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CLINICAL ARTICLE

Microsurgical anatomy of Liliequist's membrane demonstrating three-dimensional configuration

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Abstract
Object Liliequist's membrane (LM) is an important arachnoid structure in the basal cisterns. The relevant anatomic descriptions of this membrane and how many leaves it has are still controversial. The existing anatomical theories do not satisfy the needs of minimally invasive neurosurgery. We aimed to establish the three-dimensional configuration of LM.
Methods Fifteen adult formalin-fixed cadaver heads were dissected under a surgical microscope to carefully observe the arachnoid mater in the suprasellar and post-sellar areas and to investigate the arachnoid structure and its surrounding attachments.
Results It was found that the LM actually consists of three types of membranes. The diencephalic membrane (DM) was usually attached by the mesencephalic membrane (MM) from underneath, and above DM it was usually a pair of hypothalamic membranes (HMs) extending superomedially. The pair of HMs was stretched between the DM (or MM) and the hypothalamus and were seldom attached to the carotid–chiasmatic walls between the carotid cistern and the chiasmatic cistern. These three types of membranes (DM, MM, and HM) comprised the main arachnoid structure in the anterior incisural space and often presented as four connected leaves. However, only two thirds of the specimens had all three types of membranes, and there was considerable variation in the characteristics and shapes of the membranes among the specimens.
Conclusion All three types of membranes comprising LM serve as important anatomical landmarks and interfaces for surgical procedures in this area.

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Introduction

Liliequist's membrane (LM), part of the arachnoid mater in the basal cistern, is an important anatomic structure for surgical approaches to the post-sellar area. It was first described by Key and Retzius in 1875 [13]. In 1950s, Liliequist performed pneumoencephalographic studies on cadavers and found a curtain-like membrane extending from the anterior edge of the mammillary bodies to the superior border of the dorsum sellae and arching forward between the oculomotor nerves on both sides. The air bubbles of pneumoencephalography approached the interpeduncular cistern first and then gradually filled the chiasmatic cistern [2, 5, 14]. Consequently, the membrane was named after Liliequist. Notably, several recent anatomic studies on the neuroendoscopic management of hydrocephalus indicated that if the solid LM was not opened, it would block the outflow of cerebrospinal fluid from the third ventricle in neuroendoscopic ventriculostomy, leading to the failure of treatment [3, 5, 12].

However, there are different and even controversial descriptions about LM regarding its morphology, orientation, attachment, classification, and relationship with the surrounding structures. Froelich et al. [4] reported that LM consists of one membrane or two leaves, whereas Lü et al. [7] who examined eight adult cadaveric brains found that LM has more than one leaf. In 1988, Matsuno et al. [9] found that LM was orientated from the outer layer of arachnoid mater that covered the dorsum sellae, extending upward from the space between both sides of the oculomotor nerves. In the meantime, it was separated into two layers; one was the diencephalic membrane (DM) and the other was the mesencephalic membrane (MM). The DM, which was only first considered as LM in 1988, extended upwards and was attached at the posterior edge of the mammillary bodies of the mesencephalon. The MM extended to the rear and was attached at the junction of the midbrain and the pons. Nonetheless, some researchers disagreed with such a description of the DM and MM [1–3, 14]. In 2001, Vinas and Panigrahi [12] marked LM and MM several times in the figures of their paper, apparently regarding them as two different structures. However, with careful observation, it can be found that the MM they marked was a pair of arachnoid membranes located at the anterolateral side of the pons. It was exactly the same as "the anterior pontine membrane" described by Matsuno et al. [9], suggesting an inconsistency in the naming of LM. Fushimi et al. [5] used three-dimensional Fourier transformation constructive interference in steady-state MRI for the first time to study LM and divided LM into three parts, namely, the sellar, diencephalic, and mesencephalic segments, which was consistent with Matsuno's naming system. Other authors have also cited the DM and MM for these two structures [6]. On the other hand, several authors have mentioned the medial carotid membrane or the carotid–chiasmatic arachnoid in the relevant description [2, 9, 14] and concluded that this arachnoid structure was closely related with LM but did not belong to any part of LM.

Several basic questions concerning LM remain unclear now: How many leaves does LM include? What kind of three-dimensional structure does it have? What is the relationship between the carotid–chiasmatic walls and LM? Such knowledge, if applicable, should provide valuable insights into how to efficiently guide the microsurgical treatment and neuro-endoscopic management behind the sella turcica. Therefore, we aimed to study the morphologic structure of LM under a microscope in cadaveric heads in order to understand its morphological variation and three-dimensional characteristics. In addition, we also attempted to identify the surrounding attachments of LM.

Material and methods

This study included a total of 15 preserved adult heads from Han Chinese from Southeast China. The specimens were from 13 men and two women with an average age of 40 years (range 20–65 years). In all instances, the specimens were obtained through donation, and the use of the specimens was approved by the ethics committee of Fuzhou General Hospital. Fixation of the specimens was carried out from approximately 3 to 8 years after death. For fixation, common carotid artery intubation was carried out and 10% formalin was used for the infusion. After the infusion was deemed satisfactory, the specimens were immersed in 5% formalin and preserved. They were removed after 1 month, and latex (natural latex that was diluted with ammonia and red paint was added) was infused via the common carotid artery. With this method, red latex hypoperfusion can lead to poor display of small arteries, although such arteries can still be identified by careful examination under an operating microscope. Intravenous infusion was not carried out, and therefore the veins were not well displayed. After being infused, the specimens were kept preserved in formalin.

