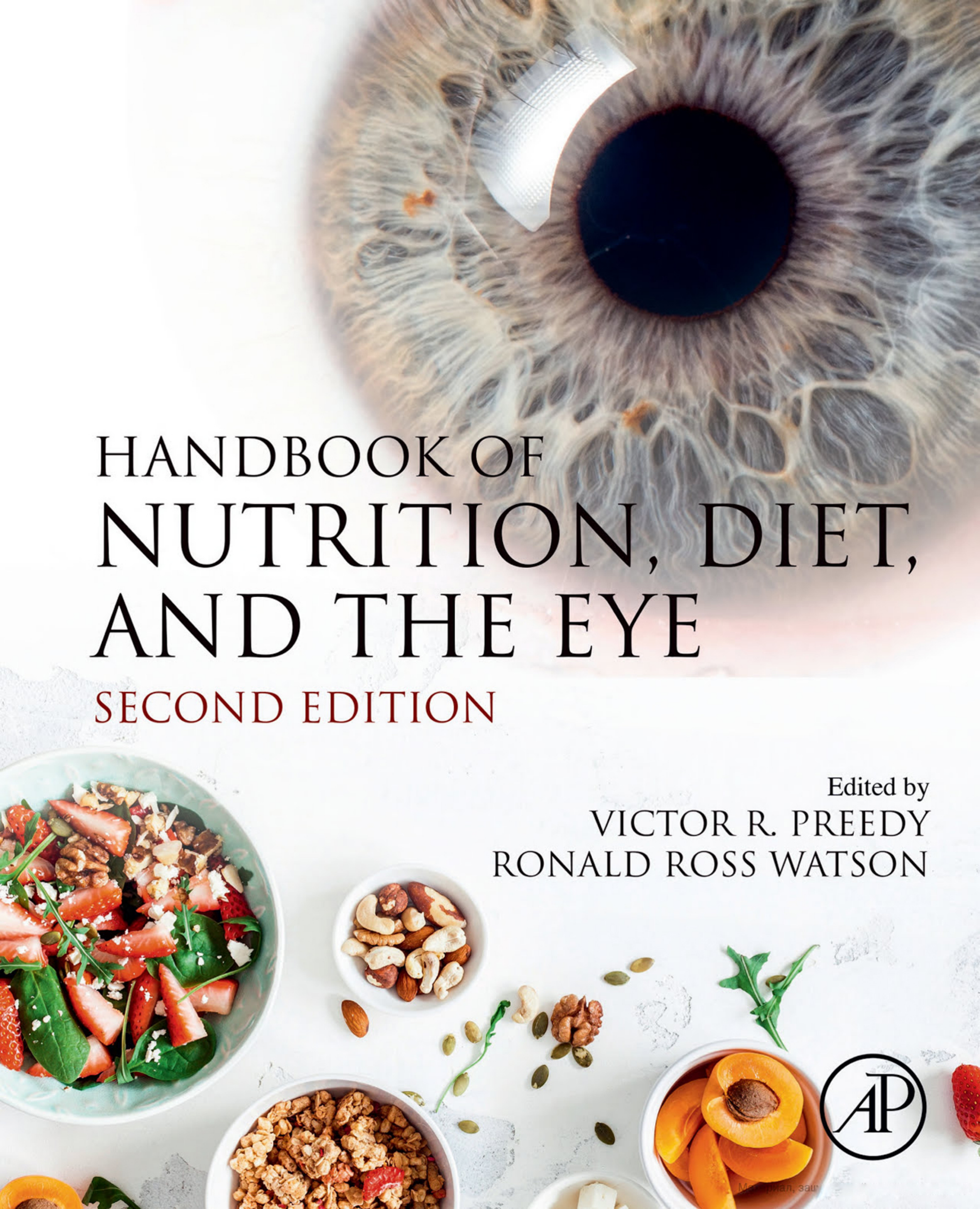

HANDBOOK OF NUTRITION, DIET, AND THE EYE

SECOND EDITION

Edited by

VICTOR R. PREEDY

RONALD ROSS WATSON

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SECTION A

Introductions and Overviews

1

The Eye and Vision: An Overview

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CHAPTER OUTLINE

List of Abbreviations

Ah aqueous humor
AMD age-related macular degeneration
BV blood vessel
C conjunctiva
CH choroid
Co cornea
EB eyebrow

