Chapter 1

Anatomy of Ciliary Body, Ciliary Processes, Anterior Chamber Angle and Collector Vessels

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1. Introduction

1.1. Anatomy of the ciliary body

The ciliary body is the site of aqueous humor production and it is totally involved in aqueous humor dynamics. The ciliary body is the anterior portion of the uveal tract, which is located between the iris and the choroid. (figure 1)

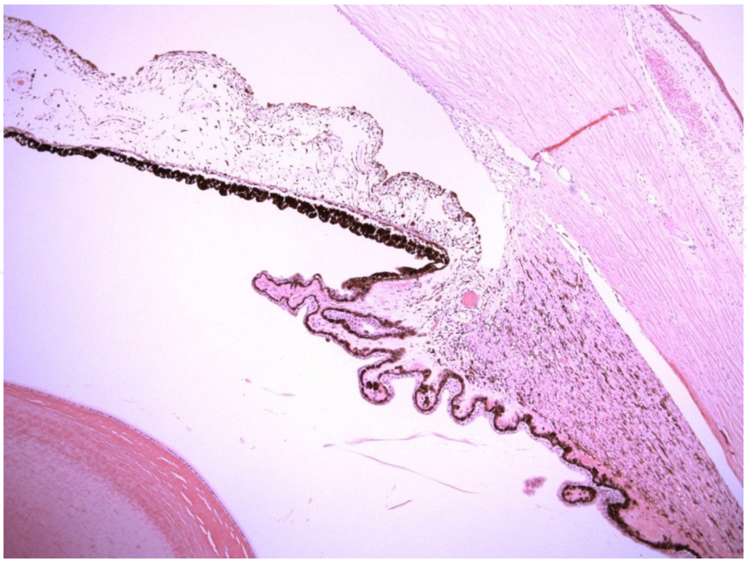

Figure 1. Histology of human ciliary body (courtesy Prof. Ruth Santo)

On cross-section, the ciliary body has the shape of a right triangle, approximately 6 mm in length, where its apex is contiguous with the choroid and the base close to the iris. Externally, it attaches to the scleral spur creating a potential space, the supraciliary space, between it and the sclera. The external surface forms the anterior insertion of the uveal tract. The internal surface of the ciliary body comes in contact with the vitreous surface and is continuous with the retina [1].

The anterior portion of the ciliary body is called the *pars plicata* or *corona ciliaris* and is characterized by ciliary processes, which consist of approximately 70 radial ridges (major ciliary processes) and an equal number of smaller ridges (minor or intermediate ciliary processes) between them [2].

The *pars plicata* is contiguous with the iris posterior surface and is approximately 2 mm in length, 0.5 mm in width, and 0.8-1 mm in height [2,3].

Thus, the ciliary processes have a large surface area, estimated to be 6 cm^2, for ultrafiltration and active fluid transport, this being the actual site of aqueous production; the *pars plicata* accounts for approximately 25% of the total length of the ciliary body (2 mm) [4] (figure 2)

The posterior portion of the ciliary body is called the *pars plana* or *orbicularis ciliaris*, which has a relatively flat and very pigmented inner surface, and is continuous with the choroid at the ora serrata.

In the adult eye, the anterior-posterior length of the ciliary body ranges 4.5-5.2 mm nasally and 5.6 -6.3 mm temporally [5].

The ciliary body is composed of muscle, vessels and epithelium.

