Ministry of Healthcare of the Russian Federation
Federal State Government-funded Educational Institution of Higher Education
Siberian State Medical University

E.O. Filippova, E.A. Gorbunova, O.I. Krivosheina

ANATOMY AND PHYSIOLOGY OF THE EYE (WITH CLINICAL CORRELATION)

textbook

Tomsk
Publishing House of SibMed
2023

УДК 617.7(075.8)
ББК 56.7я73
F 52

Filippova E.O.
F 52 Anatomy and physiology of the eye (with clinical correlation): a textbook / E.O. Filippova, E.A. Gorbunova, O.I. Krivosheina. – Tomsk: Publishing House of SibMed, 2023. – 78 p.

The textbook covers the development of the eyeball, provides a detailed description of the microscopic structure of the eye and its accessory apparatus, and thoroughly explains the blood supply and innervation of the visual organ. Clinically significant aspects of eye anatomy, histology, and physiology are presented.

The textbook is written in accordance with the federal state educational standard of higher professional education approved by the Ministry of Health of the Russian Federation in 2010 and is intended for bilingual education students specializing in «General Medicine» (31.05.01) and «Dentistry» (060105).

Reviewer: T.M. Sergeeva – Ph.D. of Medical Sciences, assistant professor of the Ophthalmology Department Siberian State Medical University

Approved and recommended for printing by the methodical committee of the medical faculty of the Ministry of Healthcare of the Russian Federation Federal State Government-funded Educational Institution of Higher Education Siberian State Medical University (protocol No 4 of 12.10.2023).

Федеральное государственное бюджетное образовательное
учреждение высшего образования
«Сибирский государственный медицинский университет»
Министерства здравоохранения Российской Федерации

Е.О. Филиппова, Е.А. Горбунова, О.И. Кривошеина

АНАТОМИЯ И ФИЗИОЛОГИЯ ГЛАЗА

(С КЛИНИЧЕСКИМИ ПРИМЕРАМИ)

Учебное пособие

Томск
Издательство СибГМУ
2023

УДК 617.7(075.8)
ББК 56.7я73
Ф 52

Ф 52

Филиппова Е.О.
Анатомия и физиология глаза (с клиническими примерами): учебное пособие / Е. О. Филиппова, Е. А. Горбунова, О. И. Кривошеина. – Томск: Изд-во СибГМУ, 2023. – 78 с.

В учебном пособии рассмотрено развитие глазного яблока, подробно расписано микроскопическое строение глаза и его придаточного аппарата, детально изложены кровоснабжение и иннервация органа зрения. Приведены клинически значимые вопросы анатомии, гистологии и физиологии глаза.

Учебное пособие написано в соответствии с федеральным государственным образовательным стандартом высшего профессионального образования, утвержденным МЗ РФ в 2010 г., и предназначено для студентов билингвального обучения по специальности «Лечебное дело» (31.05.01) и «Стоматология» (060105).

Рецензент: Т.М. Сергеева – канд. мед. наук, доцент кафедры офтальмологии ФГБОУ ВО СибГМУ Минздрава России, г. Томск.

Утверждено и рекомендовано к печати методической комиссией лечебного факультета ФГБОУ ВО СибГМУ (протокол № 4 от 12.10.2023 г.).

OVERVIEW OF THE EYE

Information regarding the external world is transmitted to the central nervous system by sensory receptors. These receptors consist of sensitive nerve endings or specialized cells that transform perceived stimuli into nerve impulses. Sensory receptors can be found in specialized organs such as the eye, ear, nose, and mouth, as well as in internal organs, such as proprioceptors, which are situated in skeletal muscles, tendons, ligaments, and joint capsules.

The eye is a complex sensory organ responsible for providing the sense of sight. Much like the optical system of a camera, the eye has the ability to track moving objects through coordinated eye movements. The photoreceptors in the retina of the eye detect variations in light intensity and color, specifically the wavelengths of visible light that are reflected by different objects. These characteristics are then encoded into electrical impulses for transmission to the brain via the optic nerve.

The eyes are paired organs that send two distinct images to the brain. The brain, in turn, processes these slightly different images from each eye, separates them into layers, and projects them onto the primary visual cortex located in the occipital lobes.

GENERAL STRUCTURE OF THE EYE

The human eyeball is roughly spherical with a diameter of around 24 mm. The anterior pole of the eyeball is at the center of the cornea, while the posterior pole is situated between the optic disk and the fovea, which is a shallow depression in the retina. The anatomic axis, also referred to as the optical axis, is the line that connects these two poles. The visual axis connects the apparent center of the pupil to the center of the fovea, effectively dividing the eyeball into nasal and temporal halves.

The eye consists of three structural layers:

- the fibrous layer formed by the cornea and the sclera (outer layer),
- the vascular layer or uvea (middle layer),
- the neural layer or retina (inner layer).

The fibrous layer includes:

- the sclera;
- the cornea.

The vascular layer includes:

- the iris;
- the ciliary body;
- the choroid.

The retina includes:

- the neural layer;
- the pigmented epithelium.

The cornea, a transparent part of the eye, lacks blood vessels and is rich in nerve endings (Fig.1). The sclera serves as an attachment point for the extrinsic eye muscles. The anatomical structure between the cornea and the sclera is known as the corneoscleral limbus. The iris functions as a diaphragm, forming the walls of the anterior and posterior chambers, with the central circular aperture being the pupil. The ciliary body, located just

posterior to the corneoscleral limbus, is involved in accommodation and production of aqueous humor. The choroid is a vascular layer that lies between the retina and the sclera. The neural layer of the retina is the innermost layer and contains intricate neural networks. Finally, the retinal pigment epithelium is a layer of cuboidal epithelial melanin-containing cells.

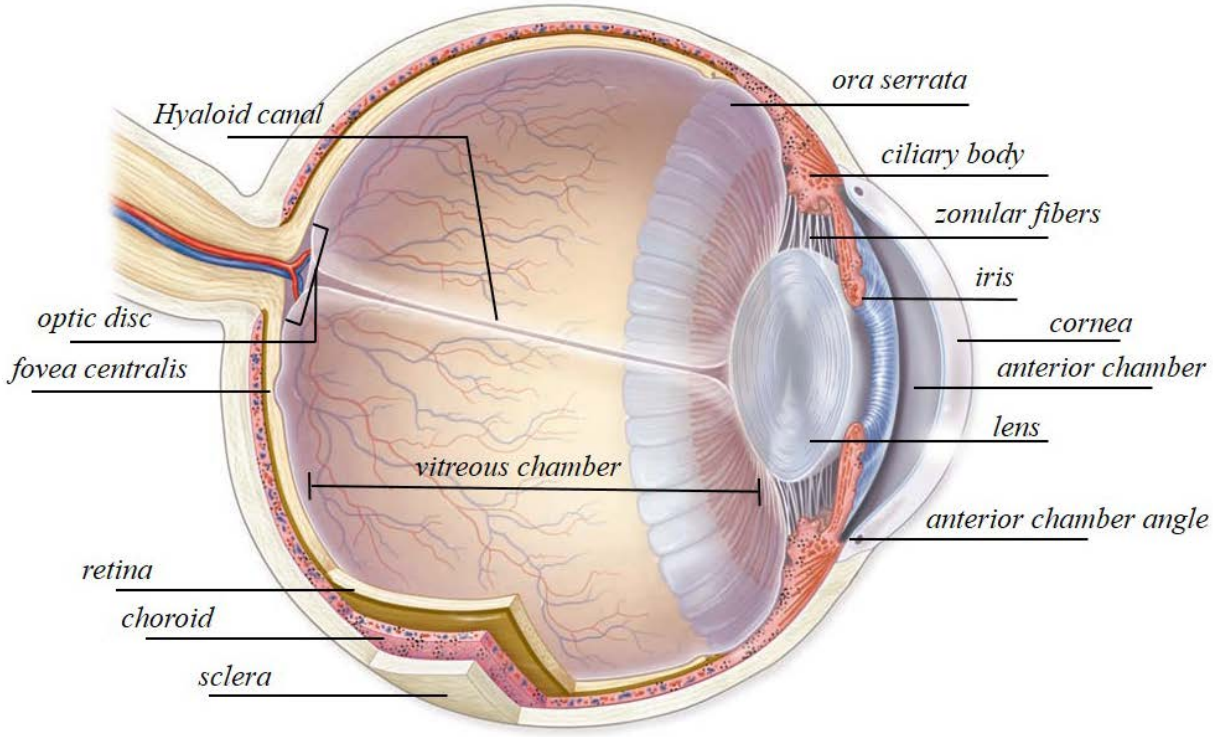


Fig. 1. Anatomy of the eye

The eye consists of three distinct chambers:

- the anterior chamber;
- the posterior chamber;
- the vitreous chambers.

The anterior chamber is the space located between the cornea and the anterior surface of the iris. The posterior chamber extends from the posterior surface of the iris to the lens. The vitreous cavity, positioned posterior to the lens, is the largest compartment. Both the anterior and posterior chambers are filled with aqueous humor, while the vitreous chamber contains the vitreous body, which is a transparent gel-like substance.

DEVELOPMENT OF THE EYE

During the 3rd week of embryogenesis, the eye bubbles emerge on the side walls of the primary cerebral vesicle. These ocular vesicles gradually increase in size, extending toward the outer ectoderm. At the point of contact, the external ectoderm thickens, forming a protrusion. The primary optic vesicle invaginates and gives rise to a secondary optic double layer. The cells of the inner wall of the optic cup divide to form the multilayered, sensory neural retina The outer wall, known as the primordial pigment epithelium, remains single-layered, and pigment grains begin to develop within it (Fig. 2).

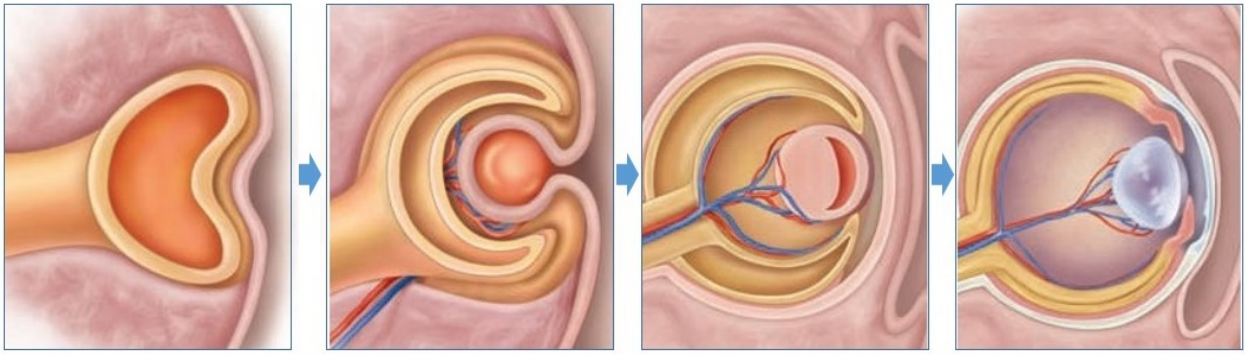


Fig. 2. Scheme of the eye development

Ectoderm cells overlying the optic cup invaginate and detach, leading to the formation of the lens germ, also known as the lens placode.

Between the 4th and 6th weeks, the embryonic fissure emerges in the lower part of the secondary optic vesicle.

From the 8th to the 11th week, the choroid, sclera, their own substances, and the posterior corneal epithelium form from the surrounding ectomesenchyme of the eye cup.

By the 4th – 5th month, all layers of the choroid have developed, blood vessels appear in the retina, and the formation of the sclera and cornea is complete.

After the 6th month, the fundus of the eye takes shape, and myelination of optic nerve fibers occurs during the 7th – 8th months, with the vitreous vessels emptying.

Table 1 presents the embryonic origins of individual structures of the eye.

Table 1. Embryonic Origins of the Individual Structures of the Eye

Source	Eye parts
Surface ectoderm	lens corneal epithelium conjunctiva lacrimal gland
Neural ectoderm	vitreous body epithelium of the retina, iris, ciliary body sphincter pupillae, dilator papillae muscles optic nerve
Mesoderm	sclera stroma of the cornea, ciliary body, iris, choroids extraocular muscles eyelids (except epithelium and conjunctiva)

MICROSCOPIC STRUCTURE OF THE EYE

The fibrous layer

The cornea is a transparent part of the eye and is continuous with the sclera. The anterior surface of the cornea is always kept moist with a film of tears retained by the microvilli of the apical epithelial cells. The cornea is one of the few organs that can be transplanted without the risk of rejection by the

host's immune system. This success can be attributed to the absence of blood and lymphatic vessels in the cornea.

Functions of the cornea:

- refraction;
- protection of structures inside the eye.

The cornea has the following characteristics:

- diameter of about 11.7 ± 0.37 mm in males and 11.77 ± 0.47 mm in females;
- thickness of 0.5–0.6 mm in the center and 0.6–0.8 mm at the periphery;
- convex and aspheric shape;
- anterior curvature of 7.8 mm and posterior curvature of 6.5 mm;
- refractive index of 1,376;
- central thickness ranging from 551 to 565 μm, and peripheral thickness ranging from 612 to 640 μm.;
- refractive power of approximately 43 diopters.

The cornea consists of five layers (Fig. 3, 4):

- epithelium;
- Bowman’s membrane or the anterior basement membrane;
- stroma;
- Descemet’s membrane or the posterior basement membrane;
- endothelium.

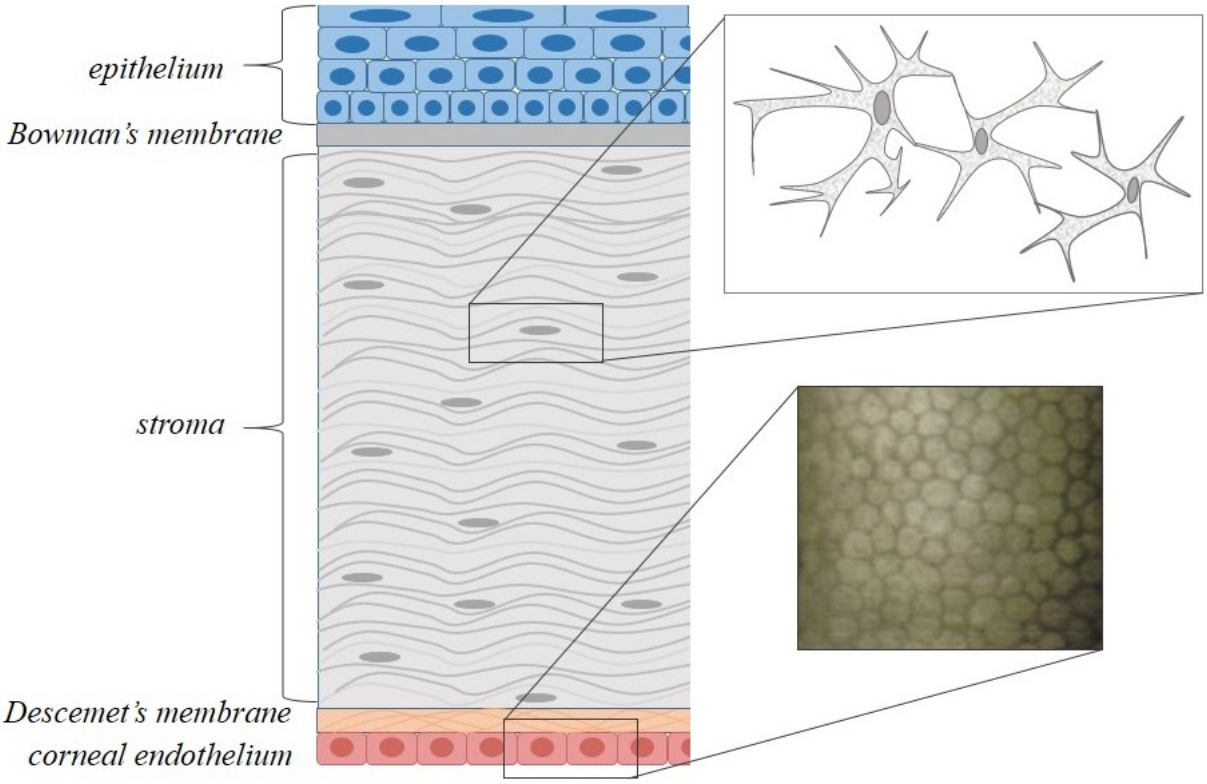


Fig. 3. Scheme of the corneal structure

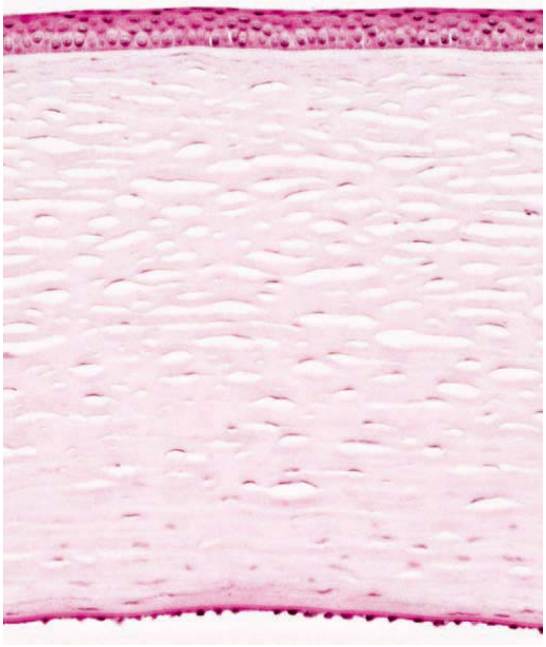


Fig. 4. Photomicrograph of the cornea. H&E, x100

The corneal epithelium is non-keratinized stratified squamous epithelium consisting of five to seven layers of cells (Fig. 5). On average, the corneal

epithelium has a thickness of 50 μm. It possesses a remarkable regenerative capacity, with a turnover time of approximately 7 days. Cells in the corneal epithelium proliferate from the basal layer and assume a squamous shape at the surface. The basal cells are low columnar, while the surface cells have a squamous or discoid morphology.

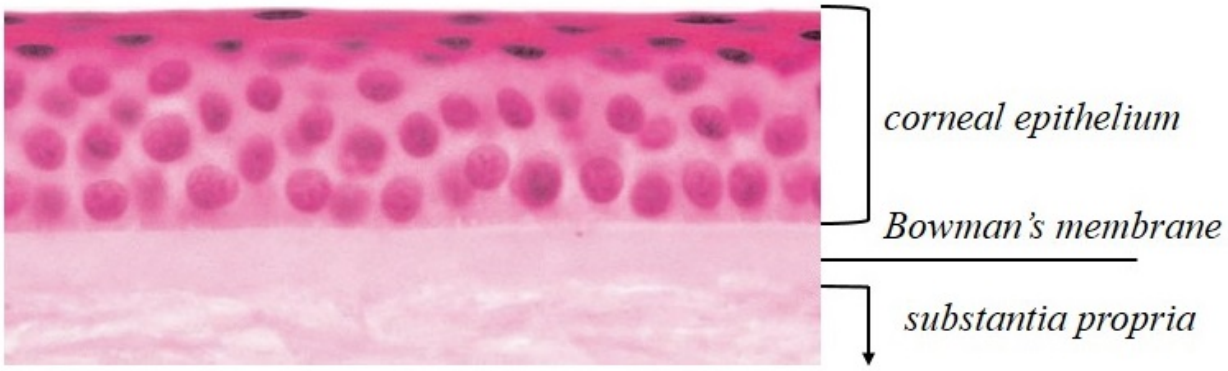


Fig. 5. Photomicrograph of the corneal epithelium. H&E, x400

The Bowman's membrane, also known as the anterior basement membrane, is a homogeneous, fibrillar lamina with an average thickness of 10 μm (Fig. 1). This membrane acts as a barrier against the spread of infections but lacks regenerative capabilities. Therefore, any damage to it results in the formation of an opaque scar.

The highly transparent stroma, or substantia propria, accounts for approximately 90% of the corneal thickness. It is composed of bundles of types I and V collagen arranged in thin layers, regularly crossing at various angles to form a lattice structure that offers high resistance to deformations and trauma. The ground substance contains proteoglycans, primarily keratan sulfate (lumican) and chondroitin sulfate. Fibroblasts are situated between parallel bundles of collagen fibrils, and fibers and layers are separated by an extracellular matrix. During an inflammatory response involving the cornea, a significant number of neutrophils and lymphocytes migrate from blood vessels at the corneoscleral limbus and penetrate the stromal lamellae.

The Descemet's membrane is one of the thickest basement membranes in the body, ranging from 5 to 10 μm in thickness. It is produced by the corneal endothelium and contains type VII collagen, forming a hexagonal array of fibers. Remarkably, the Descemet's membrane has the ability to regenerate after injury.

The corneal endothelium lines the posterior surface of the Descemet's membrane and faces the anterior chamber of the eye. It consists of a single layer of squamous cells. Physical or metabolic damage to the endothelium can lead to rapid corneal swelling and, in severe cases, to corneal opacity. The human corneal endothelium has limited proliferative capacity.

The corneal endothelium is permeable to air oxygen, which is essential for various oxidative reactions, particularly glutathione reduction and oxidation. The glutathione pathway plays a crucial role in neutralizing excess active oxygen in the cornea. Approximately 30% of glucose in the cornea is metabolized through glycolysis. Maintaining the structural and functional integrity of the corneal endothelium is vital for preserving corneal transparency.

