REVIEW PAPER

The cranial dura mater: a review of its history, embryology, and anatomy

Nimer Adeeb · Martin M. Mortazavi · R. Shane Tubbs ·
Aaron A. Cohen-Gadol

Abstract

Introduction The dura mater is important to the clinician as a barrier to the internal environment of the brain, and surgically, its anatomy should be well known to the neurosurgeon and clinician who interpret imaging.

Methods The medical literature was reviewed in regard to the morphology and embryology of specifically, the intracranial dura mater. A historic review of this meningeal layer is also provided.

Conclusions Knowledge of the cranial dura mater has a rich history. The embryology is complex, and the surgical anatomy of this layer and its specializations are important to the neurosurgeon.

Keywords Anatomy · Cranium · Meninges · Dura mater · Surgery

Introduction

History

The term meninges, singular meninx, a Greek term meaning "membrane," was first used by Erasistratus in the third century B.C., to describe a membranous covering of the central nervous system. In the second century A.D., Galen described two layers, which he called the pacheia and the lepte. These were later observed and translated into Arabic by an anonymous Muslim physician as umm al-dimagh (mother of the brain), which was later subdivided by Hali Abbas into umm al-ghalida (hard

N. Adeeb · M. M. Mortazavi · R. S. Tubbs (✉) ·
A. A. Cohen-Gadol
1600 7th Ave South ACC 400,
Birmingham, AL, USA
e-mail: shane.tubbs@chsys.org

mother) and umm al-raqiqah (thin mother). These terms were then literally translated into Latin by the twelfth century Italian monk Stephen of Antioch, as the dura (hard) mater (Fig. 1), and the pia (pious) mater. The term pia was a misnomer and should have been replaced by tenue (from tennus meaning thin), but the term pia has persisted. The first introduction of the word arachnoid (spider-like) mater was by Herophilus in the third century B.C., who also described its relation to the ventricles. It was later described by the Dutch anatomist Frederik Ruysch in the seventeenth century. The term mater is derived from ma- (from matru meaning mother) and the suffix -ter indicating a state of being [41, 53].

Embryology

Since the first known description of the embryology of the meninges by Tiedemann and Münz [73] in 1816, many investigations have been directed at describing its origin, including those of Bischoff [6] in 1842. Early investigators assumed that the cranial dura mater was derived from the ectoderm of the neural tube. However, histological studies such as those by Schwann [65] in 1839, described its connective tissue structure, which suggests a different embryological origin.

Later investigations by Kölliker [40] and His [28] and others described the origin of the meninges from a mesenchymal tissue surrounding the neural tube, which was termed the "meninx primitiva" by Salvi [61] in 1898, and denied any contribution of the neural tube. This theory received acceptance from many investigators, including Sterzi [72] in 1901 and Farrer [18] in 1907. The meninx primitiva can be subdivided into two layers, the endomeninx (or secondary meninx), which contribute to the formation of the leptomeninx, and the ectomeninx, which contributes to the formation of the dura. This division is brought on by two cellular condensations as proposed by His [28].
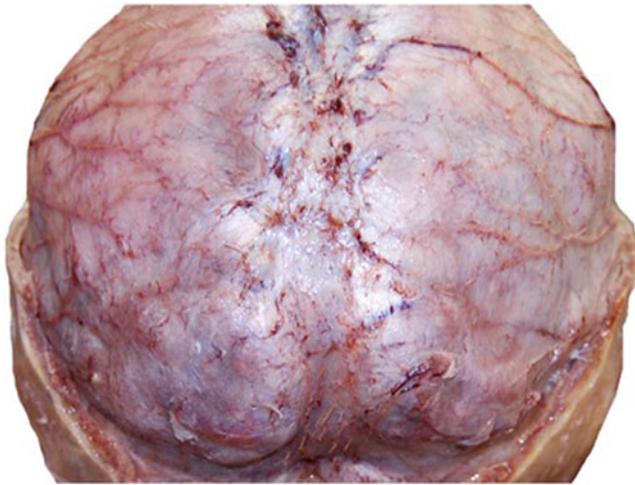
Fig. 1 Supratentorial dura (*posterior view*) seen after the removal of the overlying calvaria. Note the meningeal vessels and midline superior sagittal sinus

The theory of dual origin of the meninges was first described by Remak and Reichert and as Lillie [45] said in 1908, the use of the term mesenchyme is not very descriptive in terms of embryonic development. It was later found that neural crest cells are spread within the mesenchymal. As previously suggested by the investigations of Sayad and Harvey [63] in 1923 and Lear and Harvey [42] in 1924, Harvey and Burr [22, 23] stated that the leptomeninges (pia and arachnoid) are derived from ectodermal origins, exclusively those of the neural crest. They confirmed these results by observations on chick and pig embryos [24, 25] and confirmed the origin of the dura from the mesoderm. This theory was later accepted by many authors. In 1976, LeLièvre [44] studied the origin of the meninges in quail and chick embryos and concluded that in these birds the leptomeninges (and perhaps also the pacchymeninx) of the forebrain and midbrain receive contributions from the neural crest, while those of the hindbrain and spinal cord are derived from mesoderm. In contrast, the neural crest contributes to the development of all meninges in amphibians.