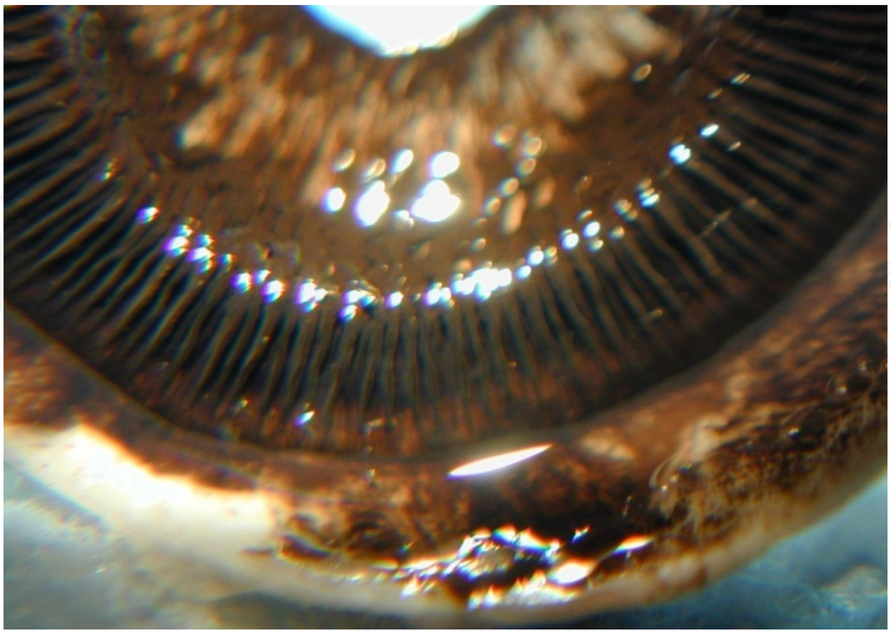

Figure 2. Pars plicata of rabbit ciliary body (courtesy of Prof. Durval Carvalho Jr.)

1.2. Ciliary muscle

The ciliary muscle consists of three separate muscle fibers: longitudinal, circular and oblique.

The longitudinal fibers (meridional), which are the most external, attach the ciliary body anteriorly to the scleral spur and trabecular meshwork at the limbus, and posteriorly to the supracoroidal lamina (fibers connecting choroid and sclera) as far back as the equator of the eye [6].

The contraction of the longitudinal muscle, opens the trabecular meshwork and Schlemm`s canal.

The circular fibers (sphincteric) make up the more anterior and inner portion, and run parallel to the limbus. This insertion is in the posterior iris. When these fibers contract, the zonules relax, increasing the lens axial diameter and its convexity.

The oblique fibers (radial or intermediate) connect the longitudinal and circular fibers. The contraction of these fibers may widen the uveal trabecular spaces.

1.3. Ciliary vessels

Traditional views hold that the vasculature of the ciliary body is supplied by the anterior ciliary arteries and the long posterior ciliary arteries, forming the major arterial circle near the root of the iris, wherefrom branches supply the iris, ciliary body and the anterior choroid. Recent studies in primates have shown a complex vascular arrangement with collateral circulation on at least three levels [7,8]: an episcleral circle formed by anterior ciliary branches; an intramuscular circle formed through the anastomosis between anterior ciliary arteries and long posterior ciliary artery branches; and the major arterial circle formed primarily, if not exclusively, by paralimbal branches of the long posterior ciliary arteries. The major arterial circle is the immediate vascular supply of the iris and ciliary processes [8,9].

1.4. Ciliary epithelia

The inner surfaces of the ciliary processes and the pars plana are lined by two layers of epithelium. (figure 3)

The outer layer is the pigmented epithelium, which is composed of low cuboidal cells and is adjacent to the stroma and continuous with the retinal pigmented epithelium.

The inner layer is formed by the nonpigmented epithelium, a columnar epithelium, adjacent to the aqueous humor in the posterior chamber and continuous with the retina.

These two layers of the epithelium are appositioned in their apical surfaces.

1.5. Innervation

The major innervation is provided by ciliary nerve branches (third cranial nerve-oculomotor), forming a rich parasympathetic plexus. There are also sympathetic fibers originating from the superior cervical ganglion which keep pace with arteries and their branches.