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EL	eyelid
GCL	ganglion cell layer
I	iris
INL	inner nuclear layer
IOP	intraocular pressure
L	crystalline lens
La	eyelashes
LGN	lateral geniculate nucleus
Lv	lens vesicle
Me	meninges
OC	optic cup
OD	optic disk
ON/O	optic nerve
ONL	outer nuclear layer
Or	orbit
OS	optic stalk
P	pupil
PE	pigment epithelium
PVD	posterior vitreous detachment
R	retina
R/C	rods and cones
Sc	sclera
SE	surface ectoderm
VB	vitreous body

Introduction

Vision is the sense that we rely on most to inform us of the state of the world. For this reason, more is known about the scientific basis of vision than any of our other senses.[1] The major organ of vision, the eye, is highly specialized for photoreception. It focuses light from an object onto the light-sensitive part of the eye, the retina. Changes in specialized neurons in the retina result in nerve action potentials, which are relayed to the brain via the optic nerve. Visual processing by the brain results in "visual perception," the construction of a sensory image, which is then consciously appreciated as vision.[2,3] All other structures of the eye are subsidiary to this function, either by facilitating focusing of light rays or supporting the tissues of the eye. This chapter is an introduction to the different parts of the eye and their various functions in achieving a visual image.

Development of the Eye

The eyes develop from outgrowths of the brain called the optic vesicles (Fig. 1).[4] Five weeks after conception, the optic vesicle has emerged from the neural ectoderm of the brain and begins to fold inwards producing an inner and an outer layer separated by a cavity. The retina and smooth muscle of the iris will develop from this structure. The optic vesicle also induces the formation of the lens placode that develops from an invagination of surface ectoderm in front of the vesicle and ultimately will develop into the

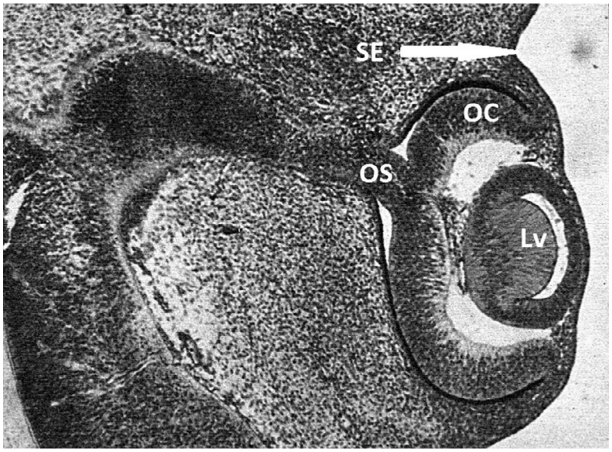

FIG. 1 The figure shows the lens vesicle, optic cup, and optic stalk, which will develop into the lens, retina, and optic nerve, respectively (*Lv*, lens vesicle; *OC*, optic cup; *OS*, optic stalk; *SE*, surface ectoderm). *Image courtesy: R.A. Armstrong.*

crystalline lens. In addition, the hyaloid artery ramifies on the back of the developing lens while the outer surface of the optic vesicle develops a network of blood vessels in the mesoderm eventually forming the choroid. Outside this, the mesoderm forms the sclera and the extraocular muscles.

Eight weeks after conception, the thicker inner layer of the optic cup has detached from the thinner outer layer thus illustrating the weak attachment that exists between inner and outer layers of the developing retina. Within the vitreous chamber, the hyaloid blood vessels have developed that nourish the developing vitreous and the crystalline lens. These vessels normally disintegrate before birth but remnants of them may persist into childhood. The crystalline lens has developed at this stage and the primary lens fibers have now filled the cavity of the lens vesicle. The cornea develops from the surface ectoderm and mesoderm and the anterior chamber is formed between the developing cornea and lens. The fused eyelids can be seen at this stage, their skin and glands developing from the surface ectoderm, while connective tissue and muscle develop from the mesoderm.

The Ocular Adnexa

The ocular adnexa refer to the accessory or adjoining parts of the eye and comprise several structures including the eyebrows, eyelids, eyelashes, lacrimal gland, and orbit. Many of these structures are illustrated in the anterior view of the eye shown in Fig. 2.

Eyebrows

Each eyebrow is a thickened area of skin with accompanying hairs, which are directed both upwards and toward the temporal side of the head. The hairs function to prevent sweat formed on the forehead from entering the eyes. In many cultures, the eyebrows are also important in facial expression.

