■ NEURAL BASIS OF VISUAL PROCESS

Retina contains the **visual receptors** (Fig. 166.1), which are also called light sensitive receptors, **photoreceptors** or **electromagnetic receptors.** Visual receptors are rods and cones. There are about 6 million cones and 12 million rods in the human eye. Distribution of the rods and cones varies in different areas of retina. Fovea has only cones and no rods. While proceeding from fovea towards the periphery of retina, the rods increase and the cones decrease in number. At the periphery of the retina, only rods are present and cones are absent.

■ STRUCTURE OF ROD CELL

Rod cells are cylindrical structures with a length of about 40 to 60 μ and a diameter of about 2 μ.

Each rod is composed of four structures:

1. Outer segment
2. Inner segment
3. Cell body
4. Synaptic terminal.

1. *Outer Segment*

Outer segment of rod cell is long and slender. So it gives the rod-like appearance. It is in close contact with the pigmented epithelial cells. Outer segment of rod cell is formed by the modified cilia and it contains a pile of freely floating flat **membranous disks.** There are about 1,000 disks in each rod. Disks in rod cells are closed structures and contain the photosensitive pigment, the **rhodopsin.**

Rhodopsin is synthesized in inner segments and inserted into newly formed membranous disks at the inner portion of outer segment. New disks push the older disks towards outer tip. Older disks are engulfed (by phagocytosis) from tip of the outer segment by cells of pigment epithelial layer. Thus, outer segment of rod cell is constantly renewed by the formation of new disks. Rate of formation of new disks is 3 or 4 per hour.

2. *Inner Segment*

Inner segment is connected to outer segment by means of modified **cilium.** Inner segment contains many types of organelles with large number of mitochondria.

3. *Cell Body*

A slender fiber called rod fiber arises from inner segment of the rod cell and passes to outer nuclear layer through external limiting membrane. In outer nuclear layer, the enlarged portion of this fiber forms the cell body or rod granule that contains the nucleus.

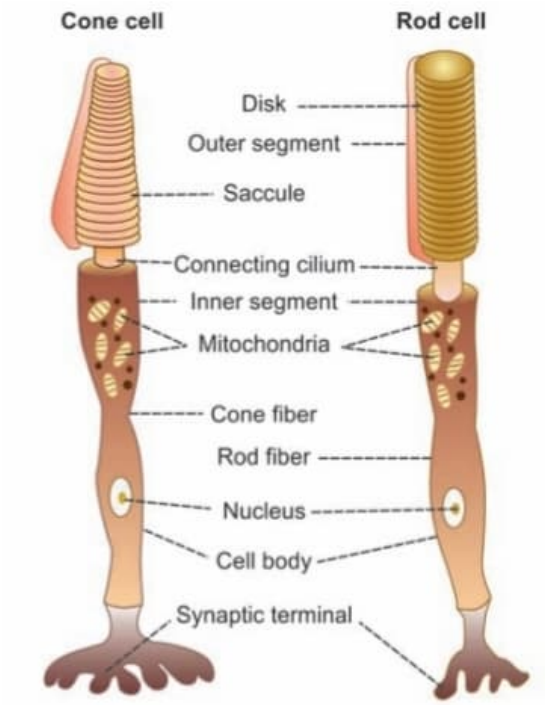

FIGURE 166.1: Structure of visual receptors

4. *Synaptic Terminal*

A thick fiber arising from the cell body passes to outer plexiform layer and ends in a small and enlarged synaptic terminal or body. Synaptic terminal of the rods synapses with dendrites of **bipolar cells** and **horizontal cells.** Synaptic vesicles present in the synaptic terminal contain neurotransmitter, **glutamate.**

■ STRUCTURE OF CONE CELL

Cone cell is the visual receptor with length of 35 μ to 40 μ and a diameter of about 5 μ. Generally, the cone cell is flask shaped. Shape and length of the cone vary in different parts of the retina. Cones in the fovea are long, narrow and almost similar to rods. Near the periphery of retina, cones are short and broad.

Like rods, cones are also formed by four parts:

1. Outer segment
2. Inner segment
3. Cell body
4. Synaptic terminal.

1. *Outer Segment*

Outer segment is small and conical. It does not contain separate membranous disks as in rods. In cone, the infoldings of cell membrane form **saccules,** which are the counterparts of rod disks.