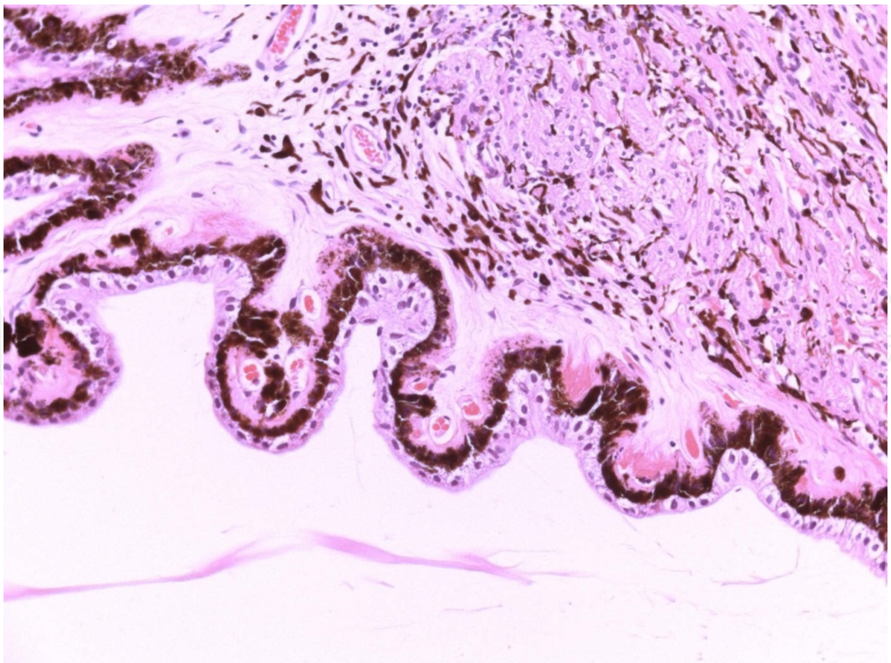

Figure 3. Histology of human ciliary epithelia

2. Ultrastructure of the ciliary processes

Each ciliary process is composed of a central stroma and capillaries, covered by a double layer of epithelium. (FIGURE 3)

The ciliary process capillaries occupy the center of each process [10]. The capillary endothelium is thin and fenestrated, representing areas with fused plasma membranes and no cytoplasm, which may have an increased permeability. A basement membrane surrounds the endothelium and contains mural cells or pericytes.

The stroma is very thin and surrounds the vascular tissues, separating them from the epithelial layers. The stroma is composed of ground substance (mucopolysaccharides, proteins and plasma of low molecular size), collagen connective tissue (especially collagen type III) and cells of connective tissue and the blood [11].

Ciliary process epithelia consist of two layers, with the apical surfaces in apposition to each other.

The pigmented epithelium is the outer layer, and the cuboidal cells contain numerous melanin granules in their cytoplasm. This layer is separated from the stroma by an atypical basement membrane, a continuation of Bruch`s membrane which contains collagen and elastic fibers [15].

The nonpigmented epithelium is composed of columnar cells with numerous mitochondria, well-developed endoplasmic reticulum seen in the cytoplasm, extensive infoldings of the membranes and tight junctions between the apical cell membranes. The basement membrane

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faces the aqueous humor, is composed of fibrils in a glycoprotein with laminin and collagens I, III and IV [16]. The apical cells of this membrane are connected by tight junctions (zonulae occludentae), creating a permeability barrier, which is an important component of the blood-aqueous barrier called the internal limiting membrane.

Adjacent cells within each epithelial layer and between the apical cells of the two layers are connected by gap junctions, tight junctions and desmosomes. The apical membranes of the nonpigmented epithelium are also joined by tight junctions [12,13,14]

These tight junctions are permeable only to low-molecular-weight solutes.

The anterior portion of the nonpigmented ciliary epithelium has the morphologic features of a tissue involved in active fluid transport, i.e., evidence of abundant sodium-potassium adenosine triphosphatase (Na+ K+ ATPase), glycolytic enzymes activity, and incorporation of labeled sulfate into glycolipids and glycoproteins [17]. There are many indications that the aqueous humor is produced in the anterior portion of the nonpigmented epithelia of ciliary processes [17,18,19].

There is a potential space between the two epithelial layers, called "ciliary channels". The aqueous humor may be secreted into this space after beta-adrenergic agonist stimulation, but this notion requires additional studies [20].

3. Anterior chamber angle

The iris inserts into the anterior side of the ciliary body and separates the aqueous compartment into a posterior and anterior chamber. The angle formed by the iris and the cornea is the anterior chamber angle[6].

The aqueous humor is formed by the ciliary process, passes from posterior chamber to the anterior chamber through the pupil, and leaves the eye at the anterior chamber angle. Most of the aqueous humor exits the eye through the trabecular meshwork, which is called the conventional or canalicular system, and accounts for 83 to 96% of aqueous outflow of normal human eyes [21,22].

The other 5-15% of the aqueous humor leaves the eye through the uveoscleral and uveovortex systems (unconventional systems), including anterior ciliary muscle and iris to reach supra-ciliary and suprachoroidal spaces [22,23,24].

3.1. Anatomy of anterior chamber angle (conventional outflow system)

a. Schwalbe`s line

This line or zone represents the transition from the trabecular to corneal endothelium, the termination of Descemet`s membrane, and the trabecular insertion into the corneal stroma.

