The dural sheath of the optic nerve: descriptive anatomy and surgical applications

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With 3 Figures

Contents

Abstract

The aim of this work was to clarify the descriptive anatomy of the optic dural sheath using microanatomical dissections on cadavers. The orbit is the rostral part of the extradural neural axis compartment; the optic dural sheath forms the central portion of the orbit.

In order to describe this specific anatomy, we carefully dissected 5 cadaveric heads (10 orbits) up to the meningeal structure of the orbit and its contents. 1 cadaveric head was reserved for electron microscopy to add to our knowledge of the collagen structure of the optic dural sheath.

In this chapter, we describe the anatomy of the interperiostal-dural concept and the anatomy of the orbit. The optic dural sheath contains three portions: the intracranial, the intracanalicular and the intraorbital segment. Each one has specific anatomic relations which result in particular surgical considerations.

Keywords: Optic nerve; dural sheath; anatomy; skull base surgery.

Introduction

The dural sheath of the optic nerve is a structure which has received little attention in the literature. Nevertheless, it illustrates a broader idea of the dura mater: the interperiostodural concept. This sheath has the particularity of being the longest of the transbasal sheaths. It courses along with the optic nerve from its foramen to the orbit. At this point, it reinforces the sclera and provides the optic globe with its characteristic biomechanical properties. In this chapter we will successively discuss the embryology of optic nerves, the principles of the interperiostodural concept followed by a descriptive anatomy of this dural sheath and try to clarify its relations to nearby structures and the surgical implications at the level of each of its three segments: intracranial, intracanalicular and intraorbital.

Embryology

The optic vesicle begins to form as an evagination on the diencephalic neural fold on day 22. The stem of the optic vesicle narrows to form the optic stalk. The nerve fibers that emerge from the retinal ganglion cells in the sixth week travel through the optic stalk to reach the brain. The optic stalk is transformed into the optic nerve. As the optic vesicle forms, it is surrounded by a sheath of mesenchyme which differentiates to form the two coverings of the optic globe: an inner, pigmented, vascular layer called the choroid (homologous in origin with the pia mater and arachnoid membranes) and an outer, fibrous layer called the sclera (homologous with the dura mater). This latter tissue gives rise to the optic dural sheath whereas the choroid gives rise to the subarachnoid space between the optic nerve and its dural sheath. The subarachnoid space extends through the bony optic canal and along the optic nerve to the globe (Fig. 1A, B). However, the extent of communication in the optic canal showed wide variation from one specimen to another. This subarachnoid space is larger distally (near the globe) than proximally (region of the optic canal). Elevation of intracranial cerebrospinal fluid pressure is transmitted to the subarachnoid space surrounding the optic nerve sheath and thence into the optic nerve parenchyma leading to stasis of normal axoplasmic flow resulting in optic disk swelling. This mechanical theory explains pathogenesis of disk swelling in patients with elevated intracranial pressure.

