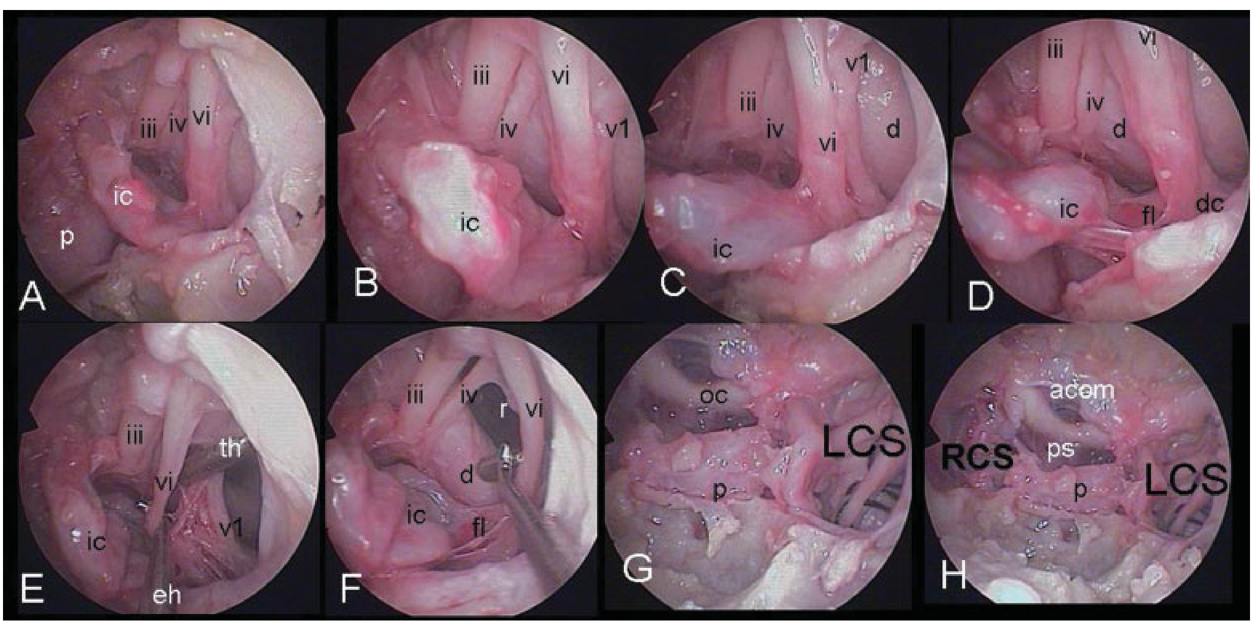

Figure 13 Endoscopic exploration and dissection of left cavernous sinus (CS). (A) ic, internal carotid artery; iii, third cranial nerve; iv, fourth nerve; vi, sixth nerve; p, pituitary gland. (B) ic, internal carotid artery; iii, third cranial nerve; iv, fourth nerve; vi, sixth nerve; v1, ophthalmic nerve. (C) d, middle fossa dura; ic, internal carotid artery; iii, third cranial nerve; iv, fourth nerve; vi, sixth nerve;v1, ophthalmic nerve. (D) d, middle fossa dura; fl, exit of ICA from foramen lacerum; dc, exit of sixth nerve from Dorello's canal; ic, internal carotid artery; iii, third cranial nerve; iv, fourth nerve; vi, sixth nerve. (E) eh, endonasally placed hook for dissection; ic, internal carotid artery; iii, third nerve; th, transcranially placed hook; vi, sixth nerve; v1, ophthalmic nerve. (F) d, middle fossa dura; fl, exit of ICA from foramen lacerum; ic, internal carotid artery; iii, third cranial nerve; iv, fourth nerve; r, transcranial retractor for retraction of temporal lobe seen endoscopically; vi, sixth nerve. (G) LCS, left CS; oc, optic chiasm; p, pituitary gland. (H) acom, anterior communicating artery complex; LCS, left CS; p, pituitary gland; ps, pituitary stalk; RCS, right CS.