The sclera is a layer of collagen and elastic fibers, typically measuring 1.0 to 0.4 mm in thickness, produced by fibroblasts. Its inner side faces the choroid, separated by a layer of loose connective tissue and an elastic tissue network known as the suprachoroid lamina. The outer surface of the sclera serves as the attachment point for the tendons of six extrinsic eye muscles. The sclera can be divided into three layers (Table 2):

- episcleral layer (episclera);
- substantia propria (sclera proper, also called Tenon's capsule);
- suprachoroid lamina (lamina fusca).

For more detailed information on the microscopic structure of the sclera, refer to Table 2.

Table 2. The microscopic structure of the sclera

Layers of the sclera	Structure
Episclera	loose connective tissue
Tenon’s capsule	a dense network of thick collagen fibers
Lamina fusca	thinner collagen fibers elastic fibers fibroblast melanocytes macrophages other connective tissue cells

The Tenon's capsule is the area situated between the episcleral layer and the substantia propria, allowing the eye to rotate freely within the orbit.

The corneoscleral limbus serves as the transitional zone between the cornea and the sclera. The surface of the limbus is comprised of two distinct types of epithelial cells:

- conjunctival cells;
- corneal epithelial cells.

Additionally, the limbus is home to corneolimbal stem cells responsible for generating and maintaining the corneal epithelium (Fig. 6).

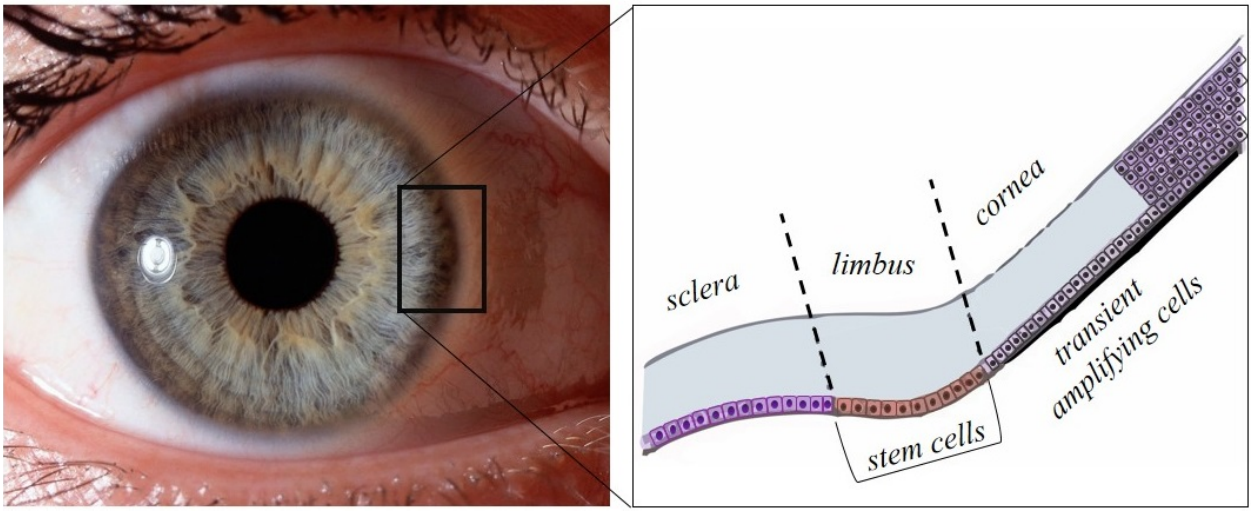


Fig. 6. Eye photo and the scheme of the limbus location

The vascular layer

The iris is a circular structure in the eye that controls the diameter and size of the pupil, which is the central aperture of this thin disc. One of the primary functions of the iris is accommodation. The iris is composed of several elements (Fig. 7):

- the anterior and posterior pigment epithelium;
- sphincter and dilator muscles;
- the basal lamina.

The anterior surface of the iris exhibits numerous ridges and grooves that are visible during a clinical examination with an ophthalmoscope. When observed under a light microscope, this surface appears as a discontinuous layer of fibroblasts and melanocytes. The number of melanocytes in the stroma is responsible for variations in eye color.

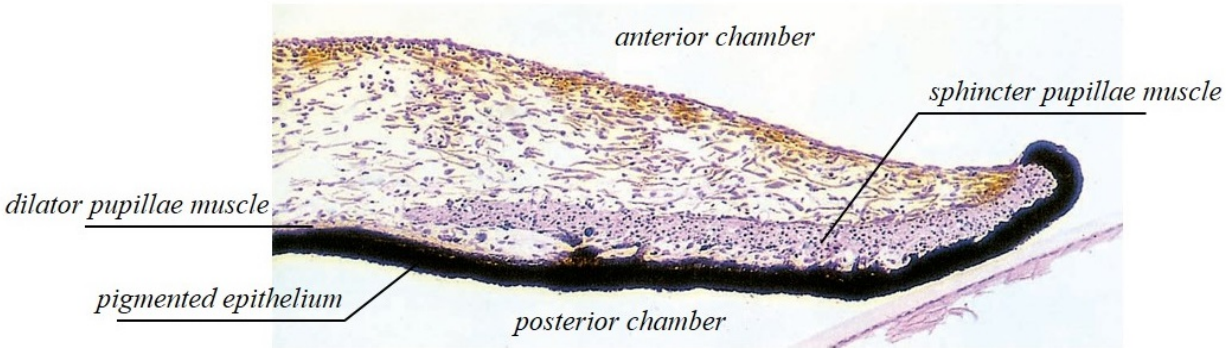


Fig. 7. Photomicrograph of the iris. H&E, x140 [1]

The sphincter pupillae muscle and the dilator pupillae muscle play a role in light adaptation. Prior to the ophthalmoscopic examination, mydriatic agents, such as atropine, are administered as eye drops to induce pupil dilation. Acetylcholine is a neurotransmitter of the parasympathetic nervous system that innervates the sphincter pupillae muscle. Addition of atropine temporarily blocks the action of the sphincter muscle by blocking muscarinic acetylcholine receptors, causing the pupil to dilate and become unresponsive to light from the ophthalmoscope.

The anterior chamber angle is the angle formed between the iris and the cornea; it houses the apparatus responsible for the outflow of aqueous humor. The anterior chamber angle comprises several components (Fig. 8):

- the trabecular apparatus;
- the Schlemm's canal;
- the scleral spur;
- the Schwalbe's line.

The trabecular apparatus consists of two parts:

- the sclerocorneal part;
- the uveal part.

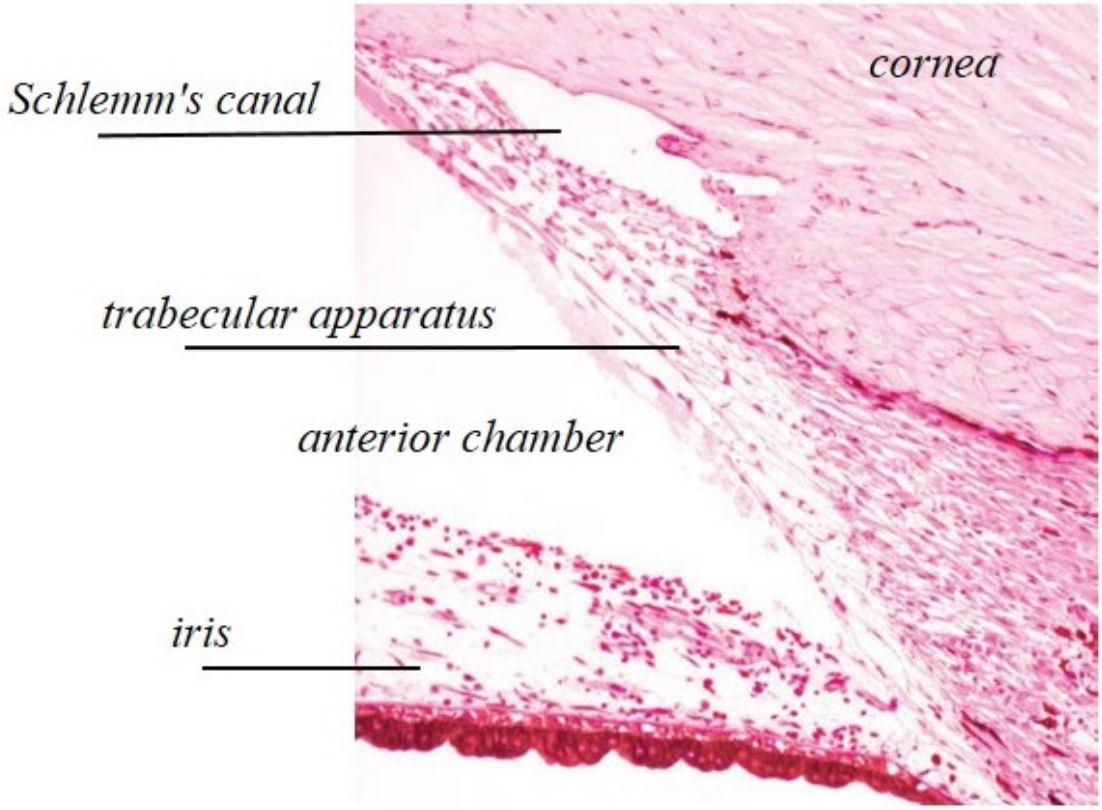


Fig. 8. Photomicrograph of the anterior chamber angle. H&E, x50 [1]

The ciliary body is a structure within the vascular layer located between the iris and the choroid. It plays a critical role in controlling the shape of the lens and producing aqueous humor. The functions of the ciliary body include:

- accommodation;
- aqueous humor secretion;
- establishment of strong attachments between the ciliary muscle and the lens capsule.

The ciliary body can be anatomically divided into two parts:

- the posterior part, known as pars plana.
- the anterior part, referred to as pars plicata.

Pars plicata is home to 70–80 ciliary processes. The layers of the ciliary body resemble those of the iris and consist of the stroma and the epithelium. The stroma comprises two layers:

- an outer layer;
- an inner layer.

The outer layer of the ciliary body stroma contains the smooth ciliary muscle, while the inner layer extends into the ciliary processes. The epithelial layer covers the inner surface of the ciliary body and is divided into two layers: pigmented and nonpigmented. The nonpigmented epithelium is rich in mitochondria, which provide energy for aqueous humor secretion, while the pigmented epithelium contains melanosomes and pigment granules, along with a few mitochondria (Fig. 9).

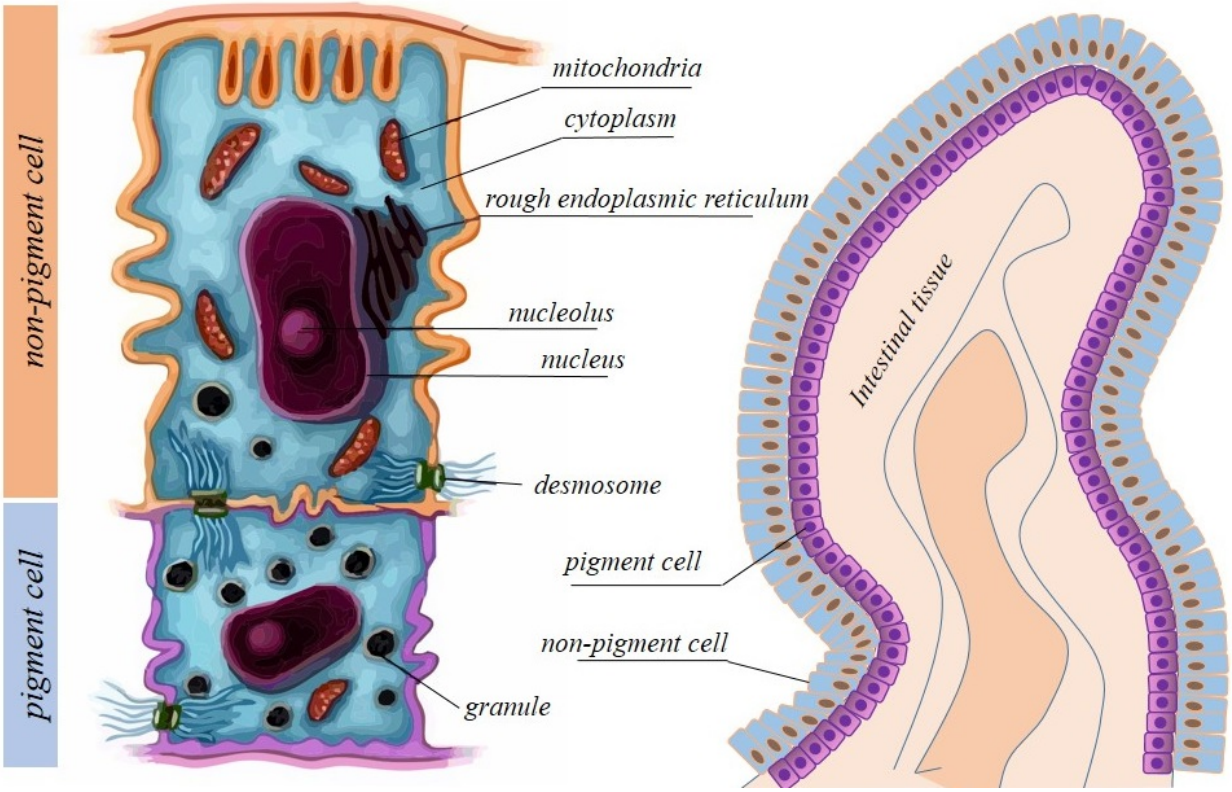


Fig. 9. Scheme of the ciliary processes and the epithelium of the ciliary body

The ciliary smooth muscle, also known as the accommodation muscle, can be categorized into three groups of muscles:

- meridional (or longitudinal, or Brücke muscle);
- radial (or oblique, or Ivanov – Erofeev muscle);
- circular (or sphincteric, or Müller muscle).

The Brücke muscle comprises the outer muscle fibers that extend posteriorly into the stroma of the choroid. The Ivanov – Erofeev muscle consists of deeper muscle fiber bundles radiating in a fan-like pattern to insert into the ciliary body. The Müller muscle is composed of inner muscle fiber bundles arranged in a circular pattern, forming a sphincter.

Clinical correlation: iritis and uveitis.

The uvea can be subject to various inflammatory processes collectively referred to as uveitis, which can affect specific components of the uvea,

including the iris (iritis) and the ciliary body (cyclitis). Uveitis may result from immune-mediated conditions or infections (e.g. cytomegalovirus). In cases of choroiditis with inflammatory exudate, there is a risk of retinal detachment. Inflammation of the choroid can lead to degeneration of photoreceptors, as their nourishment relies on the choroid integrity. The choroid is rich in melanocytes, and this cell population can give rise to ocular melanomas, which are pigmented malignant tumors with the potential for systemic metastasis.

The aqueous humor is produced by the ciliary epithelium. Water escapes from the fenestrated capillaries within the ciliary body stroma due to active transport of Na^+ and Cl^- ions. From the intercellular spaces and the ciliary channel, a narrow passage between the apical domains of nonpigmented and pigmented ciliary epithelial cells allows water, along with amino acids, glucose, and ascorbic acid, to reach the posterior chamber, forming the aqueous humor. Both types of ciliary epithelial cells exhibit basal infoldings and are connected through desmosomes and gap junctions (Fig. 10).

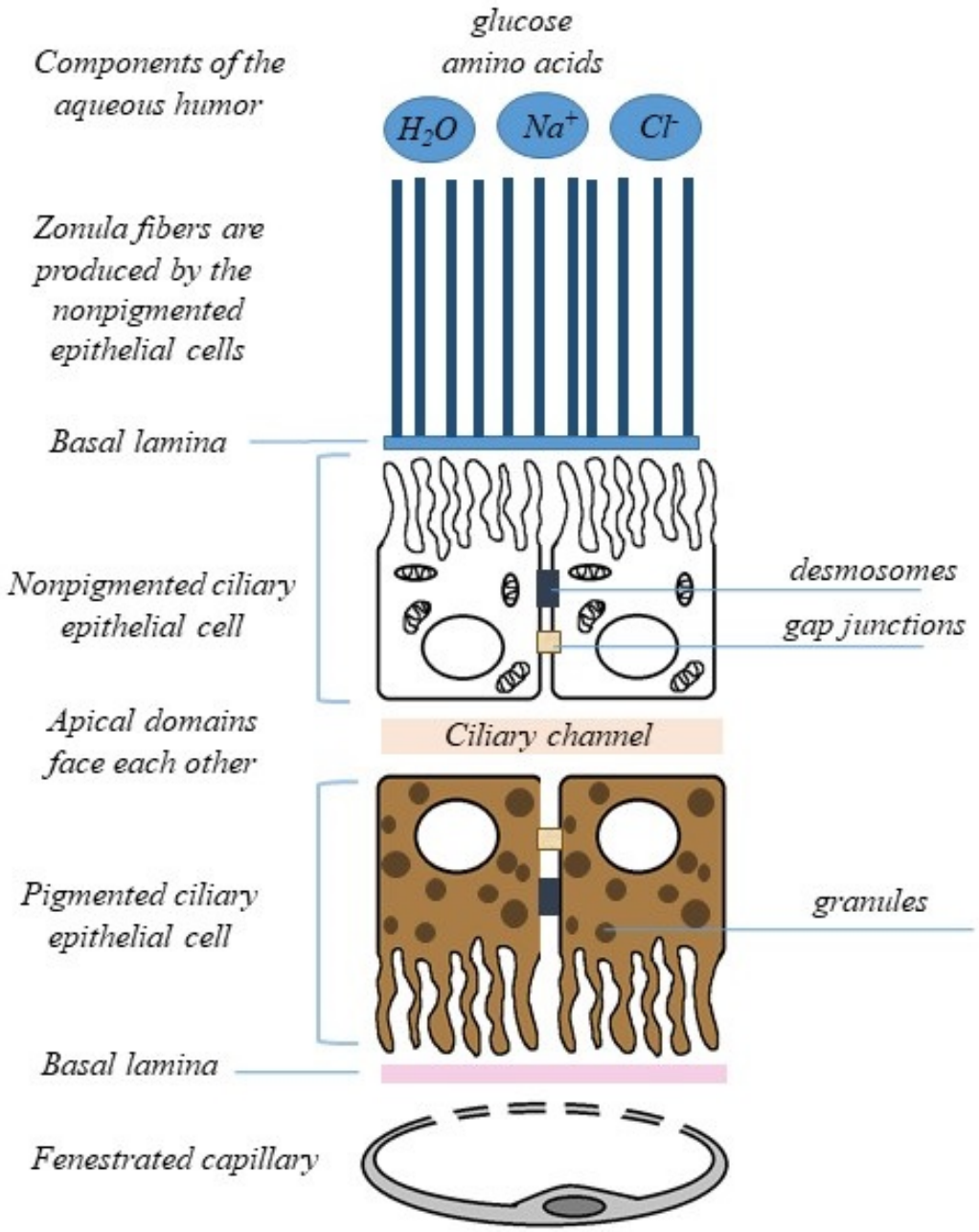


Fig. 10. Scheme of the ciliary epithelium

The aqueous humor travels from the posterior chamber into the anterior chamber, where it passes through the trabecular meshwork to enter the scleral venous sinus (Fig. 11). Collector vessels, known as aqueous veins, within the sclera transport the aqueous humor to veins located in the sclera.

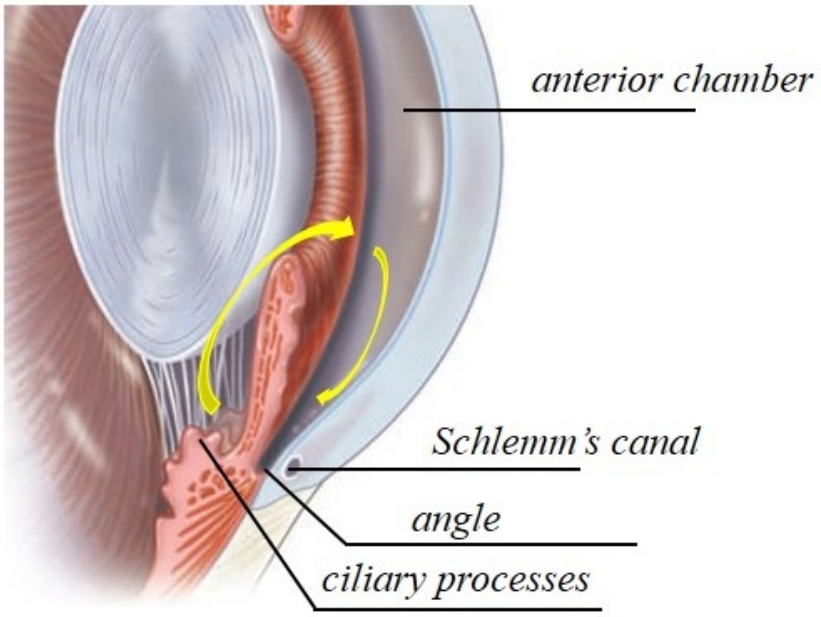


Fig. 11. Scheme of the aqueous humor circulation [1]

The balance between the rate of aqueous production and the rate of aqueous outflow is crucial in determining **intraocular pressure (IOP)**. In the general population, the mean IOP is approximately 16 mmHg.

Clinical correlation: glaucoma.

Elevated intraocular pressure can occur when the normal cycle of aqueous humor production and absorption is disrupted, causing an increase in the fluid volume. This condition is known as glaucoma and can lead to various visual problems, including blindness, which can result from compression of the retina and its blood supply.