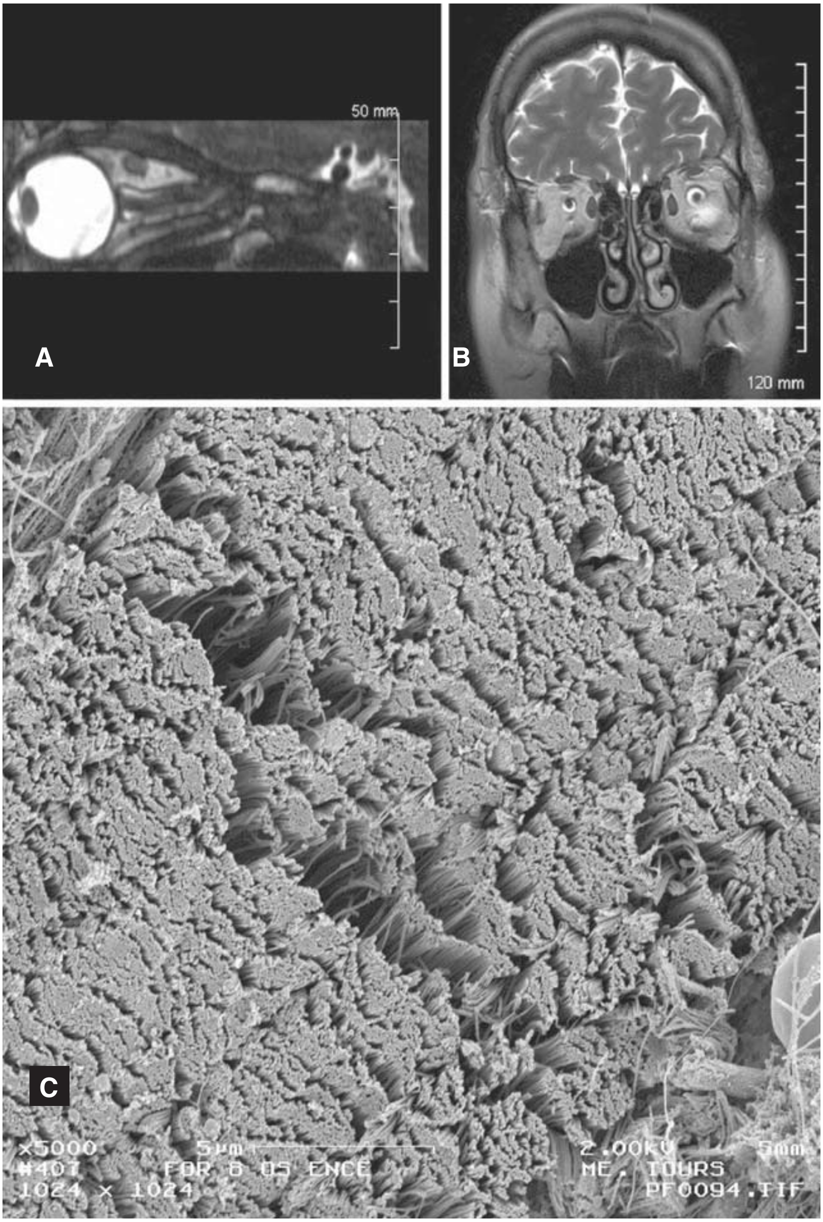

Fig. 1. Sagittal T2-weighted (A) and coronal T2-weighted (B) MRI scans of the orbit. The cerebrospinal fluid is contained in the subarachnoid space surrounding the optic nerve. This subarachnoid space extends through the bony optic canal and along the optic nerve to the globe. (C) An electron micrographic coronal section of the dural sheath of the optic nerve (X5000). The dura mater is composed of fibroblasts and extensive quantities of extracellular collagen

The interperiosteodural concept

The dura mater of the brain is comprised by two layers: an osteoperiostal layer which adheres to the bone and a thicker, encephalic layer which remains in contact to the arachnoid. These two layers adhere to one another at the level of the cranial vault but are separated at the dural sinuses and the interperiosteodural spaces represented by the orbits, the cavernous spaces and the "epidural" spinal space. These interperiosteodural spaces are filled with adipose tissue and veins. The adipose tissue serves to improve movement between the two sheets. The fatty tissue is less developed at the level of the cavernous space [7, 19]. Apart from the area of the sinuses, the venous lacunae are placed between these sheets and are more developed near the clivus where they form the petroclival venous confluence [3]. The internal carotid artery and the abducens nerve pass through this interperiosteodural space [3, 8].

The interperiosteodural concept has been especially studied at the level of the cavernous spaces. Ridley, in 1695, was the first to describe the parasellar region as a venous space surrounding the internal carotid artery [14]. In 1732, Winslow coined the term "cavernous sinus" for this region by analogy with the cavernous body of the penis since it contains fibrous trabeculae within its confines [20]. In 1949, first Taptas followed by Bonnet in 1955 described this sinus as a space located between the two layers of the dura mater [1, 16]. This space has been the object of numerous controversies. Finally, the notion of the cavernous space as being a space located between an osteoperiostal layer and an encephalic layer has since been extended to include the orbit and the spine inasmuch as the interperiosteodural concept has become an accepted anatomical concept extending from the coccyx to the sclera [9–11].

