Chapter 22. EYE VISION

22.1. EYE STRUCTURE

The eye is a very complex organ that sends a huge amount of information to the brain. It has a very specific design to capture and analyze light. In its simplest description, the eye is a spherical box, with a lens to focus the light that enters it, and cells to process the light.

The human eye is roughly spherical in shape (fig. 22.1). It is bounded by three distinct layers of tissue. The outer layer, ***sclera***, is extremely tough. It is white in color except in the front. Here it forms the transparent ***cornea***, which admits light into the interior of the eye and bends the light rays so that they can be brought to a focus. The surface of the cornea is kept moist and dust-free by the secretion from the tear glands.

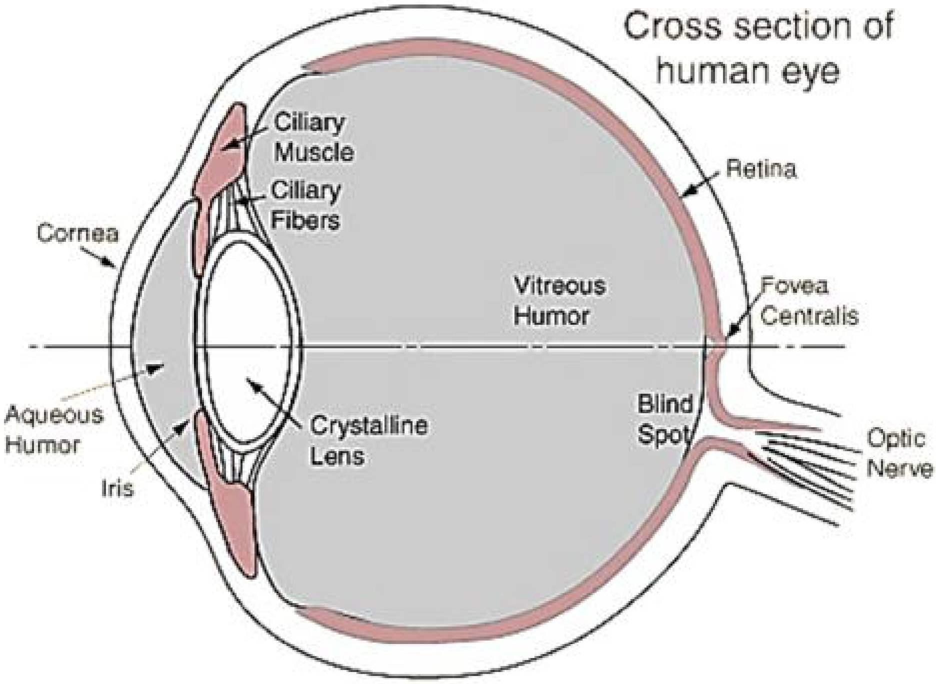

Fig. 22.1. Human eye

The middle coat of the eye, ***choroid***, is deeply pigmented with melanin and well supplied with blood vessels. It serves the very useful function of stopping the reflection of stray light rays within the eye. This is the same function that is accomplished by the dull black paint within a camera.

In the front of the eye, the choroid forms the ***iris***. This may be pigmented and is responsible for the color of the eye. An opening, the ***pupil***, is present in the center of the iris. The size of this opening is variable and under automatic control. In dim light (or times of danger) the pupil enlarges, letting more light into the eye. In bright light, the pupil closes down. This produces clearer vision, because a smaller opening, or aperture, creates a sharper image.

Behind the pupil and iris are the crystalline ***lens*** and the ***ciliary body***. The ciliary body contains muscles that support the lens and changes its shape. The lens is a colorless, nearly transparent double convex structure, similar to an ordinary magnifying glass. Its only function is to focus light rays onto the retina. By changing its curvature, the lens can focus on objects at different distances from it. This process is called accommodation.

The lens of the eye is bathed on one side by the ***aqueous humor*** and supported on the other side by the ***vitreous humor***. Aqueous humor is located in the anterior chamber of the eye, the space between the lens and the cornea. It maintains the intraocular pressure and inflates the globe of the eye. The vitreous is the transparent, colorless, gelatinous mass that fills the space between the lens of the eye and the retina and occupying about 80 % of the volume of the eyeball.

The inner coat of the eye is the ***retina***. It contains photoreceptors that translate light energy into electrical signals and sends them to the brain through the optic nerve. The center area of retina, called the ***macula***, is used for fine central vision and color vision. The ***fovea*** is located in the center of the macula. It is responsible for sharp central vision, which is necessary in humans for reading, watching, driving, and any activity where visual detail is of primary importance. The ***blind spot*** lacks photoreceptors; it is located where the optic nerve fibers leave the eye.