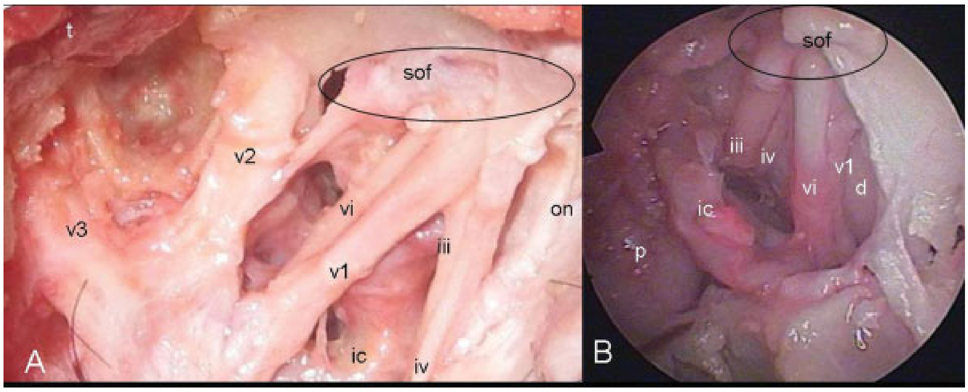

Figure 14 Comparative microscopic and endoscopic view of superior orbital fissure. (A) ic, internal carotid artery; iii, third nerve; iv, fourth nerve; on, optic nerve; sof, superior orbital fissure; t, temporalis muscle; v1, ophthalmic nerve; v2, maxillary nerve; v3, mandibular nerve; vi, sixth nerve. (B) d, dura; ic, internal carotid artery; iii, third nerve; iv, fourth nerve; p, pituitary gland; sof, superior orbital fissure; vi, sixth nerve; v1, ophthalmic nerve.