The procedure to study Liliequist's membrane was performed as follows: the front skull was sawed and then the dura mater was cut. The head was placed in the supine position, and the brain tissue was carefully removed under a microscope. The approach used was to resect the tissue block by block and piece by piece (similar to the approach used in intracapsular excision performed by neurosurgeons), trying to minimize the stretching of surrounding structures. Although the entire brain is brittle, even if the surrounding brain tissue is stretched a little, it will not have an obvious effect because the arachnoid of the sellar area is not that fragile. Special attention was taken to protect the areas that were being studied. While progressing toward the structures of interest, pieces of brain tissue were carefully removed to avoid damaging the pia mater, arachnoid, and blood vessels in the subarachnoid space connecting with the arachnoid. Care was taken not to apply obvious external force on the arachnoid structure under the microscope in order to study and observe the natural three-dimensional aspects of this fragile structure. Caution was taken at all times when observing the fine structures such as the sylvian cistern, the lamina terminal cistern, and chiasmatic cistern. Specific attention was paid when the superior area and the back of the sella turcica were approached in order to identify and retain the shape of the subarachnoid cistern, the pia mater, and the arachnoid on the top, front, back, and side, thereby observing the framework structure of the subarachnoid cistern. Because the specimens were fixed properly, the arachnoid structure could not obviously be changed without any direct mechanical pulling. Therefore, the natural three-dimensional shape and internal structure of the subarachnoid cistern can be observed. Under a microscope, the surrounding pia mater and the arachnoid mater were opened and the subarachnoid cistern was approached, which allowed the entire arachnoid structure to be gradually identified and measured (using a micrometer, precision 0.2 mm). The relationship of the arachnoid mater to the cerebral blood vessels and cranial nerves was observed as was the relationship of the divisions of subarachnoid cistern to the cerebral blood vessels and cranial nerves. The structural type, attachments, connection, and characteristics of biomechanical properties of different arachnoid structures were studied. Based on the work of Liliequist and Matsuno et al. [2, 9, 13], the relevant arachnoid structures were carefully observed and measured and compared with the results in the literature to establish the three-dimensional concept of LM.

Results

We found that typically LM consisted of three membranes: the DM, LM, and HM. The DM was usually attached by the MM from underneath and a pair of other membranes on the top, which extended superomedially and usually did not connect to the carotid–chiasmatic walls. We called these pair of membranes the HMs in this study. These three membranes were the main arachnoid structures in the anterior incisural space and were named according to their distal attachments. However, among the specimens, only two thirds had these three membranes at the same time, varying greatly in their characteristics (Table 1).

Diencephalic membrane

The DM was a piece of arachnoid extending in the anterior incisural space. In this study, it was only found in 11 of 15 specimens, and in two cases (no. 3 and no. 5), there was a high degree of dysplasia, with the structure only presenting as a small piece of net-like membrane or strips (Fig. 1). The DM in the other nine cases was described as follows (Figs. 2 and 3): The DM was roughly trapezoid in shape with a wide inferoanterior edge and narrow superoposterior edge, attached to the oculomotor nerve on both sides. In two cases, the DM was almost nonporous or only had few holes, appearing as a typical thin membrane. In other cases, the DM was net-like with differently sized holes, and in one case a large hole dominated half of the DM (Fig. 2). The trabecular directions in the DM were variable and mostly left–right with regard to direction in most areas in the center and anteroposterior with regard to direction at the anterior and posterior edges. In all cases, the DM tilted superoposteriorly, forming an average angle of 39.4° (20–70°) against the plane outlined along the upper edges of the dorsum sellae and the limbus sphenoidalis. The average distance between the inferoanterior edge and superoposterior edge was 10.8 mm (5.0–13.0 mm). The average width of the inferoanterior edge was 19.9 mm (10.0–28 mm). It was attached to the superoanterior edge, top, and superoposterior edge of the dorsum sellae and the back of the posterior clinoid in seven cases and attached at 1 and 4 mm below the top of the dorsum sellae in two cases, respectively. The average width of the superoposterior edge was 9.5 mm (5.0–14.0 mm). It was attached to the anterior edge of the tuber cinereum in one case, the middle part of the tuber cinereum in one case, the posterior surface of the tuber cinereum in three cases, the anterior or inferoanterior edge of the mammillary bodies in three cases, and the inferior edge of the mammillary bodies in three cases. There were many fibrous trabeculae connected with the posterior cerebral artery and the small arteries in the interpeduncular fossa and, in two specimens, the branches from the posterior communicating artery.

The lateral edge of the DM directly attached to the medial side of the oculomotor nerve in all cases, roughly continuing with the inferior wall of the oculomotor nerve sheath until it was attached to the arachnoid mater below the tentorium notch by the left–right collagen fibers of the inferior wall of the oculomotor nerve sheath. In most cases, there was a connection between the DM and the superior wall of the oculomotor nerve sheath, while this wall did not constitute a source of traction on the DM. Most DM structures only connected with the anterior one third of the oculomotor nerve because the posterior part of the DM was no longer a membrane-like structure but consisted of scattered fibrous trabeculae. The part of the DM between the posterior attaching point of the oculomotor nerve and the attaching point of the diencephalon was a free segment, which formed a cuff around the posterior cerebral artery. In four sides, some fibrous trabeculae arose from the lateral part of the DM and attached to the branches of the posterior communicating artery. In two sides, the main trunk of posterior communicating artery passed through the lateral part of the DM. In case no. 13, a small branch of the basilar artery passed through the middle of the DM with a diameter of 0.2 mm running upwards and then running backwards above DM into the mammillary bodies (Fig. 3).