Based on his experimental study on the development of human embryos in 1986, and with similar findings described by Hochstetter [29] in 1939, O'Rahilly et al. [53] concluded that the development of human meninges starts with the formation of the perimedullary mesenchyme (the meninx primitive described earlier), from which the scalp, skull, and all the meninges will develop. This mesenchymal sheath includes cells from different sources, including the primitive streak and the neural crest. It surrounds almost all the neural tube and its blood vessels, except for certain areas where the neural tube is in direct contact with other surfaces. The formation of the leptomeninges starts first followed later by the dura mater. The development of the dura starts at the level of the mesencephalic flexure with the formation

of two cellular condensations in the peripheral mesenchyme, which separates the dura from the leptomeninx and surrounding structures. The external and thicker condensation forms the skeletogenous layer of the head, which lies between the subcutaneous tissue and the dura and contributes to the formation of the scalp, skull, and periosteal layer of the dura. The thinner condensation forms the dural limiting layer, which separates the future dura from the leptomeninges and, according to some authors, participates in the formation of both the dura and the arachnoid mater. Between these two condensations is the area of the future dura mater and where the first signs of dural vein and venous sinus formation appear.

Anatomy

The meninges consist of three layers; dura, arachnoid, and pia mater. Sometimes, the dura is referred to as the pachymeninx (thick meninx), and both the pia and arachnoid are referred to as the leptomeninx (thin meninx). On the most superficial, cranial side of the meninges lies the thick dura mater (Figs. 1 and 2). It is composed of three layers: the endosteal (i.e. periosteal) layer, the meningeal layer, and the border (limiting) cells layer. The endosteal layer, the outermost layer, forms the periosteal lining of the inner surface of the calvaria, to which is strongly adherent, mainly at the base of the skull [47, 50, 68]. It does not communicate with the dura of the spinal cord but, instead, becomes continuous with the periosteum on the outer surface of the skull bone at the level of its foramina and with the sutural ligaments at the cranial sutures [56, 68]. At younger ages, it is difficult to separate the dura from the suture lining, while when the sutures fuse, the dura becomes separated from them. With increasing age, the dura becomes thicker, tougher, and more adherent to the inner surface of the skull [70]. Blood vessels,

Fig. 2 Following removal of the brain, the skull base, lined with endosteal dura mater, is seen. The tentorium cerebelli is folded laterally

lymphatics, and nerves present between this layer and the calvaria. The meningeal layer (dura mater proper) is firmly attached to the endosteal layer except at the sites of the venous sinuses and the sites of dural reflections (Fig. 3) [20, 50, 56, 68]. It communicates with the dura of the spinal cord at the level of the foramen magnum. At the sites where the nerves and blood vessels pierce the meningeal dura, the dura becomes continuous with its epineuria and adventitia, respectively [68, 70]. The dural border cells layer, the innermost layer, was formerly termed such names as the subdural mesothelium, neurothelium, the superficial zone, inner dural cell layer, subdural cell layer, and dural limiting layer [21, 47, 50]. The current term, dural border cells layer, was first used in an experimental study done by Nabeshima et al. [50] in 1975. It forms the interface layer between the dura and the arachnoid [21, 47, 50].

Dural reflections

The dural reflections are mainly four double folding of the meningeal dura. They divide the cranial cavity into well-supported, freely communicable subdivisions [20, 68]. The largest of these septa is the falx cerebri (Figs. 3, 4 and 5), which is a sickle-shaped, midline reflection that extends vertically between the two cerebral hemispheres. It extends from the internal frontal crest and crista galli anteriorly, to the internal occipital protuberance and the superior surface of tentorium cerebelli posteriorly [20, 68, 70]. Ossification dural reflections, mainly of the falx cerebri, albeit rare, have been reported in literature. It may be partially or completely ossified [77].

The tentorium cerebelli (Fig. 5), a second largest reflection, extends horizontally between the cerebellum and the cerebral hemispheres. It divides the cranial cavity into supratentorial and infratentorial spa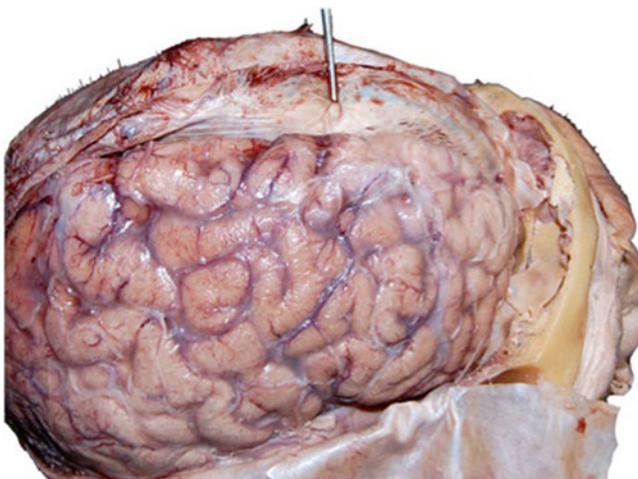ces. This crescent-shaped reflection has both free and fixed margins. The U-shaped free margin is called the tentorial notch (incisura tentoria), through which the midbrain passes. The fixed margin adheres to the clinoid processes, the superior borders of the petrous part of temporal bone laterally, and the margins of the transverse sinuses grooves on the occipital bone posteriorly [10, 20, 68]. At the apex of the petrous bone, and below the superior petrosal sinus, the lower layer of the tentorium pouch anteriorly to form a recess for the trigeminal nerve and ganglion [68]. The tentorium cerebelli is more developed in humans than subhuman species, which may reflect its role in supporting the heavier cerebral hemispheres [10].