Schwalbe`s line is just anterior to the apical portion of the trabecular meshwork, is composed of collagen and elastic tissue and has a width that varies 50-150 μm; it has been called Zone S [25].

b. Scleral spur

The posterior wall of the scleral sulcus is formed by a group of fibers, parallel to the limbus that project inward like a fibrous ring, called the scleral spur. These fibers are composed of 80% collagen (collagen type I and III) and 5% elastic fibers. The spur is attached anteriorly to the trabecular meshwork and posteriorly to the sclera and the longitudinal portion of the ciliary muscle [26].

When the ciliary muscle contracts, it pulls the scleral spur posteriorly, it increases the width of the intertrabecular spaces and prevents Schlemm`s canal from collapsing [27].

c. Ciliary body band

This is structure that is located posterior to scleral spur.

When the iris inserts into the anterior side of the ciliary body, it leaves a variable width of the latter structure visible between the iris and scleral spur, corresponding to the ciliary body band. Gonioscopically, it appears as a brownish band.

d. Trabecular meshwork

The aqueous humor leaves the eye at the anterior chamber angle through the conventional system consisting of the trabecular meshwork, Schlemm´s canal, intrascleral channels, and episcleral and conjunctival veins.

The trabecular meshwork consists of connective tissue surrounded by endothelium. In a meridional section, it has a triangular shape, with the apex at Schwalbe´s line and the base at the scleral spur.

The meshwork consists of a stack of flattened, interconnected, perforated sheets, which run from Schwalbe´s line to the scleral spur. This tissue may be divided into three portions: a) uveal meshwork, b) corneoscleral meshwork and c) juxtacanalicular tissue[6]. By gonioscopy, the trabecular meshwork can be separated into two portions: an anterior (named non-pigmented) and a posterior (pigmented).

The inner layers of the trabecular meshwork can be observed in the anterior chamber angle and are referred to as the uveal meshwork. This portion is adjacent to the aqueous humor, is arranged in bands or rope-like trabeculae, and extends from the iris root and ciliary body to the peripheral cornea. These strands are a normal variant and are called by a variety names such as iris process, pectinated fibers, uveal trabeculae, ciliary fibers, and uveocorneal fibers. The deeper layers of the uveoscleral meshwork are more flattened sheets with wide perforations.

The outer layers, the corneoscleral meshwork, consist of 8 to 15 perforated sheets. The corneoscleral trabecular sheets insert into the scleral sulcus and spur. These sheets are not visible gonioscopically.

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The perforations are elliptical and become progressively smaller from the uveal meshwork to the deep layers of the corneoscleral meshwork [28]. The aqueous humor leaves the trabecular in a tortuous route until reaching Schlemm´s canal, because the perforations are not aligned.

The ultrastructure of the trabecular, uveal and corneoscleral meshworks is similar. Each sheet is composed of four concentric layers. The trabecular beams have a central core of connective tissue of collagen fiber types I and III and elastin. There is a layer composed of elastic fibers that provides flexibility to the trabeculae. The core is surrounded by a glass membrane, which is composed of fibronectin, laminin, heparin, proteoglycan and collagen type III, IV and V. The endothelial layer is a continuous layer and covers all the trabeculae. The endothelial cells are larger, more irregular than corneal endothelial cells. They are joined by gap junctions and tight junctions and have microfilaments, including actin filaments and intermediate filaments (vimentin and desmin) [30].

3.2. Gonioscopy of the normal anterior chamber angle

On gonioscopy, starting at the cornea and moving posteriorly toward the root of the iris, the first anatomic structure encountered is Schwalbe´s line. (FIGURE 4)

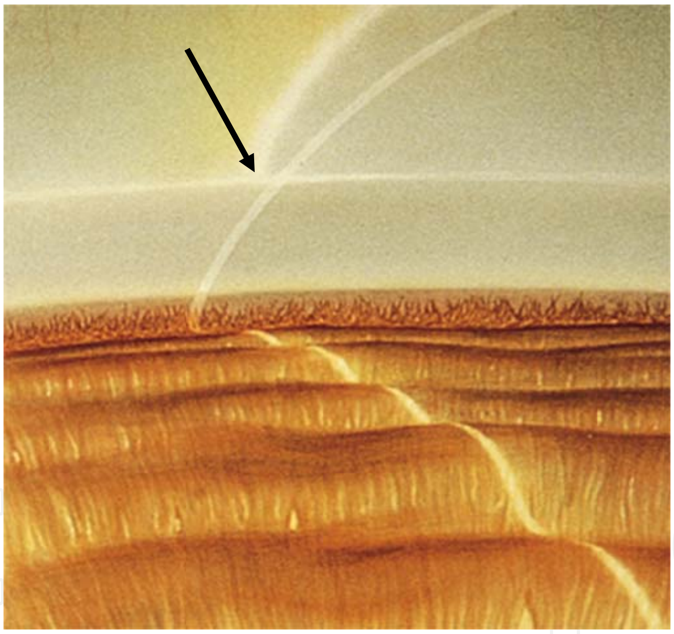

Figure 4. Normal gonioscopic vision of Schwalbe´s line (black arrow)