22.2. IMAGE FORMATION BY THE EYE OPTICAL SYSTEM

The eye function is to collect light emitted or reflected by a distant object and form an image of object for presentation to the brain. The eye can see the object under study clearly if precise real optic image of this object is built on the retina. This problem is solved by an optical system of the eye. It consists mainly of the cornea and the lens, and to a lesser extent of other structures.

Most of the refraction occurs at the cornea (40–43 diopters). The cornea has an index of refraction of 1,38. The index of refraction of the cornea is significantly greater than the index of refraction of the surrounding air. This difference in optical density combined with the fact that the cornea has the shape of a converging lens is what explains the ability of the cornea to do most of the refracting of incoming light rays. The refractive index of the aqueous humor — 1,33; the crystalline lens (on average) — 1,41; and the vitreous humor — 1,34. Total refractive power D of the eye is varied from 60 to 73 diopters; the lens refractive power D is in the range 20–30 diopters.

If all the refractive surfaces of the eye are algebraically added together and then considered to be one single lens, the optics of the normal eye may be simplified and represented schematically as a «reduced eye». This is useful in simple calculations. In the reduced eye, a single refractive surface is considered to exist, with its central point 17 millimeters in front of the retina and a total refractive power of 60 diopters when the lens is accommodated for distant vision.

Eye optical system forms on the retina a ***real inverted diminished*** image of the distant object (fig. 22.2).

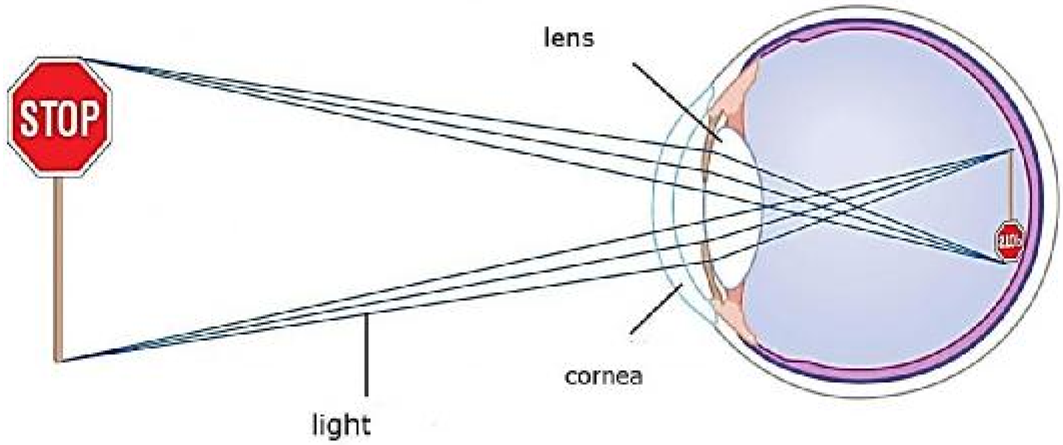

Fig. 22.2. The formation scheme of a real inverted diminished image on retina

22.3. Accommodation

Accommodation is the process by which the eye changes optical power to maintain a clear image as object distance varies.

Eye optical system makes clear image on retina, if thin-lens equation is satisfied:

$$\frac{1}{d} + \frac{1}{f} = \frac{1}{F}, \qquad (22.1)$$

where $\boldsymbol{d}$ is the object to lens distance (fig. 22.3), $\boldsymbol{f}$ **= 17 mm** is the image distance (lens to retina distance), $\boldsymbol{F}$ is the eye focal length.