Fig. 4 Figure 3 with removal of the falx cerebri. The superior sagittal sinus is noted traveling in the attached border of the falx. The inferior sagittal sinus travels in the free margin of this dural partition

Fig. 3 Lateral view noting following the removal of supratentorial endosteal layer of dura mater. Note the midline falx cerebri diving between he left and right cerebral hemispheres

Fig. 5 Right side of cadaver head following hemicraniectomy and removal of right cerebral hemisphere. Note the anatomic position of the falx cerebri and its merging with the tentorium cerebelli. In addition, note the relationships of the free edge of the tentorium cerebelli with the midbrain (transected) and posterior fossa structures. The falx cerebri is fenestrated in this image

Between the two limbs of the U-shaped tentorium extends the circular-shaped diaphragma sella (Fig. 6), which forms the roof of the sella turcica. It covers the hypophysis cerebri and has a small opening in its center that allows the passage of the infundibulum [11, 20, 68]. In the sella, the dura is inseparable from the arachnoid and pia mater [20]. The diaphragma sella extends from the tuberculum sella anteriorly to the dorsum sella posteriorly. Laterally, it is limited to the junction between the roof and medial wall of the cavernous sinuses [11].

The falx cerebelli is a small, sickle-shaped dural reflection. It extends vertically between the two cerebellar hemispheres, from the midline of the inferior surface of the tentorium, and along the internal occipital crest [20, 68, 70]. Absence of the falx cerebelli in cases of Chiari malformation type II has been reported in literature [75]. Furthermore, in certain cases, duplication of the falx cerebelli may exist [16, 26].

Dural venous sinuses

The dural sinuses are venous channels that run between the endosteal and meningeal layers of the dura. However, Inoue et al. [32] believed that these sinuses run within the dural folds and not between the dural layers. They are lined by endothelial cells and internal elastic lamina, but lack the muscular and adventitial layer of other veins and are valveless [3, 17, 68, 70]. They receive blood from the cerebral veins through the bridging veins and cerebrospinal fluid from the subarachnoid space through arachnoid villi. It also drains the extracranial veins of the skull through the emissary veins and the diploic veins [3, 36, 60, 67]. Most of the dural venous sinuses related to the inner surface of the skull and mark an impression on it.
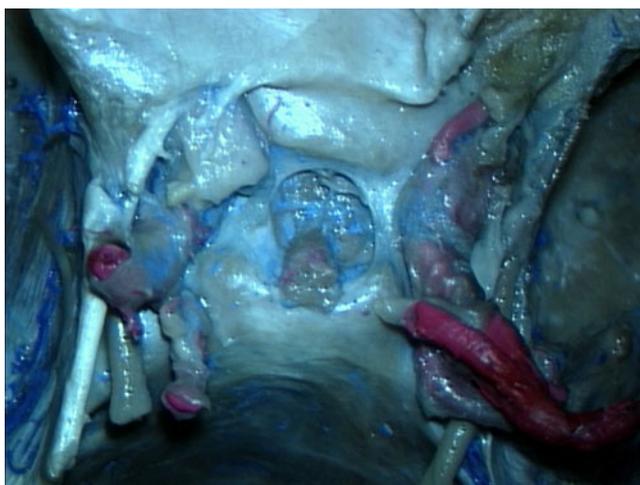

Fig. 6 Superior view of the sella turcica. Note the pituitary stalk in the center of the photo against the dorsum sella. Encircling the stalk is the free edge of the diagphragma sella. Note the laterally placed internal carotid arteries

The superior sagittal sinus occupies the upper fixed margin of the falx cerebri. It extends from the crista galli anteriorly and ends at the level of internal occipital protuberance posteriorly, where it deviates to one or other side, usually the right side, and becomes continuous with the corresponding transverse sinus. At this level, it becomes dilated and forms the confluence of sinuses [68, 70]. Through its course, the superior sagittal sinus marks a groove on the frontal, parietal, and occipital bones. It has a triangular shape in cross-section, as it is narrower near the crista galli, and widen gradually in its course. Along its course, the superior sagittal sinus receives the superior cerebral veins, diploic and meningeal veins through the lateral lacunae, and pericranial veins passing through parietal foramina [70].

