



Petroclival Clinoidal Folds and Relationships with Arachnoidal Membranes of Medial Incisural Space: Old Neuroanatomical Terms for a New Neurosurgical Speech in Cadaver Labs with Limited Resources Era. Part III: Arachnoid Membranes, Cranial Nerves, and Surgical Implications

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1 Introduction

In the first two parts of our study, in a “low resource laboratory”, we described [1, 2] the anatomy of the anterior and middle incisural spaces by describing the regional osteology, the structural anatomy of the dura mater of the middle cranial fossa, as well as the tentorial incisura and petroclinoid folds [3–14].

In the third part, we complete our study of the arachnoid membranes and cranial nerves of the anterior and middle incisural spaces. In the description of these structures, the usefulness of the dissection on fresh, non-formalin-fixed human specimens is clearly demonstrated.

Moreover, we identified and described surgical implications of these anatomical topics in different types of neurosurgical procedures dealing with this anatomic area.

Even though current literature contains plenty of anatomical studies detailing even the most hidden and tangled mean-

der of human skull base and superb dissection images and drawings are currently available, few studies demonstrated how, even in low-resource setting and without elaborate specimens preparation, good-quality dissection exploring very complex and deep skull base structures are feasible [1, 2].

2 Materials and Methods

The description of the structures in this part of the study was obtained by performing anatomical dissections only on fresh (less than 48 h post-mortem), non-formalin-fixed or injected specimens, to prevent arachnoid membranes changes and artifacts due to the formalin fixation process [14–16].

After removing the cranial vault circumferentially, leaving the brain in place, we examined the anatomy of arachnoid membranes and cranial nerves of the anterior and middle incisural spaces.

In addition, some of the photographs presented in this study were obtained “in vivo” during neurosurgical procedures involving this particular region.

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In memory of Professor Pasquale Ciappetta. Uncomparable neurosurgeon, patience master, and unforgettable friend.

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A CANON 1Ds MarkIII camera was used to take high-definition photographs, using a MacroLens 100 mm or MP-E 65 1-5X to obtain a reproduction ratio of 1:1 or more (2:1–3:1). The operating microscope (Carl Zeiss Corp., Oberkochen, Germany) was used to perform dissections and examinations.

3 Results

3.1 The Liliequist's Membrane (Figs. 1a–d, 2)

The Liliequist's membrane originates from the outer arachnoid membrane located in correspondence to the posterior clinoid processes and the dorsum sellae. As it spreads caudally and superiorly between the oculomotor nerves, it splits into two distinct membranes: the diencephalic and mesencephalic sheets. The diencephalic sheet extends upward and backward, connecting to the posterior portion of the mammillary bodies and separating the chiasmatic and the interpeduncular cistern. The lateral margin of both the mesencephalic and diencephalic sheets continues into the arachnoid membrane, surrounding the oculomotor nerves. In all the performed dissections, trabeculae originating from the superior surface of the Liliequist's membrane co-joined to the inferolateral surface of the optic chiasm and the posterior and postero-lateral surface of the pituitary stalk overlapped the basal arachnoid membrane.

3.2 Pituitary Stalk and Pituitary Stalk Cisternal Space (Figs. 1a–d, 2)

The pituitary stalk is a neural peduncle connecting the hypophysis to the floor of the third ventricle. It crosses the anterior incisural space entering the opening of the dia-

phragma sellae. The pituitary stalk is contained almost entirely within the chiasmatic cistern. A brief portion of the distal third of the pituitary stalk adjacent to the diaphragma sellae is extra-arachnoidal. In all the performed dissections, it was possible to identify the arachnoid components encircling the neural tissue of the stalk. The basal arachnoid membrane covers the stalk circumferentially and reflecting upward over its surface at the penetrating site on the diaphragma sellae.

The anterolateral surface and the posterolateral surface are also entirely and constantly encircled by trabeculae originating from the medial carotid membrane and the Liliequist's membrane, respectively. These three distinct components create a "funnel-shaped" arachnoid collar around the pituitary stalk, thus delimiting a cisternal space separated from, but at the same time contained within, the chiasmatic cistern.

3.3 Cranial Nerves (See Figs. 1, 2, 3 Part II)

Cranial nerves related to the anterior and middle incisural space are the optic nerves, oculomotor nerve, trochlear nerve, trigeminal nerve, and abducens nerve.

