Architecture of arachnoid trabeculae, pillars, and septa in the subarachnoid space of the human optic nerve: anatomy and clinical considerations

H E Killer, H R Laeng, J Flammer, P Groscurth

Aims: To describe the anatomy and the arrangement of the arachnoid trabeculae, pillars, and septa in the subarachnoid space of the human optic nerve and to consider their possible clinical relevance for cerebrospinal fluid dynamics and fluid pressure in the subarachnoid space of the human optic nerve.

Methods: Postmortem study with a total of 12 optic nerves harvested from nine subjects without ocular disease. All optic nerves used in this study were obtained no later than 7 hours after death, following qualified consent for necropsy. The study was performed with transmission (TEM) and scanning electron microscopy (SEM).

Results: The subarachnoid space of the human optic nerve contains a variety of trabeculae, septa, and stout pillars that are arranged between the arachnoid and the pia layers of the meninges of the nerve. They display a considerable numeric and structural variability depending on their location within the different portions of the optic nerve. In the bulbar segment (ampulla), adjacent to the globe, a dense and highly ramified meshwork of delicate trabeculae is arranged in a reticular fashion. Between the arachnoid trabeculae, interconnecting velum-like processes are observed. In the mid-orbital segment of the orbital portion, the subarachnoid space is subdivided, and can appear even loosely chambered by broad trabeculae and velum-like septa at some locations. In the intracanalicular segment additionally, few stout pillars and single round trabeculae are observed.

Conclusion: The subarachnoid space of the human optic nerve is not a homogeneous and anatomically empty chamber filled with cerebrospinal fluid, but it contains a complex system of arachnoid trabeculae and septa that divide the subarachnoid space. The trabeculae, septa, and pillars, as well as their arrangement described in this study, may have a role in the cerebrospinal fluid dynamics between the subarachnoid space of the optic nerve and the chiasmal cistern and may contribute to the understanding of the pathophysiology of asymmetric and unilateral papilloedema. All the structures described are of such delicate character that they can not even be visualised with high resolution magnetic resonance imaging (MRI).

MATERIAL AND METHODS
The 12 optic nerves from nine patients used in this study were removed no longer than 7 hours after death following qualified consent for necropsy. Access to the optic nerve and the globe was obtained through the orbital roof. Before removing the globe, the subarachnoid space of the intracranial segment of the optic nerve was carefully injected with fixative using a 26 gauge needle. Subsequently, the orbital portion of the optic nerve and the globe were carefully dissected in situ from the surrounding tissues and the specimens were fixed with 2.5% glutaraldehyde (0.1 M cacodylate buffer). In two cadavers the optic nerves and globes were removed with the intact sphenoid bone in order to examine the intracanalicular segment of the nerve.

Scanning electron microscopy (SEM)
The globe and optic nerve were fixed for at least 1 week in a solution of 2% glutaraldehyde (0.1 M cacodylate buffer). For examination of the intracanalicular segment the fixed specimens were decalcified with 0.5% HNO₂ for 24 hours.
Transverse sections of the bulbar, mid-orbital, and canalicular segment were then dehydrated in an acetone series, dried by the critical point method (CO2), mounted on aluminium stubs, and sputtered with gold (15 nm). The specimens were studied with an SEM 505 (Philips, Einthoven, Netherlands).

Transmission electron microscopy (TEM)
Small fragments (approximately 1 mm³) were cut from the bulbar and mid-orbital segment and postfixed for 1 day within 1% OsO₄ (0.1 M cacodylate buffer). Subsequently the specimens were dehydrated in a series of alcohol and embedded into Epon by routine procedure. Semithin sections (approximately 2 µm) were cut from each block and stained with toluidine blue to identify the meninges. Ultrathin sections (approximately 50 nm) were contrasted with uranyl acetate and lead citrate and studied with a CM 100 (Philips, Einthoven, Netherlands).

RESULTS
Bulbar segment of the orbital optic nerve portion
The bulbar segment of the optic nerve showed a distinct enlargement of the subarachnoid space (ampulla) which was detectable even macroscopically. SEM examination revealed abundant round shaped arachnoid trabeculae bridging the subarachnoid space, which were anchored in the arachnoid and pia layers without broadening (Fig 2A). The trabeculae were often branched to form a delicate network (Fig 2B). The profile of the trabeculae varied between 5 µm and 7 µm. Thin lamellae of highly flat cells were located in a veil-like pattern between adjacent trabeculae. Occasionally, larger trabeculae containing one or two blood vessels were found within the trabecular network (Fig 2C).

Each trabecula was covered by flat leptomeningeal cells with smooth surface and slender processes (Fig 2D). The continuity of the cells was occasionally interrupted by intercellular gaps and fenestrations with a diameter between 0.2 µm and 1 µm. TEM revealed that each trabecula was surrounded by a complete sheath of leptomeningeal cells (Fig 3A). Adjacent trabeculae were connected by thin cytoplasmic bridges of leptomeningeal cells running freely through the subarachnoid space. The oval shaped nucleus of the leptomeningeal cells was rich in heterochromatin and protruded

![Figure 1](http://bjophthalmol.com/)

**Figure 1** Schematic drawing of the optic nerve demonstrating the location of the (a) bulbar segment (containing trabeculae), (b) mid-orbital segment (containing septae and pillars), and (c) canalicular portion (containing pillars). The bulbar segment and the mid-orbital segment together form the orbital portion (modified according to Liu and Kahn).