On each side, the superior sagittal sinus is connected to a mean number of two or three lateral lacunae (lateral lakes of Trolard) that lie parallel to the sinus. These lacunae are named the frontal (small), parietal (large), and occipital (intermediate) lacunae. However, in older people, these lacunae tend to coalesce and form one elongated lacunae of each side. They have irregular, plexiform structures, and receive most of the arachnoid granulations, and diploid and meningeal veins [70, 79].

The inferior sagittal sinus runs in the posterior half or two thirds of the free margin of the falx cerebri [68, 70]. At the level of the free margin of the tentorium cerebelli, it joins the great cerebral vein (of Galen) to form the straight sinus [68]. It receives veins from the falx and few veins from the medial surfaces of the cerebral hemispheres [70].

The straight sinus is formed by the union of inferior sagittal sinus and great cerebral vein (of Galen). It runs posteroinferiorly in the junction between falx cerebri and tentorium cerebelli and ends posteriorly into the left, or sometimes the right, transverse sinus. It receives some superior cerebellar veins [68, 70].

The transverse sinuses start at the internal occipital protuberance, one (usually the right) as a continuation of superior sagittal sinus and the other (usually the left) as a continuation of straight sinus. They run on the fixed margins of the tentorium cerebelli and mark a groove on the occipital and parietal bones. They end by turning inferomedially to form the sigmoid sinuses [68, 70]. In certain variations, one transverse sinus (usually the right) can be larger than the other, and sometimes, an oblique sinus may exists between the two transverse sinuses and marks a groove on the inner surface of the occipital bone [69]. The transverse sinuses receive inferior cerebral, inferior cerebellar, diploic, and inferior anastomotic veins [70]

The sigmoid sinuses are S-shaped sinuses that begin as direct continuation of the transverse sinuses, which turn inferomedially as the leave the tentorium to enter the mastoid groove on the mastoid part of the temporal bone. Then,

it turns anteriorly and then inferiorly, where it enters the posterior part of the jugular foramen, to become continuous with the internal jugular vein at the superior jugular bulb [68, 70].

The occipital sinus, the smallest of all sinuses, lies in the midline, near the attachment of the falx cerebelli. It starts at the foramen magnum, where it communicates with the vertebral venous plexus and/or the marginal sinus, and ends cranially mainly at the confluence of sinuses [39]. Variation in the anatomy of the occipital sinus has been recognized. Occasionally, two, totally separated occipital sinuses may present, or sometimes, one occipital sinus divides into two, three, or four divisions, either caudally or cranially. Moreover, one right-sided or left-sided, or total absence of the occipital sinus has been reported [15]. It may also communicate with other sinuses and veins, including superior sagittal, straight, transverse, or sigmoid sinuses, or the superior jugular bulb [39]. By this wide range of communication, it has been reported that occipital sinus may play a significant role as a collateral course in case of other sinuses disease or occlusion.

The cavernous sinuses are a pair of boat-shaped dural envelopes that are located on each side of the body of the sphenoid bone. It has four walls: medial, lateral, superior, and posterior [59, 84]. The anterior narrow part is located at the supraorbital fissure, while the posterior wide part lies lateral to the dorsum sella. Its posterior wall shares its dural lining with the lateral part of the posterior wall of the basilar sinus, which extends behind the dorsum sella and forms the main communication between the two cavernous sinuses. The superior and inferior petrosal sinuses also open in the lateral part of the basilar sinus and thus creating a venous confluence. The roof is formed by the dural lining of the anterior clinoid process and the oculomotor triangle. The oculomotor triangle is a patch of dura that links the anterior and posterior clinoid process and the petrous apex, by forming the interclinoid, anterior petroclinoid, and posterior petroclinoid dural folds. The oculomotor nerve passes through the center of the triangle, and the trochlear nerve passes through the posterolateral margin. The junction of the lateral and medial walls forms the lower edge of the sinus, and hence, it gives the sinus a triangular shape on the coronal section. The lateral wall extends from the later edge of the supraorbital fissure to the medial wall of the Meckel's cave and from the posterior petroclinoid dural fold superiorly to the lower margin of carotid groove inferiorly [59]. The medial wall extends from the medial edge of the supraorbital fissure to the lateral edge of dorsum sella and from the interclinoid dural fold superiorly to the lower margin of carotid groove inferiorly [59, 84].

These dural envelopes contain the cavernous part of the internal carotid artery and its periarterial sympathetic plexus and venous plexus that receives tributaries from the orbit, sylvian fissure, and the middle and anterior cranial fossa, while they have free communication with superior and inferior petrosal, basilar, and intercavernous sinuses. It also contains the third, fourth, the ophthalmic and maxillary division of the fifth, and the sixth cranial nerves [59]. The intercavernous sinuses are a pair of venous connections that run anterior (larger) and posterior (smaller) to the hypophysis cerebri, and they form a circular sinus with the two cavernous sinuses [59, 70]. The oculomotor, trochlear, and ophthalmic and maxillary divisions of the trigeminal nerves course in the lateral wall of the cavernous sinus. The abducens nerve runs between the ophthalmic nerves laterally and internal carotid artery, which form the carotid groove on the lateral aspect of the sphenoid body and medial to the cavernous sinus along its course, medially [59, 84]. The course of the internal carotid artery through the cavernous sinus is being thought to have an importance in cooling the blood going to the brain [51].