Photopigment of cone is synthesized in the inner segment and incorporated into the folding of surface membrane forming **saccule.** Renewal of outer segment of cone is a slow process and it differs from that in rods. It occurs at many sites of the outer segment of cone.

2. *Inner Segment*

In cones also, the inner segment is connected to outer segment by a modified cilium as in the case of rods. Though various types of organelles are present in this segment, the number of mitochondria is more.

3. *Cell Body*

Cone fiber arising from inner segment is thick and it enters the inner nuclear layer through external limiting membrane. In the inner nuclear layer, cone fiber forms the cell body or cone granule that possesses nucleus.

4. *Synaptic Terminal*

Fiber from cell body of cone leaves the inner nuclear layer and enters outer flexiform layer. Here, it ends in the form of an enlarged synaptic terminal or body. Synaptic vesicle present in the synaptic terminal of cone cell also possesses the neurotransmitter, glutamate.

■ FUNCTIONS OF RODS AND CONES

Functions of Rods

Rods are very sensitive to light and have a **low threshold.** So, the rods are responsible for **dim light vision** or **night vision** or **scotopic vision.** But, rods do not take part in resolving the details and boundaries of objects (visual acuity) or the color of the objects (color vision). Vision by rod is black, white or in the combination of black and white namely, grey. Therefore, the colored objects appear faded or greyish in twilight.

Functions of Cones

Cones have high threshold for light stimulus. So, the cones are sensitive only to bright light. Therefore, cone cells are called receptors of **bright light vision** or **daylight vision** or **photopic vision.** Cones are also responsible for **acuity of vision** and the **color vision** (Table 166.1).

Achromatic Interval

When an object is placed in front of a person in a dark room, he cannot see any object. When there is slight illumination, the person can see the objects but without color. It is because, at this level, only rods are stimulated. When, the illumination is increased, the threshold for cones is reached. Now, the person can see the objects in finer details and in color. Interval between the threshold for rods and cones, i.e. interval from when an object is first seen and the time when that object is seen with color is called **achromatic interval.**

■ CHEMICAL BASIS OF VISUAL PROCESS

Photosensitive pigments present in rods and cones are concerned with chemical basis of visual process. Chemical reactions involved in these pigments lead to the development of electrical activity in retina and generation of impulses (action potentials), which are transmitted through optic nerve. Photochemical changes in the visual receptor cells are called **Wald visual cycle.**

■ RHODOPSIN

Rhodopsin or visual purple is the photosensitive pigment of rod cells. It is present in membranous disks located in outer segment of rod cells.

Chemistry of Rhodopsin

Rhodopsin is a conjugated protein with a molecular weight of 40,000. It is made up of a protein called **opsin** and a **chromophore.** Opsin present in rhodopsin is known as **scotopsin.** Chromophore is a chemical substance that develops color in the cell. Chromophore present in the rod cells is called **retinal.** Retinal is the aldehyde of **vitamin A** or retinol.

Retinal is derived from food sources and it is not synthesized in the body. It is derived from carotinoid substances like **β-carotene** present in carrots.

Retinal is present in the form of **11-*cis* retinal** known as **retinine 1.** Retinine 1 is present in human eyes. It is different from retinine 2 that is present in the eyes of some animals. Significance of 11-*cis* form of retinal is that, only in this form it combines with scotopsin to synthesize rhodopsin.

Photochemical Changes in Rhodopsin – Wald Visual Cycle

When retina is isolated and examined in dark, the rods appear in red because of rhodopsin. During exposure to light, rhodopsin is bleached and the color becomes yellow. When rhodopsin absorbs the light that falls on retina, it is split into retinine and the protein called **opsin** through various intermediate photochemical reactions (Fig. 166.2).

