Medical physics - seminary

Department of Biophysics, Medical Faculty,
Masaryk University Brno

Biophysics of hearing and vision.

Sensory perception, examination and aids.

Biophysics of sensory perception

Sensory perception – reception and perception of information from outer and inner medium.

- From outer medium: **Vision, hearing, smell, taste and sense of touch**
- From inner medium: information on **position, active and passive movement (**vestibular organ, nerve-endings in the musculoskeletal system). **Also: changes in composition of inner medium and pain.**
- **Complex feelings: hunger, thirst, fatigue etc.**

Categorising receptors

a) According to the acting energy:

mechanoceptors
thermoceptors
chemoceptors
photoceptors
- adequate and inadequate stimuli

b) According to the complexity:

free nerve-endings (pain)
sensory bodies (sensitive nerve fibre + fibrous envelope - cutaneous sensation)
sensory cells (parts of sensory organs) - specificity
non-specific: receptors of pain - react on various stimuli.

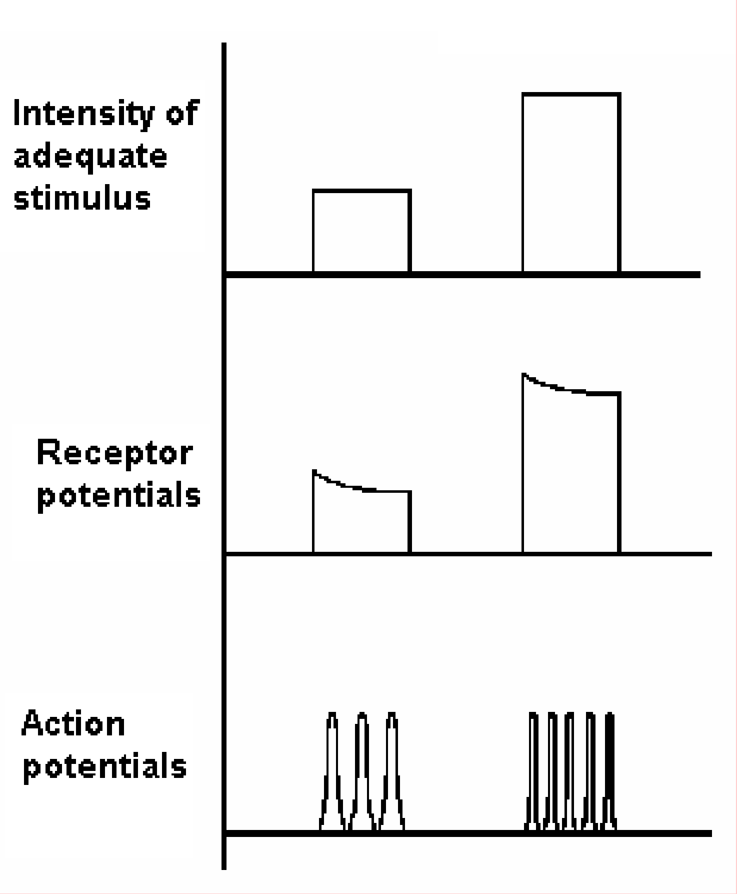
c) According to the place of origin and way of their reception:

- **teleceptors (vision, hearing, smell),**
- **exteroceptors (from the body surface - cutaneous sensation, taste),**
- **proprioceptors, in muscles, tendons, joints - they inform about body position and movement,**
- **interoceptors - in inner organs**

In biophysics, the receptors are energy transducers above all.

Conversion function of receptors

- Primary response of sensory cell to the stimulus: **receptor potential** and **receptor current** are proportional to the intensity of stimulus. The receptor potential triggers the **action potential**.
- Transformation of amplitude modulated receptor potential into the frequency-modulated action potential.
- **Increased intensity of stimulus, i.e. increased amplitude of receptor potential evokes an increase in action potential frequency.**