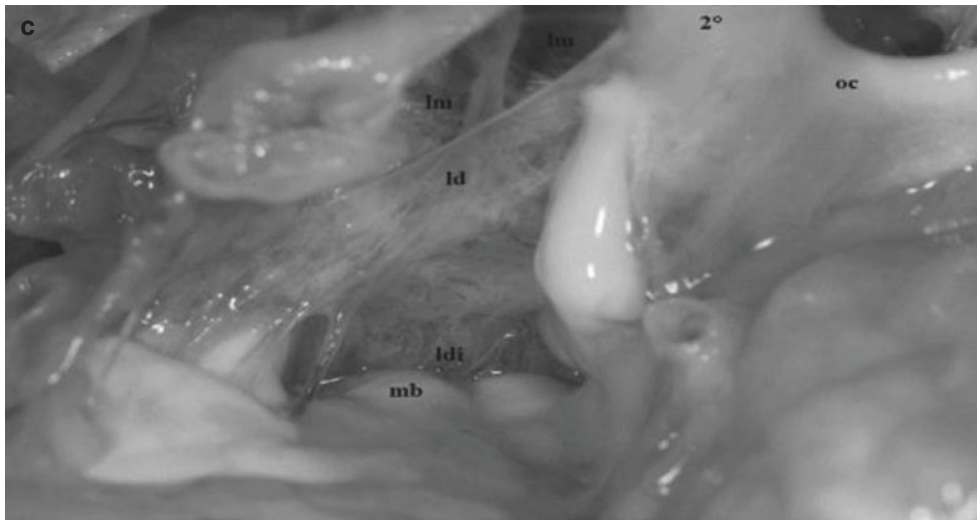
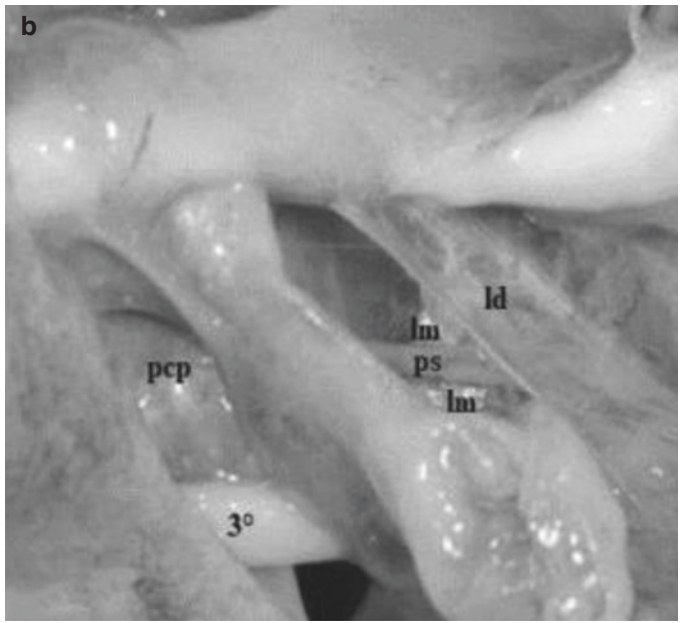
The oculomotor nerve may be subdivided into four distinct segments: cisternal, petroclinoid, trigonal, and cavernous.

The fourth cranial nerve may be divided into three distinct segments: cisternal, tentorial, and cavernous.

The trigeminal nerve originates on the anterolateral margin of the pons, and runs through the pre-pontine cistern toward the petrous apex where it lies on the trigeminal impression. Here, the dural duplication of the tentorial edge's anterior margin depicts a cavity called trigeminal porus. The trigeminal nerve, surrounded by its cistern, passes the porus entering Meckel's cave, located in the space between the periosteal and meningeal layers of the middle fossa. The

Fig. 1 a Fresh, non-formalin-fixed specimen anatomic dissection simulating a left frontotemporal trans-Sylvian approach. Some of the arachnoid membranes of the anterior space were exposed. The medial carotid membrane (mcm) origin from the inferior-medial side of the supraclinoid ICA (ica) and attaches on the inferolateral surface of the optic chiasm (oc) reflecting over the anterolateral surface of the pituitary stalk (ps). It separates the carotid from the chiasmatic cistern. Above the optic chiasm, the lamina terminalis (lt) is visible. Posteriorly and inferiorly, arachnoid trabeculae belonging to the basal arachnoid and the diencephalic portion of Liliequist's membrane are visible (a). *ot* optic tract. (b) Fresh, non-formalin-fixed specimen, anatomic dissection simulating a left frontotemporal trans-Sylvian approach, magnification. The components of Liliequist's membrane can be identified. The diencephalic portion (d) runs from the dorsum sellae to the mam-