The DM was often connected with its surrounding structures by some trabeculae or net-like membranes. In six specimens, a sagittal net-like membrane or a row of parallel fibrous trabeculae arose from the anterior middle part of the DM and connected with the infundibulum and median eminence area. In one specimen, several fibrous trabeculae arose from the middle part of the DM and extended to the HM. In another specimen, a row of coronary fibrous trabeculae arose from the anterior edge of the DM to the median eminence area. In another case, several thin and long trabeculae were attached to the anterior surface of the pons.

Table 1 The structure and characteristics of Liliequist's membrane in 15 specimens

Number	Characteristics of DM	MM		HM	
		anterior attachment	Shape	Left side	Right side
1	Membranous, nonporous	DM	Triangle, loose net-like	Triangle, membrane-like	Triangle, membrane-like
2	Membranous, nonporous	DM	Triangle, fibrous trabeculae in left–right direction	Thin net-like	Thin net-like
3	The left half was loose net-like and the right half was absent	DM	Several fibrous trabeculae	Absent	Absent
4	Absent	Dorsum sellae	Membrane-like with several small holes	Net-like with relatively big holes	Absent
5	Most part was absent	Oculomotor nerve, tuber cinereum	Net-like	Absent	Loose net-like
6	Absent	Dorsum sellae	Membrane-like with several big holes	Trapezium, net-like	Trapezium, net-like
7	Membranous with several small holes	Free edge without attachment	Small pieces, net-like	Incomplete, net-like	Incomplete, net-like
8	Net-like	DM	Loose net-like	Trapezium, net-like	Trapezium, net-like
9	Mixture with net and membrane with multiple holes and windows	DM	Net-like, trapezium	Triangle, net-like	Triangle, net-like
10	Membranous with big holes	DM	Net-like with several small holes	Membrane-like with several small holes	Triangle, net-like with relatively big holes
11	Membranous with several small holes	DM	Loose net-like	Net-like with relatively big holes	Incomplete, net-like
12	Anterior part with small holes and posterior part was membrane-like	DM	Loose net-like	Absent	Loose net-like
13	Net-like with a small artery passing through the central part	DM	Net-like with fibrous trabeculae in left–right direction	Absent	Net-like
14	Absent	Bilateral HM	Net-like	Membrane-like with small holes	Membrane-like with small holes
15	Absent	Dorsum sellae	Net-like with fibrous trabeculae in left–right direction	Triangle, net-like with relatively big holes	Triangle, net-like with relatively big holes

MM mesencephalic membrane, *DM* diencephalic membrane, *HM* hypothalamic membrane

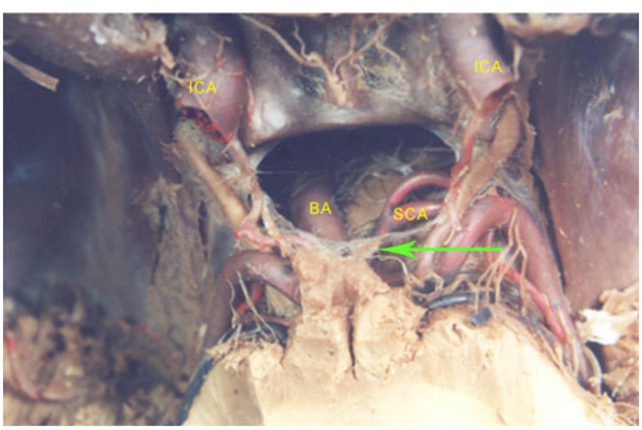

Fig. 1 In case no. 5, the top view after removal of the hypothalamus shows extremely underdeveloped meninges; a piece of arachnoid (*arrow*) under the tuber cinereum extended in the coronal section and its inferior part attached to the basilar artery bifurcation. *ICA* internal carotid artery, *BA* basilar artery, *SCA* superior cerebellar artery

Mesencephalic membrane

The MM was so named because its posterior edge is attached to the junction of the midbrain and the pons. In this study, the MM was seen in all 15 specimens. It originated from the superior edge of the dorsum sellae (Fig. 4) or from beneath the DM (Figs. 3, 5, and 6), extending posteriorly or inferoposteriorly backwards and attaching to the superior segment of the basilar artery and the anterior surface of its branches. It did not change into a cuff-like shape at the level of the basilar artery. Its posterior attachment was 2.5 mm (0–5.0 mm) above the junction of the midbrain and the pons with an average width of 8.3 mm (2.5–14.0 mm), and there was an average distance of 4.8 mm (2.5–10.8 mm) between the anterior and the posterior attachment. The MM was on the same plane as the limbus sphenoidalis–dorsum sellae in one specimen, tilted superoposteriorly to form an angle of 10–70° in six specimens and tilted inferoposteriorly to form an angle of 20–70° in eight specimens.