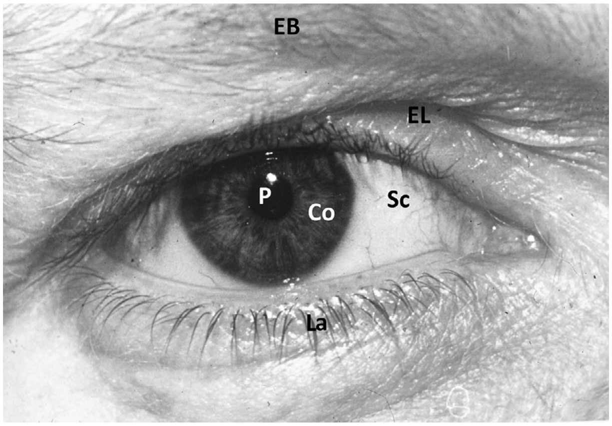

FIG. 2 The figure shows various parts of the anterior eye including the lids, cornea, sclera, and pupil (*Co*, cornea; *EB*, eyebrow; *EL*, eyelid; *P*, pupil; *Sc*, sclera). *Image courtesy: R.A. Armstrong.*

Eyelids

The eyelids are moveable folds of skin, which function to protect the eye from particulate matter in the air. They also reduce the amount of light entering the eyes and provide some of the constituents making up the tears. The ocular surface can usually resist ocular infection both as a result of the mechanical action of the eyelids, which physically remove potential pathogens, and the washing effect of tears.[5]

Eyelashes

There are two or three rows of eyelashes located on the upper edge of the upper and lower lids, the lashes numbering approximately 150 on the upper lid and 75 on the lower lid. They function to protect the eye against small particles but are vulnerable to infection, especially by bacteria, a condition called "blepharitis."

Lacrimal Gland

The lacrimal gland lies inside the eye socket above the eye and functions to produce the tears. It is divided into a large "orbital" and a smaller "palpebral" portion connected by a canal. In the orbital part, ducts join with those from the palpebral portion entering the upper temporal part of the conjunctiva. Excess tears are drained via the canaliculi into the lacrimal sac and ultimately the nasal cavity. Tears contain lysozymes, lactoferrin, B-lysin, and immunoglobulin A, which are important in defense against infection.

Orbit

The orbit is the bony socket, which contains the eye. The eye is situated in the anterior portion of the orbit closer to its lateral surface than the medial wall and nearer the roof of the orbit than the floor.[6] It comprises seven bones, including the ethmoid and sphenoid bones, and bones that make up the structure of the face such as the maxilla, frontal, and zygomatic. The purpose of the orbit is to protect the eye and to act as an anchorage point for the extraocular muscles and other ocular tissues.

Extraocular Muscles

There are six extraocular muscles, which are attached to the eye by tendons at the sclera (the white outer coat of the eye). They function to move the eyes through 360 degree of gaze and are coordinated so that the two eyes move in unison, thus preventing double vision (diplopia). There are four rectus muscles: medial, lateral, superior, and inferior, which are attached to a common tendon ring at their posterior ends (the annulus of Zinn), which in turn, is attached to the posterior surface of the orbit. The primary action of the medial rectus is to pull the eye horizontally in the nasal direction, whereas the lateral rectus pulls the eye horizontally in the temporal direction. The primary action of the superior rectus is to pull the eye upwards and the inferior rectus to pull the eye downwards. The two remaining muscles, the superior and inferior oblique muscles, are inserted more "obliquely" into the upper and lower posterior temporal quadrants of the orbit. The inferior oblique, and superior, inferior, and medial recti muscles are controlled by the third cranial nerve (the oculomotor nerve) and the lateral rectus by the sixth cranial nerve (the abducens nerve). In addition, the superior oblique muscle is supplied by the fourth cranial nerve (the trochlear nerve). The primary actions of the superior and inferior oblique muscles are also to pull the eyes in an upward or downward direction, respectively. Nevertheless, only the primary muscle actions have been described, and several of the muscles act in concert to produce secondary and tertiary actions, which can move the eyes in more complex directions. The study of muscle action of the eyes and the coordination of eye movement is called "binocular vision."

