2

Basic Anatomy and Physiology of the Eye

Introduction

The eye is the primary organ of vision. Each one of the two eyeballs is located in the orbit, where it takes up about one-fifth of the orbital volume (Figure 2.1). The remaining space is taken up by the extraocular muscles, fascia, fat, blood vessels, nerves and the lacrimal gland.

The eye is embryologically an extension of the central nervous system. It shares many common anatomical and physiological properties with the brain. Both are protected by bony walls, have firm fibrous coverings and a dual blood supply to the essential nervous layer in the retina. The eye and brain have internal cavities perfused by fluids of like composition and under equivalent pressures. As the retina and optic nerve are outgrowths from the brain, it is not surprising that similar disease processes affect the eye and central nervous system. The physician should constantly remind himself or herself of the many disease conditions that can simultaneously involve the eye and the central nervous system.

Basic Structure of the Eye and Supporting Structures

The Globe

The eye has three layers or coats, three compartments and contains three fluids (Figure 2.2).

1. The three coats of the eye are as follows:
   (a) Outer fibrous layer:
   - cornea
   - sclera
   - lamina cribrosa.

   (b) Middle vascular layer ("uveal tract"):
   - iris
   - ciliary body – consisting of the pars plicata and pars plana
   - choroids.

   (c) Inner nervous layer:
   - pigment epithelium of the retina
   - retinal photoreceptors
   - retinal neurons.
2. The three compartments of the eye are as follows:
   (a) Anterior chamber – the space between the cornea and the iris diaphragm.
   (b) Posterior chamber – the triangular space between the iris anteriorly, the lens and zonule posteriorly, and the ciliary body.
   (c) Vitreous chamber – the space behind the lens and zonule.
3. The three intraocular fluids are as follows:
   (a) Aqueous humour – a watery, optically clear solution of water and electrolytes similar to tissue fluids except that aqueous humour has a low protein content normally.
   (b) Vitreous humour – a transparent gel consisting of a three-dimensional

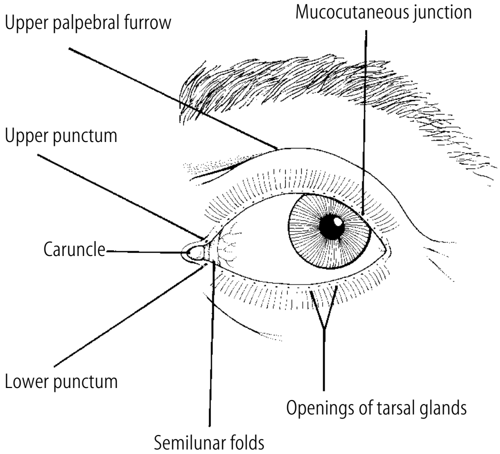


Figure 2.1. Surface anatomy.

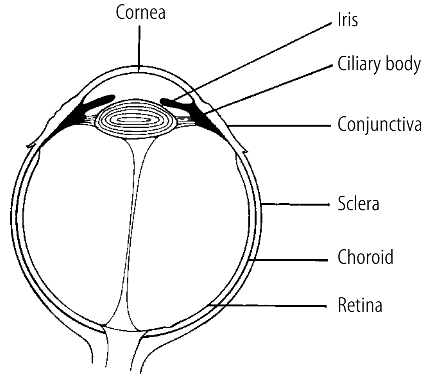


Figure 2.2. Layers of the globe.

network of collagen fibres with the interspaces filled with polymerised hyaluronic acid molecules and water. It fills the space between the posterior surface of the lens, ciliary body and retina.

(c) Blood – in addition to its usual functions, blood contributes to the maintenance of intraocular pressure. Most of the blood within the eye is in the choroid. The choroidal blood flow represents the largest blood flow per unit tissue in the body. The degree of desaturation of efferent choroidal blood is relatively small and indicates that the choroidal vasculature has functions beyond retinal nutrition. It might be that the choroid serves as a heat exchanger for the retina, which absorbs energy as light strikes the retinal pigment epithelium.