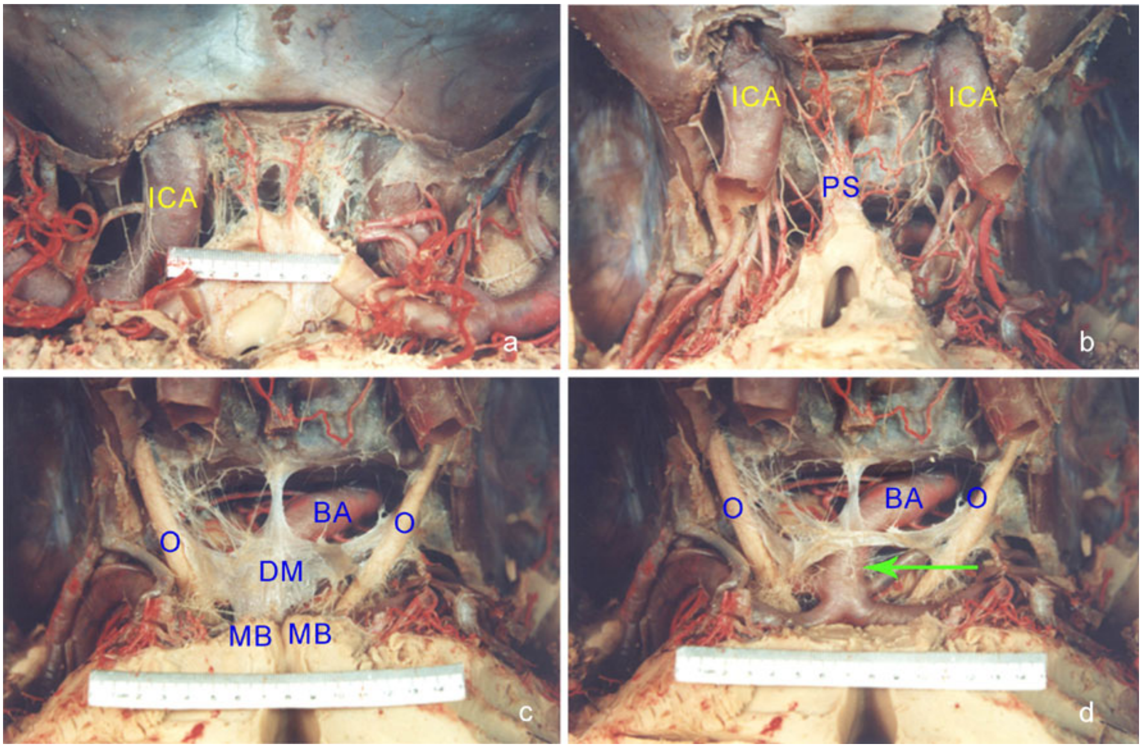

Fig. 2 The upper view of the chiasmatic cistern and Liliequist's membrane. **a** The bilateral optic nerves have been removed superiorly to expose the network of arachnoid trabeculae in the chiasmatic cistern. **b** The network has been removed to expose the small arteries in the chiasmatic cistern. **c** The diencephalic membrane is found scattered with relatively large windows. **d** The diencephalic membrane is lifted to expose the mesencephalic membrane (*arrow*) below it. *ICA* internal carotid artery, *PS* pituitary stalk, *O* oculomotor nerve, *BA* basilar artery, *MB* mammillary body, *DM* diencephalic membrane

In most cases, the MM was a trapezoid in shape and in a few cases it was a triangle. In three specimens, the anterior edge of the MM attached directly to the dorsum sellae (Fig. 4). This edge was as long as 21.0–26.0 mm, which is similar to that of the DM, and looked like a fishing net. In one of the specimens, several fibrous trabeculae arose from the MM and extended to the superior segment of the basilar artery. In the other 12 specimens, the anterior edge of the MM was not connected to the dorsum sellae (Figs. 2 and 3). It looked like a scattered net, in which the fibrous trabeculae ran in a left–right direction or gathered towards the basilar artery. Among these 12 specimens, the anterior edge of the MM in seven cases originated from the middle part of the DM, and the width of its attaching edge was 12.6 mm on average (3.0–22.0 mm); the anterior upper edge of the MM in three cases originated from the superoposterior edge of the DM; the anterior edge of the MM in one specimen originated from the inferior part of the bilateral HM; the anterior edge of the MM in another case was free.

Other surrounding structures: In three specimens, the anterior edge of the MM was attached to the dorsum sellae and the lateral edge of the MM continued with the superior and inferior walls of the oculomotor nerve sheath. In the other specimens, five lateral edges were attached to the oculomotor nerve sheaths, three lateral edges were attached to the posterior cerebral arteries or the superior cerebellar arteries, and the other lateral edges were free. In two specimens, a small net-like membrane arose from the anterior median area of the MM attaching to the pituitary stalk. In other specimens, one lateral side was connected with the trunk of the posterior communicating artery and the optic tract by some fibrous trabeculae; and one lateral side of another case was connected with the branches of posterior communicating artery. In the other two specimens, several fibrous trabeculae arose and extended backwards to connect with the small vascular branches in the interpeduncular fossa.