The Anterior Structures of the Eye

The human eye is approximately spherical in shape, 25 mm in diameter, has a volume of 6.5 mL, while average axial length of the globe is 24 mm (range: 21–26 mm). It actually comprises the parts of two spheres, which are represented anteriorly by the cornea, which has a greater curvature than that represented by the curvature of the posterior sclera. Hence, the eye can be divided into two functionally distinct regions, viz. the anterior eye and the posterior eye. The anterior segment comprises the cornea, iris, ciliary body, crystalline lens, aqueous humor, and the anterior part of the sclera (Fig. 3).

Conjunctiva

The conjunctiva is the outer membrane of the eye covering the white fibrous sclera. It is continuous with that of the transparent cornea and extends onto the surface of the upper and lower lids. It is a mucous membrane with a nonkeratinized, stratified epithelium and

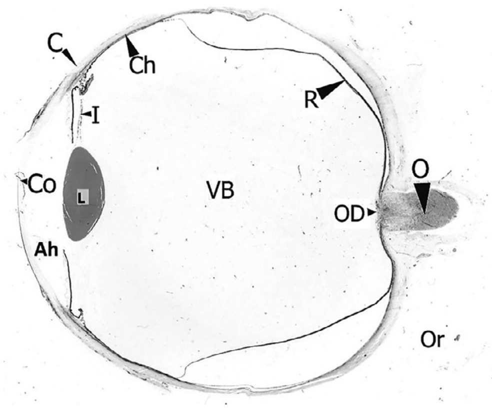

FIG. 3 The figure shows the various structures of the eye as seen in a vertical section (*C*, conjunctiva; *Ch*, choroid; *CO*, cornea; *I*, iris; *O*, optic nerve; *OD*, optic disk; *Or*, orbit; *R*, retina; *VB*, vitreous body). *Image courtesy: R.A. Armstrong.*

subepithelial layers, which are composed of adenoid and connective tissue, a region especially vulnerable to infection ("conjunctivitis").

Cornea

The cornea is the most anterior structure of the eye and comprises one-sixth of the circumference of the globe. It is a curved, transparent structure with a radius of 7.8 mm. The anterior surface is continually bathed by tears while the posterior surface is bathed by aqueous humor. The surface of the cornea together with the associated tear film is responsible for most of the refractive power of the eye. Hence, the function of the cornea is to refract light rays so that they eventually come to a focus on the retina. The main thickness of the cornea is composed of regularly arranged collagen fibers, which together with the regular smooth epithelium and lack of blood vessels, is responsible for its transparency.

Sclera

With the exception of the cornea, the sclera forms the outermost layer of the eye. It is thickest in its posterior region and thinnest at the point of attachment of the tendons to the ends of the extraocular muscles. It comprises collagen fibers, which unlike the cornea, are irregularly arranged resulting in an opaque appearance. The sclera is highly fibrous and provides protection, support, and anchorage for structures within and outside the eye such as the musculature, and also maintains the shape of the globe.

Iris

The iris is a 12-mm-diameter structure, which functions to regulate the amount of light entering the eye and also separates the eye into anterior and posterior chambers. It is analogous in action to the diaphragm of a camera. The pupil is an aperture in the center of the iris through which light rays pass on route to the retina. The iris also contains muscle, which contracts in response to bright light, making the pupil smaller and reducing the amount of light entering the posterior segment. By contrast, dim light will cause the pupil to dilate thus increasing the light entering the posterior segment. The iris is controlled by branches of the autonomic nervous system. Hence, parasympathetic stimulation, supplied by the oculomotor nerve, will constrict the pupil while sympathetic stimulation, originating from the superior cervical ganglion, acts to dilate the pupil.

The posterior surface of the iris is covered in cells, which contain the pigment melanin and which prevent light from entering the eye through the iris. The remaining part of the iris has varying amounts of pigment resulting in its characteristic color. Hence, an iris with relatively little pigment appears blue and progressively more pigment leads successively to green, hazel, and brown eyes. The amount of pigmentation present and therefore, the resulting eye color, is genetically determined. Albinism is a genetically determined condition, which results in a lack of pigment in cells in the body. In humans, pigmentation on the back surface of the iris is never completely absent, so the eyes of humans with albinism often appear blue. In animals that are albino, however, no pigmentation is present and the eyes appear pink as for example, in white mice.