Clinically, the eye can be considered to be composed of two segments:

1. Anterior segment – all structures from (and including) the lens forward.
2. Posterior segment – all structures posterior to the lens.

The Outer Layer of the Eye

The anterior one-sixth of the fibrous layer of the eye is formed by the cornea. The posterior five-sixths are formed by the sclera and lamina cribrosa. The cornea is transparent, whereas the sclera, which is continuous within it, is white. The junction of cornea and sclera is known as the limbus. The cornea has five layers antero-posteriorly (Figure 2.3):

1. Epithelium and its basement membrane – stratified squamous type of epithelium with five to six cell layers of regular arrangement.
2. Bowman's layer – homogeneous sheet of modified stroma.
3. Stroma – consists of approximately 90% of total corneal thickness. Consists of lamellae of collagen, cells and ground substance.
4. Descemet's membrane – the basement membrane of the endothelium.
5. Endothelium – a single layer of cells lining the inner surface of Descemet's membrane.

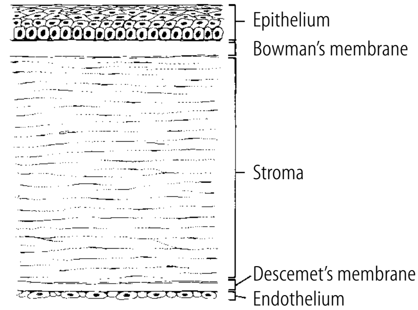


Figure 2.3. The cornea.

In the region of the limbus, the epithelium on the outer surface of the cornea becomes continuous with that of the conjunctiva, a thin, loose transparent nonkeratinising mucous membrane that covers the anterior part of the sclera, from which it is separated by loose connective tissue. Above and below, the conjunctiva is reflected onto the inner surface of the upper and lower lids. This mucous membrane, therefore, lines the posterior surface of the eyelids and there is a mucocutaneous junction on the lid margin. Although the conjunctiva is continuous, it can be divided descriptively into three parts: palpebral (tarsal), bulbar and fornix.

The sclera consists of irregular lamellae of collagen fibres. Posteriorly, the external two-thirds of the sclera become continuous with the dural sheath of the optic nerve, while the inner one-third becomes the lamina cribrosa – the fenestrated layer of dense collagen fibres through which the nerve fibres pass from the retina to the optic nerve. The sclera is thickest posteriorly and thinnest beneath the insertions of the recti muscles. There is a layer of loose connective tissue deep to the conjunctiva, overlying the sclera, called the episclera.

Middle Layer

The middle layer is highly vascular. If one were to peel the sclera away from this layer (not an easy task), the remaining structure would resemble a grape, as this middle layer, which is called the uvea, is heavily pigmented as well as being vascular. The anterior part of the uvea forms the bulk of the iris body and hence inflammation of the iris is called either anterior uveitis or iritis. The posterior part of the uvea is called the choroid.

The iris is the most anterior part of the uvea. It is a thin circular disc perforated centrally by the pupil. Contraction of the iris sphincter muscle constricts the pupil, while contraction of the dilator pupillae muscle dilates the pupil.

The ciliary body is part of the uveal tissue and is attached anteriorly to the iris and the scleral spur; posteriorly it is continuous with the choroid and retina. The ciliary body is also referred to as the intermediate uvea.

The ciliary body is triangular in cross-section. The anterior side of the ciliary body is the shortest and borders the anterior chamber angle; it gives origin to the iris. The outer side of the triangle (mainly ciliary muscles) lies against the sclera. The inner side is divided into two zones: (1) the pars plicata forms the anterior 2 mm and is covered by ciliary processes and (2) the pars plana constitutes the posterior 4.5-mm flattened portion of the ciliary body. The pars plana is continuous with the choroid and retina.