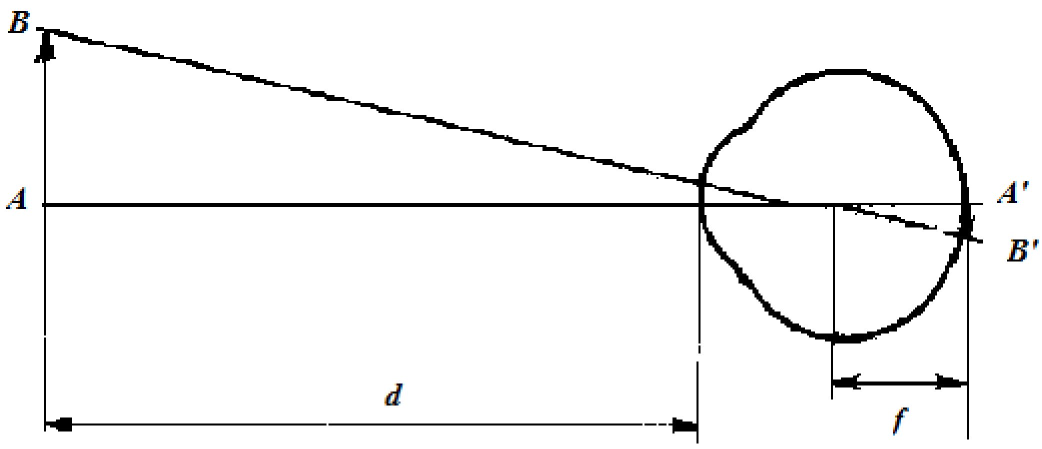

Fig. 22.3. Illustration for thin-lens equation

Light rays from distant objects ($\boldsymbol{d} \to \infty$) are nearly parallel and do not need as much refraction to bring them to a focus ($\boldsymbol{f} = \boldsymbol{F}$).

Let's compare the operation of a camera and an eye. In both cases the instrument (eye or camera) must make an adjustment to put clear images on the retina or film of objects that are a variety of distances away. In a camera, the focal length of the lens ***F*** is fixed and the image distance ***f*** is adjusted (lens to film distance is adjusted). In the eye the lens to retina distance (the image distance) ***f*** is fixed and the eye adjusts its focal length to place clear images on the retina. Eye accommodation is carried out by the lens curvature change. When the eye is relaxed, the lens has its minimum optical power for distant viewing. As the muscle tension around the ring of muscle is increased, the lens rounds out to its maximum optical power (fig. 22.4).

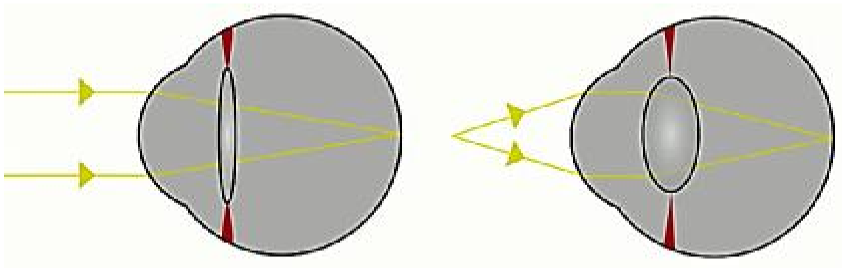

Fig. 22.4. Eye accommodation is carried out by the lens curvature change

The ability for accommodation depends on the elasticity of the eye lens and decreases with age (fig. 22.5).

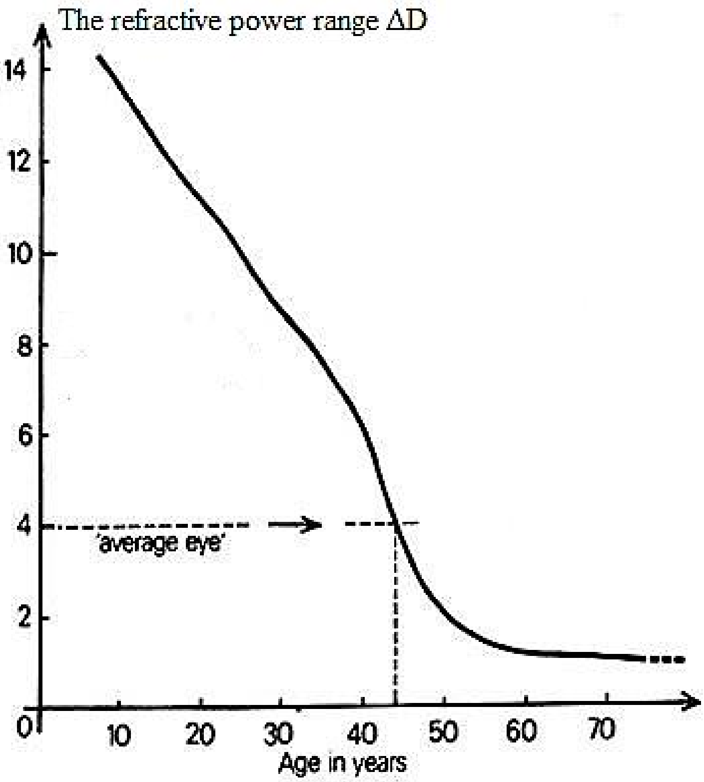

Fig. 22.5. Dependence of accommodation on the age

Far point R is the point at which an object must be placed along the optical axis for its image to be focused on the retina when the eye is not accommodating. For the normal eye the far point ***R*** is located at distance $l_R \geq 20$ m from the eye. ***Near point P*** is the point nearest the eye at which an object is accurately focused on the retina when the maximum degree of accommodation is employed. For the normal eye near point ***P*** at l_P = 10–12 cm distance from the eye. ***Range of accommodation A_{PR}*** is