Hypothalamic membranes

The HM was found in 14 specimens in this study. This membrane extended upwards from the oculomotor nerve and/or the lateral part of the DM (or MM) to attach to the lateral edge of the hypothalamus (Figs. 3, 4, and 6). It consisted of two leaves: a left one and a right one. The distance between the upper attaching edges was 2–8 mm. In most specimens, the HMs tilted medially upwards to form an angle of 30–45° against the limbus sphenoidalis–dorsum sellae plane. In a few specimens, the HMs were in a sagittal

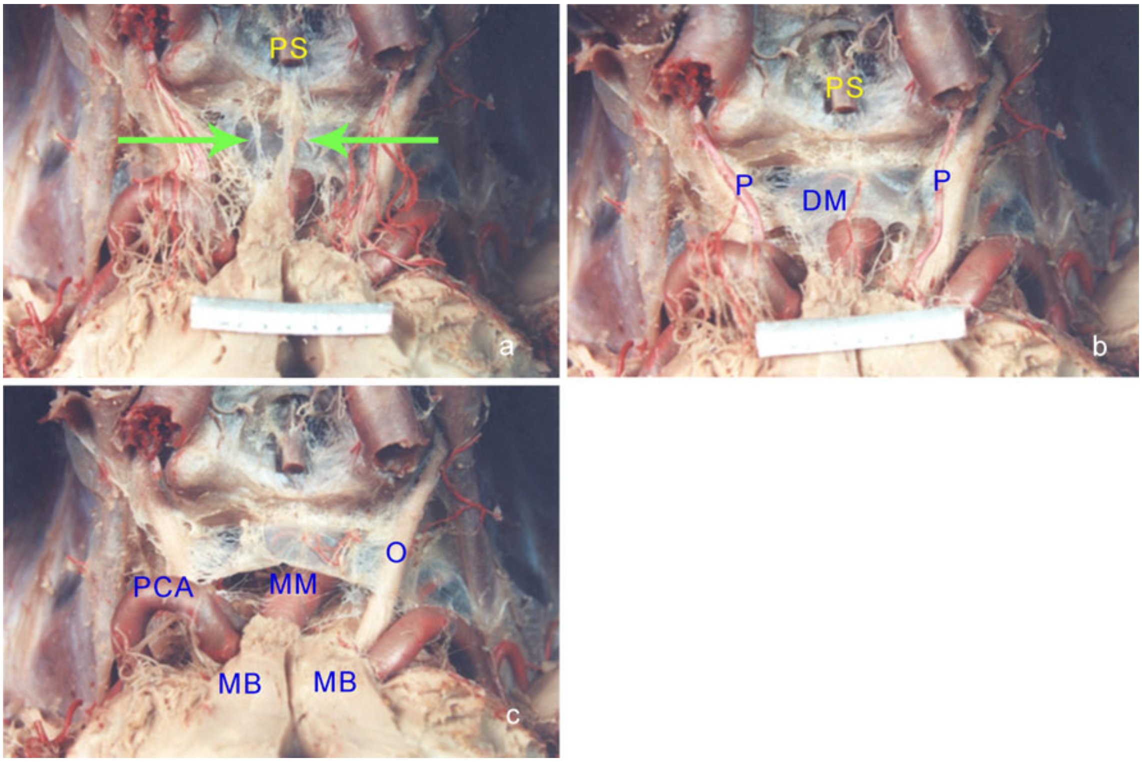

Fig. 3 The hypothalamic membrane, diencephalic membrane, and mesencephalic membrane of Liliequist's membrane. **a** The bilateral hypothalamic membranes (*arrow*) are found scattered with openings or windows. **b** The hypothalamic membranes have been removed to expose the diencephalic membrane, through which pass a small branch of the basilar artery. The small branch enters the mammillary body. **c** The diencephalic membrane is lifted to expose the loose mesencephalic membrane below it. *PS* pituitary stalk, *P* posterior communicating artery, *DM* diencephalic membrane, *MM* mesencephalic membrane, *PCA* posterior cerebral artery, *MB* mammillary body, *O* oculomotor nerve

or near-sagittal position. Most HMs looked like a fishing net, which was thinner than the DM, with few different sizes of scattered windows or holes (Figs. 3 and 4). Only a few HMs developed well into membrane-like or complete net-like shapes. In two specimens without a DM, the HMs developed so well that they seemed to replace the DM.

The HMs appeared as a quadrangle or a triangle. The attaching point of its inferolateral edge could be a line, a curve, or an area. In 30 sides of the 15 specimens, only 24 leaves of HMs were found. Fifteen leaves of the HMs were attached to the superomedial or inferomedial edge of the oculomotor nerve, one was attached to the superior wall of