Ciliary Body

The ciliary body is a 5–6 mm wide ring of tissue extending from the scleral spur anteriorly to the ora serrata posteriorly and is the anterior continuation of the choroid. It can be further divided into the pars plicata and pars plana. It consists of the ciliary muscle and a tissue, which secretes the aqueous humor. In addition, it provides attachment to the zonular fibers, which attach to the peripheral region of the crystalline lens thus maintaining it in position. Contraction and relaxation of the ciliary muscle can change the thickness of the lens, which simultaneously alters its curvature thus enabling the eye to change power and focus at different distances, a process called “accommodation.” The action of the ciliary body is also controlled by the oculomotor nerve.

Crystalline Lens

The lens consists of specialized surface ectoderm cells and is a highly elastic, circular, biconvex, transparent body lying immediately behind the pupil. It is suspended from the ciliary body by the zonular fibers and enclosed within a transparent capsule. The lens has less refractive power than the cornea and contraction of the ciliary muscle during accommodation relaxes the tension exerted by the zonular fibers on the lens, causing it to bulge, thus increasing its thickness and refractive power. This variable power enables us to focus from distant to near objects in the visual scene. The microscopic appearance of the lens is of long, thin cells, which are regularly arranged in layers, essentially like an onion. These cells are continually produced through life as a result of mitotic cell division at the periphery of the lens,[7] such that the thickness of the lens increases during a person’s lifetime. Eventually the lens may become so thick that it is no longer able to support its own metabolism, leading to increased opacity and ultimately cataract.[7] The lens also becomes yellower with age as a result of pigment cells building up within its structure. These cells are thought to be a protective mechanism against ultraviolet light. As the lens becomes thicker, it also becomes less elastic and this loss in elasticity and therefore, ability to focus, is thought to be responsible for a loss in reading ability in the middle years of life, a condition called “presbyopia.”

Aqueous Humor

The aqueous humor is a transparent liquid produced by the ciliary body and which passes through the pupil, thus filling the anterior chamber. It ultimately passes through a fine meshwork at the cornea-sclera-iris junction called the trabecular meshwork into Schlemm’s canal, and then drains into the venous system. Aqueous humor has a consistency much like water and functions to provide nutrients to, and remove waste products of metabolism from the transparent cornea and crystalline lens, both of which do not possess a blood supply. The continuous production of the aqueous humor and drainage through the trabecular meshwork results in a fluid pressure, which has a range in normal individuals of 10–20 mm of mercury. This pressure serves to maintain the shape of the eye. In some individuals, the trabecular meshwork can suddenly or more gradually become blocked leading to an increase in intraocular pressure (IOP) in the anterior chamber. This increase in IOP may be transferred to the retina damaging its function, leading to a condition called glaucoma.[8]

The Posterior Structures of the Eye

The posterior part of the eye consists largely of the vitreous body, the choroid, retina, and optic disk (Fig. 3).

Vitreous Body

The vitreous cavity is the largest cavity in the eye comprising approximately two-thirds of its volume. It is bounded anteriorly by the lens and ciliary body and posteriorly by the retinal cup. It comprises two regions, viz. a cortical zone of densely packed collagen fibers and a more liquid central region. Unlike the aqueous humor, the vitreous is a transparent, gel-like liquid with a relatively thick consistency. It is largely water (98%), with salts and collagen fibers making up the remainder. The vitreous fills the posterior eye and is only loosely attached to the retina, its function being mainly to maintain the shape of the eye. Vitreous is not continually produced, but remains fairly constant during life. Sometimes individuals complain of seeing particles or “floaters” in their visual field. Floaters are a consequence of the aggregations of collagen fibers, which circulate around the vitreous due to convection currents arising from body heat. When these particles are close to the retina, they cast a shadow, which is perceived as floaters. In some older individuals, the loose attachment of the vitreous to the retina can break leading to a posterior vitreous detachment (PVD), a process that may cause a retinal tear.

The Choroid

The choroid lies between the sclera and retina and lines the posterior portion of the inner surface of the sclera. It is rich in blood vessels and a deep chocolate brown in color due to the dense pigmentation by melanin and serves to absorb stray light within the eye. The choroid also provides a vascular supply to structures of the anterior segment and provides nutrients and removes waste products from the retinal photoreceptor cells.

The Retina

The retina is the innermost layer of the posterior eye, lining approximately three-quarters of the eyeball. It is thickest at the back of the eye and thins out anteriorly ceasing just behind the ciliary body. The retina is the light-sensitive part of the eye and responsible for converting the focused image into nerve action potentials, which are then relayed to the brain via the visual pathway. There are many layers of nerve cells within the retina, which provide complex connections between the light-sensitive cells located toward the posterior parts of its surface.