The choroid consists of the following:

- Bruch's membrane – membrane on the external surface of the retinal pigment epithelium (RPE). It consists of the basement membrane of RPE cells and choriocapillaris. Between the two layers of basement membrane are the elastic and collagenous layers. Small localised thickenings of Bruch's membrane (which increase with age) are called drusen.
- The choriocapillaris – a network of capillaries supplying the RPE and outer retina.
- Layer of larger choroidal blood vessels external to the choriocapillaris.
- Pigmented cells scattered in the choroid external to the choriocapillaris.

Inner Layer

The inner layer of the eye, which lines the vascular uvea, is the neurosensory layer. This layer forms the retina posteriorly; but, anteriorly it comes to line the inner surface of the ciliary body and iris as a two-layered pigment epithelium. These same layers can be traced into the retina, which is composed of an outer pigment epithelium and an inner sensory part, which contains the rods and cones, bipolar cells and ganglion cells (Figure 2.4). The junction of the retina and the pars plana forms a scalloped border known as the ora serrata.

It is important to note that the photoreceptor cells are on the external side of the sensory retina. The relationship of the retinal elements can be understood most readily by following the formation of the optic cup. As the single-cell layer optic vesicle "invaginates" to form the two-cell layered optic cup, the initially superficial cells become the inner layer of the cup. The RPE develops from the outer layer of the cup, facing the photoreceptors across the now obliterated cavity of the optic vesicle. The neurons of the sensory retina differentiate from the inner layer of the optic cup.

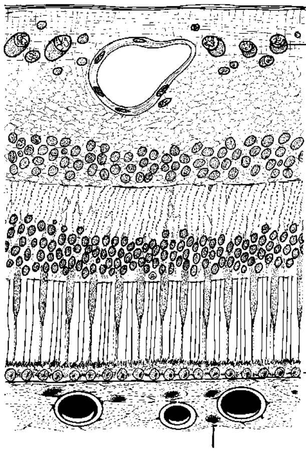


Figure 2.4. The retina.

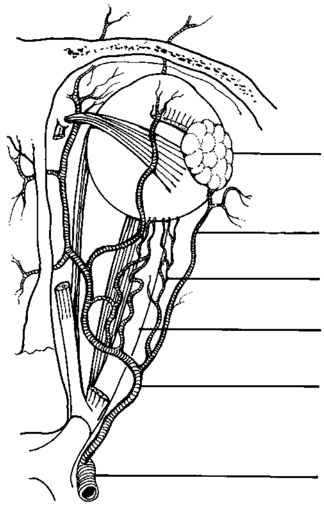


Figure 2.5. Blood supply of the eye.

Blood Supply

The blood supply of the globe is derived from three sources: the central retinal artery, the anterior ciliary arteries and the posterior ciliary arteries. All these are derived from the ophthalmic artery, which is a branch of the internal carotid. The central retinal artery runs in the optic nerve to reach the interior of the eye and its branches spread out over the inner surface of the retina supplying its inner half. The anterior ciliary arteries emerge from the insertion of the recti muscles and perforate the globe near the iris root to join an arterial circle in the ciliary body. The posterior ciliary arteries are the fine branches of the ophthalmic artery, which penetrate the posterior pole of the eye. Some of these supply the choroid and two or more larger vessels run anteriorly to reach the arterial circle in the ciliary body. The larger vessels are known as the long posterior ciliary arteries, and those supplying the choroid are known as the short posterior ciliary arteries. The branches of the central retinal artery are accompanied by an equivalent vein, but the choroid, ciliary body and iris are drained by approximately four vortex veins. These leave the posterior four quadrants of the globe and are familiar landmarks for the retina surgeon (Figure 2.5).