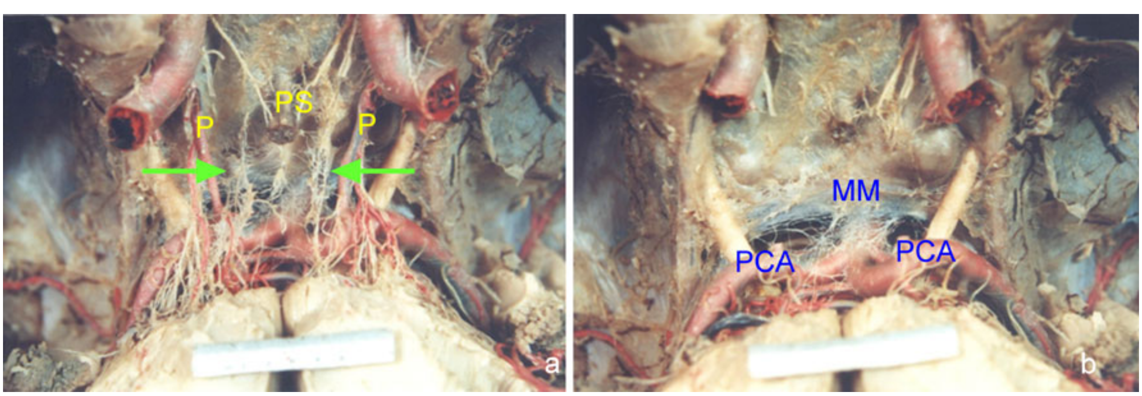

Fig. 4 The hypothalamic membrane and the mesencephalic membrane of Liliequist's membrane. **a** The bilateral hypothalamic membranes (*arrow*) are exposed superiorly and found to present as a net-like shape. **b** The bilateral hypothalamic membranes have been removed to expose the mesencephalic membrane below it. The diencephalic membrane is absent in this specimen. *PS* pituitary stalk, *P* posterior communicating artery, *MM* mesencephalic membrane, *PCA* posterior cerebral artery

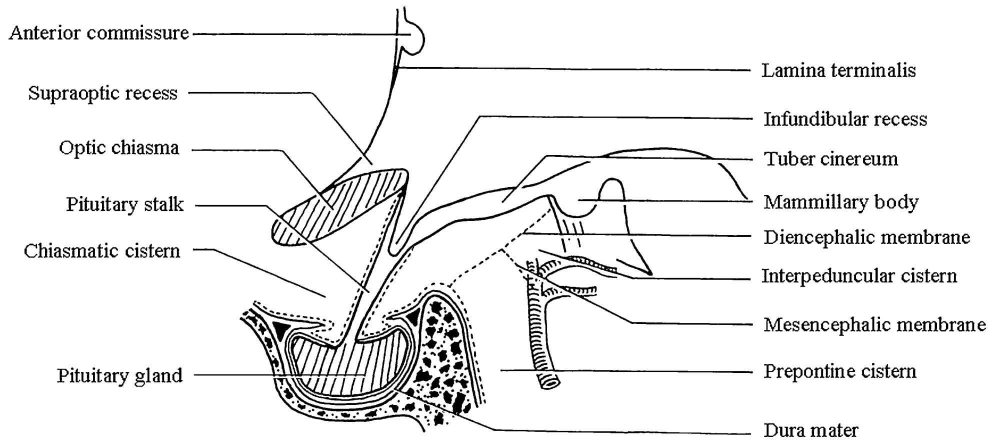

Fig. 5 Side view of Liliequist's membrane

the oculomotor nerve sheath, five were attached to the lateral part of the DM, and four were attached to the lateral part of the MM (DM was absent in these specimens). The inferoanterior part of five leaves was connected with the arachnoid membrane that covered the diaphragma sellae, the dorsum sellae, or the superior wall of the cavernous sinus by some fibrous trabeculae. Four leaves extended laterally above the oculomotor nerve attaching to the temporal lobe; the attaching line was 1.5–8 mm.

The superomedial attaching line of the HMs extended in the anterior–posterior direction, 6–20 mm in length (about 10 mm in most cases). Eighteen leaves of HMs were attached to the inferolateral surface or the lateral edge of the tuber cinereum. Twelve leaves were attached to the lateral edge of the median eminence area or the side of the infundibulum. Nine leaves were attached to the paramedian area below the optic chiasm/tract and four of them also extended backwards to attach to the inferolateral surface of the mammillary bodies.

The anterior edge of eight leaves of HMs was completely free; one leaf continued with the carotid–chiasmatic walls; three leaves were connected with the fibrous trabecular network in the chiasmatic cistern; ten leaves were attached to the posterior clinoid process or the dorsum sellae; and three leaves were attached to the anterior edge of the DM or MM.

The posterior edges of 12 leaves of HMs were completely free, surrounding the posterior cerebral artery in a cuff-like shape; several fibrous trabeculae arose from the posterior edge of eight leaves of HMs to connect with the tuber cinereum, the mammillary bodies, or the cerebral peduncle; the fibrous trabeculae arose from four leaves and connected with the posterior cerebral artery or its branches. The posterior edge of 17 leaves was adhered in multiple places to the posterior communicating artery or its branches, and the branches of the posterior communicating artery passed through half of the posterior HMs to supply blood to the tuber cinereum and the mammillary bodies.

The carotid–chiasmatic walls

The carotid–chiasmatic walls were seen in all the 15 specimens. They looked like arachnoid structures that separated the carotid cistern from the chiasmatic cistern (Fig. 2). The inferior attachment of the walls was the arachnoid mater that covered the diaphragma sellae. The superior attachment included the optic nerve, chiasm, and tract. The carotid–chiasmatic walls were not single-layer