The most posterior layer of the retina is the pigment epithelium (Fig. 4), which supplies metabolites and removes waste products from the light-sensitive cells embedded within it. The light-sensitive cells are of two types, viz. rods and cones. Rods are highly specialized cells made up of an outer segment containing the photosensitive pigment rhodopsin, an inner

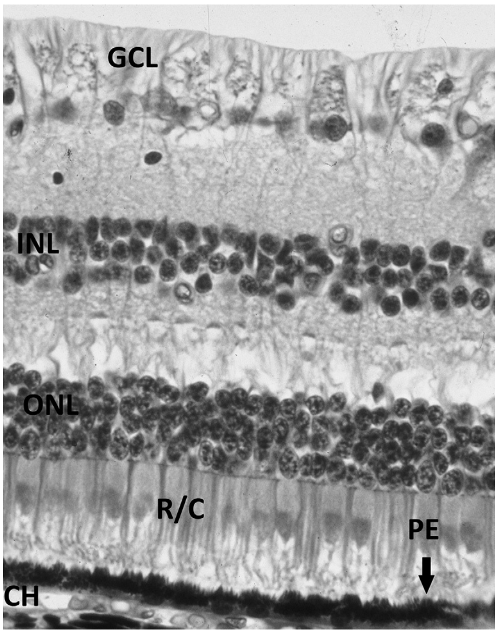

FIG. 4 The figure shows the various layers of the light-sensitive retina (*CH*, choroid; *GCL*, ganglion cell layer; *INL*, inner nuclear layer; *ONL*, outer nuclear layer; *PE*, pigment epithelium; *R/C*, rods and cones). *Image courtesy: R.A. Armstrong.*

segment containing large numbers of mitochondria, a nuclear region, and special synaptic structures. When exposed to light, rhodopsin causes a chemical cascade reaction, which converts light energy into electrical energy. Rods are most active at low light intensities and, therefore, are responsible for vision in dim light and for night vision. Rods are only sensitive to the intensity of light and not to its wavelength, so they can only represent an image in black and white. The other type of light-sensitive cell, the cones, is much less numerous than rods but capable of color detection. Hence, there are three types of cones sensitive to red, green, and blue light. Perception of a colored image is similar to that constructed on a television screen, where the red, green, and blue pixels interact to produce all colors of the visible spectrum.

When light enters the eye, it is brought to a focus by the cornea and crystalline lens on to the retina. This point of focus is called the macula lutea and located in its center is a depression called the fovea centralis. The density of cones is greatest at the macula while at the fovea centralis only cones are present. The density of cones is responsible for visual acuity, i.e., the level of detail that an individual is capable of perceiving, which is analogous to the pixel resolution of a digital camera. Hence, the greater the number (and density) of pixels, the more detailed the image that the camera is able to resolve. In addition, at the fovea centralis, there is a layer of pigment, which absorbs ultraviolet light and is therefore protective to the eye. This macular pigment can sometimes be observed with an ophthalmoscope as a tiny dot of yellow at the fovea centralis.

An image of the retina, termed the fundus, can be achieved by using an ophthalmoscope and several important features are visible. First, the retinal nerves, which are generally too small to be seen individually, collect together and leave the eye at the optic disk (Fig. 5). There are no rods or cones present within the optic disk and hence this region is also known as the "blind spot." Second, the optic disk is the entry point for the major blood supply to the anterior surface of the retina. The eye is one of the few places in the body where the capillary network can be directly observed without an invasive procedure.

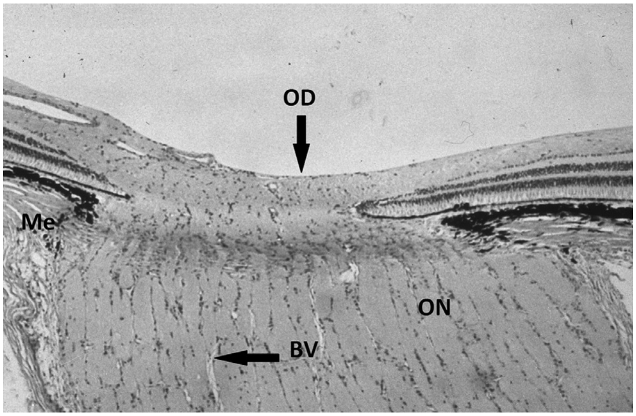

FIG. 5 The figure shows the optic disk and nerve in section (*BV*, blood vessel; *CP*, cribriform plate; *OD*, optic disk; *ON*, optic nerve; *Me*, meninges). *Image courtesy: R.A. Armstrong.*