The cavernous sinus mainly drains the orbit by the superior and inferior ophthalmic veins, the retina by the central retinal vein, the cerebral hemispheres by the middle and inferior cerebral veins, the dura by tributaries of the middle meningeal veins, and the sphenoparietal sinus [59]. It empties posteriorly into the transverse sinus via the superior petrosal sinus and into the jugular venous bulb via the inferior petrosal sinus and a plexus of veins associated with the internal carotid artery [55]. It also empties into the pterygoid venous plexus by emissary veins traversing the sphenoidal foramen, foramen ovale, and foramen lacerum, and into the facial vein via the superior ophthalmic vein [59, 70].

The superior petrosal sinus is a small sinus that drains the cavernous sinus on each side. It arises from the posterosuperior part of the cavernous sinus and course on the attached margins of tentorium cerebelli until it empties into the transverse sinus [59, 70]. The superior petrosal sinus receives cerebellar, inferior cerebral, and tympanic veins [70].

The inferior petrosal sinus is a plexiform sinus the drain the cavernous sinuses on each side. It arises from the posteroinferior part of the cavernous sinus and course between the petrous part of temporal bone and the basilar part of occipital bone. It passes through the anteromedial part of the jugular foramen and joins the jugular venous bulb on either side [19, 59, 70]. Occasionally, the inferior petrosal sinus may course parallel to the internal jugular vein up to 4 or 5 cm below the jugular foramen before joining it [19]. It receives labyrinthine veins via the cochlear canaliculus and the vestibular aqueduct, and tributaries from the medulla oblongata, pons, and inferior cerebellar surface [70].

The petrosquamosal sinus usually disappears during development. It arises from the dorsolateral portion of the transverse sinus, before the confluence of the transverse sinus with the superior petrosal sinus. It courses along the

junction of the squamous and petrous parts of temporal bone, where it marks a groove that sometimes becomes a canal. It has two emptying pathways: one anteroinferiorly into the retromandibular vein via the foramen retroarticular and one anteromedially into the pterygoid venous plexus via the foramen ovale, and ultimately drains into the external jugular vein. It receives tributaries from the middle and superficial temporal veins, the masseteric veins, and the internal maxillary vein [49].

The sphenoparietal sinus (of Breschet) is one of the most controversial venous sinuses. It was first described by Gilbert Breschet [7] in 1829 and was later quoted by Cruveilhier [13] in 1852. The first description was of a venous sinus that drains diploic and meningeal veins, and course between the middle and anterior parts of the base of the skull and ends in the cavernous sinus. In 1888, Hédon [27] added that the superficial middle cerebral vein ends in this sinus under the lesser wing of sphenoid bone or that it constitutes the sphenoparietal sinus. Many authors later rejected this termination of the superficial middle cerebral vein, and some of them [5, 52] described its termination either into this sinus or directly into the cavernous sinus. In 1890, Trolard [74] described a venous sinus that exists under the lesser wing of the sphenoid wing, later named the sinus of the lesser sphenoid wing by Wolf et al. [83] in 1963. This sinus connects with the anterior branches of the middle meningeal veins (sphenoid part) and sits in the sphenoparietal sulcus (of Trolard) before these veins along with the middle meningeal artery enter the parietal bone (parietal part) [62, 78]. Moreover, Trolard [74] proclaimed that the parietal part of the sphenoparietal sinus is actually a prolongation of the parietal part of the anterior branches of the middle meningeal veins, which was later accepted by many authors. The sphenoparietal sinus (or the sinus of the lesser sphenoid wing) connects with the anterior and superior part of the cavernous sinus, and through its course, it receives veins from the temporal lobe and from the anterior temporal diploic vein [62, 78]. In other studies, this sinus was found to end in the veins traveling through the foramen rotundum and not into the cavernous sinus [78]. The connection between the superficial middle cerebral vein and the sphenoparietal sinus remains controversial.

The marginal sinus encircles the internal aspect foramen magnum. It connects anteriorly with the basilar venous plexus on the superior surface of the inferior clivus and occipital sinus posteriorly. Extracranially, it communicates with the internal vertebral venous plexus, paravertebral or deep cervical veins in the suboccipital region. Moreover, it receives small veins from the sigmoid sinuses that pass across the intracranial surface of, and communicate with, the veins of the hypoglossal canal. It has been reported that marginal sinus may be pierced by rootlets of hypoglossal nerve and by the vertebral arteries [76].