Optic Nerve

The optic nerve meets the posterior part of the globe slightly nasal to the posterior pole and slightly above the horizontal meridian. Inside the eye this point is seen as the optic disc. There are no light-sensitive cells on the optic disc – and hence the blind spot that anyone can find in their field of vision. The optic nerve contains about one million nerve fibres, each of which has a cell body in the ganglion cell layer of the retina (Figure 2.6). Nerve fibres sweep across the innermost part of the retina to reach

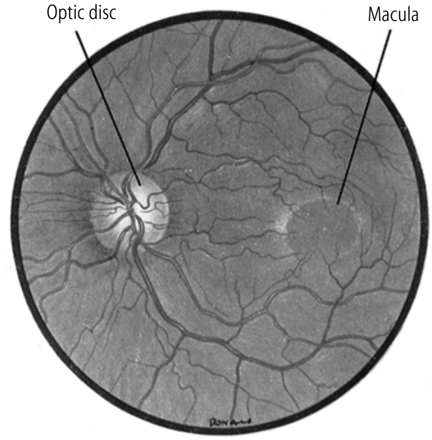


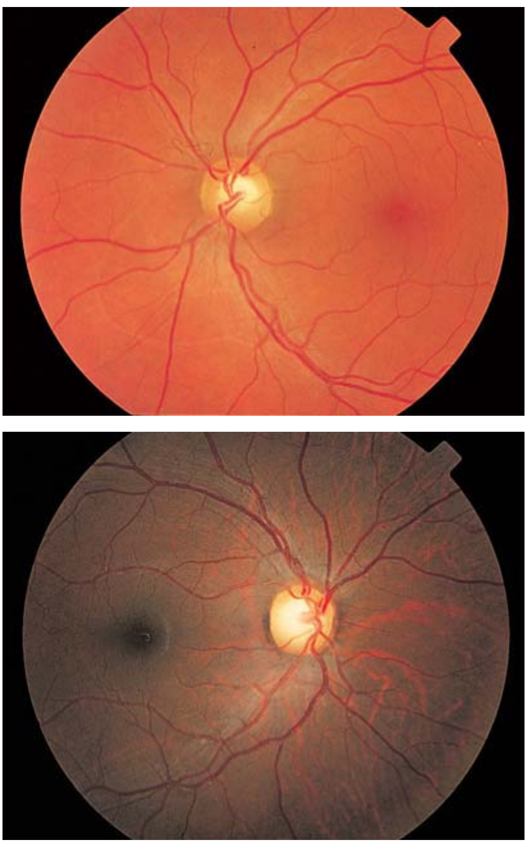
Figure 2.6. The optic fundus.

the optic disc. They can be seen with the ophthalmoscope by carefully observing the way light is reflected off the inner surface of the retina (Figure 2.7). The retinal vessels are also embedded on the inner surface of the retina. There is therefore a gap, which is the thickness of the transparent retina, between the retinal vessels and the stippled pigment epithelium. Apart from the optic nerve, the posterior pole of the globe is also perforated by several long and short ciliary nerves. These contain parasympathetic, sympathetic and sensory fibres, which mainly supply muscles of the iris (dilator and sphincter) and ciliary body (ciliary muscles). Patients can experience pain when the iris is handled under inadequate local anaesthesia, and pain is also sometimes experienced during laser coagulation treatment of the chorioretina – this would seem to prove the existence of sensory fibres in the iris and choroid. The cornea is extremely sensitive, but again, the only sensory endings are those for pain.

The visual pathways include the following:

1. The retina:
   - rods and cones
   - bipolar cells
   - ganglion cells.
2. Axons of the ganglion cells visual and pupillary reflex pathways:
   - nerve fibre layer of retina
   - optic nerve
   - optic chiasm
   - optic tract.
3. Subcortical centres and relays:
   - superior colliculus – reflex control of eye movements
   - pretectal nuclei – pupillary reflexes
   - lateral geniculate body – cortical relay.
4. Cortical connections:
   - optic radiations
   - visual cortex (area 17) – vision and reflex eye movements
   - association areas (areas 18 and 19)
   - frontal eye field – voluntary eye movements.