TABLE 166.1: Rods versus cones

Features	Rods	Cones
Number in each eye	12 million	6 million
Length	40 to 60 μ	35 to 40 μ
Diameter	2 μ	5 μ
Shape	Cylindrical	Flask shaped
Outer segment	Long and slender	Small and conical
Sensitivity to light	More sensitive	Sensitive only to bright light
Threshold	Low	High
Type of vision responsible for	Dim light vision or night vision or scotopic vision	Bright light vision or day light vision or photopic vision
Acuity of vision	Not responsible	Responsible
Color vision	Not responsible	Responsible
Photosensitive pigment	Rhodopsin	Porphyropsin or iodopsin or cyanopsin

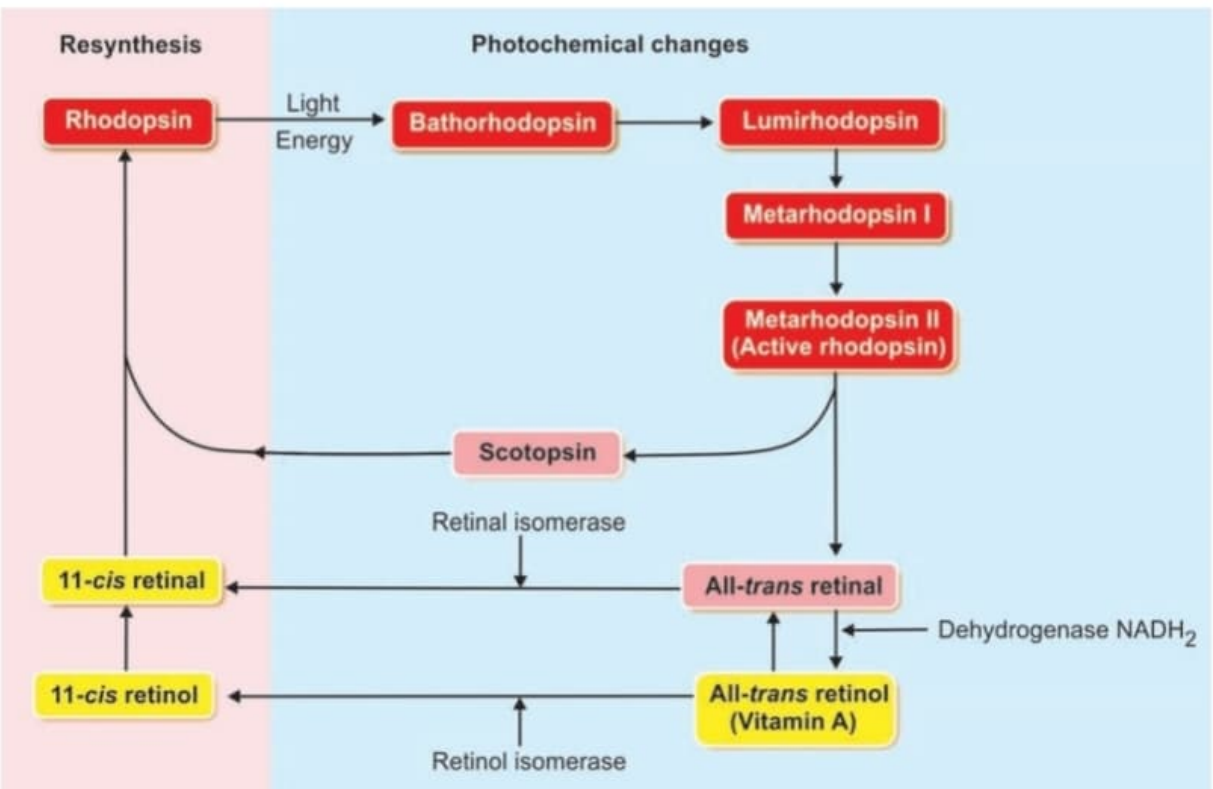

FIGURE 166.2: Photochemical changes and resynthesis of rhodopsin (Wald visual cycle).
$NADH_2$ = Reduced nicotinamide adenine dinucleotide.

Following changes occur due to absorption of light energy by rhodopsin:

1. First, **rhodopsin** is decomposed into **bathorhodopsin** that is very unstable
2. Bathorhodopsin is converted into l**umirhodopsin**
3. Lumirhodopsin decays into **metarhodopsin** I
4. Metarhodopsin I is changed to **metarhodopsin** II
5. Metarhodopsin II is split into **scotopsin** and **all-*trans* retina**l
6. All-*trans* retinal is converted into **all-*trans* retinol (vitamin A)** by the enzyme dehydrogenase in the presence of reduced nicotinamide adenine dinucleotide ($NADH_2$).