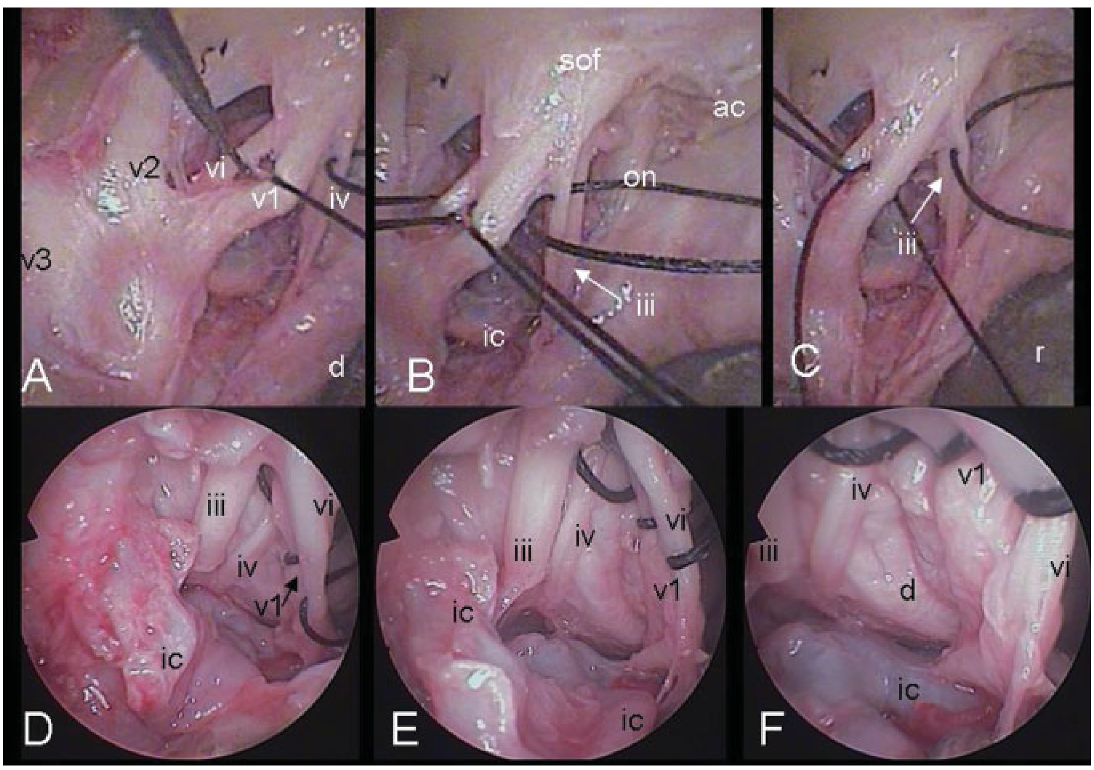

Figure 15 Comparison of transcranial (A, B, C) and endoscopic (D,E, F) view of cavernous sinus. Fourth, sixth, and ophthalmic nerve is marked by silk sling, no sling on third nerve. (A) d, dura; iv, fourth nerve; vi, sixth nerve; v1, ophthalmic nerve; v2, maxillary nerve; v3, mandibular nerve. (B) ac, (drilled) anterior clinoid process; ic, internal carotid artery; iii, third nerve; sof, superior orbital fissure; on, optic nerve. (C) iii, third nerve; r, retractor. (D) ic, internal carotid artery; iii, third nerve; iv, fourth nerve; vi, sixth nerve; v1, ophthalmic nerve. (E) ic, internal carotid artery; iii, third nerve; iv, fourth nerve; vi, sixth nerve; v1, ophthalmic nerve. (F) ic, internal carotid artery; iii, third nerve; iv, fourth nerve; vi, sixth nerve; v1, ophthalmic nerve.

Parkinson's Triangle

This space was bounded medially by the lateral aspect of the fourth cranial nerve, laterally by the medial aspect of the ophthalmic division of the trigeminal nerve, and posteriorly by the dural edge between the entry points of these two nerves (►**Fig. 5**). This triangle was relatively narrow and could be enlarged by slight retraction of the fourth cranial nerve medially and the ophthalmic division of the trigeminal nerve laterally (►**Fig. 8A**). The full intracavernous segment of the ICA from the lateral ring to the proximal ring could be explored through this route. The Parkinson triangle allows exposing the complete course of the sixth cranial nerve from its entry through Dorello's canal to its exit through the SOF.

Anterolateral (Mullan's) Triangle

It was situated between the ophthalmic and maxillary divisions of the trigeminal nerve and the bone of the middle fossa between the foramen rotundum and the SOF and could be used to expose the superior ophthalmic vein and the abducent nerve (►**Fig. 8A**).

Lateral Triangle

This triangle was defined by the maxillary and mandibular divisions of the trigeminal nerve and the bone in the middle fossa between the foramen rotundum and foramen ovale. Drilling of bone between foramen ovale and rotundum (i.e., root of pterygoid process) was needed for exposure of this triangle (►**Fig. 8A**).

Posterolateral (Glasscock's) Triangle

This triangle was bound by the greater superficial petrosal nerve medially, the posterior aspect of the mandibular division of the trigeminal nerve anteriorly, and by a line between the foramen spinosum and the arcuate eminence of the petrous bone posteriorly. The bone here must be removed to expose the horizontal intrapetrosal segment of the ICA (►**Fig. 8A**).

Posteromedial (Kawase's) Triangle

Boundaries for this area in the middle fossa were the posterior border of the mandibular division of the trigeminal nerve anteriorly, the arcuate eminence posteriorly, the greater superficial petrosal nerve laterally, and the petrous ridge with the superior petrosal sinus medially. Anterior petrosectomy through this triangle exposed the petroclival area, the anterolateral brain stem, and the vertebrobasilar junction through a corridor between the trigeminal nerve and facial-vestibulocochlear nerve complex (►**Fig. 8A**).

Inferomedial Triangle

This triangle was defined medially by a line connecting the posterior clinoid process and the sixth cranial nerve at Dorello's canal, laterally by a line connecting the fourth cranial nerve at the edge of tentorium and the sixth cranial nerve at Dorello's canal, and by the petrous apex at the base.

Inferolateral Triangle

It was lateral to the inferomedial triangle and bounded medially by the line between the sixth cranial nerve at Dorello's canal and the fourth cranial nerve at the edge of the tentorium, laterally by the line connecting the sixth cranial nerve at Dorello's canal and the petrosal vein at the superior petrosal sinus, and by the petrous apex at the base.