In the cavernous space, the lateral wall is thus constituted by a layer of encephalic dura mater which is continuous with the encephalic layer covering the middle cerebral fossa. This last-mentioned is doubled by a second plane formed by the juxtaposition of the dural sheathes of the cranial nerves coursing along the lateral wall of the cavernous space [4, 12, 18]. Consequently, these dural sheathes accompanying the cranial nerves up to the superior orbital fissure, which they cross in order to join the orbit, participate in forming the thickness of the lateral wall of the space. The medial wall of the cavernous space is formed by the hypophyseal dural sac constituted by the encephalic dura mater [2] dorsally and the periostium which covers the sphenoid ventrally. Between these two layers lie the coronary sinuses which represent intercavernous anastomoses just like the venous space of the clivus space anastomoses with the petroclival venous confluence. At the junction of the cavernous space and the orbit, the osteoperiostal layer continues through the periorbit while the encephalic layer continues through the dural sheath of the optic nerve. Thus, anatomic elements of the orbit annexed to the optic tracts are located between these two structures. The dural sheath of the optic nerve forms a fibrous sleeve which is in fact an invagination of the encephalic layer of the anterior base of the skull at the optic porus.

The orbit is therefore an interperiosteodural space corresponding to the rostral prolongation of the cavernous space. This space contains the vascular and nervous elements of the orbital cone surrounded by intra and extra-conic fatty islets. The dural sheath of the optic nerve is positioned at its center.

Described in this manner, the dural sheath of the optic nerve originates at the level of the optic canal and accompanies the optic nerve to the sclera. It is constituted by a close-knit meshwork of collagen fibers (Fig. 1C). Its collagen architecture provides indisputable mechanical properties since a 1 mm diameter collagen fiber is estimated to have a resistance of 10 kg. The dural sheath of the optic nerve includes three different segments which need to be described: the very short intracranial segment, the intracanalicular segment in the optic canal and an intraorbital segment which extends to the sclera.

Intracranial segment

This segment is very short and is essentially constituted by the invagination of the encephalic layer of the sphenoid planum at the level of the optic canal. This meningeal invagination does not adhere perfectly to the bone and gives rise to the falciform ligament. It can be a few millimeters in length. This ligament normally protects the dorsal surface of the optic nerve although, when an infraoptic tumor is present, it may shear it. Indeed, meningiomas of the tubercule of the sella turcica or of the sellar diaphragm can lift up the visual pathways and as a result, the ligament can leave its imprint on their dorsal surface. This fact may explain some preoperative visual field defects. Accordingly, the surgical approach to these tumors requires opening this falciform ligament before mobilization of the visual pathways.

Intracanalicular segment

At this level, the relations of the dural sheath are mainly with bony structures and the meninges.

Relations with bony structures

The dural sheath of the optic nerve exits the base of the skull through the optic canal which courses obliquely in a lateral and ventral direction. It is located at the junction of the lesser wing and the body of the sphenoid (Fig. 2). It comes into close contact with the anterior clinoid process which forms its lateral border. The anterior clinoid process is attached to the body of the sphenoid by two bony bridges which form the floor and the roof of the optic canal [15]. The roof of the canal is anterior to the floor; this explains why the plane of the