If the rods and cones are considered analogous to the sensory organs for touch, pressure, temperature, etc. then the bipolar cells may be compared to the first-order sensory neurons of the dorsal root ganglia. By the same token, the retinal ganglion cells can be compared to the second-order sensory neurons, whose cell bodies lie within the spinal cord or medulla.



a

b

Figure 2.7. The normal fundus of **a** a Caucasian and **b** an African. The background is darker in the African owing to increased pigment in the retinal pigment epithelium (RPE). The nerve fibre layer is noticeable, especially along the superior and inferior temporal arcades. 📖

The Eyelids

The eyelids may be divided into anterior and posterior parts by the mucocutaneous junction – the grey line (Figure 2.8). The eyelashes arise from hair follicles anterior to the grey line, while the ducts of the meibomian glands (modified sebaceous glands) open behind the grey line. The meibomian glands are long and slender, and run parallel to each other, perpendicular to the eyelid margin, and are located in the tarsal

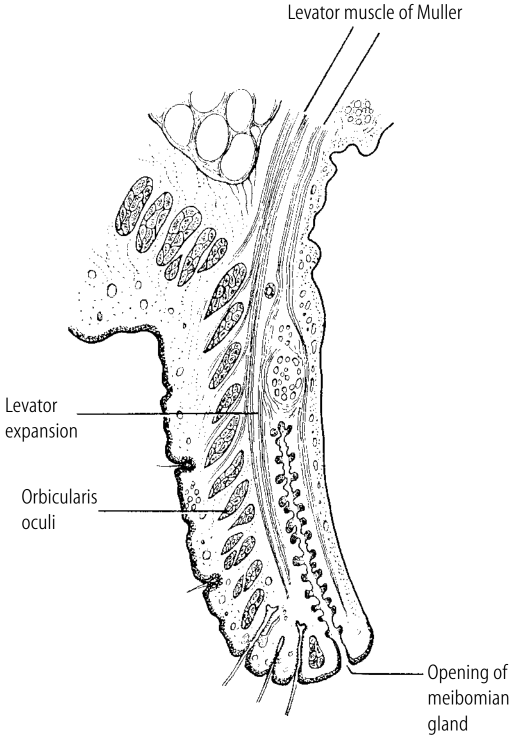


Figure 2.8. The eyelid.

plate of the eyelids. The tarsal plate gives stiffness to the eyelids and helps maintain its contour. The upper and lower tarsal plates are about 1 mm thick. The lower tarsus measures about 5 mm in height, while the upper tarsus measures about 10–12 mm.

The orbicularis oculi muscle lies between the skin and the tarsus and serves to close the eyelids. It is supplied by the facial nerve. The skin and subcutaneous tissue of the lids are thin. The inner surface of the eyelids is lined by the palpebral conjunctiva.

The Lacrimal Apparatus

The major lacrimal gland occupies the superior temporal anterior portion of the orbit. It has ducts that open into the palpebral conjunctiva above the upper border of the upper tarsus.

Tears collect at the medial part of the palpebral fissure and pass through the puncta and the canaliculi into the lacrimal sac, which terminates in the nasolacrimal duct inferiorly. The nasolacrimal duct opens into the inferior meatus of the nose.

The Extraocular Muscles

There are six extraocular muscles that help to move the eyeball in different directions: the superior, inferior, medial and lateral recti, and the superior and inferior obliques. All these muscles are supplied by the third cranial nerve except the lateral rectus (supplied by the sixth nerve) and superior oblique (fourth nerve).

All the extraocular muscles except the inferior oblique originate from a fibrous ring around the optic nerve (annulus of Zinn) at the orbital apex. The muscles fan out towards the eye to form a "muscle cone". All the recti muscles attach to the eyeball anterior to the equator while the oblique muscles attach behind the equator. The optic nerve, the ophthalmic blood vessels and the nerves to the extraocular muscles (except fourth nerve) are contained within the muscle cone (Figure 2.9).

The levator palpebrae superioris is associated with the superior rectus. It arises from just above the annulus of Zinn, runs along the roof of the orbit overlying the superior rectus and attaches to the upper lid skin and anterior surface of the tarsal plate of the upper lid. Tenon's capsule is a connective tissue covering that surrounds the eye and is continuous with the fascial covering of the muscles.