$$A_{PR} = \frac{1}{l_P} - \frac{1}{l_R}. \qquad (22.2)$$

22.4. THE EYE REFRACTION DEFECTS AND EYESIGN IMPROVEMENT

Emmetropic eye is a condition of the normal eye. It is achieved when the refractive power of the cornea and the axial length of the eye is balanced, and in this case rays are focused exactly on the retina, resulting in perfect vision. An eye in a state of emmetropia requires no correction.

In this case parallel light rays from distant objects are in sharp focus on the retina when the ciliary muscle is completely relaxed (fig. 22.6). This means that the emmetropic eye can see all distant objects clearly with its ciliary muscle relaxed. However, to focus objects at close range, the eye must contract its ciliary muscle and thereby provide appropriate degrees of accommodation.

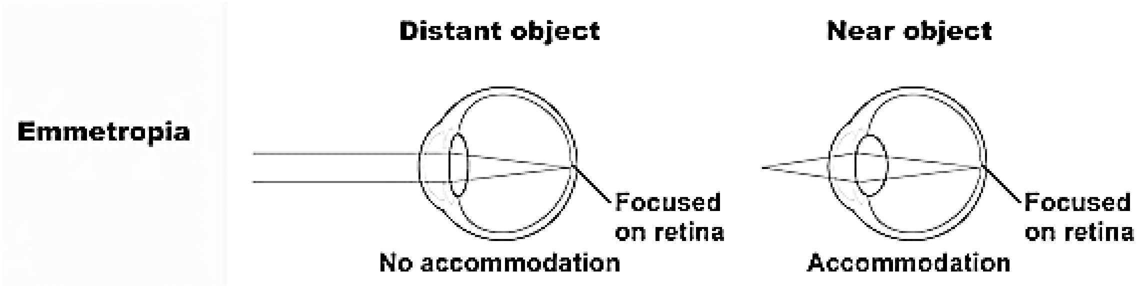

Fig. 22.6. The back focus location for normal eye

Hyperopia, which is also known as farsightedness, is usually due to either an eyeball that is too short or a lens system that is too weak. In this condition, parallel light rays are not bent sufficiently by the relaxed lens system to come to focus by the time they reach the retina (fig. 22.7, *a*). To overcome this abnormality, the ciliary muscle must contract to increase the strength of the lens. In old age, when the lens becomes **presbyopic**, a farsighted person is often unable to accommodate the lens sufficiently to focus even distant objects. Hyperopia can be corrected by adding refractive power using a convex lens in front of the eye (fig. 22.7, *b*).

Myopia (shortsightedness) is a condition of the eye where the light that comes in does not directly focus on the retina but in front of it (fig. 22.8, *a*). This is usually due to too long an eyeball. Also it can result from too much refractive power in the lens system of the eye. A myopic person has no mechanism by which to focus distant objects sharply on the retina. However, as an object moves still closer to the eye, the person can use the mechanism of accommodation to keep the image focused clearly. A myopic person has a definite limiting ***far point*** for clear vision.

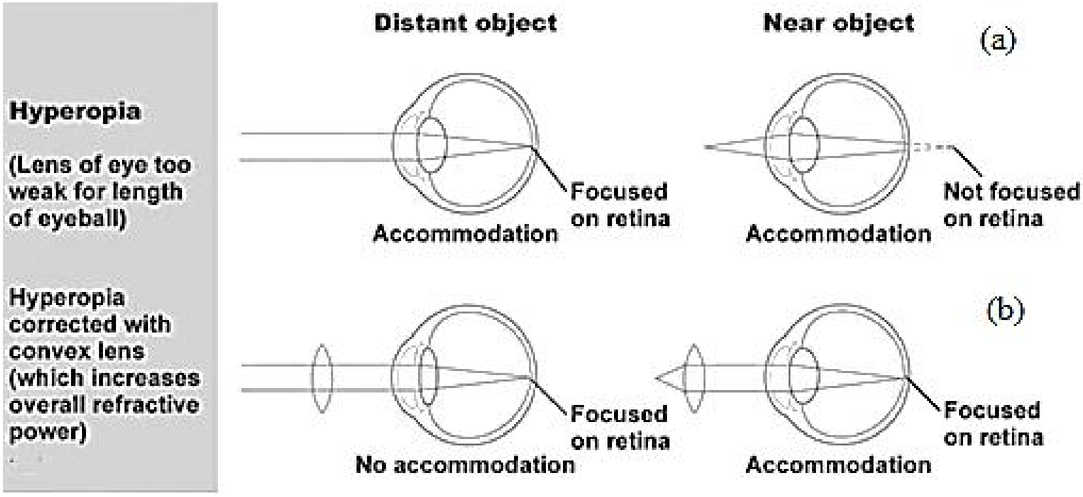

Fig. 22.7. The back focus location for far-sighted eye (*a*) and vision correction with a convex lens (*b*)