Consequently, it is possible to observe structural changes within the blood vessels associated with disease such as aneurysm, embolism, and atherosclerosis.[9] In addition, the signs of malignant hypertension (high blood pressure) can be observed, a potentially life-threatening condition. The pattern of blood vessels across the retina is unique to each individual, much like a fingerprint. Third, the photoreceptor layer at the macula is thicker and has a greater and finer blood supply, resulting in a darker appearance. The increase in thickness is due to the greater packing density of the rods and cones.

The background color of the fundus is red-orange color, due to its blood supply. Because capillary vessels in the retina are particularly fine, they are also prone to damage from various diseases such as diabetes, which can cause leaking from the blood vessels. Other diseases result in degeneration of the photoreceptors as in age-related macular degeneration (AMD). In addition, the retina itself is a delicate structure and easily dislodged by trauma, a condition resulting in a detached retina.

Visual Pathway

The visual pathway describes the anatomical pathway by which electrical signals generated by the retina are sent to the brain (Fig. 6). The nerve fibers of the retina, representing the axons of the ganglion cells, collect together at the optic disk before passing out of the eye through the orbital bones and into the brain via the optic nerve (the second cranial nerve). The nerve fibers from different areas of the retina become more organized as they pass down the optic nerve. The optic nerves from each eye meet at the optic chiasm, a structure at the base of the brain. At this point, the nerve fibers, which are associated with the nasal half of the retina from each eye cross over, so that on leaving the optic chiasm and passing into the optic tracts, the nerve fibers from the nasal retina of one eye travel

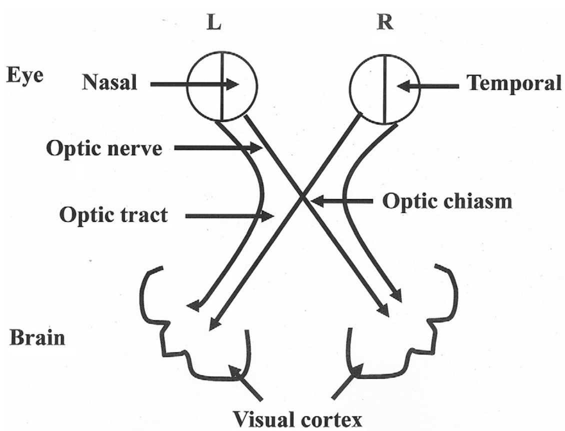

FIG. 6 The figure shows the pathway connecting the eyes to the brain, fibers form the temporal halves of each eye pass to the brain on the same side while those from the nasal halves of each eye cross over at the optic chiasm (*L*, left; *R*, right). *Image courtesy: R.A. Armstrong.*

down the optic tract with the nerve fibers originating in the temporal retina of the other eye. At the end of each optic tract, the retinal nerve fibers connect with other visual pathway nerves in a structure called the lateral geniculate nucleus (LGN) located in the midbrain. Some processing of the electrical signals occurs in the LGN before a series of radiating nerve fibers, the optic radiation, convey the information to the visual cortex in the posterior portion of the occipital lobe. Perception of sight ultimately derives from processing within this and adjacent areas of brain.

Summary Points

1. The eye is highly specialized for photoreception and focuses light from an object onto the retina.
2. Visual processing by the brain results in "visual perception," the construction of a sensory image in the brain, which is then consciously appreciated as vision.
3. The surface of the cornea together with the associated tear film is responsible for most of the refractive power of the eye.
4. The lens has less refractive power than the cornea and contraction of the ciliary muscle during accommodation relaxes the tension exerted by the zonular fibers on the lens, causing it to bulge, thus increasing its thickness and refractive power.
5. The retina is the light-sensitive part of the eye and is responsible for converting the focused image into electrical signals, which are then sent to the brain via the visual pathway.
6. There are several important landmarks visible on the fundus of the eye including the optic disk, the capillary network of the retina, and the macula.
7. The visual pathway describes the anatomical pathway by which electrical signals generated in the retina are sent to the brain.
8. Perception of sight ultimately derives from processing within the visual cortex and adjacent areas of brain.

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SECTION
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Macular Degeneration