In 1875, Key and Retzius [37] described the presence of peculiar lacunae in the dura mater. Further investigations have been employed since then to determine the exact anatomy, histology, and function of these lacunae. In 1950, Joseph Balo [3] examined the dura mater of 100 individual and mainly focused on the superior sagittal, straight, and the confluence of sinuses. He found that the posterior part of the superior sagittal sinus is surrounded by a 1–3-mm tissue, which resembled a site of hemorrhage. However, on histological examination, this spongy tissue had cavernous spaces similar to the corpora cavernosa of the penis. These cavernous tissues extend 1–2 cm along the wall of the sinus and alternating with areas without or with little cavernous tissues. It does not have a proper wall and present within the collagenous fibers of the sinus wall. Similar structures were found along the wall of the straight sinus and the confluence of sinuses. The latter has a special form of these tissues, which extend into the lumen of the sinus in a pad-like structure. While no similar structures were found in any other sinuses. The spaces of these cavernous tissues are either empty or completely filled with red blood cells. Fat drops or fat globules may also be present between these blood cells, or scattered between the collagenous fibers.

Filling or repletion of these cavernous spaces leads to narrowing of the corresponding sinus and hence passive hyperemia of the brain, and emptying leads to reopening of the corresponding sinuses, thus regulating the blood flow in the brain. Obstruction of the superior sagittal sinus causes passive hyperemia of the cerebral hemispheres, mainly the cerebral cortex. Obstruction of the straight sinus causes passive hyperemia in those area drained by the great cerebral vein (of Galen), including the choroidal veins, which leads to decrease production of cerebrospinal fluid. Similar structure and mechanism was previously described in the junction of the straight sinus and the vein of Galen by Le Gros Clark [12] in 1940 and under the name of suprapineal arachnoidal body. Some authors without sufficient evidence rejected Clark's hypotheses. Filling and emptying of these spaces is believed to be under nervous control. Based on the histological findings, Balo [3] stated that these cavernous spaces are filled from small dural arteries and drains into the sinuses.

In 1664, Willis [82] described the presence of many fibers or cords extending in the lumen in the dural sinuses, which he found resembling the cords extending in the ventricles of the heart. Later on, these and other intraluminal trabeculations, bands, cusps, and septations have been studied and described in literature, [8, 33, 58, 64], which became collectively known as chordae willisii (cords Willis). In 2007, and in a radiological study, Farb [17] described the presence of intraluminal structures in the dural sinuses. These structures include the arachnoid granulations and Willis cords. On examination of the superior sagittal sinus, he found that Willis cords are scattered in the middle third

and less frequently in the posterior and anterior thirds. Similar structures (in the form of trabeculation) were also described in 52 % of the transverse sinuses examined (58 of 112). Of these, a single trabeculation was seen in 11 patients, two trabeculations were seen in 11 patients, three trabeculations were seen in five patients, four or five trabeculations were seen in two patients, and 27 patents (48 %) with no trabeculations. Most of these cords were presented at the site of insertion of the cortical veins into the venous sinuses, which explains the prevalence in the middle third of superior sagittal sinus. Regardless of their type, the Willis cords are usually thin (1–2 mm) and extending from their broad-based attached site in the wail of the sinus, travel for 1–4 cm inside the sinus towards its tapering end.

Arachnoid granulations relation to the venous sinuses

The arachnoids granulations (AG) are spherical or ovoid structures that form the major site for absorption of cerebrospinal fluid. It mainly extends into the lateral lakes (of Trolard) and also into the venous sinuses itself [68, 70]. It can be seen as small filling defect on the radiological study. Small arachnoid granulations (1–3 mm) were seen clustered in the middle third of the superior sagittal sinus and sparsely scattered elsewhere in this sinus. More efforts were spent on counting the larger granulations (4 mm or more) in the dural sinuses. Twenty-nine granulations of this size were identified in 20 patients (36 %): 15 patients with one, four patients with two or three, and one patient with four granulations. No granulations were found in 36 patients (64 %). Of these 29 granulations, 14 occurred in the transverse sinuses, seven at the vein of Galen, three within the superior sagittal sinus, three within the straight sinus, and two at the torcula [17].

Dural vascularity

It has long been suggested that the dura mater is a metabolically inert, avascular, fibrous covering of the brain, except in its periosteal layer. However, with recent studies, many authors proclaimed the highly vascular character of the dura, and this includes a study by Kerber and Newton [36] in 1973. The major bloods vessels that supply the dura run in its outer (periosteal) surface and can be divided according to different areas of the skull. These arteries are derived from the internal carotid, ethmoidal, maxillary, ascending pharyngeal, lacrimal, occipital, and vertebral arteries [36, 60, 66].

In the anterior cranial fossa, the anterior meningeal branches of the anterior and posterior ethmoidal and internal carotid arteries and a branch of the middle meningeal artery supply the dura. In the middle cranial fossa, the middle and accessory meningeal branches of the maxillary artery, a branch of the ascending pharyngeal artery branches of the internal carotid and a recurrent branch of the lacrimal artery

supply it. In the posterior cranial fossa, it is supplied by the meningeal branches of the occipital, the posterior meningeal branches of the vertebral artery, and occasional small branches of the ascending pharyngeal artery [68, 70].