illary bodies, whereas the mesencephalic portion (lm) extends from the dorsum sellae to the pontomesencephalic sulcus (3°, oculomotor nerve; pcp, posterior clinoid process; ps, pituitary stalk). (c) Fresh, non-formalin-fixed specimen, anatomic dissection, left side. The frontal lobe has been spatulated, and through a more frontal trajectory, the diencephalic portion of Liliequist's membrane (d) can be observed and followed until its attachment (ldi) to the mammillary bodies (mb). Below the diencephalic component, the mesencephalic portion (lm) separating the interpeduncular from the pre-pontine cistern is visible. (oc, optic chiasm; 2°, optic nerve). (d) Fresh non-formalin-fixed specimen, superolateral view, left side. The dissector has been placed below the mesencephalic portion of Liliequist's membrane to demonstrate how it separates the pre-pontine cistern from the interpeduncular one



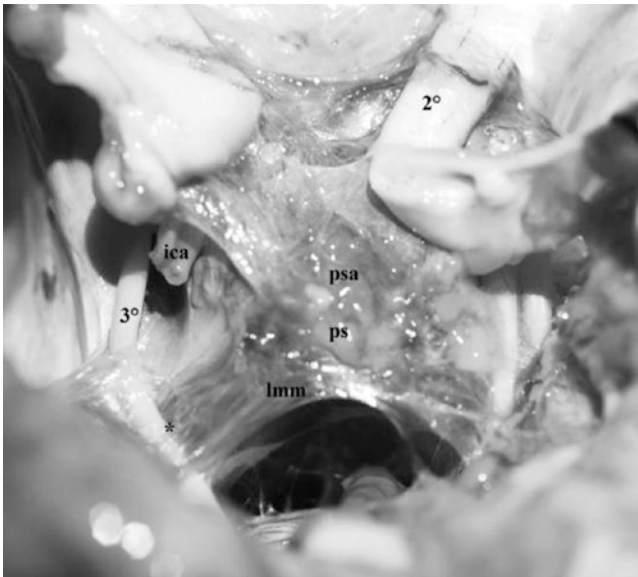


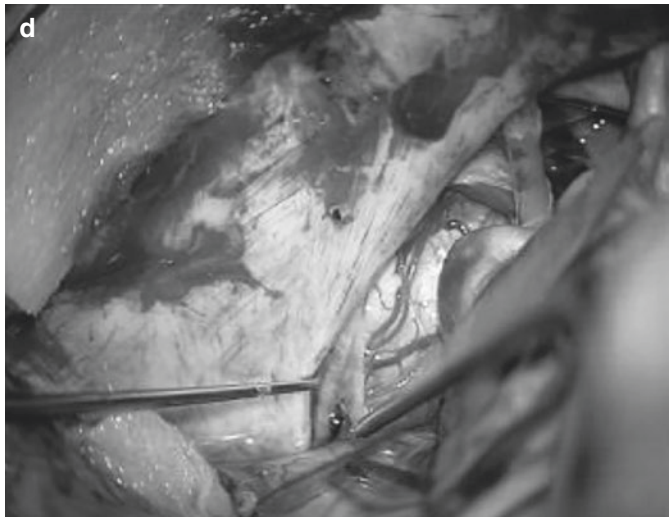
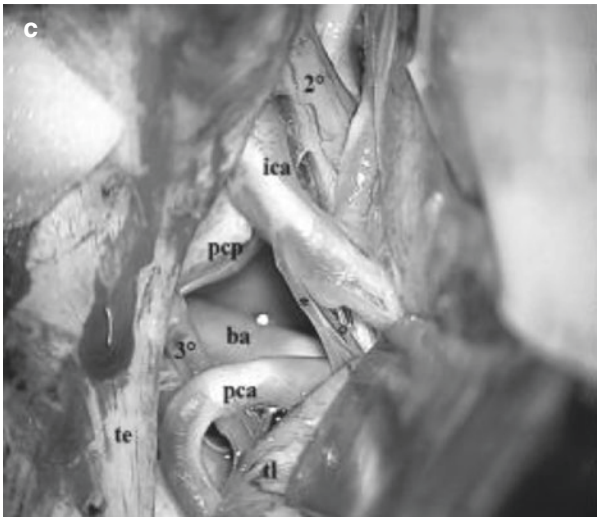
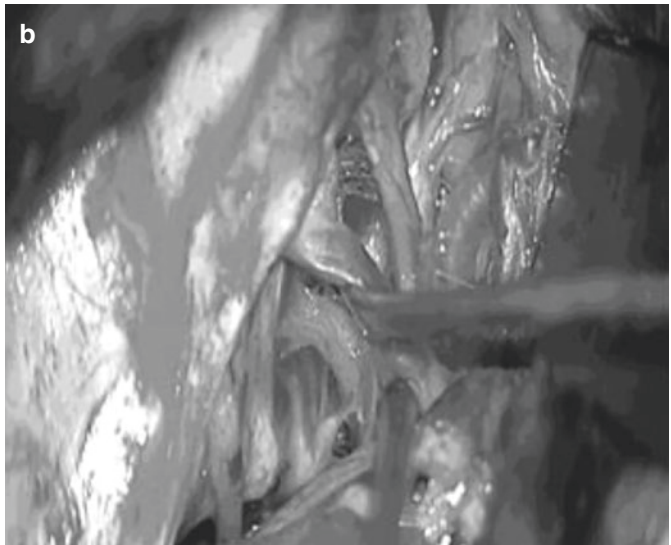
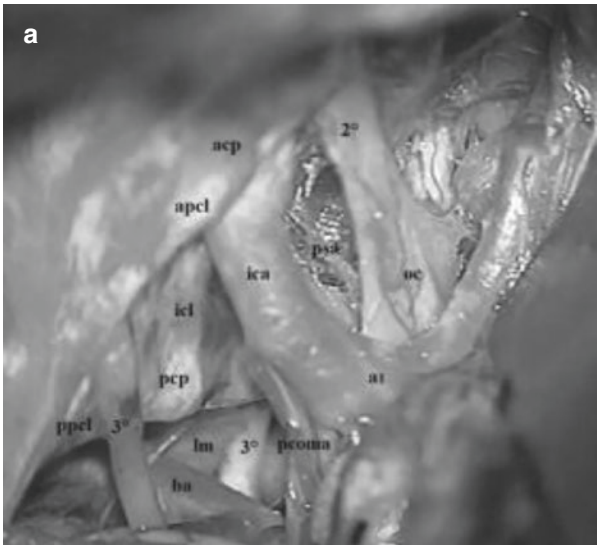
Fig. 2 Fresh, non-formalin-fixed specimen anatomic dissection, superior view. The frontal and temporal lobes were removed leaving the basal arachnoid membrane in place, and the optic chiasm was dissected. In this dissection, the anterior incisural space and the arachnoid membranes of the region can be visualized. The pituitary stalk (ps) is approximately localized in the central part of the anterior incisural space. Anteriorly, it is covered by arachnoid trabeculae (psa) originating from the medial carotid membrane and the basal arachnoid membrane of the frontal lobes. Posteriorly, the mesencephalic portion of Liliequist's membrane (lmm) runs from the dorsum sellae to the ponto-mesencephalic sulcus separating the pre-pontine incompletely from the interpeduncular cistern. Ventral trabeculae of Liliequist's membrane cover the posterior surface of the pituitary stalk completing, together with the arachnoid membrane as mentioned above, the funnel-shaped arachnoid collar delimiting the pituitary stalk cisternal space. Posterolaterally, note the accurate reflection of Liliequist's membrane over the oculomotor nerve (*)

cave hosts the Gasserian Ganglion, which is the origin of the three sensory roots of the fifth cranial nerve.

The abducens nerve ascends from the infra-tentorial part of the anterior incisural space. The nerve originates from the pontomedullary sulcus, and runs upward in the pre-pontine cistern, which represents the sole intracranial visible portion of this nerve. Then, it pierces the dura mater covering the clivus and passes below the petrosphenoid ligament to enter the cavernous sinus.