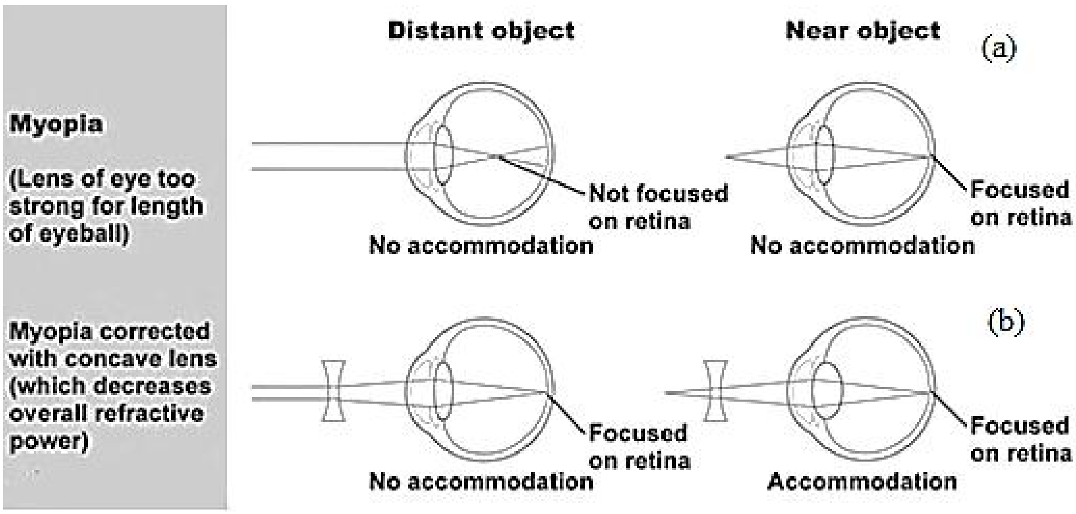

Fig. 22.8. The back focus location for short-sighted eye (*a*) and vision correction with a concave lens (*b*)

The corrective lenses have a negative optical power (i. e. are concave) which compensates for the excessive positive diopters of the myopic eye (fig. 22.8, *b*).

22.5. VISUAL ACUITY

Visual acuity is a quantitative measure of the ability to identify black symbols on a white background at a standardized distance as the size of the symbols is varied. Visual acuity is related with ***visual angle*** — the minimum angle at which resolution is just possible. It is the angle φ under which object *AB* is seen from the optical center of the eye (fig. 22.9).

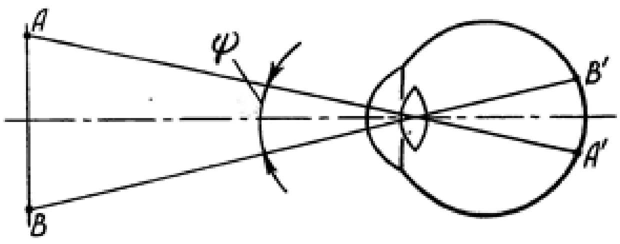

Fig. 22.9. Visual angle

The sensation of vision occurs when light is absorbed by the photosensitive rods and cones. To resolve two points, the light from each point must be focused on a different cone and the exited cones must be separated from each other by at least one cone that is not exited. The minimum distance between exited cones is d ≈ 5 μm, so the minimum visual angle for which two luminous points (or two black points over a white background) are perceived by the eye as separate is about one angular minute:

$$\varphi\text{min} = \frac{d}{f} = \frac{5 \cdot 10^{-3}\ \mu\text{m}}{17\ \text{mm}} = 3 \cdot 10^{-4}\ \text{rad} = 1', \qquad (22.3)$$

where f = 17 mm is the lens to retina distance.

The eye poorly recognizes the details of an object seen at an angle less than 1 ′.

The angle 1′ is an angle at which a segment having a length of 1 cm is seen at a distance of 34 m from the eye. At an insufficient illumination (in twilight), the minimum angle of resolution becomes larger and may reach 1°.