Metarhodopsin is usually called **activated rhodopsin** since it is responsible for development of receptor potential in rod cells.

Resynthesis of Rhodopsin

First, the all-*trans* retinal derived from metarhodopsin II is converted into 11-*cis* retinal by the enzyme **retinal isomerase.** 11-*cis* retinal immediately combines with scotopsin to form rhodopsin.

All-*trans* retinol (vitamin A) also plays an important role in the resynthesis of rhodopsin. All-*trans* retinol is converted into 11-*cis* retinol by the activity of enzyme retinol isomerase. It is converted into 11-*cis* retinal, which combines with scotopsin to form rhodopsin. All-*trans* retinol is also reconverted into all-*trans* retinal.

Rhodopsin can be synthesized directly from all-*trans* retinol (vitamin A) in the presence of nicotinamide adenine dinucleotide ($NADH_2$). However, the synthesis of rhodopsin from 11-*cis* retinal (retinine) is faster than from 11-*cis* retinol (vitamin A).

■ PHOTOTRANSDUCTION

Visual or phototransduction is the process by which l**ight energy** is converted into **receptor potentia**l in visual receptors.

Resting membrane potential in other sensory receptor cells is usually between –70 and –90 mV. However, in the visual receptors during darkness, negativity is reduced and resting membrane potential is about –40 mV. It is because of influx of sodium ions. Normally in dark, sodium ions are pumped out of inner segments of rod cell to ECF. However, these sodium ions leak back into the rod cells through membrane of outer segment and reduce the **electronegativity** inside rod cell (Fig. 166.3). Thus, **sodium influx** maintains a decreased negative potential up to –40 mV. This potential is constant and it is also called **dark current.**

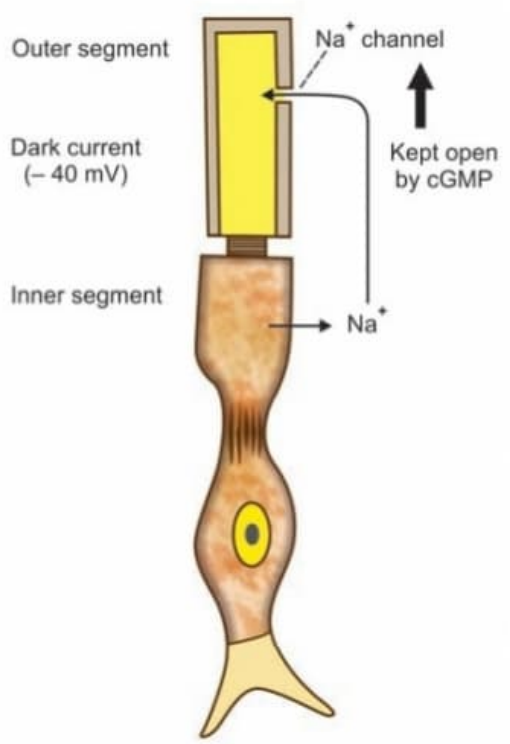

FIGURE 166.3: Maintenance of dark current (resting potential) in outer segment of rod cell

Influx of sodium ions into outer segment of rod cell occurs mainly because of cyclic guanosine monophosphate (cGMP) present in the cytoplasm of cell. The cGMP always keeps the sodium channels opened. Closure of sodium channels occurs due to reduction in cGMP. Concentration of sodium ions inside the rod cell is regulated by sodium potassium pump.

When light falls on retina, rhodopsin is excited leading to development of receptor potential in the rod cells.

Phototransduction Cascade of Receptor Potential

Following is the phototransduction cascade of receptor potential (Fig. 166.4):

1. When a **photon** (the minimum quantum of light energy) is absorbed by rhodopsin, the **11-*cis* retina**l is decomposed into **metarhodopsin** through few reactions mentioned earlier. Metarhodopsin II is considered as the active form of rhodopsin. It plays an important role in the development of receptor potential.
2. Metarhodopsin II activates a **G protein** called **transducin** that is present in rod disks