Fig. 3 Neurosurgical applications in skull base surgery. (a) Intraoperative photograph. A clinical case illustrating the pre-temporal view from the left side. A left temporal polectomy was performed for the removal of a glioblastoma cerebri. The anterior incisural space was exposed. The component of the oculomotor triangle can be clearly observed. *apcl* anterior petroclinoid ligament, *ppcl* posterior petroclinoid ligament, *icl* interclinoid ligament. In the central part of the triangle, the oculomotor nerve (3°) enters the oculomotor foramen. The oculomotor nerve can be followed posteriorly in its cisternal within the interpeduncular cistern until it reaches its origin at the brainstem below the posterior cerebral artery. On the left side, the arachnoid membranes, including Liliequist's membrane, were dissected. Conversely, on the right side, the mesencephalic portion of Liliequist's membrane attaching on the contralateral third cranial nerve (3°) can be identified. Anteriorly, on the left side, between the ICA (ica) and the optic nerve (2°), trabeculae coming from the medial carotid membrane and reflecting over the pituitary stalk can be observed (psa). *al* anterior cerebral artery, *oc* optic chiasm, *acha* anterior choroideal artery. (b) After the dissection of the arachnoid membranes of the anterior incisural space

has been completed, the ICA can be easily mobilized. In this picture, the dissector has been used to show the pituitary stalk dislocating the ICA anteromedially. (c) Another clinical case illustrating the subtemporal view from the left side. The left temporal lobe (tl) has been lifted, and the middle incisural space can be exposed. A more lateral route increases the operative view of the interpeduncular cistern. The third cranial nerve (3°) can be followed until its origin below the posterior cerebral artery (pca). Medially, both the anterior-posterior communicating artery (*) and its perforators constituting the pre-mammillary artery (°) can be identified. (te, tentorial edge; ica, ICA; pcp, posterior clinoid process; 2°, optic nerve). (d) The tentorial edge (te) has been lifted up through the use of a microsurgical hook. Below the microsurgical hook, the fourth cranial nerve running within the ambient cistern can be observed. (e) Intraoperative photograph, another clinical case. A right temporal suboccipital approach has been performed, and the tentorium has been opened. The infratentorial compartment of the middle incisural space has been exposed and the sixth cranial nerve entering the Dorello's channel can be observed



4 Discussion

4.1 Anatomic Considerations

In the third part of the study of this complex and fascinating region of the skull base, we focused our attention on the description of the anatomy of the arachnoid membranes and cranial nerves of the middle and incisural spaces. In the previous studies, we demonstrated how, even in the presence of limited resources, a detailed and clear anatomic study can be performed [1, 2]. In this last part, beyond the anatomic description, we also discuss the neurosurgical applications of this study.

The peculiarity of our study is that it was mainly performed on fresh non-formalin-fixed specimens to avoid the changes and artifacts due to the formalin fixation process [15–17].

Dissecting fresh specimens gave us the possibility to better understand and describe the anatomical relationships between the dural folds and the arachnoid membranes in this region.

Just above the distal dural ring, it was possible to appreciate the arachnoid sheets of the medial arachnoid membrane. This membrane separated the chiasmatic cistern from the carotid one and contributed to the formation of the anterolateral portion of the funnel-shaped arachnoid collar delimiting the pituitary stalk cistern [7, 14] (Figs. 1a–d, 2).

Our dissection on fresh specimens was particularly useful to explore the dorsum sellae allowing to discern the anatomy of the Lilliequist's membrane accurately, thus identifying both the mesencephalic and the diencephalic portions. To the best of our knowledge, no other studies were able to show both the components of the Lilliequist's membrane.

In particular, our research highlights that the diencephalic portion of the Lilliequist's membrane joins the mammillary bodies. We also observed that the cisternal portion of the oculomotor nerve represents the pillar attaching to the mesencephalic part of the membrane, thus separating the prepontine from the interpeduncular cistern incompletely [7, 14] (Figs. 1a–c, 2).

Furthermore, it was possible to identify the trabeculae from Lilliequist's membrane running from the dorsum sellae toward the posterior surface of the pituitary stalk, completing the arachnoid collar, and encircling the same pituitary stalk and delimiting its cisternal space [14].

In our dissections, the following structures were clearly identified: the petroclinoid ligaments running below the posterior petroclinoid ligament and forming the roof of the Dorello's canal (through which the abducens nerve penetrates the cavernous sinus) (Fig. 3, part II); the fourth cranial nerve in its cisternal and tentorial segment (Figs. 1, 2 part II); the trigeminal root passing from the prepontine cistern to Meckel's cave through the trigeminal porus at the petrous apex [3, 4, 9, 10] (Figs. 1, 2, 3 part II).

The superior dissection experience provided by fresh cadavers in our study, above all regarding cisternal anatomy, demonstrates the feasibility of establishing a neurosurgical cadaver dissection laboratory for training and research purposes even in the presence of limited resources, in a context in which sophisticated embalming techniques are not exploited.