B. Endoscopic Endonasal Transsphenoidal CS Study

After entering into the CS through the floor, the intracavernous ICA was seen. Endoscopically it extended from Dorello's canal and the foramen lacerum (posteriorly) to the SOF and the carotid collar anteriorly. Between the carotid collar and the SOF, the OCR (i.e., the root of the anterior clinoid process) was seen. The medial wall was formed by the dorsum sella posteriorly and the pituitary gland anteriorly, along with the endosteal layer of dura. The floor was formed by the lateral part of the roof of the sphenoid sinus along with the endosteal layer of dura. Bony elevation on the floor due to the intracavernous ICA—known as the carotid protuberance—was although an important anatomical landmark during the endoscopic procedure. Endoscopically the lateral wall was formed by the ophthalmic nerve, which could be clearly seen after lateral mobilization of the ICA and the abducent nerve. Visualized endoscopically, the CS roof was formed by the oculomotor and trochlear nerves anteriorly and the meningeal layer of dura posteriorly. The roof was seen after lateral mobilization of the anterior part of the intracavernous ICA. Endoscopically, the CS compartments were somewhat difficult to identify due to two-dimensional views. Endoscopically, gross compartment of CS were medial, lateral, superior, and inferior compartment according to the relation of ICA. The medial compartment contained the meningohypophyseal trunk (►**Fig. 11**), and the lateral compartment contained the inferolateral trunk and the vi nerve (►**Figs. 11**, **12**). The CS contents seen by the endoscope were the ICA, the abducent nerve, and the meningohypophyseal and inferolateral trunk (►**Figs. 9–13, 14B, 15D, E, F**).

Internal Carotid Artery

The cavernous portion of the ICA was seen from the entrance of the ICA into the CS through the foramen lacerum to the intracranial ICA. It occupied almost all of the space of the CS. It was sinuous and, because of the two-dimensional endoscopic view, it was difficult to realize the exact three-dimensional orientation. The meningohypophyseal trunk and inferolateral trunk originated from the intracavernous ICA on its medial and lateral side, respectively. Endoscopically, the meningohypophyseal trunk and inferolateral trunk were seen in all CS (100%) (►**Figs. 10–13, 14B, 15D, E, F**).

Abducent Nerve

After medial mobilization of the ICA, the abducent nerve was seen, usually on the medial surface of ophthalmic nerve, which can be easily separated from V1. Anteriorly, it could be traced up to the SOF and posteriorly up to the exit of Dorello's canal, where it entered into the CS above the ICA at the foramen lacerum (►**Figs. 10C, D, 11, 12, 13, 14B, 15D, E, F**).

Oculomotor Nerve

Endoscopically, the oculomotor nerve was seen at the anterior roof of the CS medial to the trochlear nerve from its dural entry point at the roof to the SOF, coursing anterolaterally to enter into the orbit (►**Figs. 10D, 11, 12A, 13, 14B, 15D, E, F**).

Trochlear Nerve

Endoscopically, the trochlear nerve was seen at the anterior roof of the CS lateral to the iii nerve from its dural entry point at the roof to the SOF, coursing anterolaterally to enter into the orbit (►**Figs. 11, 12, 13, 14B, 15D, E, F**).

Discussion

Though the CS anatomy is widely studied, there is still much interest in its anatomy. In recent years, endoscopic neurosurgery has evolved rapidly. Some articles addressing the endoscopic anatomy has been published, but for thorough understanding of endoscopic anatomy further studies are needed.

Microsurgical approaches to lesions of the CS became possible because of improvements in neuroradiological imaging and microsurgical techniques. Different surgical routes to the CS have been described that include the subtemporal approach through the lateral wall,[1,8,12,24,28] the pterional approach through the superior wall,[17,29] the transpetrosal-transtentorial approach through the posterior wall,[30] the contralateral pterional transsylvian approach through the medial wall,[17,29] and the transsphenoidal approach through the inferior wall.[31] Most of these approaches can be broadly classified as either extradural or intradural. Dolenc,[13,15,32] however, described a combined extradural-intradural approach that has been commonly used for lesions in this region.[33]