The minimum visual angle of patient is determined using the special tables. Then ***visual aquity*** can be calculated as

$$\gamma = \frac{1'}{\varphi_{\text{minpatient}}}. \qquad (22.4)$$

For example, if φ_{min} = 2′, then the visual acuity for this patient: $\gamma = \frac{1}{2} = 0{,}5$.

By bringing an object close to the eye, one increase the angle of view, and hence make it possible to resolve finer details. However, objects cannot be brought too close to the eye since it has a limited capacity for accommodation. The most favorable distance for seeing object with a normal eye is d_0 = 25 cm. At this distance the eye recognized details well enough without being tired. This is the ***distance of normal vision***.

The eye ***resolution limit*** for the distance of normal vision is equal to:

$$AB = 1' \cdot d_0 = 3 \cdot 10^{-4}\ \text{rad} \cdot 250\ \text{mm} = 73\ \mu\text{m}. \qquad (22.5)$$

22.6. RETINA ANATOMY AND FUNCTION

After light passes through the eye lens system and then through the vitreous humor, it enters the retina from the inside. Light passes first through several layers before it finally reaches the layer of rods and cones located on the outer edge of the retina (fig. 22.10). This distance is a thickness of several hundred micrometers; visual acuity is decreased by this passage through such nonhomogeneous tissue. However, in the central foveal region of the retina the inside layers are pulled aside to decrease this loss of acuity.

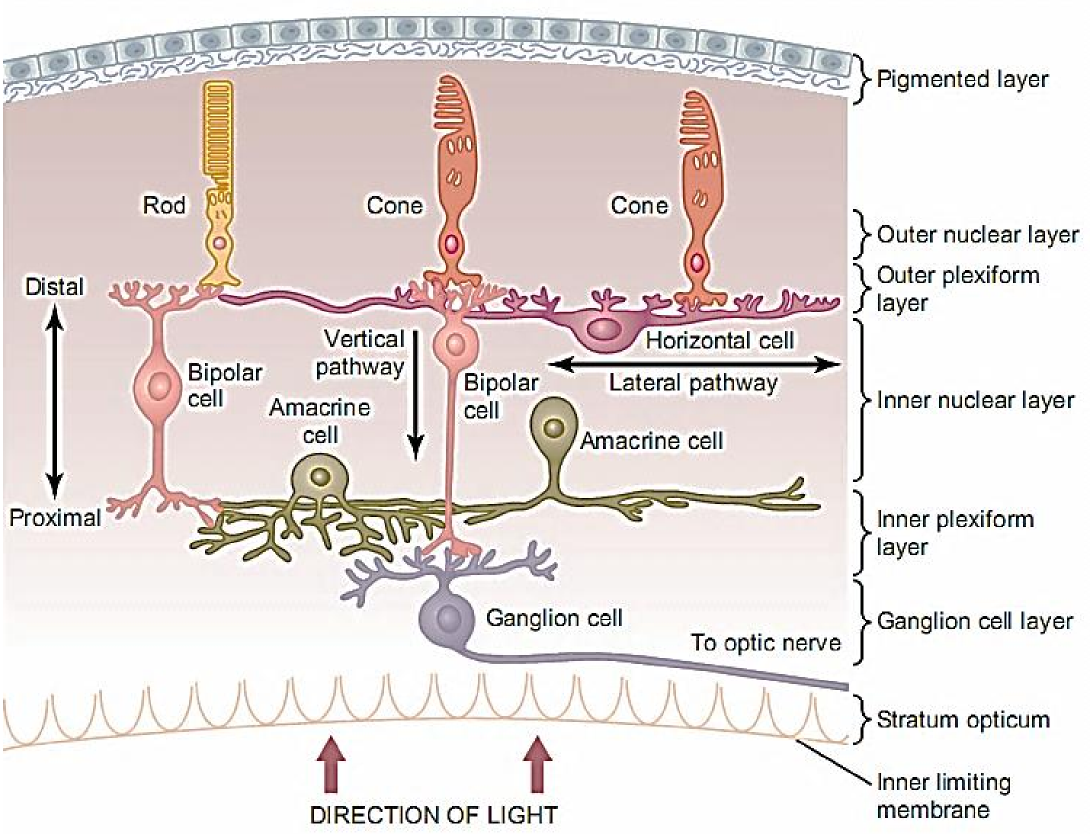

Fig. 22.10. Layers of retina

The retina contains two types of photoreceptors, termed rods and cones. (fig. 22.11). ***Rods*** are concentrated at the outer edges of the retina and are used in peripheral vision. There are approximately 125 million rods in the human retina. More sensitive than cones, rods are almost entirely responsible for ***night vision*** — vision under low illumination levels.