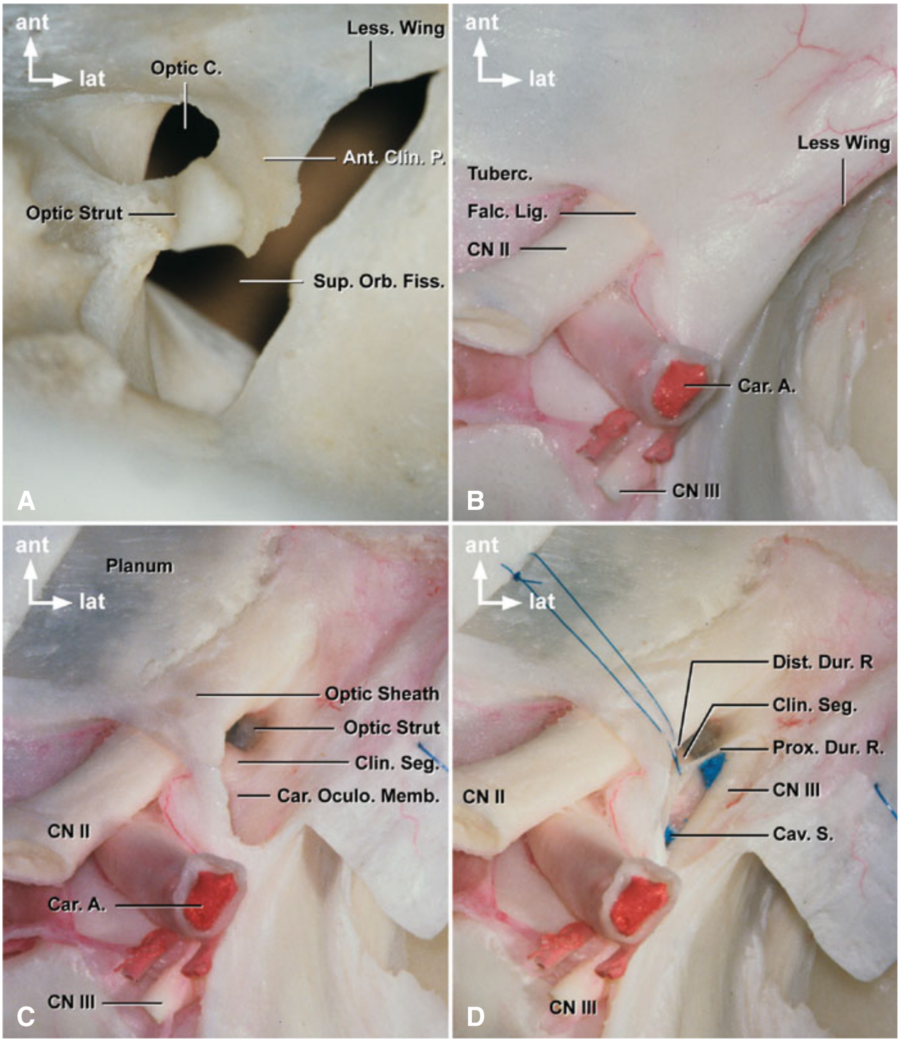

Fig. 2. (A) Superior view of the right optic canal. The dura mater has been removed. The optic canal, which provides passage for the optic nerve and the ophthalmic artery, opens into the orbital apex. It is separated from the superior orbital fissure by the optic strut which forms the floor of the optic canal. The optic strut and the roof of the optic canal constitute the anterior and posterior roots of the lesser wing of the sphenoid bone. (B) Superior view of the roof of the cavernous sinus without dissection. (C) The anterior clinoid process and the optic strut have been drilled to expose the anterior clinoid space. The dura that lines the lower margin of the anterior clinoid process and extends medially above the oculomotor nerve to surround the internal carotid artery and form the proximal dural ring is referred to as the carotidoculomotor membrane. The clinoid segment of the carotid artery is located between the proximal and distal dural rings. Above the distal dural ring, the carotid artery lies in the subarachnoid space and below it the cavernous sinus can be seen. (D) The proximal dural ring around the carotid artery has been opened to expose the oculomotor nerve in the lateral wall of the cavernous sinus (blue latex)