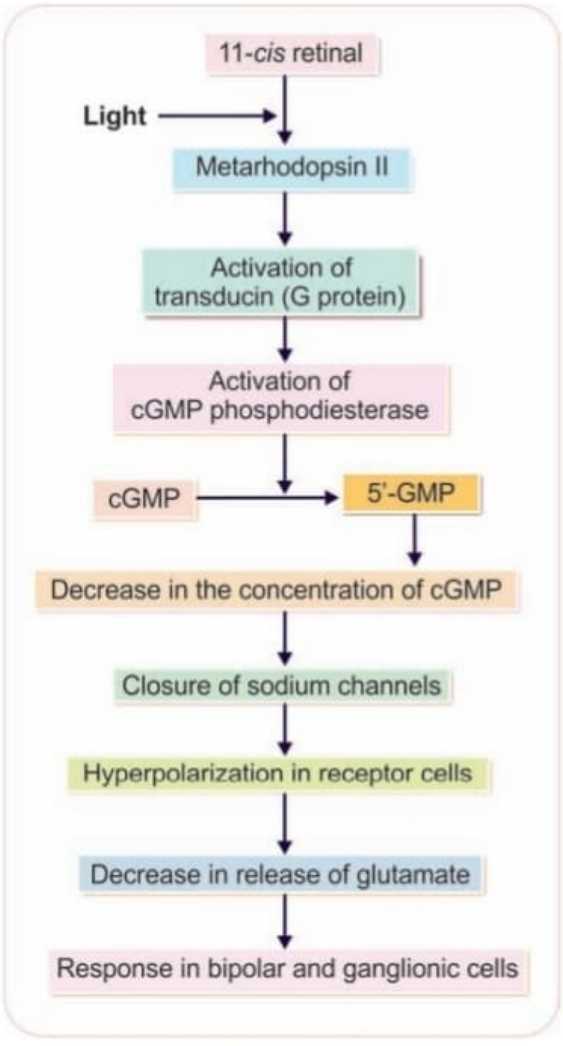

FIGURE 166.4: Phototransduction cascade. cGMP = Cyclic guanosine monophosphate.

3. Activated transducin activates the enzyme called cyclic guanosine monophosphate phosphodiesterase **(cGMP phosphodiesterase),** which is also present in rod disks
4. Activated cGMP phosphodiesterase hydrolyzes cGMP to 5'-GMP
5. Now, the concentration of cGMP is reduced in rod cell
6. Reduction in concentration of cGMP immediately causes closure of sodium channels in the membrane of visual receptors
7. Sudden closure of sodium channels prevents entry of sodium ions leading to **hyperpolarization.** The potential reaches –70 to –80 mV. It is because of sodium-potassium pump.

Thus, the process of receptor potential in visual receptors is unique in nature. When other sensory receptors are excited, the electrical response is in the form of **depolarization (receptor potential).** But, in visual receptors, the response is in the form of **hyperpolarization.**

Significance of Hyperpolarization

Hyperpolarization in visual receptor cells reduces the release of synaptic transmitter glutamate. It leads to development of response in bipolar cells and ganglionic cells so that, the action potentials are transmitted to cerebral cortex via optic pathway.

■ PHOTOSENSITIVE PIGMENTS IN CONES

Photosensitive pigment in cone cells is of three types, namely **porphyropsin, iodopsin** and **cyanopsin.** Only one of these pigments is present in each cone. Photopigment in cone cell also is a conjugated protein made up of a protein and chromophore. Protein in cone pigment is called **photopsin,** which is different from scotopsin, the protein part of rhodopsin. However, chromophore of cone pigment is the retinal that is present in rhodopsin. Each type of cone pigment is sensitive to a particular light and the maximum response is shown at a particular light and wave-length. Details are given in the Table 166.2.

Various processes involved in phototransduction in cone cells are similar to those in rod cells.

■ DARK ADAPTATION

Definition

Dark adaption is the process by which the person is able to see the objects in dim light. If a person enters a dim-lighted room (darkroom) from a bright-lighted area, he is blind for some time, i.e. he cannot see any object. After sometime his eyes get adapted and he starts seeing the objects slowly. Maximum duration for dark adaptation is about 20 minutes.

Causes for Dark Adaptation

Dark adaptation is due to the following changes in eyeball:

1. *Increased sensitivity of rods as a result of resynthesis of rhodopsin*

Time required for dark adaptation is partly determined by the time for resynthesis of rhodopsin. In bright light, most of the pigment molecules are bleached (broken down). But in dim light, it requires some time for regeneration of certain amount of rhodopsin, which is necessary for optimal rod function.