The largest and most important of these arteries is the middle meningeal artery (MMA). In most individuals, MMA arises from the maxillary artery branch of the external carotid artery. In rare cases, it may have other origins, including branches of the internal carotid artery. One of the most described origins is the ophthalmic artery [9]. Earliest observations of this origin can be traced back to the nineteenth century by Curnow [14] in 1873 and Zuckerkandl [85] in 1876. Another very rare origin from the stapedial artery has been reported [30], as early as 1836, by Hyrtl [31]. The MMA then enters the cranial cavity by foramen spinosum, and rarely by the petrosphenoid fissure, and runs in an anterolateral groove on the squamous part of the temporal bone. In certain cases, the foramen spinosum may be hypoplastic or absent, especially when the MMA has alternate origin. It divides into three branches, namely the anterior (bregmatic), middle (obelic), and posterior (lambdoidal) branches. The anterior branch runs posterior to the coronal suture, the middle branch runs along the area of the lateral sulcus, and the posterior branch follows the lower border of the temporal lobe. Anatomic variations can be associated with the origin of the middle branch, and a scoring system named Adachi has been used to determine its origin. It may arise from the anterior branch (Adachi type I), posterior branch (Adachi type II), or both (Adachi type III) [9].

According to Kerber and Newton [36], three subbranches of the main meningeal arteries are responsible for the rich arterial anastomoses in and around the dura. As mentioned above, the main meningeal arteries lie on the outer (periosteal) surface of the dura, and it has an inner diameter of 400–800 μm. These arteries give rise to the primary anastomotic arteries (PAA) and have an inner diameter of 100–300 μm. They also lie on the outer layer, cross over the superior sagittal sinus, and anastomose freely with other PAA and main meningeal arteries. These vessels give rise to four smaller arterial units: the arteries to the skull, the secondary anastomotic arteries (SAA), penetrating vessels, and arteriovenous shunts. Many of these arteries supply the skull and the diploic contents and are visible on the outer surface of the skull. Due to rupture of many of these vessels during removal of the dura from the skull, it was hard to study them. The SAA are 50–90 μm in diameter and anastomose freely on the outer surface of the dura. The last sets of anastomosing vessels are 20–40 μm in diameter. They arise from the PAA or the SAA and penetrate obliquely to the juxta arachnoid surface of the dura. These arteries anastomose freely with each other and give rise to many capillaries that form extensive anastomosing networks. The

orientation of these capillaries corresponds to the architecture of the base of the dura, which has multiple parallel layers with oblique interconnections.

Regarding the venous drainage of the dura, two distinguishable drainage routs have been identified: one by the satellite veins accompanying the meningeal arterial trunks, and the other ends in the dural venous sinuses [60]. Two satellite veins accompany each primary meningeal artery. Most of these veins end by entering the superior sagittal sinus or the transverse sinuses, or they may end in the lateral lakes, which also receive the diploic, emissary, and intracranial veins [60, 67, 70].

The other route consists of plexiform, irregular venous connections that form the lateral lakes, and receives intracranial veins from the brain, diploic veins from the skull, emissary veins from the scalp, and sometimes the satellite veins. The lumina of these lakes are separated from the surrounding cartilaginous fibers of the dura only by an endothelial layer and have no elastic lamina. The intracranial veins form an anastomosing plexus that ultimately drains the superficial and deep structures of the brain into the dural sinuses via bridging veins [60, 67, 70].

Dural innervation

Sir Thomas Willis first described the innervation of supratentorial dura in 1664 [82]. Since his first description, further investigations were applied to identify the origin, distribution, and physiological function of this innervation. Of these investigations are the works of Arnold et al. [2] in 1834, Luschka [46] in 1850, Kimmel [38] in 1961, and Steiger et al. [71] in 1982. However, the sympathetic innervation of the dura was suggested by Alexander [1] in 1875. Supratentorial and infratentoial dura and dural vessels have both sensory and sympathetic innervation. In an experimental study by Keller et al. [35] on rat models, he stated that the sympathetic innervation of the dura is mainly derived from the perivascular sympathetic plexus that originate from the cervical sympathetic ganglia and accompany the internal carotid and middle meningeal arteries and their branches in the supratentorial area. However, in the posterior circulation of the rats, these fibers are derived from the stellate ganglion and accompany the vertebral and the basilar arteries and their branches. In the supratentorial area, these sympathetic fibers were mainly scattered around the middle meningeal artery and its branches (which in rats is derives from the internal carotid artery), around the dural sinuses (mainly the superior sagittal sinus and the transverse sinuses), and free sympathetic fibers, which are not associated with any vascular structure. The former two are thought to be related to the regulation of blood flow in the brain, while the function of the latter is still unclear.

Based on his experimental study on the posterior fossa dura in 14 cats, Keller et al. [34] described the innervation of this area. His findings were similar to Kimmel's [38] findings on humans. The dorsal rami of the first three cervical nerves enter the cranial cavity through the foramen magnum and supply the base of the posterior cranial fossa and clivus. Nerves derived from the ventral rami of the first two cervical nerves enter the cranial cavity through the jugular or hypoglossal foramina and accompanying the vagus or hypoglossal nerves, respectively. These nerves supply the dura of the sigmoid, petrosal, occipital, and transverse sinuses, dura along the lateral margin of the foramen magnum, the falx cerebella, and lateral and posterior portions of the posterior fossa. He also described the role of the trigeminal nerve (mainly the ophthalmic division) and the vagus nerve in the innervation of this area. Nerve fibers from the glossopharyngeal and hypoglossal nerves also play a role.