![Figure 2](http://bjophthalmol.com/)

**Figure 2** SEM appearance of the subarachnoid space in the bulbar segment. (A) Overview of the subarachnoid space showing the complex network of trabeculae. The arrows point to veil-like cytoplasmic extensions between adjacent trabeculae (bar = 150 µm). (B, C) Delicate subarachnoid space network formed by branching trabeculae (bar = 50 µm). The arrow points to a trabeculum with a blood vessel. Note again the veil-like cytoplasmic extensions connecting adjacent trabeculae (bar = 2 µm). Surface of trabeculae covered by flattened cells with distinct intercellular clefts and fenestrations (bar = 0.2 µm).
into the subarachnoid space. The leptomeningeal cells formed, with their slender processes, either single or multiple layers of surface lining cells (Fig 3B). In multiple layers the cells were attached to each other by well defined desmosomes. The size of the intercellular space varied distinctly and it was often widened forming small lacunae between leptomeningeal cells. The basal portion of the leptomeningeal cells was supported either by a fine fibrillar extracellular matrix resembling a basal lamina or by delicate collagenous fibrils in close contact with the cell membrane. The centre of the trabeculae was filled by densely packed collagenous fibrils which were arranged in small bundles (Fig 3A). Occasionally, single fibroblasts were detected within the trabeculae in close contact with the collagenous fibrils. Blood capillaries, lymphatic vessels, and nerve fibres were not present.

Mid-orbital segment of the orbital optic nerve portion
The subarachnoid space was distinctly smaller than in the bulbar segment. It contained numerous broad septa running in various directions (Fig 4A and B). They divided the subarachnoid space into chambers that were connected to each other by large perforations within the septae and by interseptal spaces. In addition, single round shaped pillars were detectable which, in contrast with trabeculae, ended with broadened ends at the pial and dural surface of the subarachnoid space and had a diameter of 10–30 µm (Fig 4C). At the orbital opening of the canal the trabeculae were more numerous running in parallel and bridging the subarachnoid space in oblique direction (Fig 5C). Again the surface of the pillars and trabeculae was covered by flat, smooth surfaced cells with small intercellular clefts. Occasionally single leucocytes were found closely attached to the leptomeningeal cells (Fig 5D).

DISCUSSION
The present study has used SEM and TEM to describe in detail for the first time both the fine anatomy of trabeculae, septa, and pillars in the subarachnoid space of the human optic nerve and their relation to location within the different portions of the nerve.

The morphology of the cranial and spinal meninges and of the subarachnoid space have been described in previous studies on dogs, cats, rats, and humans. In order to find appropriate terminology for the structures transversing the subarachnoid space, Parkinson used the terms arachnoid septa, trabeculae, and “rough strands.” A classification of cranial arachnoid trabeculae in stout, columnar or sheet-like
Some of the larger trabeculae contain blood vessels (Fig 2B) as arachnoid trabeculae are arranged in a reticular fashion. In the intraorbital segment of the optic nerve, there is a multitude of delicate trabeculae in the subarachnoid space of the optic nerve. In a paper dedicated to cerebrospinal fluid pressure in the ocular subarachnoid space, the arachnoid villi in the cranial subarachnoid spaces were observed. Because of the influence of the measuring process itself pressure measurements in small and non-homogeneous compartments are technically difficult to perform and the measurements are not necessarily reliable (personal experience) although other groups published their results with more confidence.

Our morphological study of trabeculae and septa within the subarachnoid space of the optic nerve provides strong anatomical evidence that the hydrodynamics between and within the different cerebrospinal fluid segments, especially within the subarachnoid space of the optic nerve, is more complex than within the ideal Bernoulli tube. Cerebrospinal fluid dynamics should therefore not simply be regarded as an undeflected continuum in a series of interconnecting chambers. Because the subarachnoid space ends blindly in the bulbar segment behind the globe, cerebrospinal fluid needs to communicate between the different cerebrospinal fluid compartments. Hydrodynamics between and within the different cerebrospinal fluid segments, especially within the subarachnoid space, is more complex than within the ideal Bernoulli tube. Cerebrospinal fluid dynamics should therefore not simply be regarded as an undeflected continuum in a series of interconnecting chambers.
unidirectionally from the chiasmal cistern to the subarachnoid space of the optic nerve in the manner of a hydraulic pump. Pressure could therefore build up in this small anatomical compartment that ends blindly behind the globe.

Morgan pointed out that the optic disc is located between two pressure compartments—the globe and the subarachnoid space. The pressure in the subarachnoid space largely determines the retrolaminar pressure. While the optic disc protrudes into the globe in papilloedema, it is excavated in glaucoma. Both diseases are associated with loss of ganglion cell axons. As axonal transport is influenced by pressure gradients, a steady trans laminar pressure is expected to be critical in order to allow optimal axonal transport. The retrolaminar pressure depends mainly on the cerebrospinal fluid pressure in the bulbar segment. The architecture of the trabecular meshwork is believed to be important for pressure homeostasis. Since the compression and distortion of the lamina cribrosa may contribute to the development of glaucomatous optic neuropathy, likewise the anatomy of the subarachnoid space and the local cerebrospinal fluid pressure may influence both the lamina cribrosa and the retrobulbar part of the optic nerve.

Because of the small size of the trabeculae and septa even high resolution magnetic resonance imaging is not useful in demonstrating their anatomy in normal or in diseased states of the optic nerve. We suggest that further studies should aim to demonstrate possible changes of the arachnoidal trabeculae and septa in pathological conditions such as asymmetric and unilateral papilloedema and optic neuritis.

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