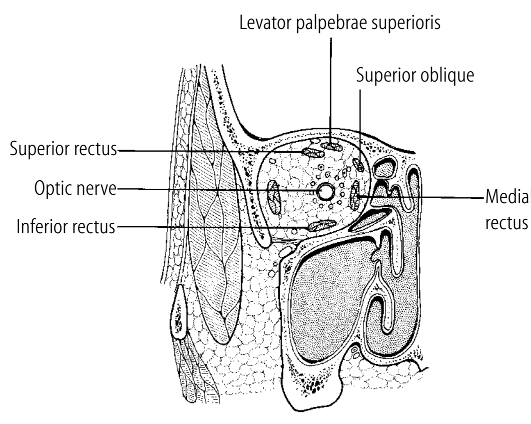


Figure 2.9. Anatomy of the orbit.

Physiology of the Eye

The primary function of the eye is to form a clear image of objects in our environment. These images are transmitted to the brain through the optic nerve and the posterior visual pathways. The various tissues of the eye and its adnexa are thus designed to facilitate this function.

The Eyelids

Functions include: (1) protection of the eye from mechanical trauma, extremes of temperature and bright light, and (2) maintenance of the normal precorneal tear film, which is important for maintenance of corneal health and clarity.

Normal eyelid closure requires an intact nerve supply to the orbicularis oculi muscles (facial nerve). Eyelid opening is affected by the levator palpebrae superioris supplied by the IIIrd cranial nerve.

The Tear Film

The tear film consists of three layers: the mucoid, aqueous and oily layers.

The mucoid layer lies adjacent to the corneal epithelium. It improves the wetting properties of the tears. It is produced by the goblet cells in the conjunctival epithelium.

The watery (aqueous) layer is produced by the main lacrimal gland in the superotemporal part of the orbit and accessory lacrimal glands found in the conjunctival stroma. This aqueous layer contains electrolytes, proteins, lysozyme, immunoglobulins, glucose and dissolved oxygen (from the atmosphere).

The oily layer (superficial layer of the tear film) is produced by the meibomian glands (modified sebaceous glands) of the eyelid margins. This oily layer helps maintain the vertical column of tears between the upper and lower lids and prevents excessive evaporation.

The tears normally flow away through a drainage system formed by the puncta (inferior and superior), canaliculi (inferior and superior), the common canaliculus (opening into the lacrimal sac) and the nasolacrimal duct (which drains into the nose).

The Cornea

The primary function of the cornea is refraction. In order to perform this function, the cornea requires the following:

- transparency
- smooth and regular surface
- spherical curvature of proper refractive power
- appropriate index of refraction.

Corneal transparency is contributed to by anatomical and physiological factors:

1. Anatomical:
   - absence of keratinisation of epithelium
   - tight packing of epithelial cells
   - mucous layer providing smooth lubricated surface
   - homogeneity of membranes – Bowman's and Descemet's
   - regular arrangement of corneal lamellae (parallel collagen fibres within each lamella, with adjacent lamellae being perpendicular). Regularity produces a diffraction grating
   - paucity of corneal stromal cells, which are flattened within lamellae
   - interspaces – absence of blood vessels.
2. Physiological
   - active dehydration of the cornea through Na^+/HCO_3^- metabolic pump located in the corneal endothelium. This dehydration is supplemented by the physical barrier provided by the corneal epithelium and endothelium.

The Aqueous Humour

The aqueous humour is an optically clear solution of electrolytes (in water) that fills the space between the cornea and the lens. Normal volume is 0.3 ml. Its function is to nourish the lens and cornea.

The aqueous is formed by active secretion and ultrafiltration from the ciliary processes in the posterior chamber. The fluid enters the anterior chamber through the pupil, circulates in the anterior chamber and drains through the trabecular meshwork into the canal of Schlemm, the aqueous veins and the conjunctival episceral veins.

The aqueous normally contains a low concentration of proteins, but a higher concentration of ascorbic acid compared with plasma. Inflammation of the anterior uvea leads to leakage of proteins from the iris circulation into the aqueous (= plasmoid aqueous).