The choroid is a component of the vascular layer situated between the sclera and the retina. It provides nourishment to the outer layers of the retina, participates in maintaining intraocular pressure, and serves as a filter for thermal energy generated by light absorption.

The primary function of the choroid is to supply nutrients to the outer layers of the retina. The choroid consists of the following layers:

- Haller's layer;

- Sattler's layer;
- the choriocapillaris layer;
- the Bruch's membrane.

The Haller's layer represents the outermost layer of the choroid, comprising larger diameter blood vessels. The Sattler's layer consists of medium diameter blood vessels. The choriocapillaris layer is composed of capillaries with an approximate diameter of 20 μm.

The Bruch's membrane is the retinal pigment epithelium membrane composed of several layers:

- the basal lamina of the endothelial cells in the choriocapillaris layer;
- a layer of collagen fibers;
- a layer of elastic fibers;
- a second layer of collagen fibers;
- the basal lamina of the retinal pigment epithelial cells.

Clinical correlation: drusen (Fig. 12).

Accumulation of proteins (including apolipoprotein E, amyloid protein, complement protein C5, and the C5b–9 complex, among others) on the inner side of the Bruch's membrane is referred to as drusen (derived from the German term “Drusen”, meaning “stony nodule”). Large drusen can displace photoreceptors from their blood supply. If this separation becomes too extensive, both the pigment epithelium and photoreceptors can degenerate. The presence of drusen is often the earliest sign of age-related macular degeneration.

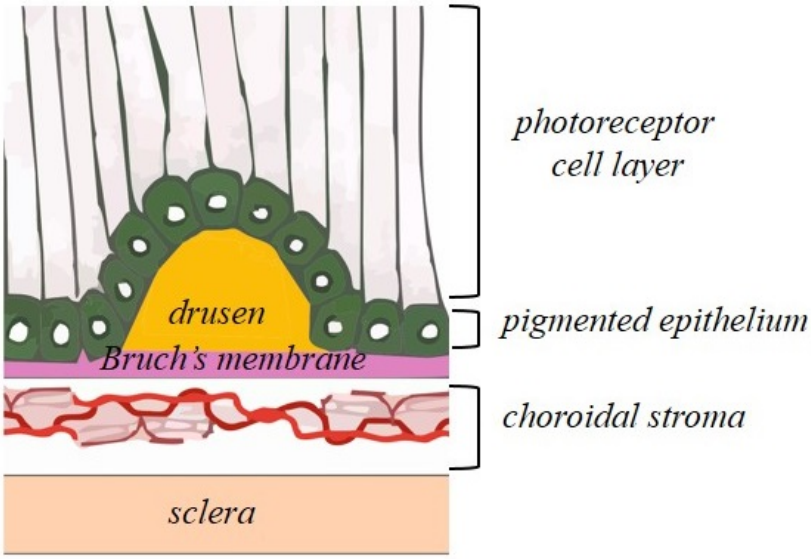


Fig. 12. Scheme of the drusen position in the retina

Retina

The retina, which is the innermost layer of the eye, consists of two fundamental layers:

- the neural retina;
- the pigment epithelium.

Anatomically, the retina can be divided into distinct regions, including the optic disc (or optic nerve head) and the macula lutea. The thickness of the retina varies in different areas:

- near the optic nerve head – 0.4 mm;
- in macula lutea area – from 0.1 to 0.05 mm;
- near the ora serrata – 0.1 mm.

The retina has two areas of adhesion:

- around the optic nerve head;
- along the ora serrata.

The photograph of the eye fundus is presented in Fig. 13.

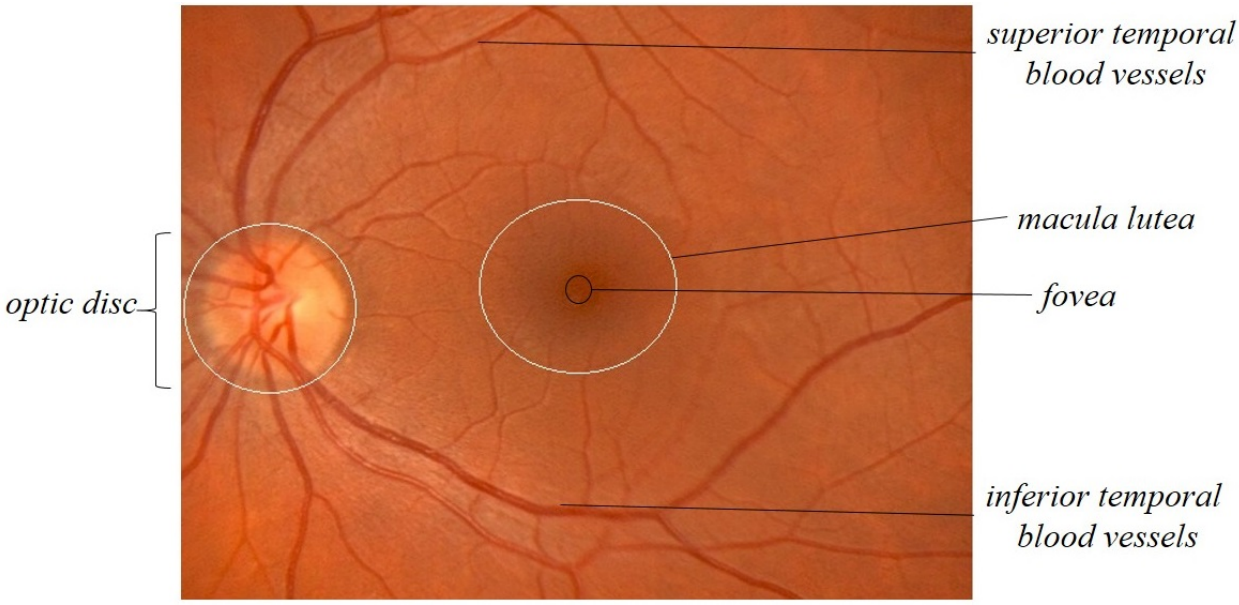


Fig. 13. Photograph of the eye fundus

Because the optic disc lacks rod and cone cells, it is a blind spot. The macula lutea is a yellow pigmented region of the retina and contains the highest concentration and most precisely ordered arrangement of visual elements. Its yellowish color is due to the presence of a yellow pigment known as xanthophyll. The macula lutea contains approximately 17,000 cones and also includes rods at its periphery. This region lacks blood vessels.

Retinal pigment epithelium is the outer layer of the retina which consists of a single layer of cuboidal cells with the width of about 14 μm and the height of 10 to 14 μm. The pigment epithelium serves to shield the retinal cells from substances present in the bloodstream, contributes to restoring photosensitivity to visual pigments, and is responsible for phagocytosis and disposing of membranous discs from the rods and cones. Additionally, it absorbs light passing through the neural retina to prevent reflection and resultant glare.

The neural retina comprises various neurons and supporting cells (Table 3).

Table 3. Cells of the neural retina

Type of cells	Name of cells
Photoreceptor cells	rods cones
Conducting neurons	bipolar neurons ganglion cells
Association neurons	horizontal neurons centrifugal neurons interplexiform neurons amacrine neurons
Supporting (neuroglial) cells	Müller's cells microglial cells astrocytes

Rods and **cones** are the two types of photoreceptors in the retina. Cones are predominantly located in the fovea centralis and are responsible for color perception and fine detail. Rods are concentrated at the periphery of the fovea and function in peripheral and dim light vision. In the human eye, there are approximately 120 million rods and 7 million cones.

Each photoreceptor consists of three parts:

- the outer segment;
- the inner segment;
- the connecting stalk.

The outer segment is conical (for cones) or cylindrical (for rods). The connecting stalk includes a cilium composed of nine peripheral microtubule doublets extending from a basal body. The inner segment comprises:

- an outer ellipsoid;
- an inner myoid portion.

The outer segment is the site of photosensitivity, while the inner segment contains the metabolic machinery that supports the photoreceptor cell functions. The outer segment is considered a highly modified cilium as it

connects to the inner segment through a short connecting stalk containing a basal body (Fig. 14).

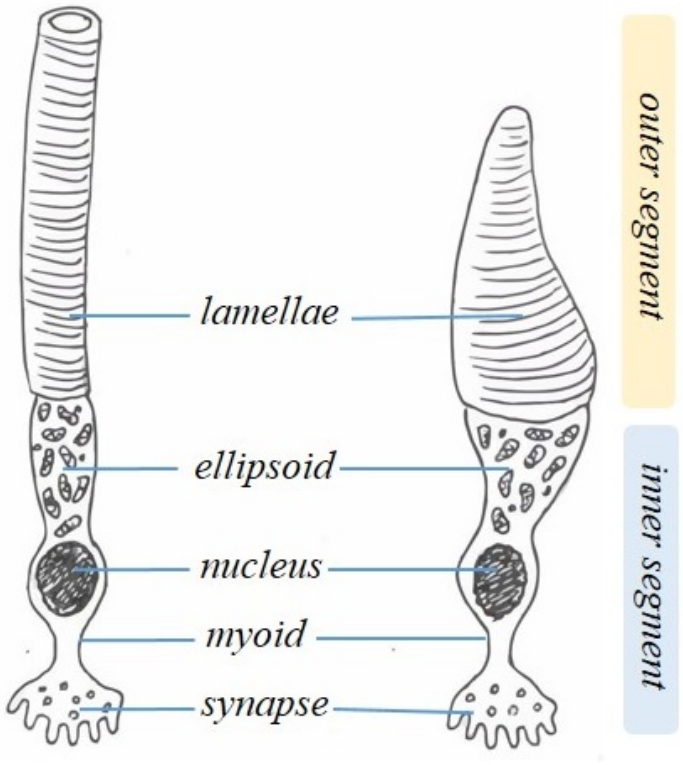


Fig. 14. Scheme of the rod and the cone

Rod cells contain the visual pigment rhodopsin, while cone cells contain the visual pigment iodopsin. **Rhodopsin** (also known as visual purple) in rod cells initiates the visual stimulus when it is bleached by light. In cone cells, the visual pigment found on membranous discs is called **iodopsin**. Each cone cell is specialized to respond maximally to one of three colors: red, green, or blue. Both rhodopsin and iodopsin consist of a membrane-bound subunit called opsin and a second small light-absorbing component known as chromophore. Rods contain scotopsin as their opsin, and cones contain photopsins. The chromophore in rods is a vitamin A-derived carotenoid called retinal, emphasizing the importance of vitamin A for normal vision. Prolonged dietary deficiency of vitamin A can lead to night blindness.

Cones are categorized into three classes:

- long-wavelength L cones, responsible for red vision,
- middle-wavelength M cones, responsible for green vision,
- short-wavelength S cones, responsible for blue vision.

Each class of cones contains a distinct visual pigment molecule that is activated by absorption of light in the blue spectrum (420 nm), green spectrum (531 nm), and red spectrum (588 nm).

Clinical correlation: color blindness (Fig. 15).

There are three types of color blindness: protanopia, deuteranopia, and tritanopia. Protanopia results from a defect in L cones, deuteranopia is characterized by a defect in M cones, and tritanopia is associated with a defect in S cones.

Protanopia and deuteranopia are sex-linked disorders due to the genes encoding L and M cone photoreceptor proteins residing on the X chromosome. Tritanopia, on the other hand, is an autosomal disorder caused by a mutation in a single gene encoding S cone photoreceptor proteins located on chromosome 7.

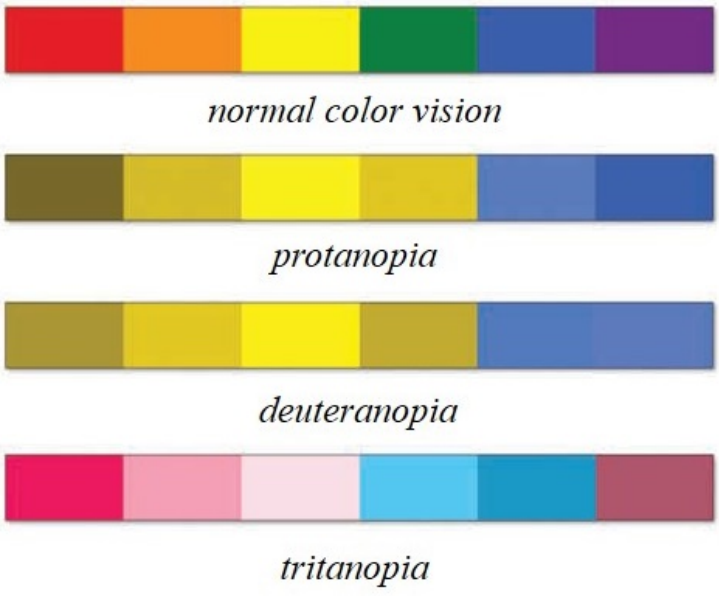


Fig. 15. Charts of six-color spectrum in normal color vision and in individuals with the three types of color blindness

Bipolar cells, along with their processes, extend to both the inner and outer plexiform layers. In the peripheral regions of the retina, the axons of bipolar cells pass to the inner plexiform layer, where they synapse with multiple ganglion cells.

Ganglion cells are large multipolar cells, measuring about 30 μm in diameter; they are characterized by a well-defined chromatophilic substance. The dendrites of ganglion cells receive input from the central processes of association neurons, while their axons extend to the brain as part of the optic nerve. These nerve cells possess lightly staining round nuclei with prominent nucleoli and Nissl bodies in their cytoplasm.

Müller's cells are supporting glial cells that offer trophic and anti-oxidative support to photoreceptors and neurons. The processes of these cells form the inner and outer limiting membranes. The inner limiting membrane represents the basal lamina of the Müller cells, serving to separate the retina from the vitreous body.

Horizontal cells are retinal neurons that form a network beneath the photoreceptors. They play a critical role in contrast signaling by averaging visual activity over space and time.

Amacrine cells are a type of association neurons located in the inner plexiform layer of the retina.

Horizontal and amacrine cells lack axons or dendrites but instead possess neuritic processes that conduct signals bidirectionally. Nuclei of these cells contribute to the inner nuclear layer. Horizontal cells give rise to neurites that end on cone pedicles, with a single branching neurite synapsing with both rod spherules and cone pedicles. These neuritic synapses occur in the outer plexiform layer of the retina, indicating that horizontal cells integrate the input from cones and rods in adjacent areas of the retina.

Amacrine cells are situated at the inner edge of the inner nuclear layer, and they possess a single neuritic process that branches to establish

connections between the axonal terminals of bipolar cells and the dendritic branches of ganglion cells (Fig. 16).

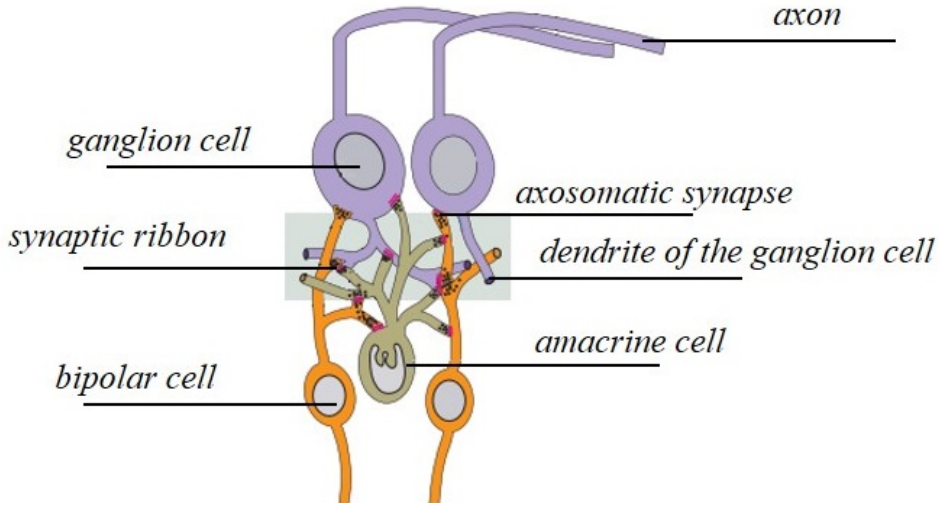


Fig. 16. Connection between the amacrine cell and conducting neurons

The layers of the retina, as observed in the photomicrograph, are represented in Fig. 1. Axons of the cones and rods project into the outer plexiform layer and synapse with dendrites of the bipolar cells. Nuclei of the bipolar cells contribute to the inner nuclear layer. Axons of the bipolar cells synapse with dendrites of the ganglion cells in the inner plexiform layer. Axons of the ganglion cells become a part of the optic nerve. Müller cells span most of the retina. The inner limiting membrane represents their basal lamina. Their nuclei form a part of the inner nuclear layer. The outer limiting membrane corresponds to junctional complexes (zonula adherens) between rods, cones, and Müller cells. Horizontal cells synapse with several rods and cones. Amacrine cells synapse with axons of bipolar cells and dendrites of ganglion cells.

In this way, the following layers of the retina can be distinguished, from the outer to the inner region (Fig. 17):

- pigment epithelium;
- layer of rods and cones;

- outer limiting membrane;
- outer nuclear layer;
- outer plexiform layer;
- inner nuclear layer;
- inner plexiform layer;
- ganglion cell layer;
- nerve fiber layer;
- inner limiting membrane.

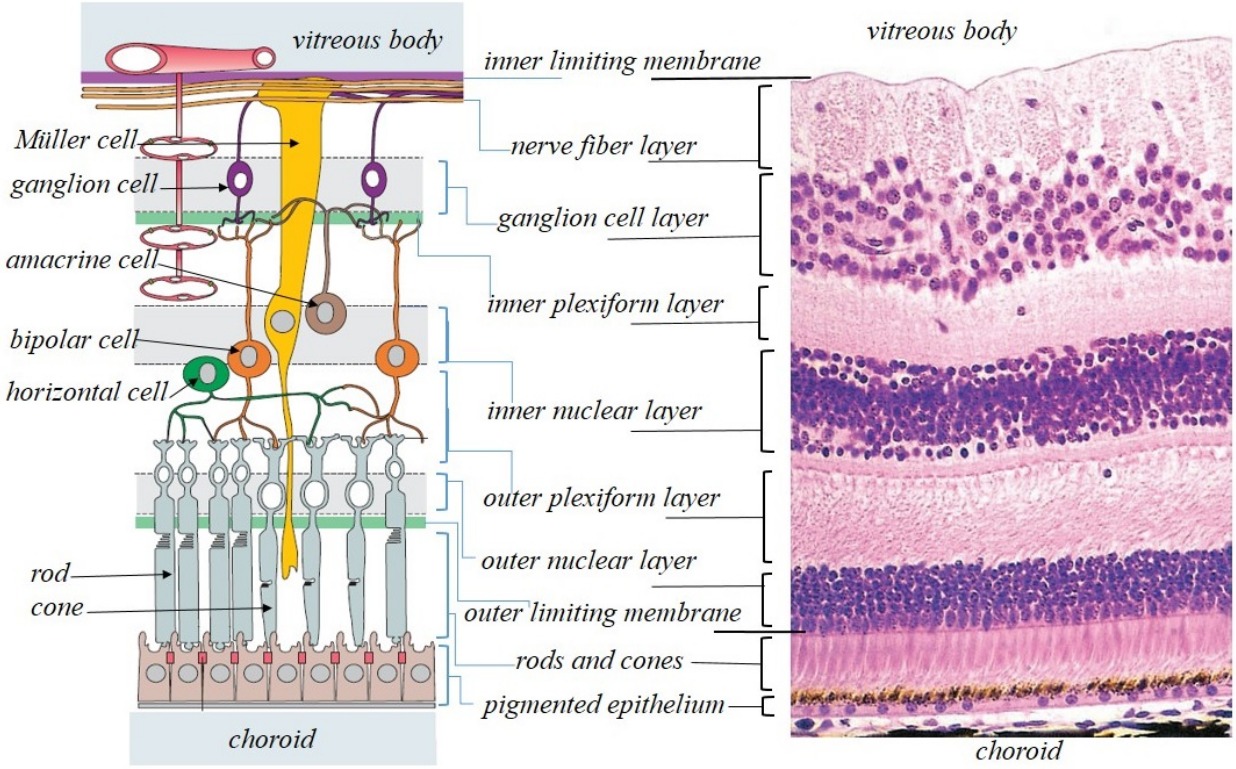


Fig. 17. Scheme and photomicrograph [1] of the retina. H&E, x150

Clinical correlation: retinitis pigmentosa (Fig. 18).

Retinitis pigmentosa (RP) encompasses various inherited defects of the retina that lead to blindness. The initial symptom of RP is night blindness, which results from degeneration of rod photoreceptor cells. Blood supply to the retina decreases, and pigment is observed on the retinal surface, hence the name “retinitis pigmentosa”. RP genes are located on the X chromosome and

chromosome 3. The gene for the visual pigment rhodopsin also maps to the same chromosome 3 region, and mutations in the rhodopsin gene can cause RP. Peripherin, a protein component of rods, is encoded by a gene within the RP family on chromosome 6.