Two intradural (superior and lateral) and three extradural (inferior, anterolateral, and medial) approaches are surgically important.[8] The intradural superior approach removes the anterior clinoid process and enters the CS through the superior wall, either medially or laterally. It provides an excellent view of the anterior loop of the ICA and the anterior parts of the lateral and posterosuperior venous spaces. The lateral approach enters the CS through the lateral wall. The lateral surface of the vertical and horizontal segments of the intracavernous ICA, the medial loop, and the lower part of the anterior loop of the ICA are exposed through this approach. The lateral, anteroinferior, and posterosuperior spaces, as well as the cranial nerves in the wall of the CS and the intracavernous portion of the sixth cranial nerve, are also exposed. The origins of the meningohypophyseal trunk and the inferolateral trunk can also be visualized.[33]

The inferior extradural approach is used to expose the horizontal segment of the intrapetrous ICA and the junction of the intracavernous and intrapetrous segments. The anterolateral approach permits extradural access to the floor of the anterior and middle cranial fossae for removal of the anterior clinoid process and the roof of the orbit and optic canal. This approach exposes the entire clinoid segment of the ICA. The medial approach may be utilized to expose the medial venous space and the anterior and medial surfaces of the anterior loop of ICA.[33]

A combination of extradural and intradural approaches provides generous exposure of this area and different working angles through the various triangles.[33]

Despite the advances in neuroimaging, neuroanesthesia, and microsurgical techniques, complications (cranial nerve injuries, cerebrovascular complications, and cerebrospinal fluid leakage) associated with microsurgery or endocscopy in the CS region still remain high.[11] Thus, the indications for surgery still remain a matter of debate. When surgery is considered, it is important to take the exact anatomical location, the pathology of the lesion, the likelihood of achieving a cure, and the risk of operative complications into account. The surgeon's judgment and the patient's informed preferences remain the most important factors in planning management strategies for lesions in the CS.[33] This especially holds true, because alternative treatment modalities, such as stereotactic radiosurgery, endovascular techniques, and medical therapy in certain tumors (e.g., bromocriptine for treatment of prolactinomas) are available.[33]

For clear understanding of endoscopic CS anatomy, one must although have an understanding of the anatomy of the CS, seen from transcranially. Transcranial microsurgical anatomy is the superiolateral view of the CS, whereas endosurgical anatomic view is the inferomedial view. Transcranially, the CS can be approached extradurally or intradurally where the anterior and posterior clinoid process, the anterior tentorium cerebelli, the cranial nerves III, IV and VI, and various triangles may come in view. In approaching the CS transcranially, sometimes anterior clinoid process removal is needed. In the endoscopic approach, initial important landmarks at the skull base are the sellar floor, carotid protuberance, optic protuberance, and the OCR. After entering into the CS, important anatomical structures are the ICA and the abducent nerve. Its relationship to the oculomotor, trochlear, V1 nerves, SOF, Dorello's canal, and the foramen lacerum should be kept in mind. In endoscopic approaches, unlike transcranial approaches, the neurosurgeon enters into the CS through the endosteal layer of dura at its floor and not via one of the well described triangles as in transcranial surgery. In endonasal endoscopic exposure of the CS, same-sided ethmoidectomy, use of both nostrils with middle turbinate lateralization, and removal of the posterior part of the nasal septum are essential providing space for up to four small endosurgical instruments including the endoscope. A single-nostril approach with middle turbinectomy or ethmoidectomy is not adequate for approaching different parts of the CS.[34] Main indications for endoscopic CS exposure are pituitary tumors extending into the CS and CS tumors, in which a biopsy should be taken.[35–37]

Endoscopic removal of CS tumors other than pituitary adenomas is still in its infancy but will hopefully evolve rapidly in the near future. Large CS lesions possibly can be managed with simultaneous transcranial and endonasal transsphenoidal approaches. Endosurgical management of CS vascular lesions is, at this point, not possible.

Conclusion

The anatomy of the CS is not straightforward or easy to learn. A microsurgical and endoscopic cadaveric study is an important adjunct for developing a clear three-dimensional anatomical idea of the CS. With experience (cadaveric study and practice), the CS may be explored via transcranial microsurgery, endonasal endoscopy, or both (simultaneously) for surgical purposes, according to the nature and extension of the pathology.

Conflict of Interest
None

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