The Vitreous Body

The vitreous consists of a three-dimensional network of collagen fibres with the interspaces filled with polymerised hyaluronic acid molecules, which are capable of holding large quantities of water. The vitreous does not normally flow but is percolated slowly by small amounts of aqueous. There is liquefaction of the jelly with age, with bits breaking off to form floaters. This degeneration occurs at an earlier age in myopes.

The Lens

The lens, like the cornea, is transparent. It is avascular and depends on the aqueous for nourishment. It has a thick elastic capsule, which prevents molecules (e.g., proteins) moving into or out of it.

The lens continues to grow throughout life, new lens fibres being produced from the outside and moving inwards towards the nucleus with age.

The lens is comprised of 65% water and 35% protein. The water content of the lens decreases with age and the lens becomes less pliable.

The lens is suspended from the ciliary body by the zonule, which arises from the ciliary body and inserts into the lens capsule near the equator.

The Ciliary Body

The ciliary muscle (within the ciliary body) is a mass of smooth muscle, which runs circumferentially inside the globe and is attached to the scleral spur anteriorly. It consists of two main parts:

1. Longitudinal (meridional) fibres – form the outer layers and arise from the scleral spur and insert into the choroid. Contraction of this part of the muscle exerts traction on the trabecular meshwork and also the choroid and retina.
2. Circular fibres – form the inner part and run circumferentially. Contraction moves the ciliary processing inwards towards the center of the pupil leading to relaxation of the zonules.

Accommodation

Accommodation is the process whereby relaxation of zonular fibres allows the lens to become more globular, thereby increasing its refractive power. When the ciliary muscles relax, the zonular fibres become taut and flatten the lens, reducing its refractive power. This is associated with constriction of the pupil and increased depth of focus.

Accommodation is a reflex initiated by visual blurring and/or awareness of proximity of the object of interest. The maximum amount of accommodation (amplitude of accommodation) is dependent on the rigidity of the lens and contractility of the ciliary muscle. As the lens becomes more rigid with age (and contractions of the ciliary body reduce), accommodation decreases. Reading and other close work become impossible without optical correction – presbyopia.

The Retina

This is the "photographic film" of the eye that converts light into electrical energy (transduction) for transmission to the brain. It consists of two main parts:

1. The neuroretina – all layers of the retina that are derived from the inner layer of the embryological optic cup.
2. The RPE – derived from the outer layer of the optic cup. It is comprised of a single layer of cells, which are fixed to Bruch's membrane. Bruch's membrane separates the outer retina from the choroid.

The retinal photoreceptors are located on the outer aspect of the neuroretina, an arrangement that arose from inversion of the optic cup and allows close proximity between the photosensitive portion of the receptor cells and the opaque RPE cells, which reduce light scattering. The RPE also plays an important role in regeneration/recycling of photopigments of the eye and during light–dark adaptation.

In order for the light to reach the photoreceptors to form sharp images, all layers of the retina inner to the photoreceptors must be transparent. This transparency is contributed to by the absence of myelin fibres from the retinal neurons. The axons of the retina ganglion cells normally become myelinated only as they pass through the optic disc to enter the optic nerve.

There are two main types of photoreceptors in the retina – the rods and the cones. In the fovea centralis the only photoreceptors are cones, which are responsible for acute vision (visual details) and colour vision. Outside the fovea, rods become more abundant towards the retinal periphery. The rods are responsible for vision in poor (dim) light and for the wide field of vision.

The retinal capillary network (derived from the central retinal artery) extends no deeper than the inner nuclear layer and nourishes the neuroretina from inside up to part of the outer plexiform layer. It is an end-arterial system. The choroid serves to nourish the RPE and the photoreceptors (by diffusion of nutrients). There are no blood vessels in the outer retina. The central fovea is completely avascular and depends on diffusion from the choroidal circulation for its nourishment. Thus, normal functioning of the retina requires normal retinal and choroidal circulation.