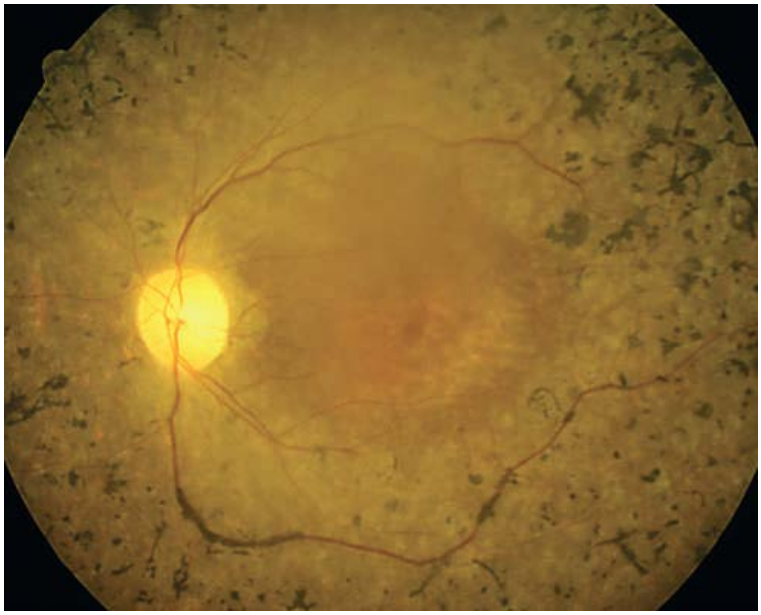


Fig. 18. Photograph of the eye fundus of a patient with retinitis pigmentosa (moderate changes) [3]

Fovea centralis and optic disk

The fovea centralis, surrounded by the macula lutea, is a specialized area of the retina for accurate vision under normal and dim illumination. The optic disk, which includes the optic papilla, is not suitable for vision.

The fovea centralis is located on the temporal side of the optic disk and is surrounded by the macula lutea. This area contains abundant cones but lacks rods and capillaries (Fig. 19, 20). The cones synapse with the bipolar cells, both oriented at an angle around the margins of the fovea. This histologic feature enables free access of light to the photoreceptors.

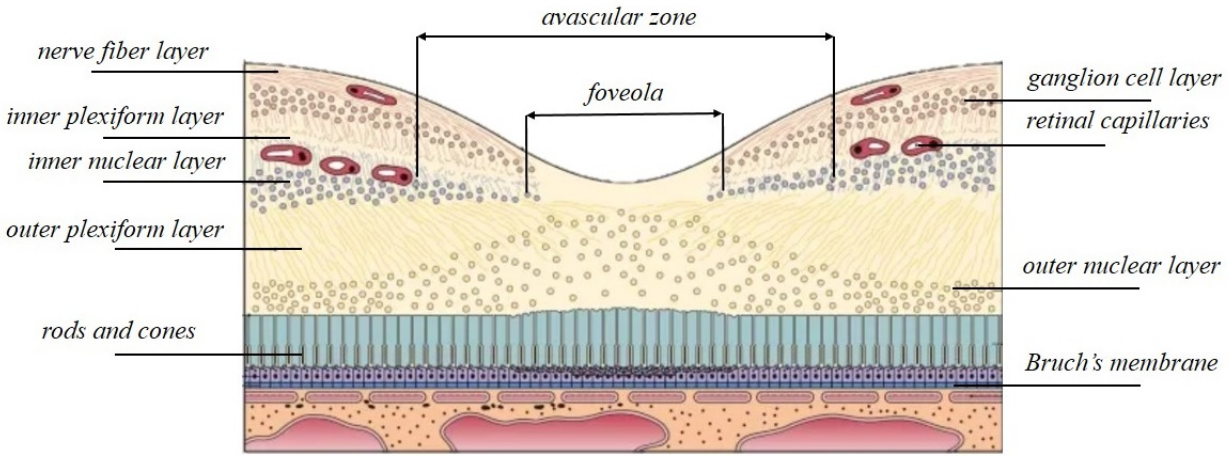


Fig. 19. Cross-section of the fovea

https://entokey.com/acquired-macular-disorders-2/

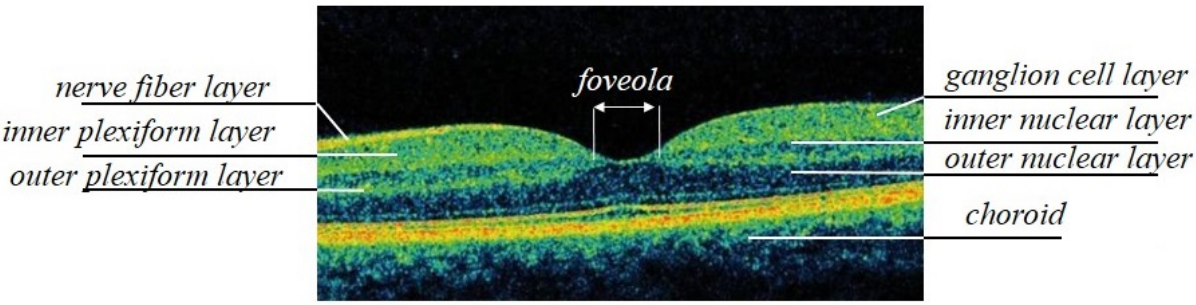


Fig. 20. OCT photograph of the macula lutea zone

Clinical correlation: age-related macular degeneration (Fig. 21).

Age-related macular degeneration (AMD) occurs when photoreceptor cells and the retinal pigment epithelium at the macula break down (dry AMD) or when abnormal blood vessels grow under the macula. New blood vessels leak blood and fluid, causing the macula to detach from its close association with the choriocapillaris (wet AMD). Damage to the macula occurs rapidly, and vision loss is painless in either form of AMD. The primary risk factor is age (over 60 years), and one of the most common early signs of dry AMD is drusen.

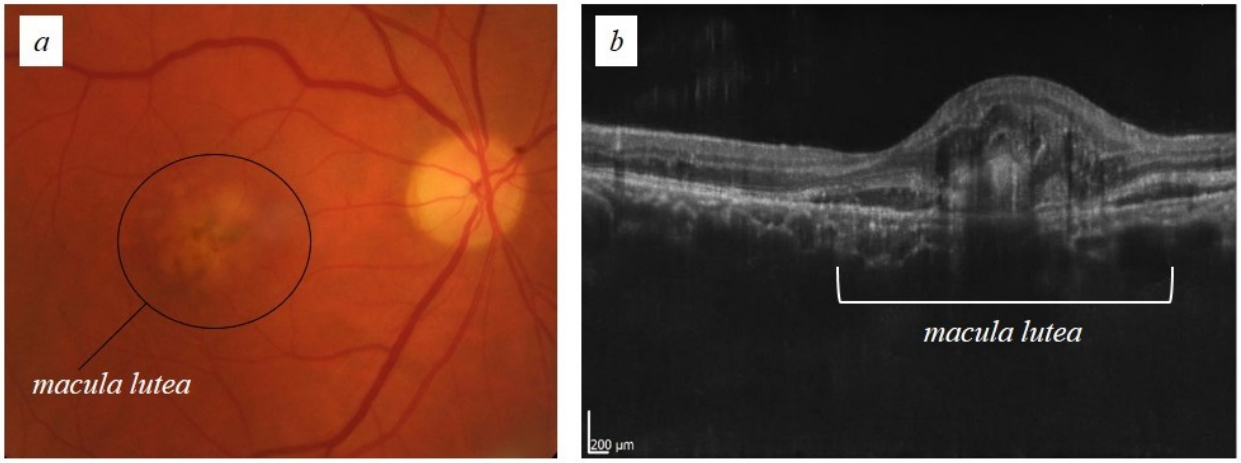


Fig. 21. Photograph (a) of the eye fundus and optical coherence tomography (b) of the macula lutea zone of the patient with age-related macular degeneration, wet stage

The exit site from the retina for axons derived from ganglion cells is represented by the optic disk.

The optic disk includes (Fig. 22):

- The optic papilla, a protrusion formed by the axons entering the optic nerve.
- The lamina cribrosa of the sclera.

Photoreceptors terminate at the edges of the optic disk, representing the blind spot of the retina. The central artery and vein of the retina pass through the optic disk.

The axons of the ganglion cells turn into the optic nerve at the optic disk, which lacks photoreceptors and corresponds to the blind spot of the retina. The optic disk has a central depression, known as the optic cup, which appears pale in comparison to the surrounding nerve fibers. In cases of glaucoma, the loss of nerve fibers results in enlargement of the optic cup area.

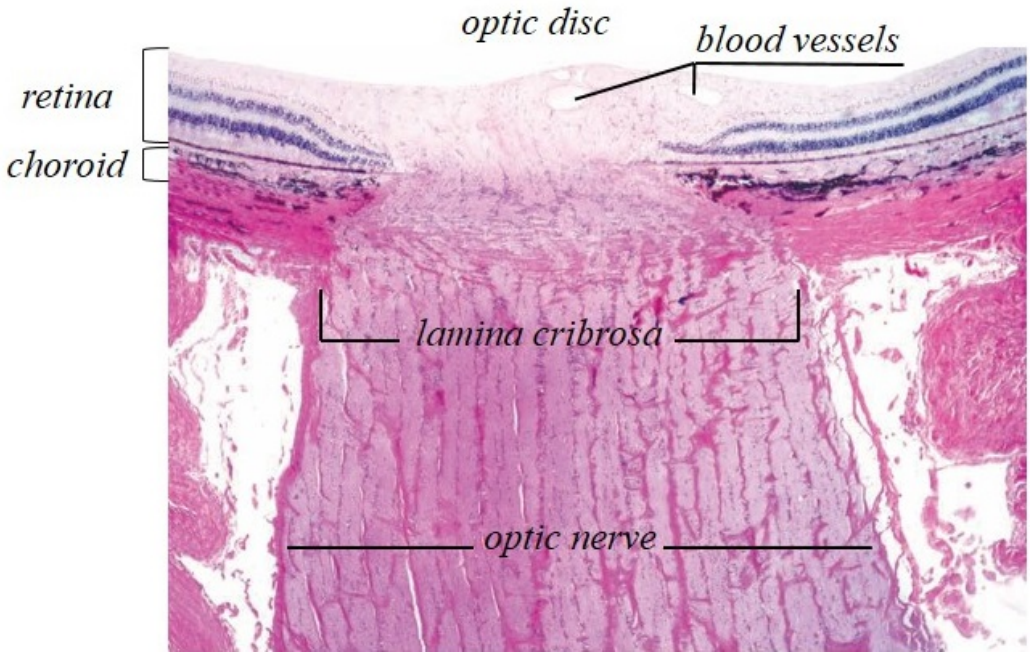


Fig. 22. Photomicrograph of the optic disc. H&E, x65 [2]

Lens

The lens is a transparent, biconvex, elastic, and avascular structure. Its functions are to transmit and focus light onto the retina.

The lens has the following characteristics:

- the diameter is about 9.0–10.0 mm in adults;
- the thickness is 4.0–5.0 mm;
- the mean power in newborns is 45D, which decreases to 25D by the age of 6 years;
- the refractive index of the cortex is 1.386, and the refractive index of the nucleus is 1.406.

The lens consists of a series of concentric shells or layers forming the lens substance. The inner part of the lens is the nucleus, and the outer part is the cortex. The anterior epithelium has a single layer of epithelial cells and is the source of new lens cells. The posterior epithelium disappears early in the formation of the lens. The anterior epithelium and lens substance are

enclosed by the lens capsule, and there is no epithelial cell layer under the posterior surface of the capsule.

The lens capsule is a thick, flexible, acellular, and transparent basement membrane-like structure containing type IV collagen fibrils and a glycosaminoglycan matrix. Beneath the anterior portion of the capsule is a single layer of cuboidal epithelial cells that extend posteriorly up to the equatorial region.

At the equatorial region of the lens, cells begin to elongate and rotate so that their longitudinal axes are parallel to the cortical surface, and they begin to divide by mitosis (Fig. 23).

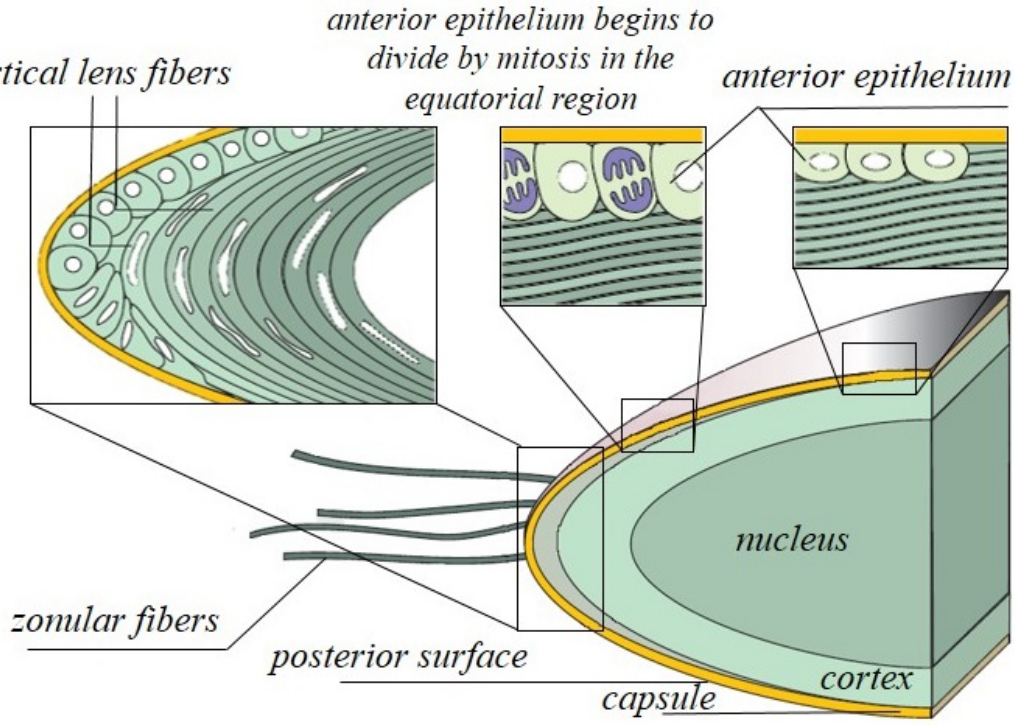


Fig. 23. The scheme of the lens structure

Clinical correlation: cataract (Fig. 24).

Cataracts are opacities of the lens caused by changes in the solubility of lens proteins as they age. This condition results in high light scattering by the aggregated filensin and crystallins, impairing accurate vision. Cataracts can be cortical, nuclear, or posterior subcapsular. Most age-related cataracts are

cortical cataracts, and they absorb and scatter more light than the normal regions of the lens, producing increased light spread and decreased contrast in the retinal image. This leads to reduced visual acuity.

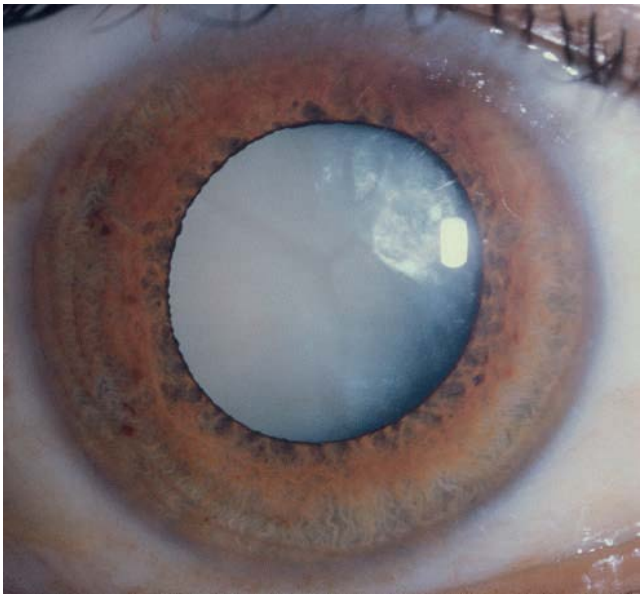


Fig. 24. Photomicrograph of dense cortical cataract [3]

Vitreous body

The vitreous body occupies a large vitreous chamber located behind the lens. It consists of a transparent, gel-like connective tissue that is 99% water (known as vitreous humor), with collagen fibrils and hyaluronate contained within an external lamina called the vitreous membrane. The only cells present in the vitreous body are a small mesenchymal population located near the membrane called hyalocytes, which synthesize hyaluronate and collagen, along with a few macrophages.

Collagens of the vitreous body:

- type II;
- type V;
- type XI;
- type IX;

- type XVIII.

Noncollagenous components of the vitreous body:

- fibrillin;
- fibronectin;
- opticin;
- tenascin.

Collagen II, together with collagens V/XI, and IX, forms the dominant fibrillar network of the extracellular matrix in the vitreous body, which is responsible for the gel-like nature of the vitreous humor. Many other extracellular matrix proteins, such as fibronectin, tenascin, and opticin, are noncovalently associated with these collagen fibrils.

Water-binding components of the vitreous body consist of highly charged glycosaminoglycans that exist either by themselves (e.g., hyaluronic acid) or are covalently connected to the core proteins of collagen IX and versican, the two chondroitin sulfate proteoglycans found in the vitreous body. The gelatinous nature and high water content of the vitreous body are responsible for its transparency and enable the passage of light to the retina. Additionally, a high water concentration within the vitreous body gel helps to buffer the interior of the eye, presses the retina against the pigment epithelium, and creates the intraocular pressure that supports eye expansion during ocular development.

The hyaloid canal (also known as Cloquet's canal or Stilling's canal), which may not always be visible, runs through the center of the vitreous body from the optic disc to the posterior lens capsule. It represents the remnant of the pathway of the hyaloid artery during eye development. In the fetus, the hyaloid artery supplies blood to various parts of the eye, traveling through the optic nerve head to the posterior aspect of the lens, where it branches into the tunica vasculosa lentis (Fig. 25). During normal development at around 30 weeks of gestational age, this blood supply is reabsorbed and forms the Cloquet's (hyaloid) canal. Incomplete resorption of these structures during

development can result in persistent fetal vasculature, leading to conditions like the Mittendorf dot and the Bergmeister papilla. It is suspected that defects in genes guiding cell apoptosis result in persistent fetal vasculature.

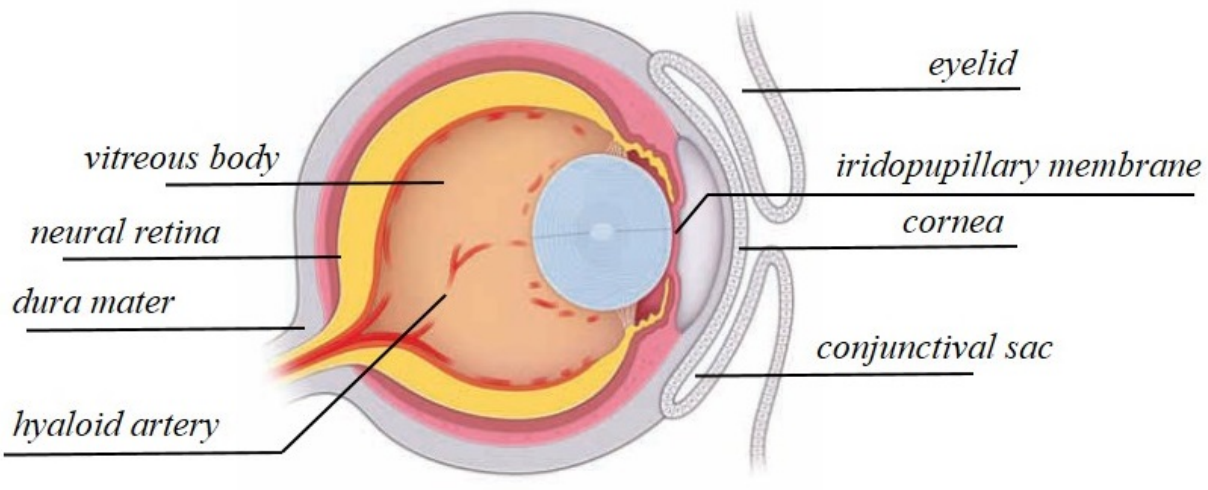


Fig. 25. Scheme illustrating the development of the eye [2]

Clinical correlation: asteroid hyalosis (Fig. 26).

Asteroid hyalosis is a common degenerative process in which calcium pyrophosphate particles collect within the vitreous gel. It is seen clinically as numerous tiny round yellow – white opacities of varying size and density. These move with the vitreous body during eye movements but do not sediment inferiorly when the eye is immobile.

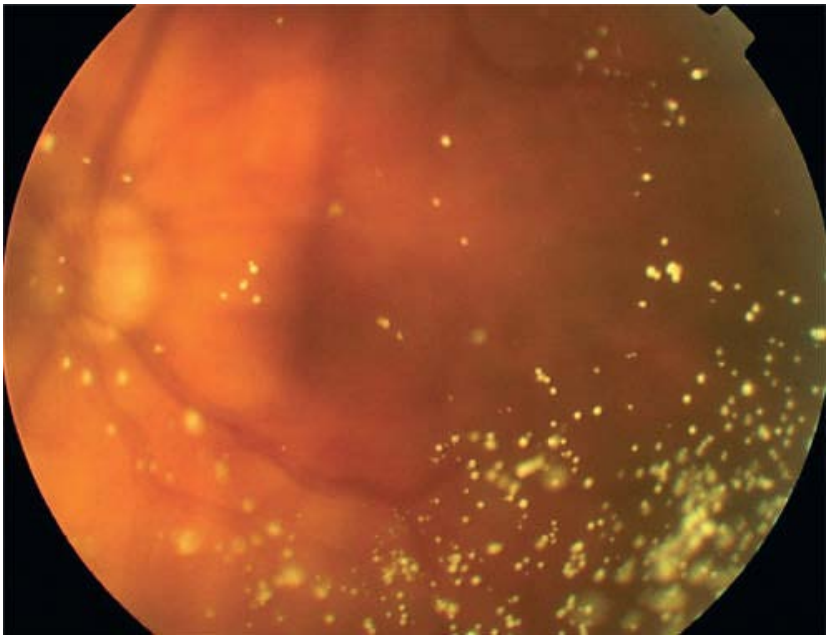


Fig. 26. Photomicrograph of asteroid hyalosis [3]

ACCESSORY STRUCTURES OF THE EYE

Eyelid

The eyelid is an adnexa of the eye, and its primary function is the protection of the eye globe.