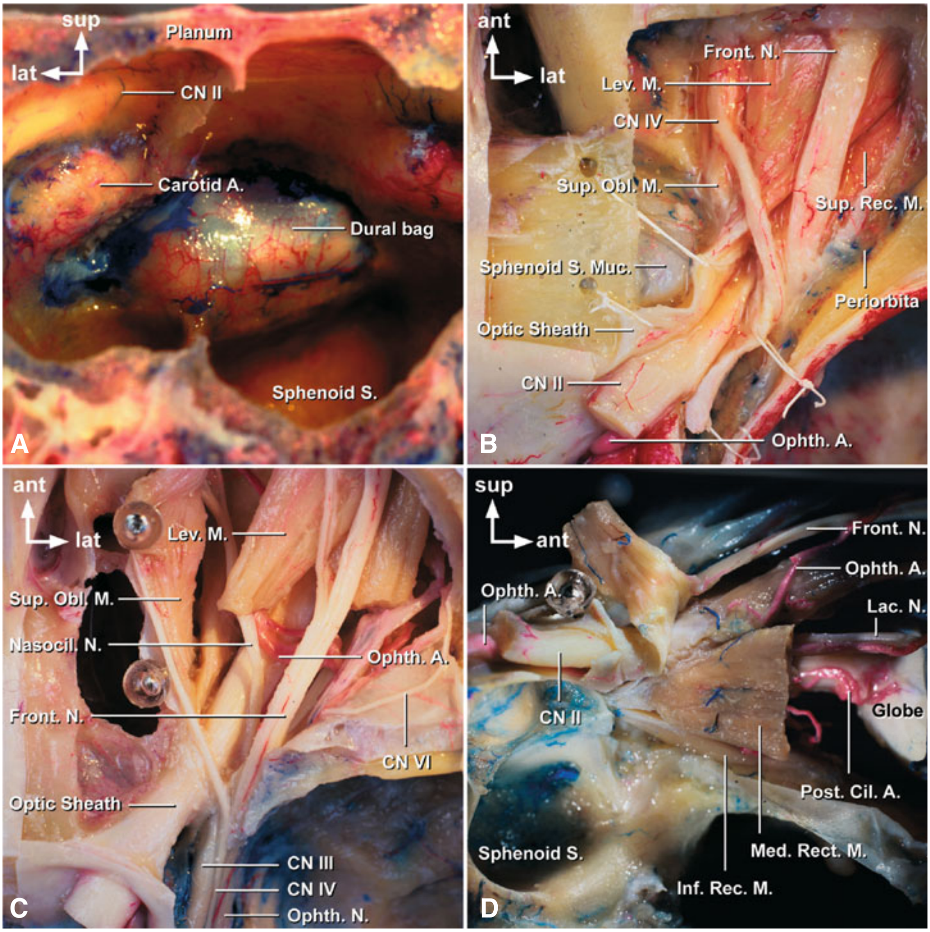

Fig. 3. (A) Coronal section of the sphenoid sinus. The bone has been drilled to expose the hypophyseal dural sac containing the hypophysis. The optic nerve lies above the anterior loop of the carotid artery in the cavernous sinus. (B) Superior view of the right optic canal. The bone has been drilled and the dural sheath of the optic nerve has been opened to expose the optic nerve. The trochlear and frontal nerves cross the optic nerve and lie outside muscles just below the periorbit. The ophthalmic artery arises from the intracranial internal carotid artery and extends along the inferolateral aspect of the optic sheath. (C) Superior view of the right orbit. The frontal nerve and the levator and superior rectus muscles have been divided and reflected to expose the ophthalmic artery and the nasociliary nerve as they pass above the optic nerve. The abducens nerve courses on the medial side of the ophthalmic nerve in the cavernous sinus, but it passes below the ophthalmic nerve in the superior orbital fissure to enter the medial surface of the lateral rectus muscle. (D) Medial view of the left orbit. The levator and medial rectus muscles have been sectioned to expose the distal dural sheath of the optic nerve near the globe. After passing above the optic nerve (85% of the cases), the ophthalmic artery courses between the superior oblique and the medial rectus muscles where it gives rise to the anterior and posterior ethmoidal arteries, the posterior ciliary artery and the meningeal branch for the dural sheath of the optic nerve

optic porus is not coronal. The optic canal has a truncal form and is wider in the back (elliptical shape) than in the front (circular shape). The optic porus is separated from the superior orbital fissure by a bony bridge called the "optic strut". This structure is an important surgical landmark when accessing the extra-dural portion of the anterior clinoid process. The "optic strut" joins the lesser wing of the sphenoid to the lateral wall of the sphenoid sinus. During the surgical treatment of spheno-orbital meningiomas, loss of vision in the patient requires that drilling be extended to the dural sheath of the optic nerve. The optic strut should constitute the medial limit of the drilling process; if drilling is continued further medially the sphenoid sinus will be opened, exposing the patient to postoperative rhinorrhea and possible infectious complications. The floor of the optic canal forms a relief in the sphenoid sinus which is an important landmark during endoscopic surgery of the pituitary gland. At this level, it is located above the anterior bend of the intracavernous carotid, lateral to the floor of the sella turcica. The bone can be very thin or even absent and when that is the case, the dural sheath of the optic nerve is in direct contact with the mucosa of the sphenoid sinus (Fig. 3A).