Dark adaptation occurs in cones also.

2. *Dilatation of pupil*

Dilatation of pupil during dark adaptation allows more and more light to enter the eye.

Inner Hair Cells

Inner hair cells are flask-shaped cells and are broader than the outer hair cells. Inner hair cells are arranged in a single row and occupy only the upper part of epithelial layer. Rounded base of each cell rests on the adjacent supporting cells called the inner phalangeal cell. Surface of the inner hair cell bears a **cuticular plate** and a number of short stiff hairs, which are called **stereocilia**. Each hair cell has about 100 sterocilia. One of the sterocilia is larger and it is called **kinocilium.** Stereocilia are in contact with the **tectorial membrane.** Inner hair cells and outer hair cells together form the receptor cells. Sensory nerve fibers are distributed around the hair cells. Both inner hair cells and outer hair cells have afferent and efferent nerve fibers (Chapter 173).

Outer Hair Cells

Outer hair cells are the columnar cells occupying the superficial part of epithelium of organ of Corti. Their bases are supported by outer phalangeal cells. Structure of outer hair cells is similar to that of inner hair cells (see above).

■ ROLE OF HAIR CELLS

Inner hair cells and outer hair cells have different roles during sound transduction.

Role of Inner Hair Cells

Inner hair cells are responsible for sound transduction, i.e. these receptor cells are the primary sensory cells, which cause the generation of action potential in auditory nerve fibers.

Role of Outer Hair Cells

Outer hair cells have a different action. These hair cells are shortened during depolarization and elongated during hyperpolarization. This process is called electromotility or mechanoelectrical transduction. This action of outer hair cells facilitates the movement of basilar membrane and increases the amplitude and

sharpness of sound. Hence, the outer hair cells are collectively called **cochlear amplifier**. The electromotility of hair cell is due to the presence of a contractile protein, **prestin** (named after a musical notation **presto**).

Role of Efferent Nerve Fibers of Hair Cells

Efferent nerve fibers (Chapter 173) of hair cells also play important role during sound transduction by releasing acetylcholine.

Efferent nerve fiber to inner hair cell terminates on the auditory (afferent) nerve fiber where it leaves the inner hair cell. It controls the generation of action potential in auditory nerve fiber by inhibiting the release of glutamate from inner hair cells.

Efferent nerve fiber to outer hair cell terminates directly on the cell body. It inhibits the electromotility of this cell.

■ EXCITATION OF HAIR CELLS

Stereocilia of hair cells in organ of Corti are embedded in tectorial membrane. Hair cells are tightly fixed by cuticular lamina reticularis and the pillar cells or rods of Corti.

When traveling wave causes vibration of basilar membrane at the resonance point, the basilar fiber, rods of Corti, hair cells and lamina reticularis move as a single unit. It causes movements of stereocilia leading to excitement of hair cells and generation of receptor potential.

Receptor potential or cochlear microphonic potential is the **mild depolarization** that is developed in the hair cells of cochlea when sound waves are transmitted to internal ear. Resting membrane potential in hair cells is –60 mV. Sensory transduction mechanism in cochlear receptor cells is different from the mechanism in other sensory receptors.

When sound waves reach internal ear traveling wave is produced. It causes vibration of basilar membrane, which moves stereocilia of hair cells away from modiolus (towards kinocilium). It causes opening of mechanically gated potassium channels (Chapter 3) and influx of potassium ions from endolymph, which contains large amount of potassium ions. Influx of potassium ions causes development of **mild depolarization** (receptor potential) in hair cells up to –50 mV.

Cochlear microphonic potential is non-propagative. But, it causes generation of action potential in auditory nerve fiber. Due to depolarization hair cells release a neurotransmitter, which generates action potential in the auditory nerve fibers. Probable neurotransmitter may be **gulatamate.**

Movement of stereocilia away from modiolus (towards kinocilium) causes **depolarization** in hair cells. Movement of stereocilia in the opposite direction (away from kinocilium) causes **hyperpolarization.** Ionic basis of hyperpolarization is not clearly known. It is suggested that **calcium** plays an important role in this process. Hyperpolarization in hair cells stops generation of action potential in auditory nerve fiber.