Schwalbe´s line corresponds to the termination of Descemet´s membrane and marks the most anterior extension of the trabecular meshwork.

It can be seen, by slit-lamp examination, as a fine white ridge, just anterior to the meshwork, and with an indirect contact gonioscopic lens, it is identified at the point where the anterior and posterior beams of the cornea converge (parallelepiped method to identify the transition between the cornea and the meshwork).

The trabecular meshwork lies between Schwalbe´s line and the scleral spur, and it may be considered as two separate portions: (a) anterior part, which is composed of corneoscleral sheets and is not pigmented, meaning it is not visible gonioscopically; (b) posterior part, which is the primary site of aqueous outflow and is the pigmented trabecular meshwork composed of a syncytium of fibers. Gonioscopically, it has an irregular roughened pigmented surface. The amount and distribution of the pigment deposition varies considerably with age and race. At birth, it has no pigment, and develops color with age from light to dark brown, depending on the degree of pigment dispersion in the anterior chamber angle.

The scleral spur is just posterior to the pigmented trabecular band, and it is the most anterior projection of the sclera internally. Gonioscopically, it is seen as a prominent white line between the ciliary body band and pigmented trabecular. It can be obscured by excessive pigment dispersion, and is not visible at variable degrees of narrow or occluded angles.

The iris processes, thickenings of the posterior uveal meshwork, may be frequently seen crossing the scleral spur. They have the appearance of a variable number of fine and pigmented strands.

The ciliary body band is the portion of ciliary body that is visible in the anterior chamber. The width of the band depends on the point of the iris insertion on the ciliary body. Gonioscopically, it appears as a densely pigmented band, gray or dark-brown, posterior to the scleral spur and anterior to the root of the iris.

4. Juxtacanalicular tissue

The corneoscleral meshwork is separated from the endothelium of Schlemm´s canal by a thin tissue, the juxtacanalicular tissue [29].

The juxtacanalicular tissue is the outermost portion of the meshwork in contact with the inner wall of Schlemm`s canal. This tissue consists of a layer of connective tissue (types III, IV and V collagen, fibronectin) and ground substance (glycosaminoglycans and glycoproteins), and it is lined on either side by endothelium [31,32]. There is evidence that the juxtacanalicular tissue contains elastic fibers that provide support for Schlemm`s canal and that these fibers are attached to the tendons of the ciliary muscle.

5. Schlemm`s canal

Schlemm`s canal is a 360-degree endothelial-lined channel that runs circumferentially around the globe. Generally, it has a single lumen, but occasionally it is like a plexus with multiple branches.

The outer wall of Schlemm`s canal is a single layer of endothelium, without pores but with numerous large outlet channels and series of giant vacuoles, which form projections into the lumen of Schlemm`s canal, possibly serving as a pathway for fluid moviment [33].

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6. Collector channels

Schlemm`s canal drains into the episcleral and conjunctival veins by a complex system of vessels (collector channels or outflow channels). This system is composed of innumerous intrascleral aqueous vessels and aqueous veins of Ascher, which arise from the outer wall of Schlemm`s canal up to the episcleral and conjunctival veins. These collector vessels can run like a direct system, draining directly into the episcleral venous system or like an indirect system of more numerous, fine channels, forming an intrascleral plexus before draining into the episcleral venous system [34,35].

7. Episcleral and conjunctival veins

The aqueous humor reaches the episcleral venous system by several routes [36]. Most aqueous vessels run posteriorly draining into episcleral and conjunctival veins. Some aqueous vessels run parallel to the limbus before heading posteriorly toward the conjunctival veins.

The episcleral veins drain into the cavernous sinus by the anterior ciliary and superior ophthalmic veins.

The conjunctival veins drain into superior ophthalmic or facial veins via the angular or palpebral veins [37].

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