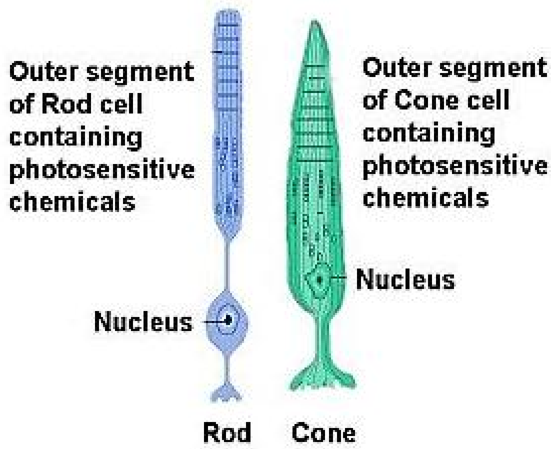

Fig. 22.11. Photoreceptors

Rods contain the light-sensitive pigment ***rhodopsin*** (visual purple) which undergoes a chemical reaction (the rhodopsin cycle) when exposed to visible light. Rhodopsin consists of a lipoprotein called opsin and a chromophore (a light-absorbing chemical compound called 11-cis-retinal). Rods cannot discriminate different wavelengths of light, and vision under low illumination conditions is essentially «colorblind». More than 100 rods are connected to each ganglion cell, and the brain cannot discriminate among these photoreceptors to identify the origin of an action potential transmitted along the ganglion.

Cones are responsible for color vision. Cone cells are densely packed in the fovea — a part of the eye, located in the center of the retina and responsible for ***sharp vision***. There are approximately 6 million cones in the retina.

Cones are less sensitive to light than the rods, but allow the perception of color. They are also able to perceive finer detail and more rapid changes in images, because their response times to stimuli are faster than those of rods. Cones are maximally sensitive to light of about 550 nm, in the yellow-green region of the visible spectrum. Cones are much less sensitive than rods to light, but in the fovea there is a 1:1 correspondence between cones and ganglions, so the visual acuity is very high.

Essential components of a photoreceptor (either a rod or a cone) are the outer segment, the inner segment, the nucleus, and the synaptic body. The light-sensitive photochemical is found in the outer segment. In the case of the rods, this is ***rhodopsin***; in the cones, it is one of three «color» photochemicals, usually called simply color pigments, that function almost exactly the same as rhodopsin except for differences in spectral sensitivity.

22.7. RHODOPSIN-RETINAL VISUAL CYCLE

When light energy is absorbed by rhodopsin, the rhodopsin begins to decompose. The cause of this is photoactivation of electrons in the rhodopsin, which instantaneously changes of the cis-form of retinal into an trans-form (fig. 22.12). This form has the same chemical structure as the cis-form but has a different physical structure — a straight molecule rather than an angulated molecule.

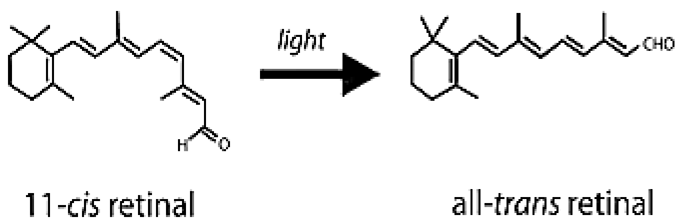

Fig. 22.12. Cis-form and trans-form of retinal

Because the three-dimensional orientation of the reactive sites of the trans-retinal, it begins to divide into opsin and a 11-cis-retinal.

This process excites electrical changes in the rods, and the rods then transmit the exciting on nerve cell and the visual image transmit into the central nervous system in the form of optic nerve action potential.

The excitation of the rod causes increased negativity of the membrane potential, which is a state of hyperpolarization. It means that there is more negativity potential than normal inside the rod membrane. This is exactly opposite to the decreased negativity (the process of «depolarization») that occurs in almost all other sensory receptors.

22.8. LIGHT AND DARK ADAPTATION OF EYE

Light and dark adaptation is the ability of the eye to adjust to various levels of darkness and light.

Light adaptation occurs when we move from the dark into bright light. Rods and cones are both stimulated and large amounts of the photopigment are broken down instantaneously, producing signals resulting in the light.

Adaption occurs in two ways:

1. By the pupil constriction, it takes about 0,3 sec.
2. By the decreasing of rhodopsin concentration in rods and iodopsin concentration in cones.