Meningeal relations

The meningeal relations of the dural sheath of the optic nerve are complex in the region of the sella turcica. In order to clearly understand them, the anterior clinoid process has to be drilled in order to expose the anterior clinoid space. The dura mater covering the ventral surface of the clinoid process forms a "carotidoculomotor membrane" strung between the internal carotid artery medially and the dural sheath of the oculomotor nerve. This membrane forms the meningeal roof of the cavernous space (Fig. 2C). The carotidoculomotor membrane is constituted by encephalic dura mater; medially it forms the proximal and distal carotid rings (Fig. 2D). The clinoid segment of the internal carotid is comprised between these two rings. The internal carotid forms its cavernous segments ventrally to the proximal carotid ring. Dorsally to the distal ring, it penetrates into the subarachnoid spaces. At this point, the dural sheath of the optic nerve is in contact with the distal carotid ring (Fig. 2D). The ophthalmic artery constitutes the first branch of the internal carotid artery, arising medial to the anterior clinoid process. It then joins the orbit after traversing the optic canal.

During the surgical treatment of carotid and ophthalmic aneurysms, the anterior clinoid process should be drilled in order to clearly expose the origin of the ophthalmic artery and allow the aneurysm to be isolated with a clip. Hashimoto [5] insisted on the fact that a preoperative 3D angioscan can help the surgeon determine the exact location of the aneurysm's collar in relation to the optic strut (a radiological landmark) and thereby improve subsequent therapeutic strategy. When the aneurismal collar is dorsal to the optic strut, the aneurysm should most often be treated surgically. However, when the collar is ventral to the optic strut, the aneurysm is intracavernous and should be treated with an endovascular technique.

Yang *et al.* [21] reviewed the principles involved in extradural anterior clinoidectomy when techniques for the post-traumatic decompression of the optic nerve are employed. He underlined the fact that the clinoid segment of the internal carotid is only separated from the medial border of the anterior clinoid process by a thin meningeal sheet: the carotid collar. This meningeal structure is stretched between the carotid rings. The proximal ring is often incomplete while the distal ring is tightly packed. This fact explains why venous blood coming from the cavernous spaces can surround the clinoid segment of the internal carotid. A clinoidectomy using the extradural approach which is indispensable for gaining access to the dural sheath of the optic nerve, can prove to be difficult especially when the sheath is prominent caudally. It should be carefully drilled so as to avoid injury to the internal carotid. After this preparatory bony procedure, the dural sheath of the optic nerve is exposed then incised along the optic nerve from the falciform ligament to the anular tendon (anulus of Zinn) between the insertion of the lateral and superior rectus muscles.

Intraorbital segment

In its orbital segment, the relations of the dural sheath of the optic nerve are essentially with the vascular and nervous elements going to the orbit. At the exit of the optic canal, the meninges of the sheath of the optic nerve become particularly dense (Fig. 3B). At this level, it helps form the anular tendon ring where the muscles providing mobility to the ocular globe and its annexes (eyelid) insert. The anular tendon forms the apex of the orbital cone through which course the dural sheath of the optic nerve dorsally in addition to the abducens nerve, the nasociliary nerve, the superior and inferior branches of the oculomotor nerve and the ophthalmic artery. The dural sheath of the optic nerve is an essential surgical landmark beyond the anular tendon since it represents the central element in the orbital cone formed by the rectus, levator and oblique muscles. It is surrounded by adipose tissue which facilitates eye movements in the three spatial planes.