Each eyelid consists of two portions:

- an outer cutaneous portion;
- an inner conjunctival portion.

The outer cutaneous portion is lined by a stratified squamous epidermis that overlies a loose connective tissue dermis and the orbicularis oculi muscle. The cutaneous portion contains several skin appendages, including:

- sweat and sebaceous glands;
- the eyelashes at the eyelid margins.

Eyelashes are associated with modified sweat glands known as the **glands of Moll**.

Facing the conjunctival lining is the tarsal plate, a fibroelastic dense connective tissue containing large sebaceous tarsal glands, also known as Meibomian glands. Each tarsal gland opens at the margin of the eyelid and is responsible for the rigidity of the eyelids.

Tarsal glands (also known as **Meibomian glands**) secrete a lipid-containing product that retards evaporation of the tear film (Fig. 27). Tears are produced by the lacrimal gland to protect the cornea. Infection and disruption of the walls of the tarsal glands can lead to the development of a chalazion.

Glands of Zeis are modified sebaceous glands associated with lash follicles.

Eccrine sweat glands are distributed throughout eyelid skin and are not confined to the lid margin, in contrast to the glands of Moll.

Pilosebaceous units comprise hair follicles and their sebaceous glands.

The conjunctiva is continuous with the skin lining and extends up to the periphery of the cornea.

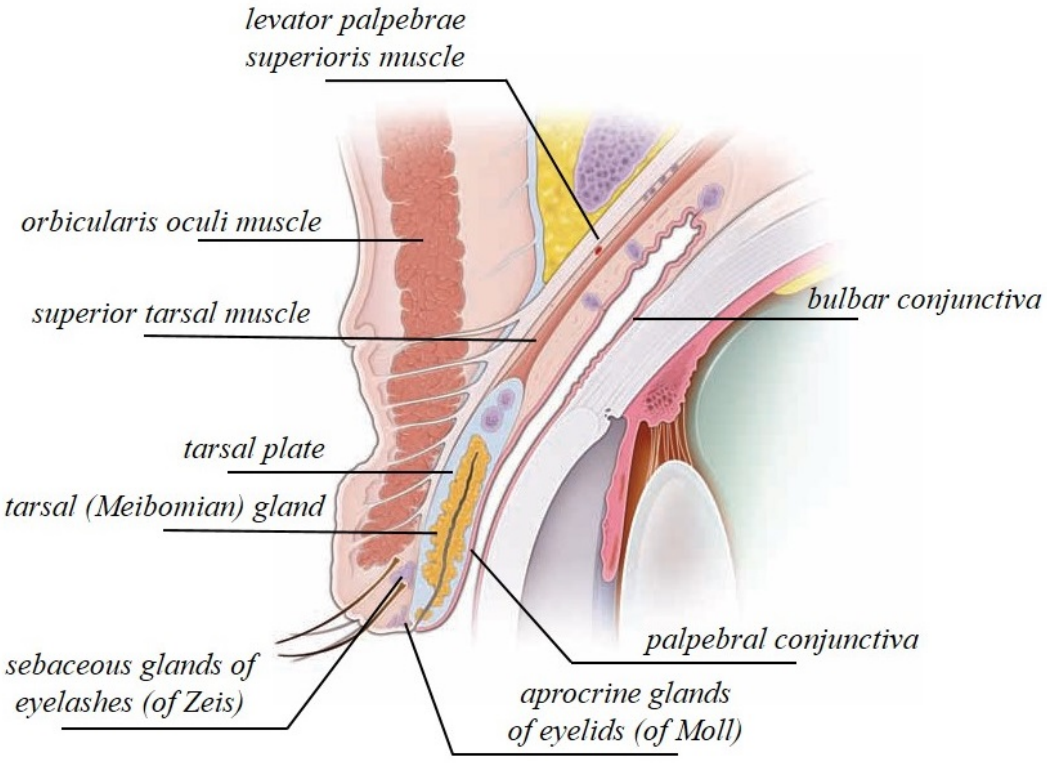


Fig. 27. The scheme of eyelid anatomy

Clinical correlation: chalazion (Fig. 28).

A chalazion is a sterile chronic granulomatous inflammatory lesion (lipogranuloma) of the Meibomian or sometimes Zeis glands, caused by retained sebaceous secretions. Histopathology reveals a lipogranulomatous chronic inflammatory pattern with extracellular fat deposits surrounded by lipid-laden epithelioid cells, multinucleated giant cells, and lymphocytes.

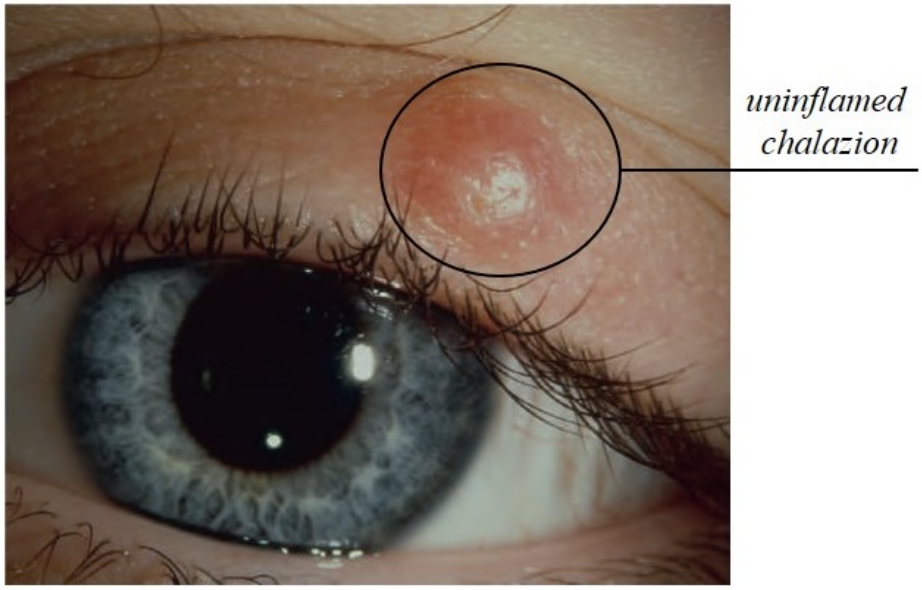


Fig. 28. Photograph of the eye with uninflamed chalazion [3]

Conjunctiva

The conjunctiva is a mucous membrane composed of stratified squamous-to-columnar epithelium with mucus-secreting goblet cells, supported by a thin lamina propria. It lines the anterior surface of the eyeball up to the limbus (known as bulbar conjunctiva) and the inner surface of the eyelid (referred to as palpebral conjunctiva). Continuous exposure to dust, wind, and sun can lead to the development of pinguecula, characterized by the proliferation of subconjunctival connective tissue stroma and yellow thickening of the bulbar conjunctiva.

The conjunctiva is a transparent mucous membrane that lines the inner surface of the eyelids and the anterior surface of the globe, terminating at the

corneoscleral limbus. It is richly vascular, supplied by the anterior ciliary and palpebral arteries, and features a dense lymphatic network with drainage to the preauricular and submandibular nodes, corresponding to the drainage pattern of the eyelids. It plays a vital role in protecting the eye, mediating both passive and active immunity.

Anatomically, the conjunctiva can be divided into three parts:

- the palpebral conjunctiva;
- the fornix conjunctiva;
- the bulbar conjunctiva.

The palpebral conjunctiva starts at the mucocutaneous junction of the lid margins and is firmly attached to the posterior tarsal plates. The tarsal blood vessels are vertically oriented. The fornix conjunctiva is loose and redundant. The bulbar conjunctiva covers the anterior sclera and is continuous with the corneal epithelium at the limbus.

Histologically (Fig. 29), the conjunctiva comprises the superficial epithelium, the basal epithelium, the adenoid layer, the fibrous layer, and the conjunctiva-associated lymphoid tissue (CALT). The epithelium is non-keratinized and approximately five cell layers deep.

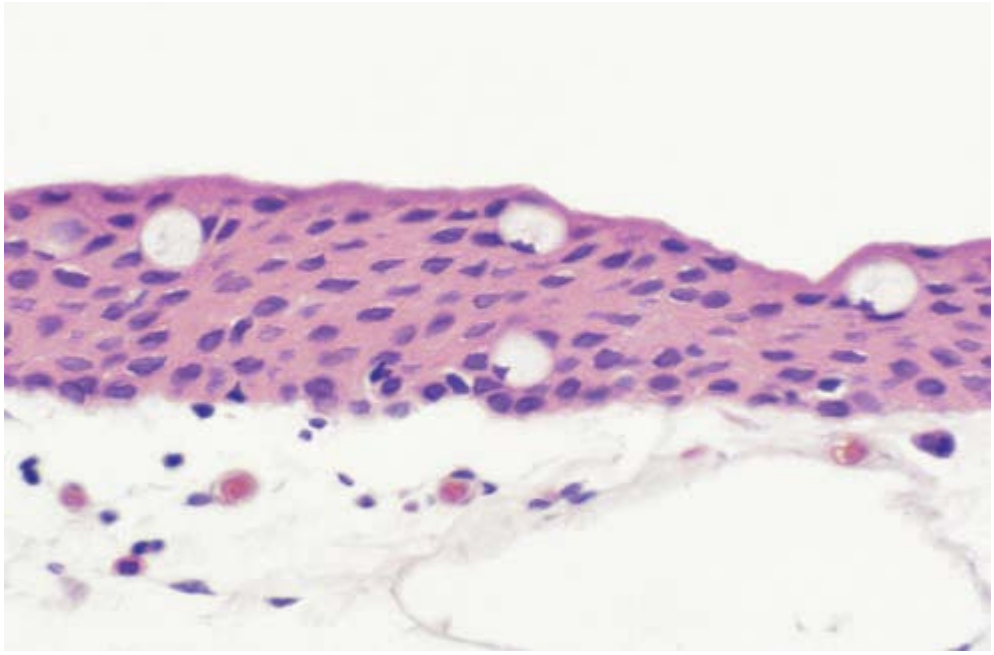


Fig. 29. Photomicrograph of the conjunctiva. *H&E, x65 [3]*

The adenoid layer and the fibrous layer, known as the substantia propria, are separated from the basal epithelium by a thin basement membrane (Fig. 30). The stroma (substantia propria) consists of richly vascularized loose connective tissue. The accessory lacrimal glands of Krause and Wolfring are located deep within the stroma.

CALT plays a crucial role in initiating and regulating ocular surface immune responses. It includes lymphocytes within the epithelial layers, lymphatics, and associated blood vessels, along with a stromal component consisting of lymphocytes and plasma cells, including follicular aggregates.

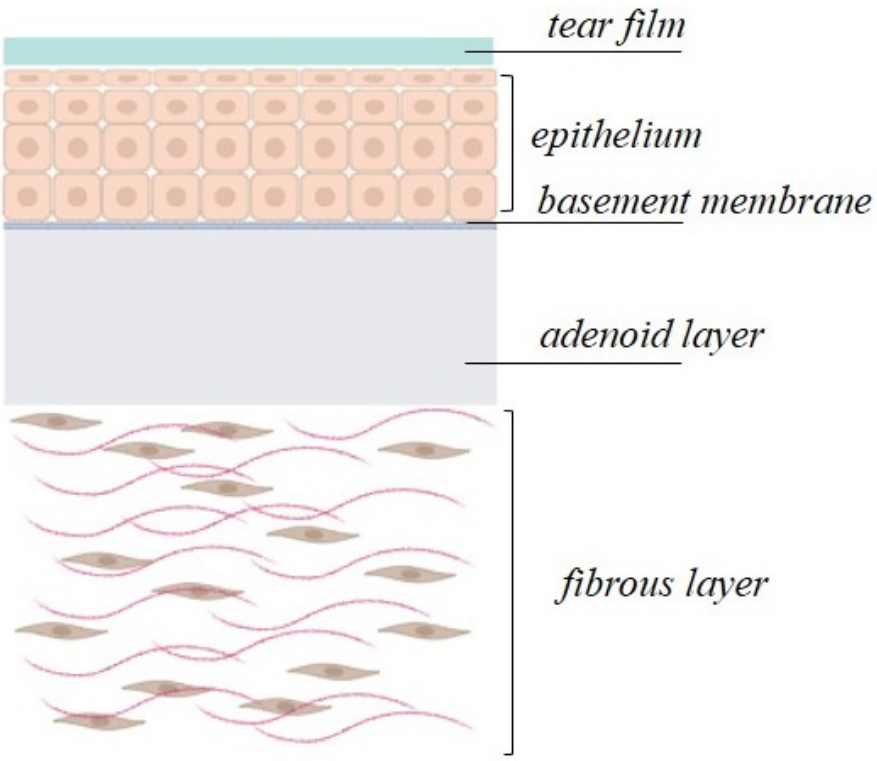


Fig. 30. Schematic diagram showing the histological layers of the conjunctiva

Clinical correlation: chemosis (Fig. 31).

Chemosis, or conjunctival edema, presents as a translucent swelling that may protrude through the eyelids. Acute chemosis typically indicates a hypersensitivity response, such as exposure to pollen, but can also occur in cases of severe infective conjunctivitis.

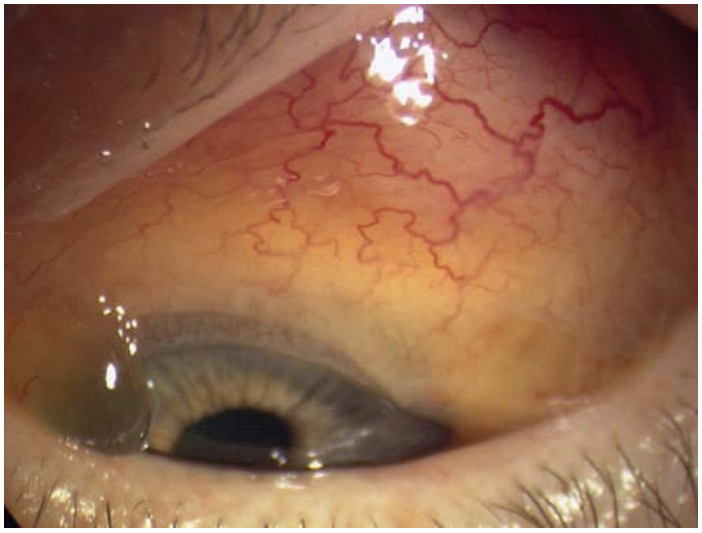


Fig. 31. Photograph of the eye with chemosis

The lacrimal gland

The lacrimal gland is an exocrine gland responsible for secreting the aqueous layer of the tear film.

This gland produces tears, a fluid that initially accumulates in the conjunctival sac before draining into the nasal cavity through a drainage duct known as the nasolacrimal duct.

The lacrimal gland is a tubuloacinar serous gland with myoepithelial cells (Fig. 32). It is organized into separate lobes, each with 12 to 15 independent excretory ducts. Tears enter the excretory canaliculi through the puncta and eventually reach the nasolacrimal sac and duct, where they ultimately drain into the inferior meatus within the nasal cavity.

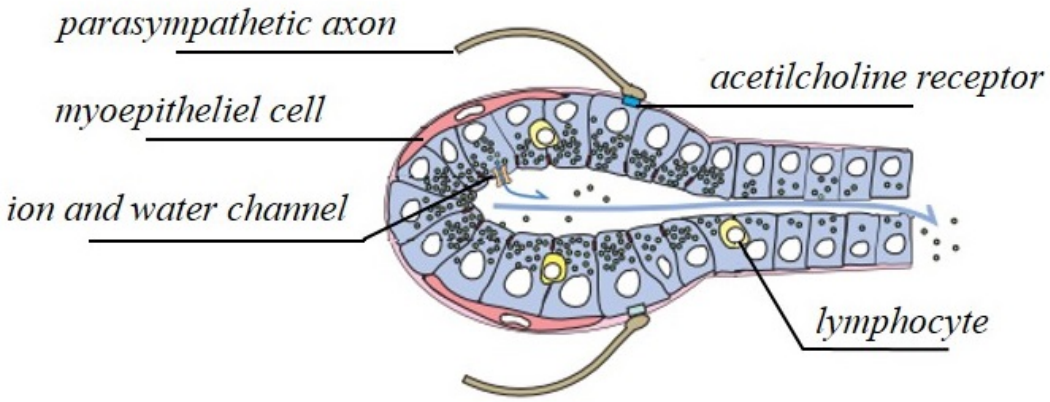


Fig. 32. The scheme of the lacrimal gland structure

Lacrimal glands receive neural input from two sources:

- Parasympathetic nerve fibers that originate in the pterygopalatine ganglion; glandular cells have acetylcholine receptors that respond to acetylcholine released at the nerve terminals.
- Sympathetic nerve fibers arising from the superior cervical ganglion.

Clinical correlation: dry eye syndrome.

Alterations in tear composition or inadequate tear production can lead to dry eye syndrome, a common condition that often results in eye irritation, light sensitivity, and blurred vision. It is frequently associated with advanced age, menopause in women, and side effects of certain medications. Severe dry eye can occur in patients with Sjögren syndrome, a chronic autoimmune disease affecting multiple organs.

Tears

Tears protect the corneal epithelium and contain antibacterial and UV-protective agents. They play a crucial role in keeping the conjunctiva and corneal epithelium moist while also helping to wash away foreign materials as they flow across the corneal surface toward the medial angle of the eye.

The thin film of tears that covers the corneal surface is not homogeneous but instead consists of a mixture of products secreted by various sources, including the lacrimal glands, accessory lacrimal glands, goblet cells of the conjunctiva, and tarsal glands of the eyelid.

The tear film contains:

- proteins (tear albumins, lactoferrin);
- enzymes (lysozyme);
- lipids;
- metabolites;
- electrolytes;
- medications, which can be introduced during therapy and secreted with tears.

Lactoferrin, a cationic protein in tears, enhances the activity of various antimicrobial agents, such as lysozyme.

The tear film is organized into three distinct layers (Fig. 33):

- the lipid layer;
- the aqueous layer;
- the mucous layer.

The lipid layer is secreted by the meibomian glands, while the aqueous layer is produced by the lacrimal glands. The mucous layer is secreted by conjunctival goblet cells.

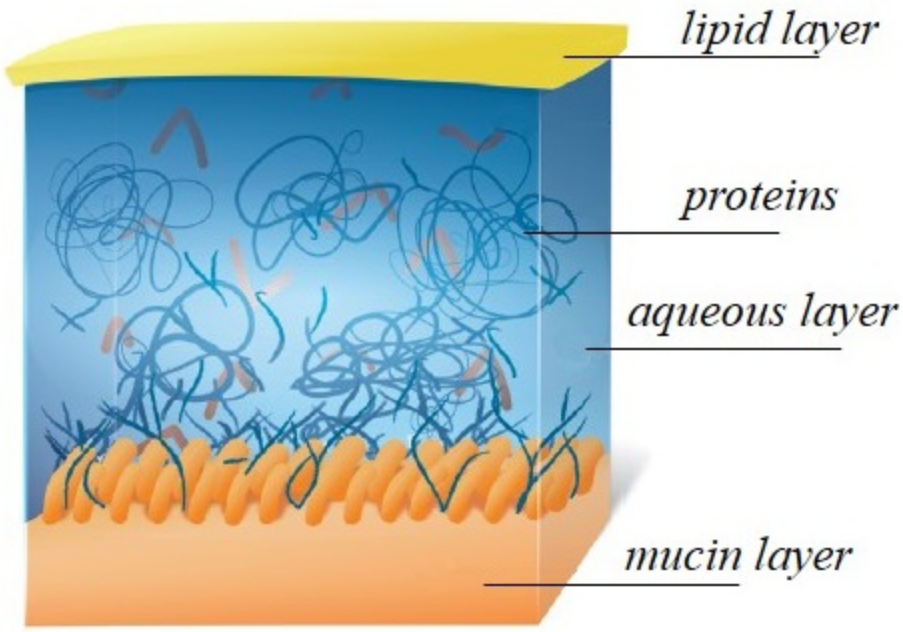


Fig. 33. Cross-section of the tear film

https://oceanoptometry.ca/dry-eye-a-new-approach/

The outer lipid layer consists of a polar phase containing phospholipids adjacent to the aqueous – mucin phase and a non-polar phase containing waxes, cholesterol esters, and triglycerides. The polar lipids are bound to lipocalins within the aqueous layer. Lipocalins are small secreted proteins that can bind hydrophobic molecules and contribute to tear viscosity. Blinking plays a crucial role in releasing lipids from the glands. The thickness of this layer can be increased through forced blinking and reduced with infrequent blinking.

Functions of the lipid layer:

- preventing evaporation of the aqueous layer and maintaining tear film thickness;
- acting as a surfactant to enable the spread of the tear film;
- deficiency can result in evaporative dry eye.

The primary lacrimal glands produce about 95% of the aqueous component of tears, with the accessory lacrimal glands of Krause and

Wolfring contributing the remaining 5%. Tear secretion involves both basic (resting) and much greater reflex components. Reflex secretion occurs in response to corneal and conjunctival sensory stimulation, tear break-up, ocular inflammation, and is mediated via the fifth cranial nerve. It is reduced by topical anesthesia and decreases during sleep. Secretion can increase up to 500% in response to injury.