Innervation of the supratentorial dura is mainly derived from the anterior and posterior ethmoidal nerves and the maxillary and mandibular divisions of the trigeminal nerves. The latter two has more contribution in the innervation of the middle cranial fossa. The supratentorial falx cerebri and the tentorium cerebelli (on both surfaces) are mainly innervated by nerve fibers derived from the ophthalmic division of the trigeminal nerve.

These sensory nerves end in the dura, venous sinuses, and the blood vessels, and none were found in the brain tissue, pia, and arachnoid mater [57, 70]. Whatever the stimulus, the cranial dura gives rise only to a sensation of pain that is either localized or referred, while stimulation of the dural sinuses always gives rise to a pain referred to a distant area [57]. The nerve supply of the dura has also clinical importance in the phenomenon of the trigeminocardiac reflex, which was first described by Kumada et al. in 1977. In this reflex arc, the stimulation of the distribution of the trigeminal nerve can lead to bradycardia (and sometimes asystole), hypotension, apnea, and gastric hypermobility. Such stimulation may occur during intracranial or ophthalmic surgeries [4].

Histology

Our major understanding of the histology of the meanings is derived from Weed's [81] experimental studies in the early twentieth century. However, later investigations were applied to explore the characteristics of this important covering of the nervous system. These include an experimental study by Nabeshima et al. [50] in 1975. Based on this study, the outermost (periosteal) layer of the dura is composed of few elongated, somehow flattened cells, which processes lie parallel to the axis of the underlying neural parenchyma. These (dural) cells have slightly branched processes that have no contact with the processes of the neighboring cells. Most of these cells have the same characteristic of fibroblast, including its organelles and elongated nucleus, and

with varying degree of fibrils formation. However, other, although few, flattened cells with more organelles and oval nucleus and no fibrils formation tendency have been recognized. These cells lie between extensive amounts of extracellular criss-crossed collagen fibrils, intermingled with much less amount microfibrills and elastic fibers. This extensive extracellular material is responsible for the strength of this layer. Some osteocytes, nerve fibers, and blood vessels have also been found in this layer. In contrast, the meningeal layer of the dura contains more fibroblast and less extracellular matrix, which render a more flexible layer.

The most controversy, however, are related to the innermost layer, the boarder cells layer. It consists of one or more layers of fattened cells that are connected to each other by maculae adherents (desmosomes), no extracellular collagen, and prominent extracellular spaces filled with amorphous, nonfilamentous material [50, 81]. Some authors, starting with Key and Retzius [37] and including Weed [81], considered these cells to be mesothelial cells similar to those lining the serous spaces. This theory was opposed by many other authors starting with Mallory [48] in 1920 and including an experimental study by Leary and Edwards [43], who compared the histology of the inner surface of the dura to the lining of serous cavities, including pericardial, pleural, and peritoneal cavities. They found that the lining of these serous cavities is different from the lining of the innermost layer of the dura, which has a flattened cells lining that are similar to the flattened fibroblast in the other layers of the dura. Nabeshima et al. [50] named these cells the dural boarder cells. This layer is directly applied to the arachnoid mater and with no or few recognizable junctions between them. It was earlier called the subdural space, which was later modified by Orlin et al. [54] to subdural compartment. Accumulation of blood in this layer is responsible for the pathology of subdural hemorrhage. This hemorrhage results from rupture of the bridging veins, which connect the veins draining the brain into the dural sinuses [47]. Through its course, these veins traverse the dural boarder layer and have a weak attachment with its cells, in contrast to its strong attachment to the cells of the arachnoid mater. Atrophy of the brain associated with advancing age results in stress on the bridging veins and the cells of this boarder cell layer and is relieved by separation and space formation in this layer [21]. Rupture of the bridging veins results in bleeding into these spaces.

Comparison between the structure of the parasellar dura (including the dura of the cavernous sinuses) and the surrounding dura (mainly of the middle cranial fossa) have been mainly made by Vucetic [80] in 2005 on the dura of 80 fetuses at 20–40 weeks of gestational age. He found that the periosteal layers of both areas have the same thickness of 0.4 mm, while the meningeal layer of parasellar dura in 4 mm in thickness, compared to 1 mm in the adjacent dura. On further examination, he found that the meningeal layers of both areas are multilayered and consist of two types of lamellae of connective tissues: compact and loose lamellae. The meningeal layer of the parasellar dura consists of four loose and four compact lamellae, compared to three loose and three compact lamellae in the adjacent dura. These extra lamellae are related to the cranial nerves and blood vessels traveling and contained within the parasellar and cavernous dura and has importance in microsurgical anatomy.

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