Within about one minute the cones are sufficiently excited by the bright light to take over. Visual accuracy and color vision continue to improve over the next ten minutes. During light adaptation retinal sensitivity is lost.

Dark adaptation is essentially the reverse of light adaptation. It occurs when going from a well light area to a dark area. Initially blackness is seen because our cones cease functioning in low intensity light. Also, all the rod pigments have been bleached out due to the bright light and the rods are initially nonfunctional.

Once in the dark, rhodopsin regenerates and the sensitivity of the retina increases over time (maximum sensitivity reaches approximately in hour). During these adaptation processes reflexive changes occur in the pupil size.

The eye is extremely sensitive to small amounts of light. For example, as few as 10 photons can generate a visual stimulus in an area of the retina where the rods are present at high concentration.

Differences in signal intensity that can just be detected by the human observer are known as ***just noticeable differences (dI)***. This concept applies to any type of signal, including light that can be sensed by the observer. The smallest difference in signal that can be detected depends on the magnitude of the signal. The JND is directly proportional to the intensity of the signal:

$$dI \sim I \cdot dS$$

$$dS \sim \frac{1}{I},$$

where I is the intensity of stimulus, dS is an increment of perception, and k is a coefficient. The integral form of this expression is known as the ***Weber–Fechner Law***:

$$S = k \log \frac{I}{I_0}. \qquad (22.6)$$

The Weber–Fechner law is similar to the expression for the intensity of sound in decibels.

22.9. COLOR VISION

Different cones are sensitive to different colors of light. Let's discuss of the mechanisms by which the retina detects the different gradations of color in the visual spectrum.

All theories of color vision are based on the well-known observation that the human eye can detect almost all gradations of colors can be received when only red, green, and blue monochromatic colors are appropriately mixed in different combinations.

The spectral sensitivities of the three types of cones in humans are the same as the light absorption curves for the three types of pigment found in the cones with maximum absorption on 440, 540 and 590 nm respectively. The absorption maximum for rods corresponds to 510 nm (fig. 22.13).

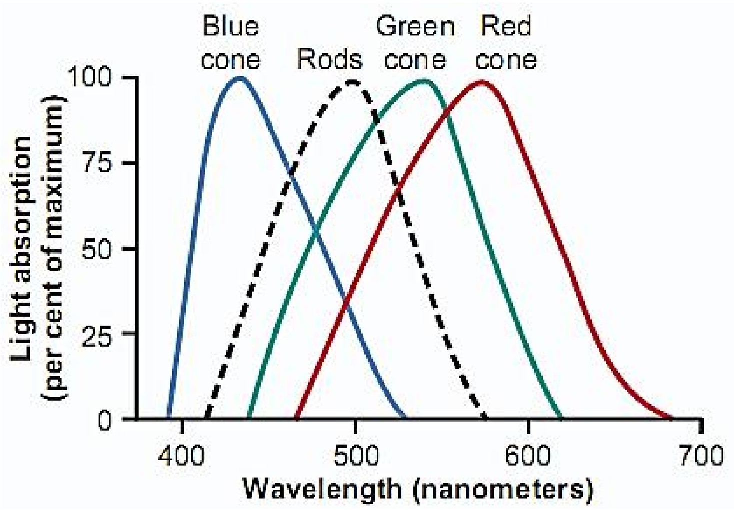

Fig. 22.13. Light absorption for cones and rods

For example, an orange monochromatic light with a wavelength of 580 nm stimulates the red cones; it stimulates the green cones to a less stimulus value, but the blue cones not at all. The nervous system interprets the ratios of stimulation of the three types of cones as the sensation of orange.

About equal stimulation of all the red, green, and blue cones gives one the sensation of seeing white. Yet there is no single wavelength of light corresponding to white; instead, white is a combination of all the wavelengths of the spectrum.

The rods are maximally sensitive to light of about 510 nm, in the blue-green region of the visible spectrum.

***Questions*:**

1. Describe eye structure. What are the eye mediums optical properties?
2. Explain the eye optical system functions. Specify eye refractive power.
3. What is the eye accommodation? Describe mechanism of the accommodation. What is range of accommodation? How does it depend on age?
4. Characterize the main eye refraction defects. How are these defects corrected?
5. How is the visual aquity determined? What is the visual angle? Specify the eye resolution limit.
6. What is the eye retina construction? Describe two type photoreceptors, explain quantity and distribution of photoreceptors.
7. What are the differences between rods and cones? Describe rhodopsin-retinal visual cycle.
8. What difference between daylight vision and twilight one? Specify the light absorption spectrum for cones and rods.
9. What is the eye adaptation? Specify basic mechanisms of adaptation.