The aqueous layer consists of:

- water;
- electrolytes;
- dissolved mucins and proteins;
- growth factors produced by the lacrimal gland, with production increasing in response to injury;
- proinflammatory interleukins that accumulate during sleep when tear production is reduced.

Functions of the aqueous layer:

- providing atmospheric oxygen to the corneal epithelium;
- offering antibacterial protection through proteins like IgA, lysozyme, and lactoferrin;
- facilitating the removal of debris and noxious stimuli and supporting the transport of leukocytes after injury;
- optically enhancing the corneal surface by smoothing minute irregularities.

The mucous layer is made up of mucins, high-molecular-weight glycoproteins, which may be transmembrane or secretory in type. Secretory mucins are further classified as gel-forming or soluble. They are primarily produced by conjunctival goblet cells but are also produced by the lacrimal glands.

Superficial epithelial cells of the cornea and conjunctiva produce transmembrane mucins, forming their glycocalyx, an extracellular coating.

Staining of diseased epithelium with rose Bengal indicates the absence of transmembrane and gel mucous layers, leaving the cell surface exposed. Damage to epithelial cells can hinder normal tear film adherence.

Functions of the mucous layer:

- allowing for wetting by transforming the corneal epithelium from a hydrophobic to a hydrophilic surface;
- providing lubrication;
- deficiency of the mucous layer may be observed in cases of both aqueous deficiency and evaporative conditions. Goblet cell loss occurs in cicatrizing conjunctivitis, vitamin A deficiency, chemical burns, and medication toxicity.

The lacrimal drainage system

The lacrimal drainage system comprises several components (Fig. 34):

- the puncta;
- the canaliculi;
- the lacrimal sac;
- the nasolacrimal duct.

The puncta are located at the posterior edge of the lid margin, at the junction of the lash-bearing lateral five-sixths (pars ciliaris) and the medial non-ciliated one-sixth (pars lacrimalis). Normally, they face slightly posteriorly and can be examined by everting the medial aspect of the eyelids.

The canaliculi pass vertically from the lid margin for about 2 mm (ampullae). They then turn medially and run horizontally for about 8 mm to reach the lacrimal sac. The superior and inferior canaliculi usually (> 90% cases) unite to form the common canaliculus, which opens into the lateral wall of the lacrimal sac.

The lacrimal sac measures 10–12 mm in length and is situated in the lacrimal fossa, between the anterior and posterior lacrimal crests.

The nasolacrimal duct is 12–18 mm long and represents the inferior continuation of the lacrimal sac. It descends and angles slightly laterally and posteriorly to open into the inferior nasal meatus, located lateral to and below the inferior turbinate. The opening of the duct is partially covered by a mucosal fold, known as the valve of Hasner.

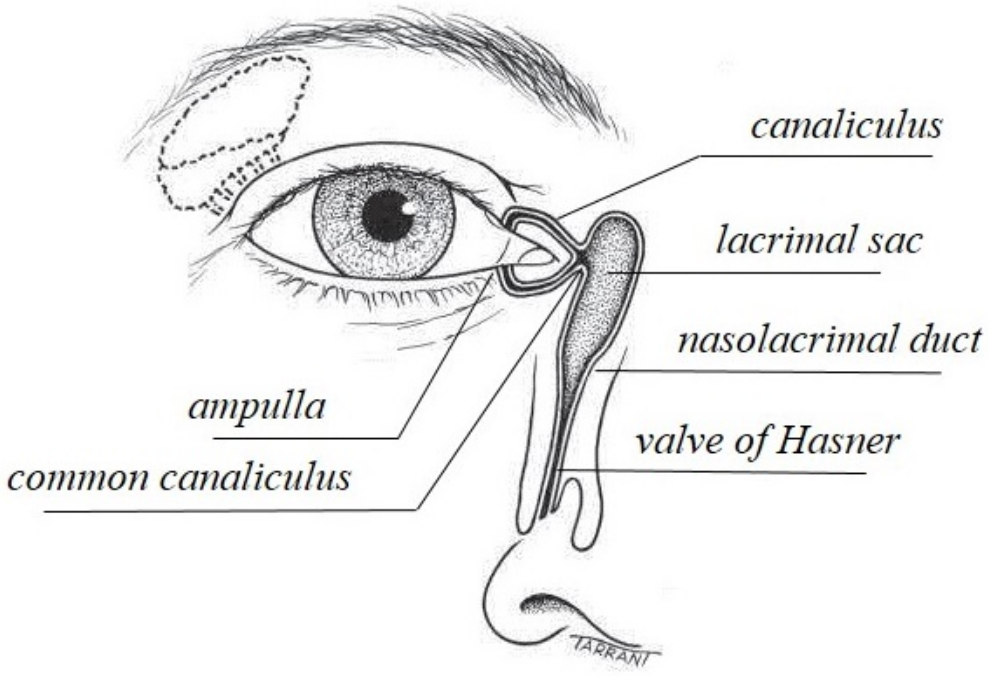


Fig. 34. Anatomy of the lacrimal drainage system [3]

Clinical correlation: epiphora.

Epiphora refers to the overflow of tears at the eyelid margin, and it can be attributed to two main mechanisms:

- hypersecretion, which is secondary to anterior segment diseases, such as dry eye or inflammation;
- defective drainage, resulting from compromised function within the lacrimal drainage system.

Defective drainage may be caused by various factors, including malposition, obstructions anywhere along the drainage system (from the punctal region to the valve of Hasner), and lacrimal pump failure. Lacrimal

pump failure can occur as a result of lower lid laxity or weakness in the orbicularis muscle.

The extrinsic muscles of eyeball (extraocular muscles)

The extraocular muscles are responsible for moving the eyeball and raising the upper eyelids.

The extraocular muscles include (Fig. 35, Table 4):

- the levator palpebrae superioris;
- superior rectus;
- inferior rectus;
- medial rectus;
- lateral rectus;
- superior oblique;
- inferior oblique.

Table 4. The extraocular muscles

Muscle	Innervation	Function
Levator palpebrae superioris	Oculomotor nerve [III] – superior branch	Elevation of upper eyelid
Superior rectus	Oculomotor nerve [III] – superior branch	Elevation, adduction, medial rotation of the eyeball
Inferior rectus	Oculomotor nerve [III] – inferior branch	Depression, adduction, lateral rotation of the eyeball
Medial rectus	Oculomotor nerve [III] – inferior branch	Adduction of the eyeball
Lateral rectus	Abducent nerve [VI]	Abduction of the eyeball
Superior oblique	Trochlear nerve [IV]	Depression, abduction, internal rotation of the eyeball
Inferior oblique	Oculomotor nerve [III] – inferior branch	Elevation, abduction, external rotation of the eyeball

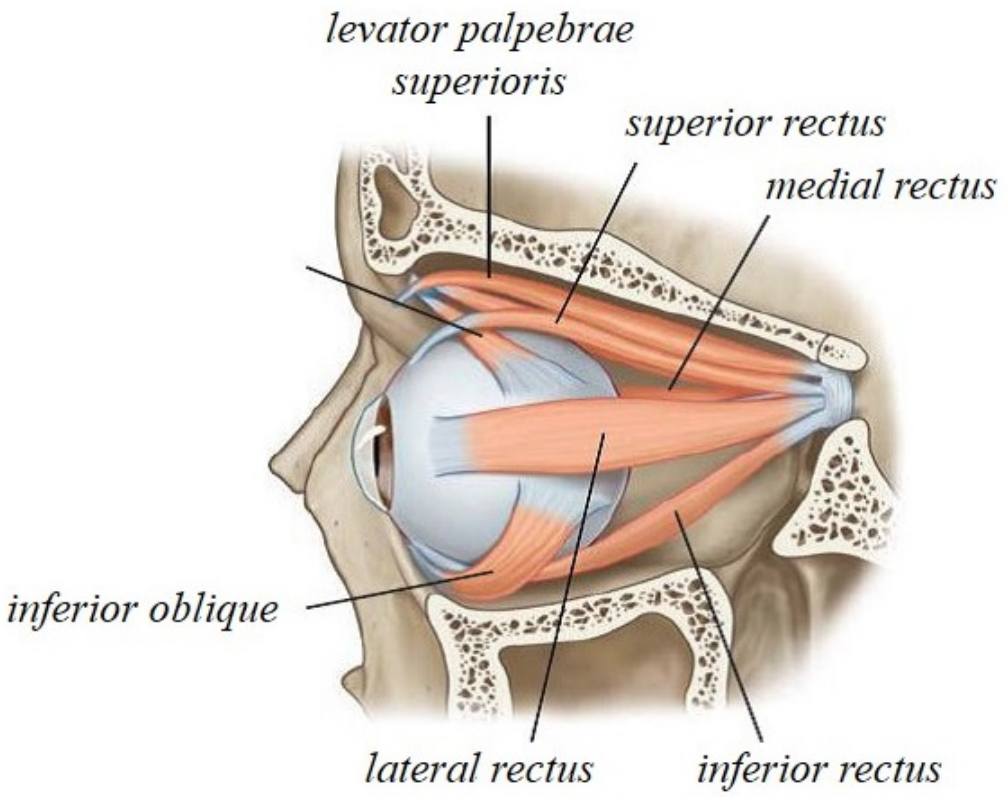


Fig. 35. Muscles of the eyeball

The movements of the eyeball include the following (Fig. 36):

- elevation – this movement raises the pupil superiorly;
- depression – this movement lowers the pupil inferiorly;
- abduction – this movement shifts the pupil laterally;
- adduction – this movement brings the pupil medially;
- internal rotation (intorsion) – this movement involves moving the upper part of the pupil medially (toward the nose);
- external rotation (extorsion) – this movement entails moving the upper part of the pupil laterally (toward the temple).

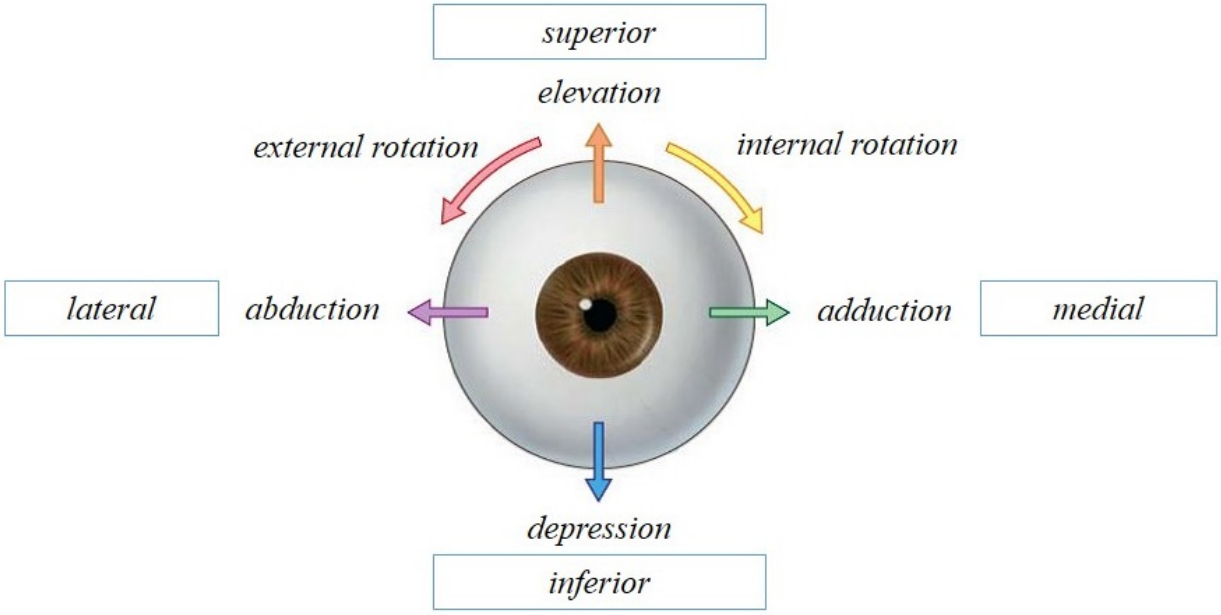


Fig. 36. Movements of the eyeball

Specific muscle movements are depicted in Figure 37.

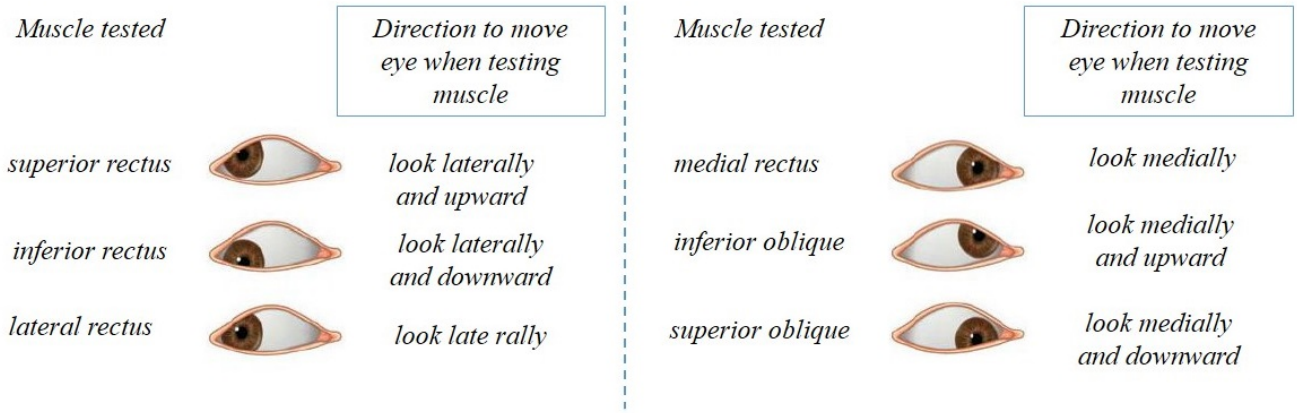


Fig. 37. Movements of the eye when testing specific muscles (clinical testing) [4]

BLOOD SUPPLY OF THE EYE

Arterial blood supply of the eye

The arterial blood supply of the eye originates from the internal carotid artery (*a. carotis interna*), which branches from the common carotid artery. Once it enters the cranial cavity, the internal carotid artery gives rise to a crucial branch – the ophthalmic artery (*a. ophthalmica*), which plays a pivotal role in providing nourishment to the eye structures.

The a. ophthalmica divides into several components:

- central retinal artery (*a. centralis retinae*);
- posterior short ciliary arteries (*aa. ciliares posteriores breves*);
- posterior long ciliary arteries (*aa. ciliares posteriores longae*);
- muscular arteries (*aa. musculares*).

The central retinal artery (*a. centralis retinae*) departs from the ophthalmic artery approximately 7–12 mm from the posterior pole of the eye. It enters deep into the optic nerve through the dura mater and proceeds toward the optic disc, as a single trunk without anastomoses.

The orbital part of the optic nerve receives its blood supply from a small vascular branch known as *a. centralis nervi optici*. In some instances, it originates from *a. centralis retinae*, while in others, it arises directly from *a. ophthalmica* (Fig. 38).

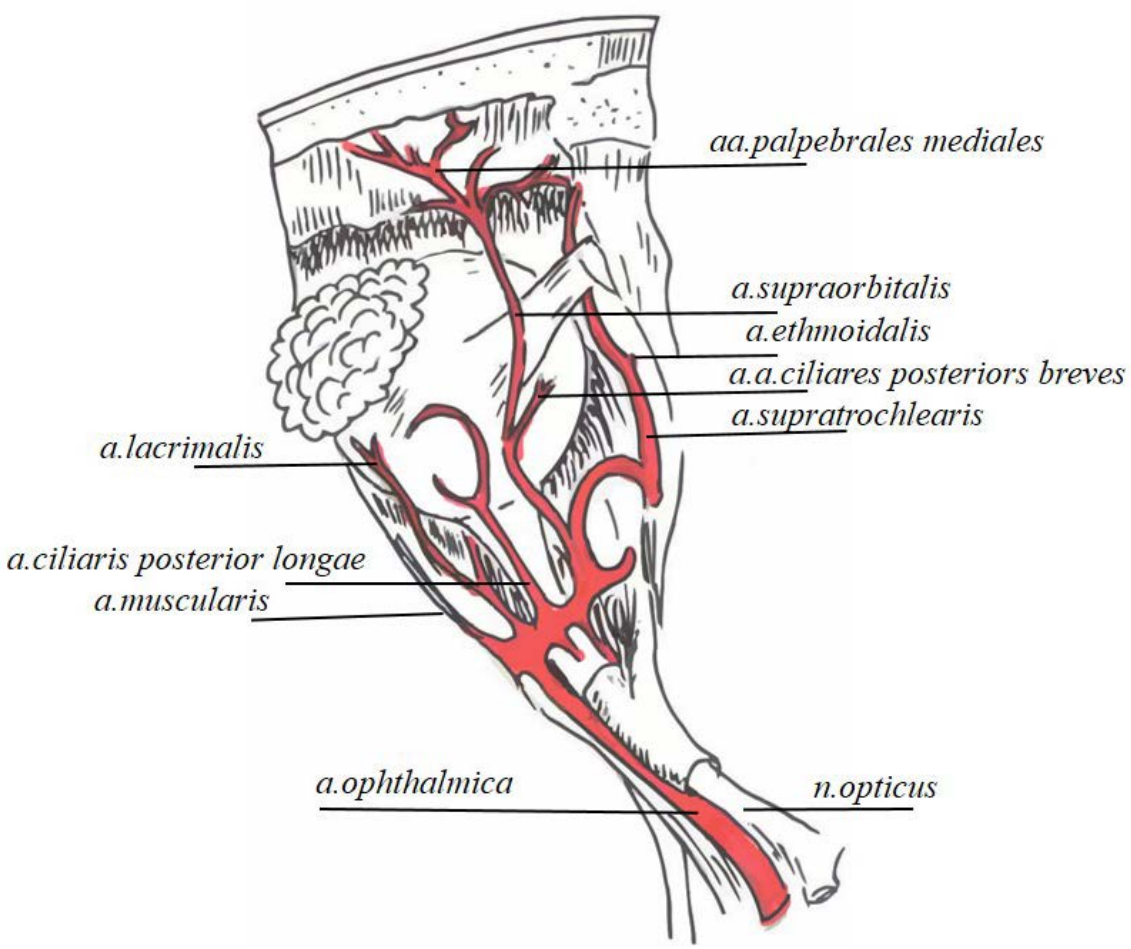


Fig. 38. The scheme of arterial blood supply of the left eye

A. centralis retinae continues through the optic disc to the fundus, where it dichotomously branches into four arterioles:

- superior temporal retinal arteriole;
- inferior temporal retinal arteriole;
- superior nasal retinal arteriole;
- inferior nasal retinal arteriole.

The posterior short ciliary arteries (*aa. ciliares posteriores breves*) arise from the ophthalmic artery, approach the posterior pole of the eye, and perforate it around the optic nerve to form:

1. circulus arteriosus n. optici Zinni – Halleri.

2. The choroid.

The choroid extends from the posterior pole of the eye to the ciliary body and nourishes the retina. The posterior short ciliary arteries do not anastomose with other choroid plexuses of the eye. Therefore, inflammatory processes developing in the choroid proper are not accompanied by hyperemia of the eyeball. *A. cilioretinalis* arises from the posterior short ciliary artery or the arterial circle of Zinni – Halleri. The role of *a. cilioretinalis* is to provide additional nutrition to the macular zone.

The posterior long ciliary arteries (*aa. ciliares posteriores longae*), arising from the ophthalmic artery, pass through the sclera on the sides of the optic nerve, enter the suprachoroidal space at 3 and 9 o'clock and reach the ciliary body.

The posterior long ciliary arteries anastomose with the anterior ciliary arteries and form the large arterial circle of the iris (circulus arteriosus iridis major).

From the large arterial circle of the iris, the vessels extend in the radial direction and form the small arterial circle of the iris (circulus arteriosus iridis minor) at the border of the pupillary and ciliary belts.

The large arterial circle of the iris is involved in the blood supply to the ciliary body.

Muscular arteries (*aa. musculares*) are represented by two large vessels:

- the superior artery (blood supplies to the eyelid levator, superior rectus, and superior oblique muscles);
- the inferior artery (blood supplies to the other extraocular muscles).

The anterior ciliary arteries (*aa. ciliares anteriores*) arise from the muscular arteries and form the large arterial circle of the iris (circulus arteriosus iridis major).

Branches of the arteries (*a. supraorbitalis, aa. ethmoidales posterior et anterior; aa. palpebrales mediales, a. supratrochlearis, a. dorsalis nasi*)

arise from the ophthalmic artery and supply the lacrimal gland, muscles, and soft tissues of the eyelids.

Venous blood supply of the eye

The outflow of venous blood from the eyeball occurs through:

- vorticose veins (*vv. vorticosae*), which drain blood from the choroid, ciliary body, and iris;
- these vorticose veins pass through the sclera obliquely in each of the quadrants of the eyeball at the level of its equator (Fig. 39).

The superior pair of veins drains into the superior ophthalmic vein, while the inferior pair of veins drains into the inferior ophthalmic vein.

The central retinal vein (*v. centralis retinae*) runs alongside a corresponding artery and either flows into the superior ophthalmic vein (*v. ophthalmica superior*) or directly into the cavernous sinus (*sinus cavernosus*).