4.2 Surgical Considerations

This study highlights the need for a detailed anatomical comprehension of this region when performing neurosurgical practice with particular regard to the surgical treatment of pathologies involving the anterior and middle skull base.

Accurate knowledge of the anterior and middle incisural spaces with the related bony, dural, arachnoidal, and neurovascular structures is crucial in neurosurgical practice. In fact, vascular and neoplastic pathologies commonly involve these anatomical areas, making them frequently exposed during surgical procedures using pterional, pre-temporal, and sub-temporal approaches [7, 10–14, 17] (Fig. 3a–e). Although the above-mentioned anatomic structures contribute to maintaining the anatomical relationships between the neurovascular components of these regions, at the same time, their presence may impair the surgical exposure by occluding a complete view of the same neurovascular elements [3–10]. As a consequence, the partial or complete removal of these osteo-dural structures is required to expand the operative corridors, allowing a proper surgical procedure [6, 11–14, 17].

For example, intradural or extradural removal of the anterior clinoid process is commonly performed in neurosurgical practice [6, 12, 17]. This allows exposing the clinoidal segment of the ICA ensuring the “proximal control” in the management of paraclinoidal aneurysms arising within the carotid cave, as well as hypophyseal and carotid-ophthalmic aneurysms [6, 12, 17].

The removal of the anterior clinoid process allows unroofing the optic canal to remove tumors spreading within the canal, such as meningiomas and craniopharyngiomas [6, 12, 14, 17].

Regarding craniopharyngiomas, accurate knowledge of the arachnoid membranes around the pituitary stalk is crucial during surgical removal. A strong relationship exists between the tumor, the basal arachnoid membrane, and the trabecular components of the medial carotid and Lilliequist's membrane attaching over the pituitary stalk. As a result, it may jeopardize the search on a plane of dissections between the tumor, the pituitary stalk, the optic-chiasm structures, and the arterial components of the region [14].

After a proper anterior clinoidectomy, more surgical space may be obtained by the incision of the dura mater of the distal dural ring and by opening of the carotid oculomo-

tor membrane. It must be completed by a meticulous dissection of the arachnoid adhesions of the region [6].

These maneuvers are particularly relevant if a pre-temporal approach is requested, since they allow an extensive exposure of the oculomotor nerve from the trigonal to the cisternal portion, widely exposing the interpeduncular cistern [6, 12] (Fig. 3a, b).

For these reasons, a well performed pre-temporal approach accompanied by extensive mobilization of dural and arachnoid membranes should be reasonably considered as the main surgical option for the management of aneurysms placed at the high basilar bifurcation level, as well as other pathologies located in the upper and ventral brainstem [6, 12, 17].

Moreover, a posterior clinoidectomy with occlusion of the posterior communicating artery at the P1–P2 junction makes the pre-temporal approach a valid second option to the subtemporal route for aneurysms in low lying basilar bifurcation [6, 12, 17].

The subtemporal approach is mainly performed to expose the middle incisural space [13, 17] (Fig. 3c, d). Using this approach, the ambiens and the interpeduncular cisterns may be widely exposed [13, 17].

In neurosurgical practice, this approach is used primarily for the management of low lying basilar bifurcation aneurysms, meningiomas of the free margin of the tentorium, and other lesions involving the lateral portion of the mesencephalon and the upper lateral pons at the trigeminal root origin. Using this approach, the possibility to make an incision on the tentorial edge after visualization of the entrance of the fourth cranial nerve, together with the dissection of Liliequist's membrane, allows enlarging the surgical view exposing both the supratentorial and infratentorial portions of the upper brainstem [13, 17] (Fig. 3c–e).

5 Conclusions

1. A systematic approach based on the stepwise analysis of the dural, bony, and neurovascular structures, by dissections performed on fresh specimens, including arachnoid membranes and cisterns, provides neurosurgeons the necessary neuroanatomical understanding required to successfully manage the numerous pathologies involving the anterior and middle incisural spaces.
2. Detailed anatomical knowledge of these regions finds actual applications in neurosurgical practice since the anterior and middle incisural spaces are often surgically exposed to the high prevalence of neoplasms and vascular events. The high-definition pictures reported in this study could represent useful support to understand the anatomy of this complex region.

3. Finally, our study could provide guidance to neurosurgical centers in which resources are limited that are either planning to establish their own cadaver dissection laboratory or failed to do so because of the supposed high-costs.

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