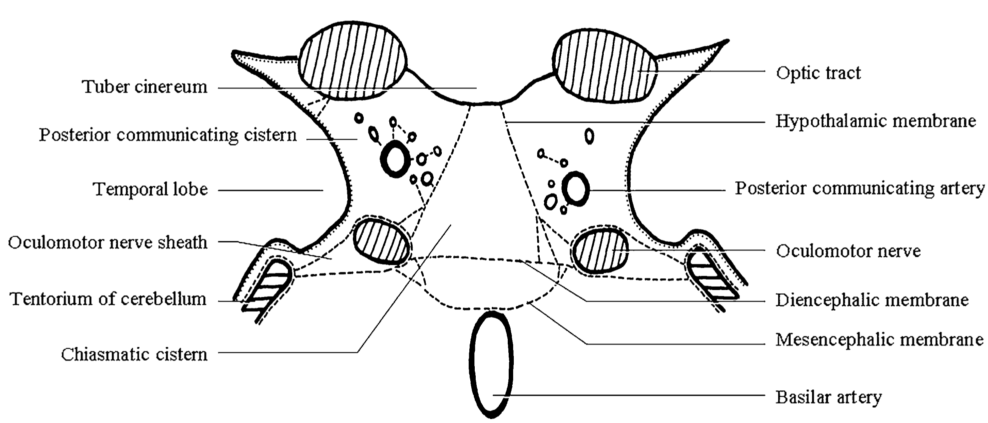

Fig. 6 The coronary cross-sectional view of Liliequist's membrane

membrane structures but a three-dimensional network interwoven by a group of fibrous trabeculae. Most were irregular, and some were incomplete and not sagittal. They only served as symbolic intercistern separating structures. Some fibrous trabeculae arose from the walls to connect with the fibrous trabecular network in the chiasmatic cistern or with the internal carotid artery.

Discussion

We found that LM consists of three membranes, the DM, MM, and HM. However, only two thirds of the specimens in our study had all three membranes, indicating that the presentation of LM is variable. We also established the three-dimensional structure of LM. In doing so, we helped clarify the relationship between the HM and the carotid–chiasmatic wall which has been a source of confusion.

Notably, although the name diencephalic membrane suggests that this arachnoid structure in the subarachnoid space is a tight layer of membrane, in fact, all the arachnoid structures in the subarachnoid space are arachnoid trabecular structures (strip-like) and essentially consist of “ropes” stretching across most of the adjacent structures. Hence, some are membrane-like (although they may have orifices or be incomplete) whereas some are really not a membrane at all but rather consist of only a few trabeculae. However, from a functional perspective, they are all the same and they have consistent structure and function. It should also be noted that the appearance of the DM as net-like or with having a hole was not due to artifact related to the methods of dissection. There are obvious differences between artificial and natural defects found in this type of dissection. The hallmarks of artificial defects are irregular broken edges and broken fibers. In contrast, defects from natural causes are sleek and more regular in character. When a large orifice or window occurs naturally, the appearance is a sleek orifice or window surrounded by a fibrous ring with no evidence of rupture. In this study, all the observations were consistent with natural defects and not with artifacts associated with the procedure. Another point to be noted is that the lateral attachment of the DM was mainly to the oculomotor nerve and the cerebellar tentorial incisura. The cerebellar tentorial incisura might therefore be a reliable lateral adherent point and serve as the “backbone” with regards to the mechanics. With regards to the anatomical relationships between the DM and the tuber cinereum and mammillary bodies that we observed, these relationships were to some extent not in agreement with those of previous reports. However, variation of these anatomical relationships is normal and there are some uncertainties in the arachnoid structure and their variation is great.

Relationship between the hypothalamic membrane and the carotid–chiasmatic wall

Many researchers have described “the medial carotid membrane” and “the carotid–chiasmatic walls,” which basically include the HM and the carotid–chiasmatic walls which we have mentioned in our study. Matsuno et al. [9] described the medial carotid membrane as a structure that “separates the chiasmatic and carotid cisterns.” In a study by Brasil and Schneider [2], in five of seven specimens, a pair of carotid–chiasmatic walls in the sagittal position was found that separated the subarachnoid cistern in front of the DM into three parts: the right carotid cistern, the chiasmatic cistern, and the left carotid cistern. Vinas and Panigrahi [12] provided a set of anatomic figures for the sellae area and described the structures of arachnoid mater with various terms, including “the posterior communicating membrane” that “arises laterally from Liliequist’s membrane and surrounds the posterior communicating artery.” However, this membrane looks very similar to the HM in one of their figures.

Zhang and Po-Chung [14] considered the DM as LM and found that the anterior LM was connected with a pair of carotid–chiasmatic walls, which “consisted mainly of accumulated arachnoid trabeculae; they were present in all of the specimens we examined. The orientation of each trabecula is irregular, but in general, these trabeculae connect the anterior surface of Liliequist’s membrane to the pia mater covering the surface of the optic chiasm.” However, a careful examination of the figures in the paper reveals that “the carotid–chiasmatic walls” must be part of the HM.

The HM in this study as well as “the medial carotid membrane” and “the carotid–chiasmatic walls” described by other authors are actually the arachnoid mater of the paramedian area in the central part of the intracranialis that presents in the sagittal position. However, we found that the carotid–chiasmatic walls are structures in the suprasellar area while the HM is a structure in the posterior sellar area. The two structures were found to be continuous into each other only in a few specimens and their attachments above and below appeared different in structure. The HM appeared more frequently than the carotid–chiasmatic walls. That is why we designated the HM as an independent structure in this study. The HM is thinner than the DM. Liliequist did not describe the MM. It was found later that some of the MM connects with the DM, and therefore the MM was considered part of LM. In this report, the DM, MM, and HM were considered as a whole with regard to the mechanical structure of the suprasellar and posterior sellar regions, and all three have variations. However, they complement each other in development and function, and therefore we considered these three membranes to comprise LM. Further study is needed to provide stronger evidence.