The outflow of venous blood is conducted through two main trunks:

- V. ophthalmica superior;
- V. ophthalmica inferior.

V. ophthalmica superior collects blood from:

- the two superior vorticose veins of the eyeball;
- the central retinal vein;
- muscular veins (partially);
- veins of the upper eyelid.

The *V. ophthalmica superior* then penetrates the cranial cavity through the superior orbital fissure and enters the cavernous sinus (*sinus cavemosus*).

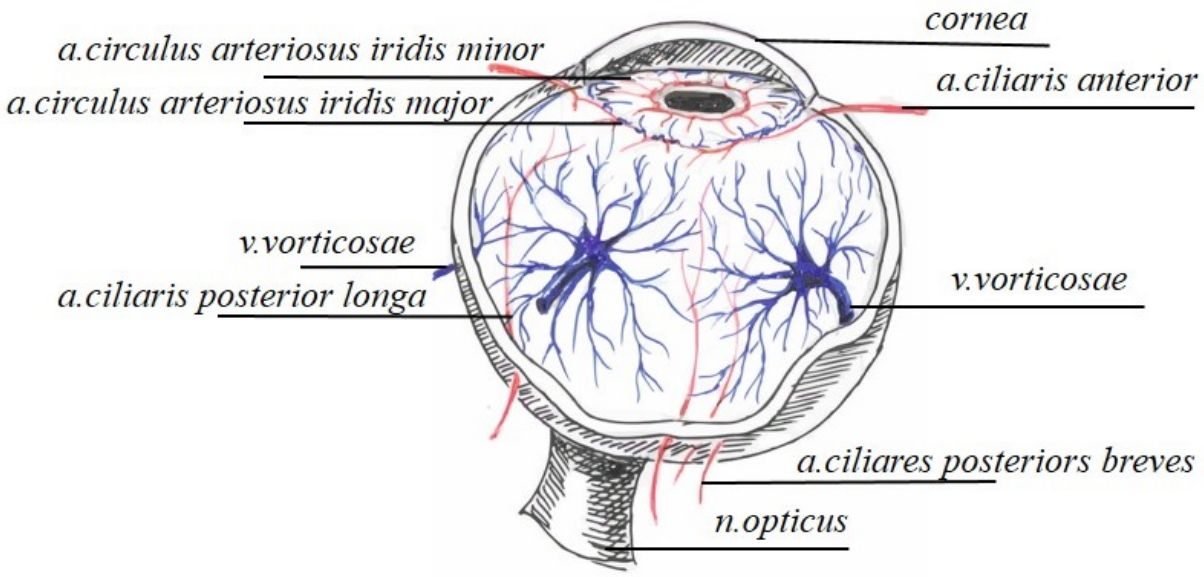


Fig. 39. The scheme of arteries and veins of the choroid

Inferior ophthalmic vein collects blood from:

- the two inferior vorticose veins;
- the muscular veins (partially);
- the lacrimal vein (partially);
- the veins of the lower eyelid.

The inferior ophthalmic vein flows into the cavernous sinus or, through an anastomosis, connects to the pterygoid plexus of veins (Fig. 40).

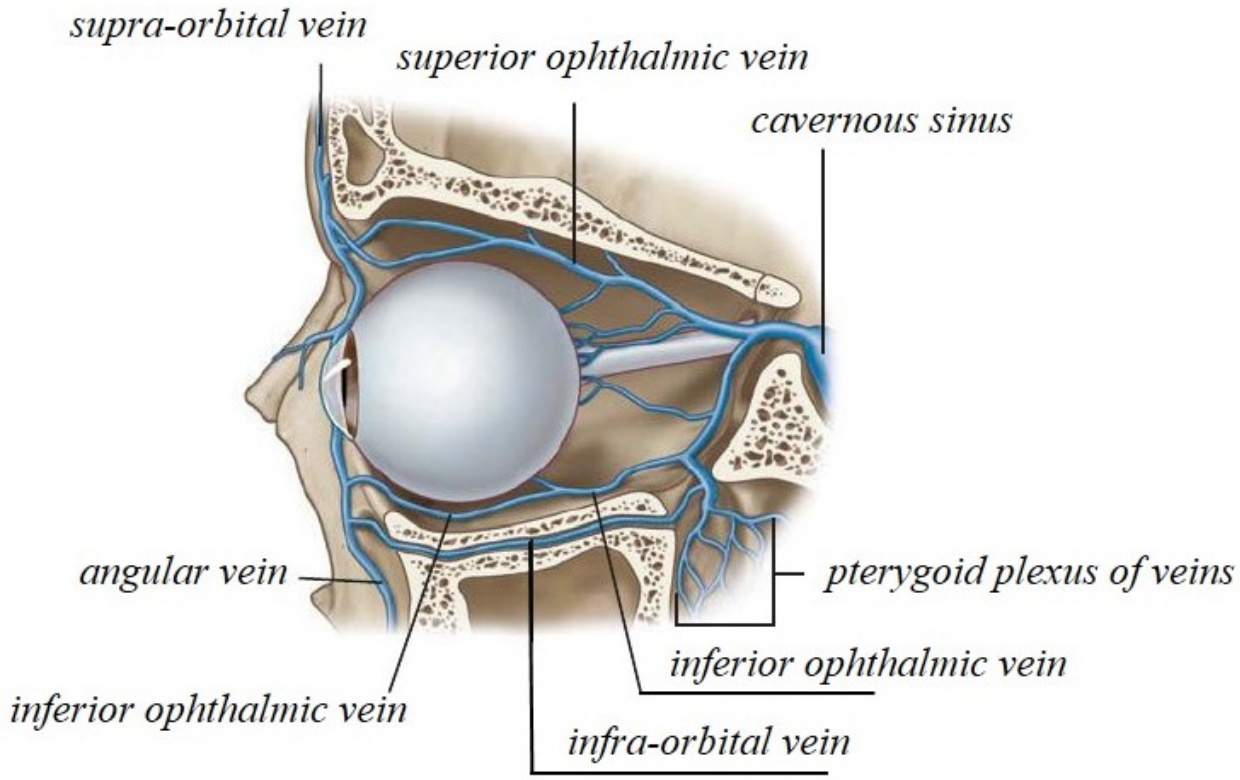


Fig. 40. Venous drainage of the orbit and eyeball [4]

Subsequently, the blood is drained into the internal jugular vein (*v. jugularis interna*). Since venous vessels lack valves, the outflow of blood can occur in various directions, either toward the cavernous sinus or toward the facial veins (Fig. 41).

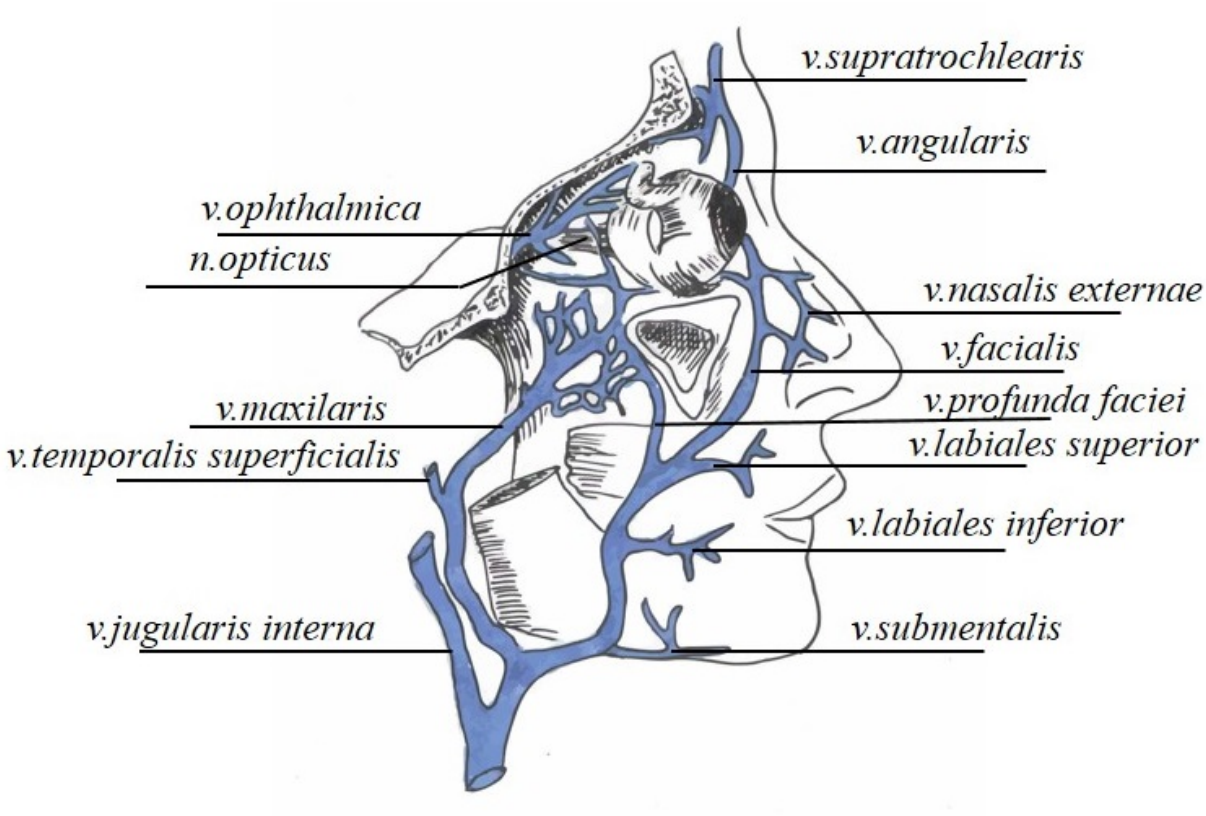


Fig. 41. The scheme of veins of the head and the eye socket

The peculiarities of venous outflow contribute to the potential spread of purulent infection from the facial skin or paranasal sinuses into the cavernous sinus, which can be a dangerous complication.

NERVES OF THE EYE

The optic nerve (*nervus opticus*)

The optic nerve (II) is one of the cranial nerves formed by the axons of ganglion cells. Just behind the cribriform plate, these nerve fibers acquire a myelin sheath that they maintain along their entire length.

The length of the optic nerve ranges from 35 to 55 mm. It is anatomically divided into the following segments.

- Intraocular segment. This segment, which is approximately 1 mm deep and 1.5 mm in vertical diameter, resides within the eyeball. The portion of this segment that is visible through ophthalmoscopy is referred to as the optic disc.
- Intraorbital segment. Measuring 25–35 mm in length, this segment is bounded anteriorly by the sclera and posteriorly by the orbital foramen of the optic canal. Its diameter is 3–4 mm due to the addition of myelin sheaths to the nerve fibers.
- Intracanalicular segment. Spanning 5–8 mm in length, this segment extends from the orbital to the intracranial foramen of the optic canal.
- Intracranial segment. This segment, 4–17 mm in length, runs from the point of entry into the skull to the optic chiasm. Longer intracranial segments are particularly susceptible to damage from adjacent lesions, such as pituitary adenomas and aneurysms.

The orbital portion of the optic nerve travels inside the muscular funnel, closer to the inner wall of the orbit. Within the orbit, the optic nerve forms an S-shaped bend, which increases the length of its intraorbital part. This configuration ensures the mobility of the eyeball, protecting the nerve from tension and injury.

Beyond the sclera, the diameter of the optic nerve expands from 3 mm to 4–5 mm due to the presence of three cranial meninges:

- the dura mater;
- the arachnoid mater;
- the pia mater.

The dura mater is a thick outermost layer that merges with the sclera at the posterior pole of the eyeball and consists of dense collagen and elastic fibers.

The arachnoid mater lies between the dura mater and the pia mater.

The pia mater covers the optic nerve trunk, separated from it by a thin layer of glial tissue. The pia mater sends connective tissue septa within the

optic nerve, dividing it into separate bundles and providing additional structural support.

Clinical correlation: papilledema (Fig. 42).

Any increase in intracranial pressure results in increased pressure in the subarachnoid space surrounding the optic nerve. This can impede venous return along the retinal veins, resulting in optic disc edema (papilledema), which is observable during a retinal examination with an ophthalmoscope.

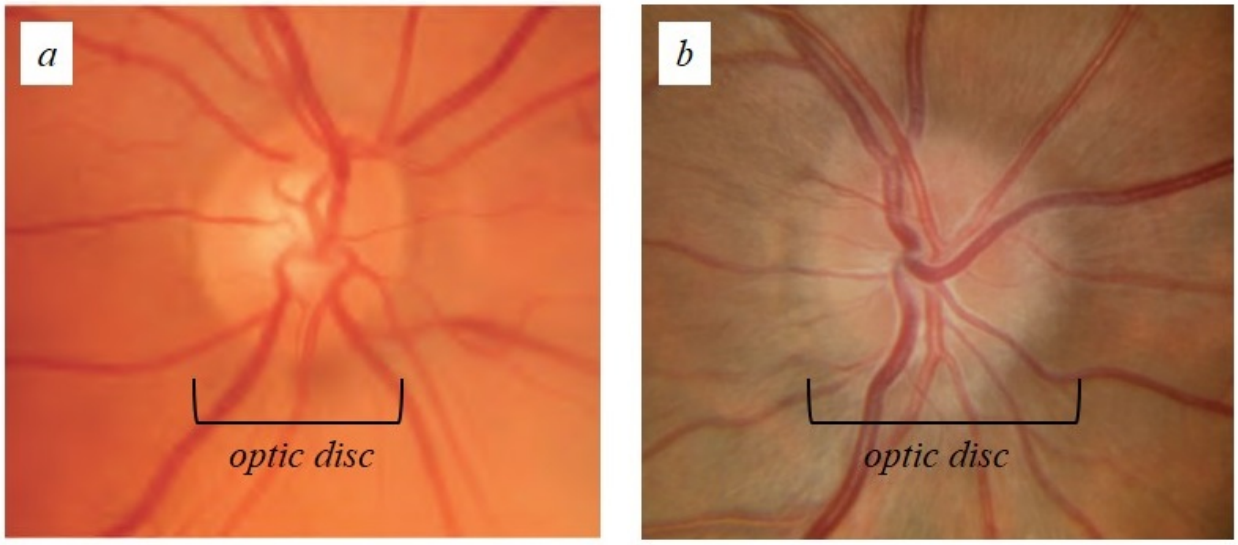


Fig. 42. Photograph (a) of the clinical appearance of the normal optic disc and of papilledema (b), early stage

All the nerve fibers that constitute the optic nerve are organized into three primary bundles. The papillomacular fascicle comprises the axons of ganglion cells extending from the central (macular) area of the retina and enters the temporal half of the optic nerve head. Fibers from the ganglion cells of the nasal half of the retina travel along radial lines into the nasal half of the optic nerve head, while fibers from the ganglion cells of the temporal half of the retina run along the vertical and horizontal directions.

The optic nerve is accompanied in the optic canal by the ophthalmic artery.

The oculomotor nerve (*n. oculomotorius*)

Oculomotor nerve (III) divides into two branches (see fig. 43):

- superior branch;
- inferior branch.

The superior branch courses along the outer surface of the optic nerve, providing innervation to the muscle responsible for elevating the upper eyelid (*m. levator palpebrae superior*) and the superior rectus muscle of the eye (*m. rectus oculi superior*).

The inferior branch divides into three branches:

- One branch passes below the optic nerve, then proceeds to the medial side of the orbit to innervate the medial rectus muscle (*m. rectus oculi medialis*).
- Another branch descends to innervate the inferior rectus muscle (*m. rectus oculi inferior*).
- The third branch descends and runs forward along the floor of the orbit to innervate the inferior oblique muscle (*m. obliquus inferior*).

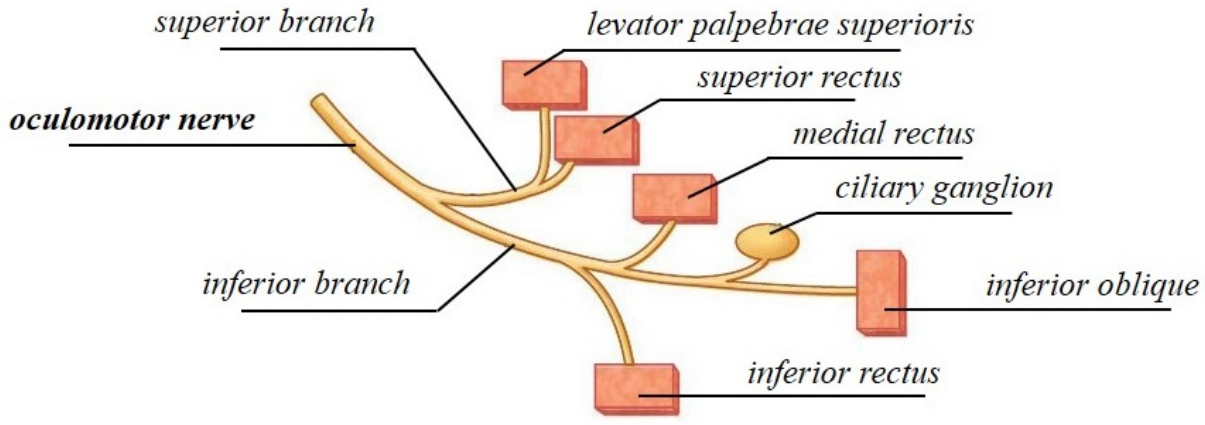


Fig. 43. The scheme of the oculomotor nerve and its divisions [4]

As the third branch descends, it gives off the branch to the ciliary ganglion. This branch serves as the parasympathetic root to the ciliary

ganglion, carrying preganglionic parasympathetic fibers that will synapse in the ciliary ganglion with postganglionic parasympathetic fibers. The postganglionic fibers are then distributed to the eyeball through the short ciliary nerves, where they innervate the sphincter pupillae and ciliary muscles.

The trochlear nerve (*n. trochlearis*)

The trochlear nerve (IV) follows a course within the orbit adjacent to the orbital nerve. It moves medially toward the superior oblique muscle (*m. obliquus superior*).

Just before entering the orbit, the trochlear nerve ascends, passing over the oculomotor nerve. It then enters the orbit through the superior orbital fissure, positioned above the common tendinous ring. Within the orbit, the trochlear nerve ascends and turns medially, crossing above the levator palpebrae superioris muscle to enter the upper border of the superior oblique muscle (Fig. 44).

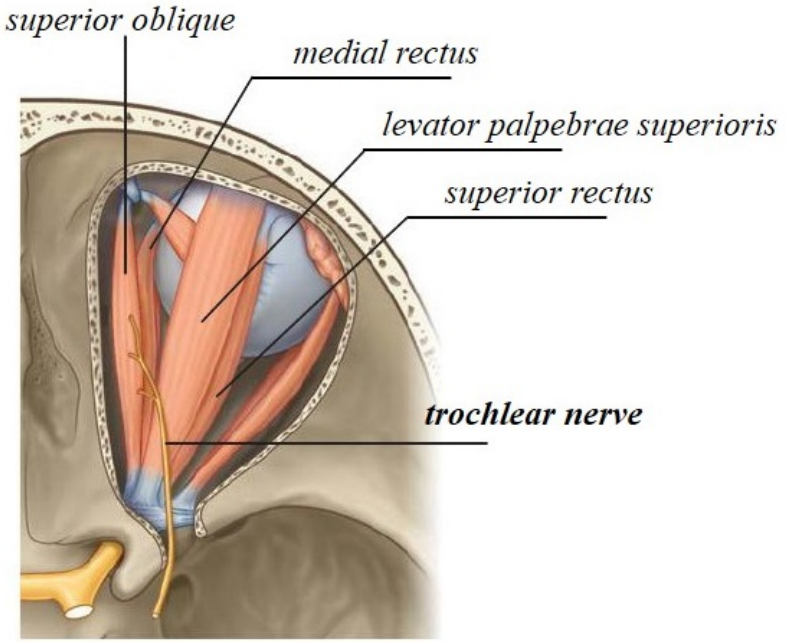


Fig. 44. Trochlear nerve in the orbit

The abducens nerve (*n. abducens*)

The abducens nerve (*n. abducens*) is situated within the orbit beneath the oculomotor nerve and provides innervation to the lateral rectus muscle (*m. rectus oculi lateralis*).

This nerve enters the cavernous sinus and travels alongside the internal carotid artery within the sinus. It then exits the sinus, entering the orbit through the superior orbital fissure within the common tendinous ring.

The ophthalmic nerve (*n. ophthalmicus*)

The ophthalmic nerve represents the smallest and most superior division of the trigeminal nerve. This purely sensory nerve receives input from structures within the orbit and from additional branches on the face and scalp.

The ophthalmic nerve (*n. ophthalmicus*) divides into three branches.

1) **Frontal nerve (*n. frontalis*).** This branch passes directly beneath the upper wall of the orbit, above the muscle responsible for elevating the upper eyelid. In the middle part of the orbit, it divides into:

- Supratrochlear nerve (*n. supratrochlearis*). It extends inward, passes over the superior oblique muscle, penetrates the circular muscle of the eye (m. orbicularis oculi), and ultimately innervates the skin and conjunctiva of the upper eyelid, the root of the nose, the lower forehead, and the lacrimal sac.
- Frontal branch (*ramus frontalis*). This branch courses toward the supraorbital edge of the frontal bone and provides innervation to the skin of the forehead.
- Supra-orbital nerve (*n. supraorbitalis*). Located laterally to the previous one, it exits the orbit through an opening of the same name, innervating the skin of the forehead, parietal area, and part of the temporal region.