The ophthalmic artery arises at the medial border of the internal carotid, in general beyond the distal carotid ring, but sometimes at the level of the clinoid segment between the two carotid rings or at the cavernous sinus (8% of the cases) [13, 15], below the proximal carotid ring. When this is the case, it joins the orbit through the superior orbital fissure. The ophthalmic artery accompanies the optic nerve in its sheath, traveling along its inferomedial border (Fig. 3D). Beyond the optic canal, it travels obliquely through the sheath of the optic nerve and joins the orbital apex lateral to the optic nerve. Occasionally, it gives off a recurrent branch in the optic canal which takes part in the vascularization of the intracanalicular segment of the optic nerve [17]. In 85% of the cases, the ophthalmic artery crosses the dural sheath of the optic nerve dorsally where it lies between the medial rectus and superior oblique muscles before giving rise to the anterior and posterior ethmoid arteries. The ophthalmic artery also gives rise to the lacrymal, the ciliary, the supraorbital, the medial palpebral, the infratrochlear and the dorsal nasal arteries. The central retinal artery is the smallest of its branches considering its diameter but the most important according to its function since it is a terminal branch which provides vascularization to the macula. The central retinal artery enters the lower surface of the optic nerve at the junction between the anterior 1/3 and median 1/3 about twenty millimeters from the optic canal following a short, serpiginous trajectory. There it passes to the center of the optic nerve up to the globe and vascularizes the retina. The central retinal artery can present anatomical variations: origin by a common trunk along with the posterior ciliary or muscular arteries, a proximal origin with a long intraorbital trajectory before penetrating the dural sheath of the optic nerve, or finally, with a distal origin and a very short intraorbital trajectory. The intraorbital portion of the optic nerve derives its blood supply from a rich anastomotic vascular network located in the pia mater which is supplied by the ciliary arteries. Optic nerve meningiomas are derived from arachnoidal cap cells and may grow in a subdural, extradural or combined location. It may focally enlarge or may extend axially along the nerve to the intracranial compartment. Optic sheath meningioma in the posterior orbit are virtually impossible to resect completely without resulting in blindness. Optic neuropathy after surgical treatment may be due to inadvertent retraction, vascular compromise or heat transmission from bipolar coagulation energy or drilling.

In summary, five different elements cross the orbital segment of the dural sheath of the optic nerve dorsally:

- The trochlear nerve in the back of the orbit which exits the cavernous space through the superior orbital fissure. It has an extra-conic trajectory under the periorbit and joins to the superior oblique muscle which it innervates (Fig. 3B).
- The frontal nerve, the dorsal dividing branch of the ophthalmic nerve, which arises at the superior orbital fissure outside the common tendon ring and lies under the periorbit in front of the trochlear nerve. It courses above the levator muscle and gives off the supratrochlear and supraorbital nerves (Fig. 3C).
- The nasociliary nerve is the second dividing branch of the ophthalmic nerve. It also arises at the superior orbital fissure ventrally to the frontal nerve. It travels in the orbital cone and joins the anteromedial compart-

ment of the orbit. It gives off the long ciliary nerves and distributes sympathetic fibers to the dilator muscle of the pupil. These fibers course around the intracavernous carotid and join the ophthalmic nerve at the cavernous space.

- The ophthalmic artery crosses over the optic nerve's dural sheath. It sometimes crosses the dural sheath of the optic nerve ventrally before reaching the anteromedial compartment of the orbit.
- The superior ophthalmic vein receives anastomoses from the facial and supraorbital veins. It travels under the superior rectus muscle and crosses over the dural sheath of the optic nerve before taking up a position along the sheath's lateral border. It empties into the cavernous space by exiting the orbit through the superior orbital fissure, outside the anular tendon.

Orbital lesions can be approached by the transcranial, transmandibular, transnasal, transethmoid, or finally, the lateral or transconjunctival orbital route [13]. The choice of surgical approach depends on the lesion's localization, size, and characteristics as well as the operator's experience and preference. Most of the time, two approaches are available to neurosurgeons: the transcranial and the lateral approach. The transcranial provides access to the orbital apex through its dorsal wall and to the compartment located medial to the dural sheath of the optic nerve when the space between the levator muscles of the eyelid and the superior oblique are open. In order to treat lesions which have appeared in front of the superior orbital fissure or along the lateral border of the dural sheath of the optic nerve, the surgeon must open the space located between the superior and the lateral rectus muscles [6]. These upper approaches require a craniotomy and drilling of the roof of the orbit. The trochlear and frontal nerves are particularly exposed to injury due to their extraconic location, under the periorbit. In contrast, the central retinal artery is protected by the dural sheath of the optic nerve. In lateral approaches to the orbit, drilling removes the lateral wall of the orbit and provides access to the inferolateral quadrant of the orbit by passing under the lateral rectus muscle. This approach minimizes the risks of injury to the trochlear and frontal nerves but opens the door to injuring the central retinal artery or the short ciliary nerves.

Conclusion

The optic dural sheath is the longest dural sheath. It describes an intracranial, intracanalicular and intraorbital segments with specific surgical implications. The optic dural sheath forms the encephalic layer of the orbital compartment of the extra dural axis compartment which is an anatomic concept applied from the coccyx to the orbit.

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