The separation of the subarachnoid cistern by LM

We found that the posterior communicating cistern was located superolaterally to the bilateral HM. The posterior segment of the chiasmatic cistern was located between the HM and DM. If HMs are directly connected to MM, the chiasmatic cistern and interpeduncular cistern merge into one cistern. This does not mean that there is no cistern at the interpeduncular fossa. A space filled with cerebrospinal fluid is still present. At least in imaging, there is still an “interpeduncular cistern.” Therefore, we have called the area between the HM and MM the interpeduncular cistern. The space between the diencephalic part of the DM and MM below is also the interpeduncular cistern, in which the MM attached to the bottom of the DM forms the anterior wall of the interpeduncular cistern. The sellar segment of the DM, the anterior part of the MM, and the posterior part of the superior clivus constitute a cistern, which is anterior–inferior to the interpeduncular cistern and was called as the post-dorsum cistern in this study. There is no arachnoid mater separating the post-dorsum cistern from the prepontine cistern. When the DM is absent, as it is in some cases, the space beneath the MM becomes the prepontine cistern, and the MM constitutes the superior wall of the prepontine cistern. The division and classification of the subarachnoid cistern are relative and correspond to certain arachnoid membranes as their boundaries. All the intracranial cisterns are actually open to each other, and each leaf of LM cannot block the normal flow of the cerebrospinal fluid but can prevent the air bubbles from floating and prevent the spread of bleeding, especially when there are only small holes.

Surgical significance

When the pterional approach is used, if the operation is performed through the space between the optic nerve and the internal carotid artery, the first arachnoid mater to be seen will be the carotid–chiasmatic wall, and the second may be LM (its DM in most cases). When the upper clivus is approached through the space between the optic nerve and the internal carotid artery and the lateral space of the internal carotid artery or when the bifurcation of the basilar artery is approached by the subtemporal approach, LM should be cut off [8, 10, 11]. The operation should then be performed with great care and with pulling as lightly as possible because there are branches of the posterior communicating artery adherent to the HM and the lateral part of the DM. In our study, in most specimens, the DM was found to be a membrane with holes or windows, with blood vessels passing through in individual cases. The DM did not always consist of double layers. This finding is not in agreement with that of Zhang and Po-Chung [14]. Although there are seldom vessels that adhere to or pass through the central part of the DM and MM, the two membranes should always be incised with great care.

When the operation continues to the upper basilar complex by supratentorium approaches, the HM and DM should be opened with the oculomotor nerve as an important anatomic marker. They should be dissected along the medial surface of the oculomotor nerve, and the posterior communicating artery is pushed away superiorly. LM should be dissected sharply without pulling or stripped gently under direct vision because there are many structures adhering to or connected with it. By using the retrosigmoidal approach to the tentorium notch, arachnoid mater might be seen on the upper clivus that extends backwards. When the cerebrospinal fluid is being suctioned from all the cisterns, the oculomotor nerve can be seen clearly. It might be safe to cut off the membrane carefully through the central space between the bilateral oculomotor nerves. Care should be taken because there might be branches of the posterior communicating artery that adhere to the superomedial area of the oculomotor nerve. Apart from these considerations, there is the superior cerebellar artery and the posterior cerebral artery that form an intersection (about 90°) against the posterior segment of the oculomotor nerve. The initial segment of the superior cerebellar artery runs in the same direction as the oculomotor nerve, often close or adherent to it.

Some authors only pay attention to the value of the DM rather than the MM and HM in the endoscopic third ventriculostomy [3, 12, 14]. In only a few cases does the DM extend backwards to attach to the posterior mammillary bodies, which are close to the surgical stoma on the bottom of the third ventricle. During the operation, the thin anterior–medial area of the mammillary bodies and the DM further down should be punctured and expanded by a balloon one by one. Otherwise, the cerebrospinal fluid cannot flow smoothly from the third ventricle to the interpeduncular cistern. The posterior edge of the DM may extend backwards to the inferoposterior surface of the mammillary bodies and forwards to the anterior edge of the tuber cinereum. There is variability. In addition, the density of the posterior part of the DM also varies from case to case. Therefore, the surgical significance of the DM varies. We believe that when the bottom of the third ventricle is opened, any arachnoid layers need to be cut open even when only one layer is found. The surgery would be considered complete only if no arachnoid layer is found. Therefore, the variation in the DM at that site is clearly of some surgical significance. Even in some patients without hydrocephalus, the DM may have surgical significance because the bottom of the third ventricle may still be attached to the DM. If such patients do develop hydrocephalus, the attachment will be closer.

The conclusions of this study are limited by the small sample size. We only studied 15 specimens. Also, all of the specimens were from Han Chinese. Studies using a larger number of specimens are needed to gain more information on the variability of LM. The surgical significance of the findings in this study is limited because in most cases the failure of endoscopic third ventriculostomy is probably not due to additional membranes but mainly because of insufficient cerebrospinal fluid absorption capacity.

Conclusion

The basic structure of LM includes the DM which stretches superoposteriorly, a thin layer of MM that extends inferoposteriorly, and a pair of HMs that run superomedially. Neither the DM, MM, nor HM is dispensable. The DM, MM, and HM all play important roles in the overall function of LM. They are also important anatomic landmarks for surgical approaches to the post-sellar area.

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Conflicts of interest None.

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