2) **Lacrimal nerve (*n. lacrimalis*).** This branch travels along the outer wall of the orbit near the edge of the external rectus muscle. It provides innervation to the skin of the outer corner of the eye, the conjunctiva of the outer part of the upper eyelid, and the lacrimal gland.

3) **Nasociliary nerve (*n. nasociliaris*).** This nerve passes between the superior rectus and oblique muscles, the optic nerve, and further divides into branches (Fig. 45):

- the infratrochlear nerve (*n. infratrochlearis*);
- the anterior ethmoidal nerve (*n. ethmoidalis anterior*);
- the posterior ethmoidal nerve (*n. ethmoidalis posterior*);
- the long ciliary nerves (*nn. ciliares longi*).

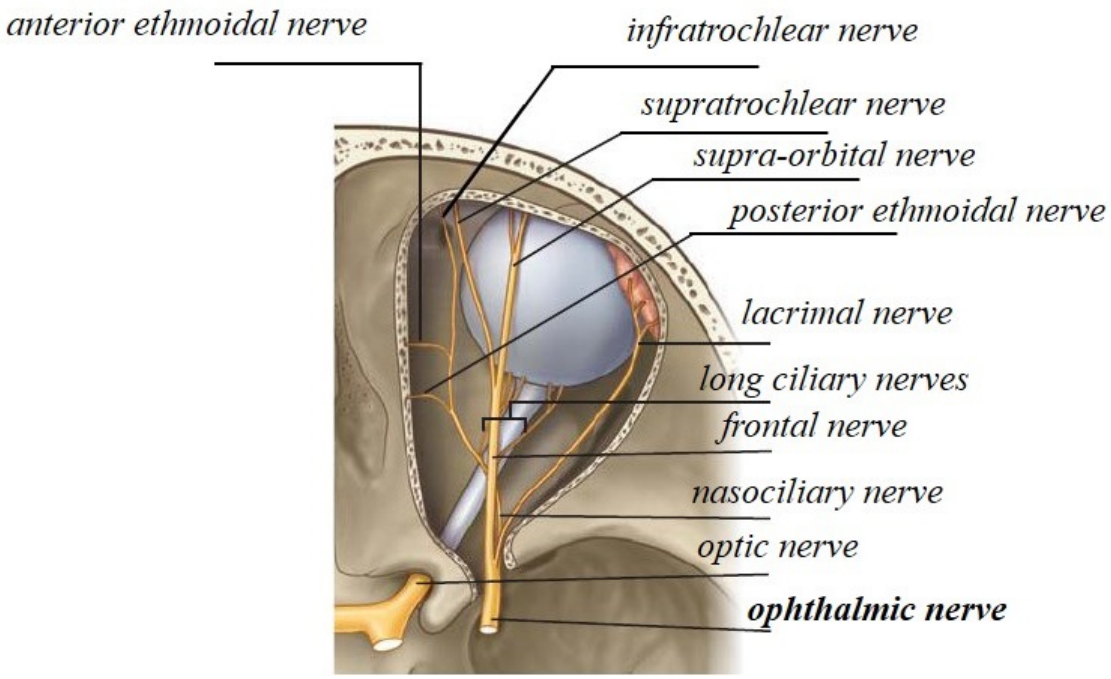


Fig. 45. Ophthalmic nerve and its divisions

Ciliary ganglion

The ciliary ganglion, associated with the nasociliary branch of the ophthalmic nerve and part of the parasympathetic division of the oculomotor nerve, serves as the site where preganglionic and postganglionic

parasympathetic neurons synapse. These fibers from the autonomic division of the peripheral nervous system travel to the eyeball.

The ciliary ganglion is a relatively small ganglion located in the posterior part of the orbit, situated immediately lateral to the optic nerve and positioned between the optic nerve and the lateral rectus muscle. It is typically described as receiving at least two, and potentially three, branches or roots from other nerves within the orbit (Fig. 46).

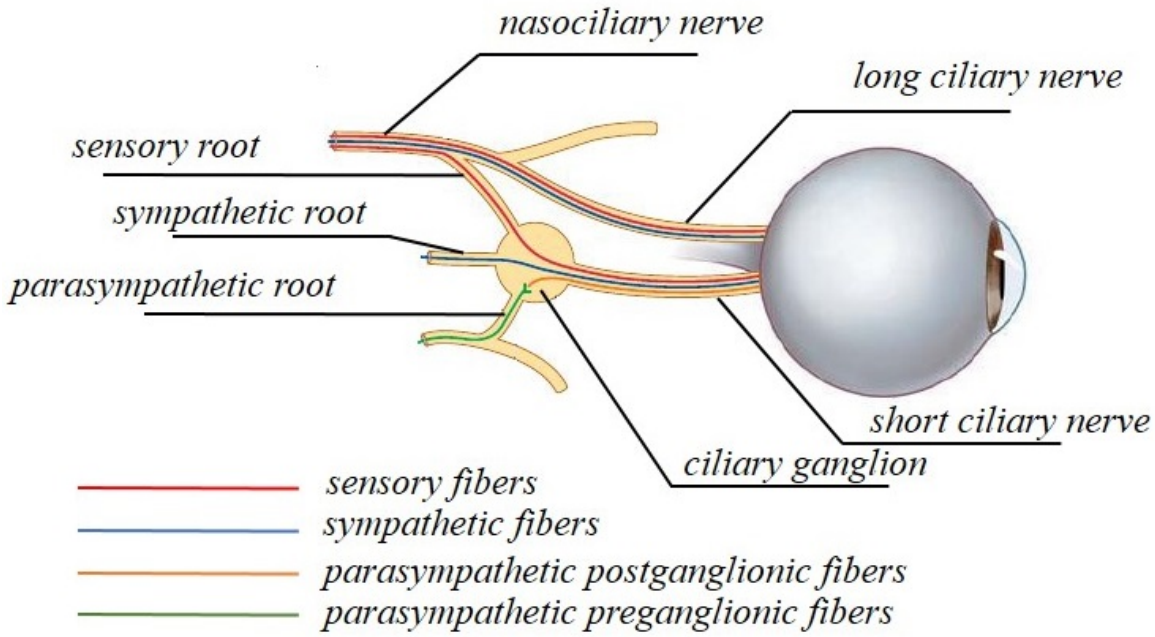


Fig. 46. Ciliary ganglion scheme

VISION PROCESS

Vision is a complex process that involves the conversion of light striking the retina into electrical impulses that are transmitted to the brain. These impulses, generated by light reaching the photoreceptor cells, are conveyed to the brain through an intricate network of nerves. The transformation of incident light into electrical nerve impulses is referred to as visual processing and encompasses several steps.

Photoreceptors respond to light through a process called bleaching. During bleaching, the photopigment rhodopsin absorbs a photon and undergoes a chemical change, becoming less sensitive to light. While most sensory receptors depolarize in response to a stimulus and release neurotransmitters, the activation of a photoreceptor by light results in hyperpolarization of the plasma membrane, leading to the cessation of neurotransmitter release. Hyperpolarization occurs due to the inhibition of ion inflow into the photoreceptor.

Rhodopsin, a visual pigment found in the membrane of the disks within rods and cones, comprises two essential components: opsin and the chromophore retinal (a derivative of vitamin A). Opsin determines the light wavelength that retinal will absorb. When light strikes rhodopsin, 11-cis-retinal is isomerized into all-trans-retinal, causing a change in the conformation of rhodopsin, leading to bleaching (Fig. 47). This change activates a second membrane-bound signal-coupling protein called transducin, a member of the G-protein family.

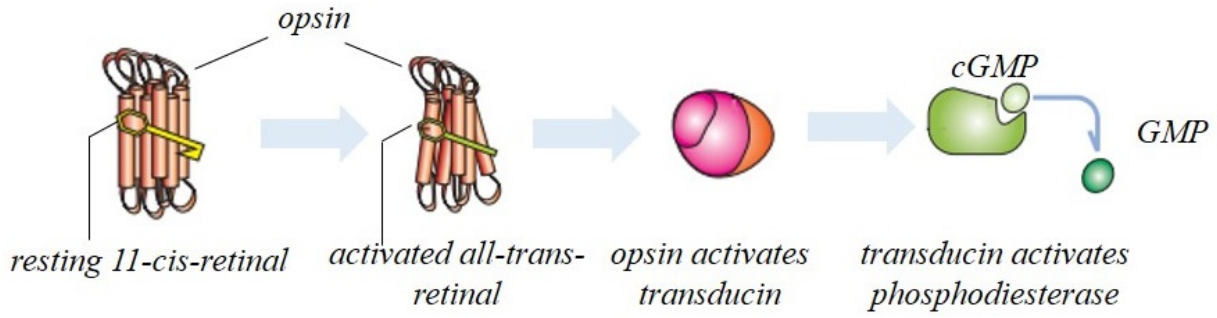


Fig. 47. Activation of phosphodiesterase

Transducin, in turn, triggers the activation of cGMP phosphodiesterase. This enzyme breaks down cyclic guanosine monophosphate (cGMP) into guanosine monophosphate (GMP). The breakdown of cGMP results in the closure of gated Na+ channels, preventing the entry of Na+ into the photoreceptor cell (Fig. 48). This, in turn, increases electronegativity within

the plasma membrane, leading to hyperpolarization of the entire rod plasma membrane and the cessation of neurotransmitter release.

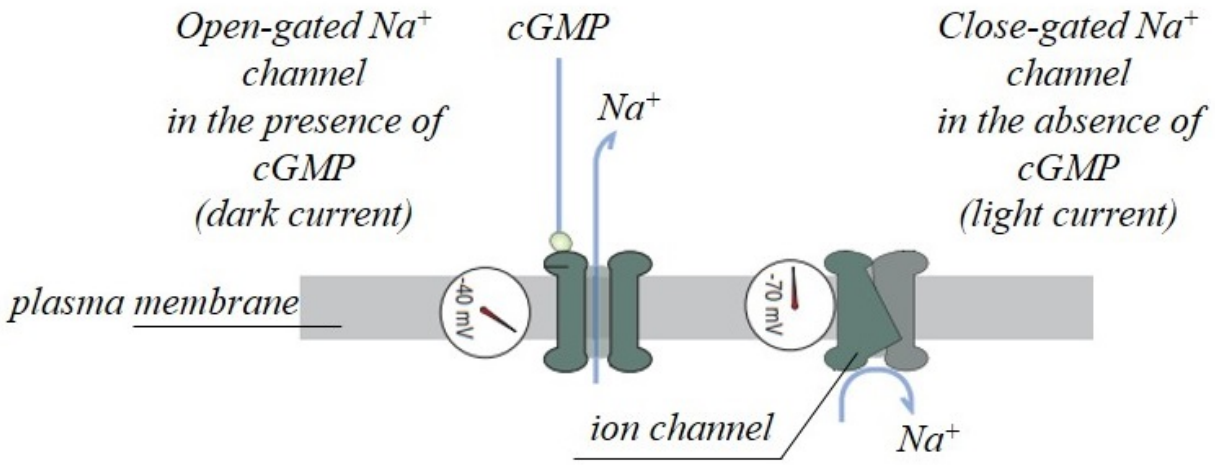


Fig. 48. The process of opening and closing of Na^+ channels

As phosphodiesterase breaks down cGMP into GMP and the gated Na+ channels close, neurotransmitter release at the synapse diminishes. The cell membrane hyperpolarizes because more Na+ ions exit the rod than flow into the cytoplasm of the photoreceptor cell. After light stimulation, rhodopsin disassembles into opsin and retinal, a process known as bleaching. 11-trans-retinal is enzymatically converted by cells of the pigment epithelium into all-cis-retinal. Then, 11-cis-retinal is transported back by interstitial retinoid-binding protein to the photoreceptor, where it recombines with opsin, leading to the regeneration of rhodopsin molecules. While rhodopsin regeneration is ongoing, membrane permeability to Na+ returns to normal, as cGMP is synthesized and the gated Na+ channels reopen.

TESTS

1. The part of the eye that controls the amount of light entering the eye is called the:

A) lens;
B) cornea;
C) iris;
D) retina.

2. The function of cones is:

A) they register distance;
B) they are responsible for sharp central vision;
C) they are responsible for night vision;
D) they contribute to depth of field.

3. How many layers does the cornea have?

A) 3
B) 4
C) 5
D) 6

4. Conducting neurons of the retina are:

A) bipolar neurons, horizontal neurons;
B) amacrine neurons, horizontal neurons;
C) ganglion cells, bipolar neurons;
D) rods, cones.

5. The Haller's layer is:

A) the outermost layer of the choroid consisting of larger diameter blood vessels;
B) a layer of medium diameter blood vessels in the choroid;
C) the choriocapillary layer of the choroid;
D) the membrane of the retinal pigment epithelium.

6. The anterior chamber is:

A) the space between the iris and the lens;
B) the space between the cornea and the iris;
C) the space between the cornea and the lens;
D) the space between the lens and the retina.

7. *V. ophthalmica superior* collects blood from:

A) the two superior vorticose veins of the eyeball, the lacrimal vein, muscular veins, veins of the upper eyelid;
B) the two superior and inferior vorticose veins of the eyeball, muscular veins, veins of the upper eyelid;
C) the two superior vorticose veins of the eyeball, the central retinal vein, muscular veins, veins of the upper eyelid;
D) inferior vorticose veins of the eyeball, muscular veins, veins of the upper eyelid.

8. The type of the lacrimal gland is:

A) acinar serous gland;
B) tubular serous gland;
C) tubuloacinar mucous gland;
D) tubuloacinar serous gland.

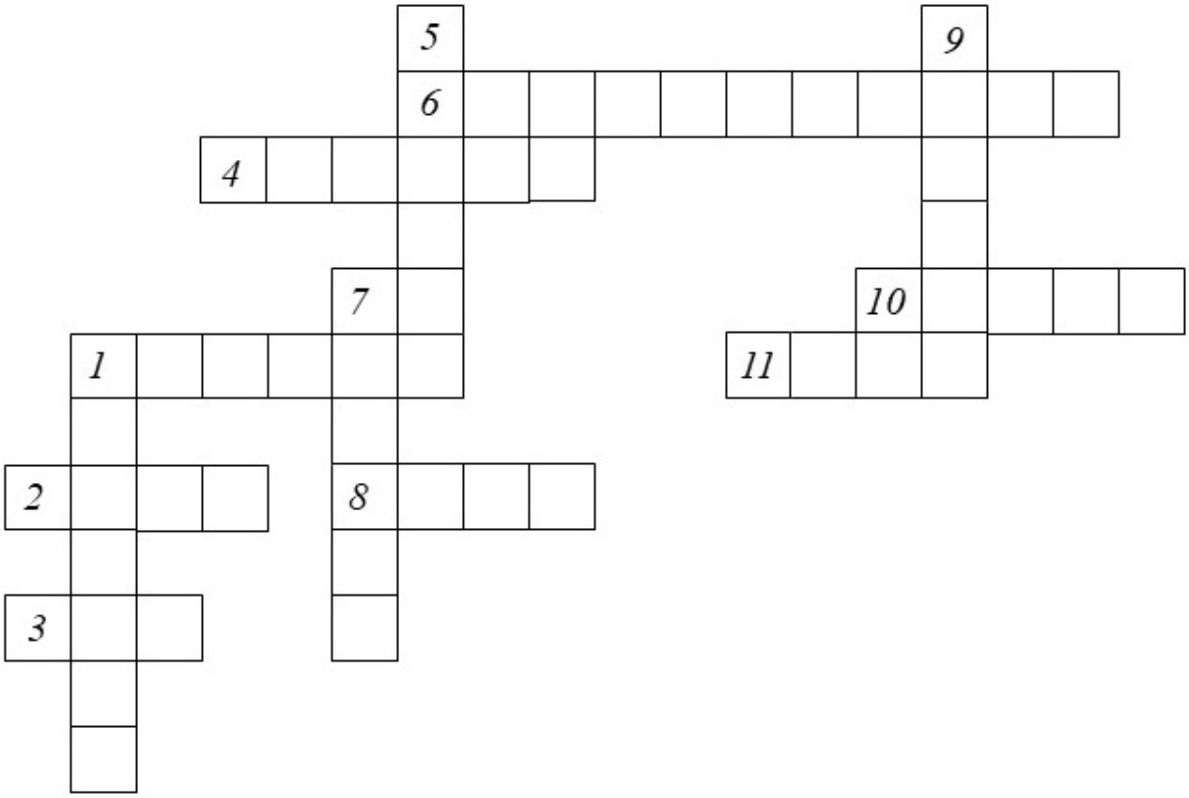
9. The choroid forms:

A) between 8 and 11 weeks of embryogenesis from the ectomesenchyme;
B) between 5 and 8 weeks of embryogenesis from the ectomesenchyme;
C) between 8 and 11 weeks of embryogenesis from the neural ectoderm;
D) between 5 and 8 weeks of embryogenesis from the neural ectoderm.

10. The vascular layer includes:

A) the cornea, the ciliary body, the choroid;
B) the iris, the limbus, the choroid;
C) the iris, the ciliary body, the choroid;
D) the cornea, the ciliary body, the sclera.

CROSSWORD



Horizontal clues:

1. The transparent front part of the eye that covers the iris, pupil, and anterior chamber.

Vertical clues:

1. The part of the vascular layer that lies between the sclera and the retina.
2. Name of the photoreceptor that contains the visual pigment iodopsin.
3. Name of the photoreceptor that contains the visual pigment rhodopsin.
4. A thin fold of skin that covers and protects the eye.
5. A structure of the eye that provides attachment for the extrinsic eye muscles.
6. A thin, transparent mucous membrane covering the entire back surface of the eyelid and eyeballs.
7. The inner layer of the eye.

8. A circular structure of the eye controlling the diameter and size of the pupil.
9. The transitional zone between the cornea and the sclera.
10. The central aperture of this thin disc.
11. A transparent body located inside the eyeball between the vitreous body and the iris.

ANSWERS

Answers to the test:

Question number	Answer number
1	C
2	B
3	C
4	C
5	A
6	B
7	C
8	D
9	A
10	C

Answers to the crossword:

Horizontal clues: 1. Cornea.

Vertical clues: 1. Choroid 2. Cone 3. Rod 4. Eyelid 5. Sclera 6. Conjunctiva 7, Retina 8. Iris 9. Limbus 10. Pupil 11. Lens.

LIST OF RECOMMENDED LITERATURE

Primary literature:

1. Ophthalmology [Electronic resource]: national guidelines / Ed. by S.E. Avetisov, E.A. Egorov, L.K. Moshetova, V.V. Neroev, H.P. Takhchidi. – Moscow: GEOTAR-Media, 2013. : Access mode: http://www.studentlibrary.ru (in Russ.)
2. Ophthalmology [Electronic resource] / Sidorenko E.I. – Moscow: GEOTAR-Media, 2013. : Access mode: http://www.studentlibrary.ru/ (in Russ.)
3. Ophthalmology [Text]: a textbook for students of medical universities, studying in the specialties 040100 – General Medicine, 040200 – Pediatrics, 040300 – Medical and Preventive Care, 040400 – Dentistry / Ed.: E.I. Sidorenko. – Moscow: GEOTAR-Media, 2006. – 408 p. (in Russ.)

Additional literature:

1. Eye Diseases [Text]: a textbook for students of medical universities / Ed. by V.G. Kopaev. – Moscow: Medicine, 2002. – 560 p. (in Russ.)
2. Egorov, Evgeny Alekseevich (ophthalmology; 19440318). Clinical Lectures on Ophthalmology [Electronic resource]: a teaching aid for postgraduate professional education of doctors / E.A. Egorov, S.N. Basinsky. - Electronic text data. – Moscow: GEOTAR-Media, 2007. – 288 p. : Access mode: http://www.studentlibrary.ru (in Russ.)
3. Kanski, Jack D. Clinical Ophthalmology [Electronic resource]: a systematic approach: translated from English / D.D. Kanski; ed. V.P. Eryshev. – 2nd ed. – Electronic text data. – Wroclav: Elsevier Urban & Partner; Moscow: Logosphere [Translation into Russian], 2009. – 944 p. : Access mode: http://books-up.ru (in Russ.)

REFERENCES

1. Anthony L. Mescher Junqueira’s Basic Histology. Text and atlas // McGraw Hill / Medical; 15th edition (August 9, 2018) 576 pages.

2. Michael H. Ross, Wojciech Pawlina Histology A Text and Atlas With Correlated Cell and Molecular Biology.

3. John Salmon_ Brad Bowling – Kanski's Clinical Ophthalmology_ A Systematic Approach (2019, Elsevier) – libgen.li (1).

4. Richard Drake, A. Wayne Vogl, Adam W. M. Mitchell-Gray’s Basic Anatomy-Elsevier (2017).

CONTENTS

Educational publication

Ekaterina Olegovna Filippova

Evgenia Alexandrovna Gorbunova

Olga Ivanovna Krivosheina

ANATOMY AND PHYSIOLOGY OF THE EYE (WITH CLINICAL CORRELATION)

TEXTBOOK

Published by SibMed (Siberian State Medical University)
634050, Tomsk, Lenin Avenue, 107
Tel. +7(3822)901-101, ext. 1760
E-mail: izdatelstvo@ssmu.ru

Signed for printing 08.12.2023.
Format 60x84 1/16. Offset paper.
Print the risograph. Headset «Times». Printed paper 5
Edition 100 copies. Order No. 44

Printed at the operational printing laboratory of SibSMU.
634050, Tomsk, Moskovsky Trakt Street, 2
E-mail: lab.poligrafii@ssmu.ru