Biophysical relation between the stimulus and sensation

- **The intensity of sensation increases with stimulus intensity non-linearly.** It was presumed earlier the sensation intensity is proportional to the logarithm of stimulus intensity **(Weber-Fechner law).** Intensity of sensation is I_R, intensity of stimulus is I_S, then:

$$\mathbf{I_R = k_1 \cdot \log(I_S).}$$

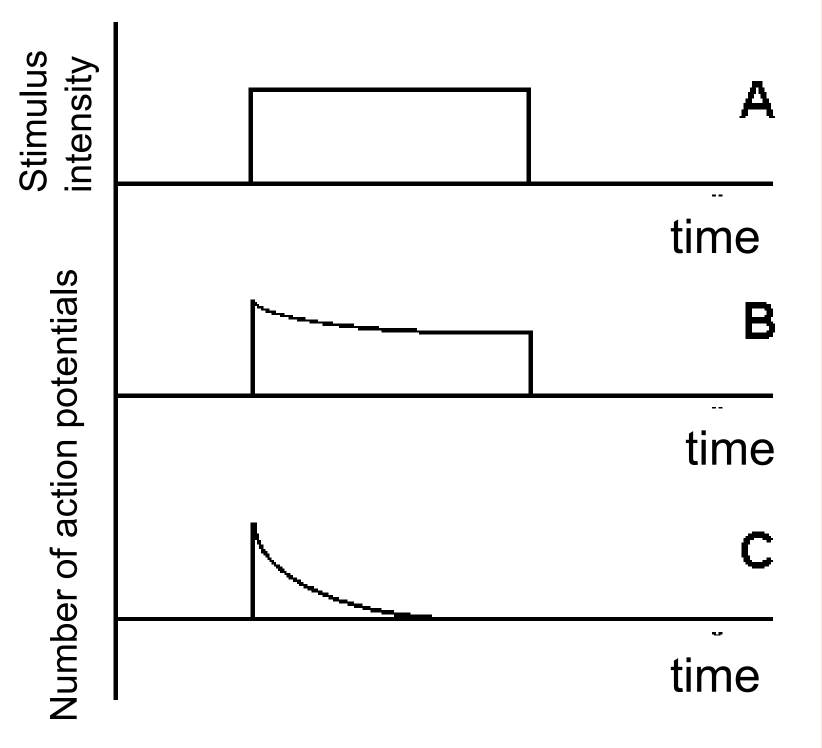
- Today is the relation expressed **exponentially** (so-called **Stevens law**):

$$\mathbf{I_R = k_2 \cdot I_S^a,}$$

- k_1, k_2 are the proportionality constants, a is an exponent specific for a sense modality. **The Stevens law expresses better the relation between the stimulus and sensation at very low or high stimulus intensities.**

Adaptation

- **If the intensity of a stimulus is constant for long time, the excitability of most receptors decreases.** This phenomenon is called **adaptation.** The adaptation degree is different for various receptors. It is low in pain sensation - protection mechanism.



Adaptation time-course. A - stimulus, B - receptor with slow adaptation, C - receptor with fast adaptation

Biophysics of sound perception

Physical properties of sound:

- **Sound - mechanical oscillations of elastic medium, f = 16 - 20 000 Hz.**
- It propagates through elastic medium as particle **oscillations around equilibrium positions**. In a **gas or a liquid**, they propagate as **longitudinal waves** (particles oscillate in direction of wave propagation - it is alternating compression and rarefaction of medium). In solids, it propagates also as transversal waves (particles oscillate normally to the direction of wave propagation).
- **Speed of sound - phase velocity (c)** depends on the physical properties of medium, mainly on the **elasticity and temperature**.
- The product $\rho.c$, where ρ is medium density, is **acoustic impedance**. It determines the size of acoustic energy reflection when the sound wave reaches the interface between two media of different acoustic impedance.
- **Sounds: simple (pure) or compound.** Compound sounds: musical (periodic character) and non-musical - noise (non-periodic character).

Main characteristics of sound: (tone) pitch, colour and intensity

- The **pitch** is given by **frequency**.
- The **colour** is given by the presence of **harmonic frequencies** in spectrum.
- **Intensity** - amount of energy passed in 1 s normally through an area of 1 m^2. It is the **specific acoustic power** [$W.m^{-2}$].

Intensity level

- The **intensity level** allows to compare intensities of two sounds.
- Instead of linear relation of the two intensities (interval of 10^{12}) logarithmic relation with the unit **bel (B)** has been introduced. In practice: **decibel (dB).** Intensity level *L* in dB:

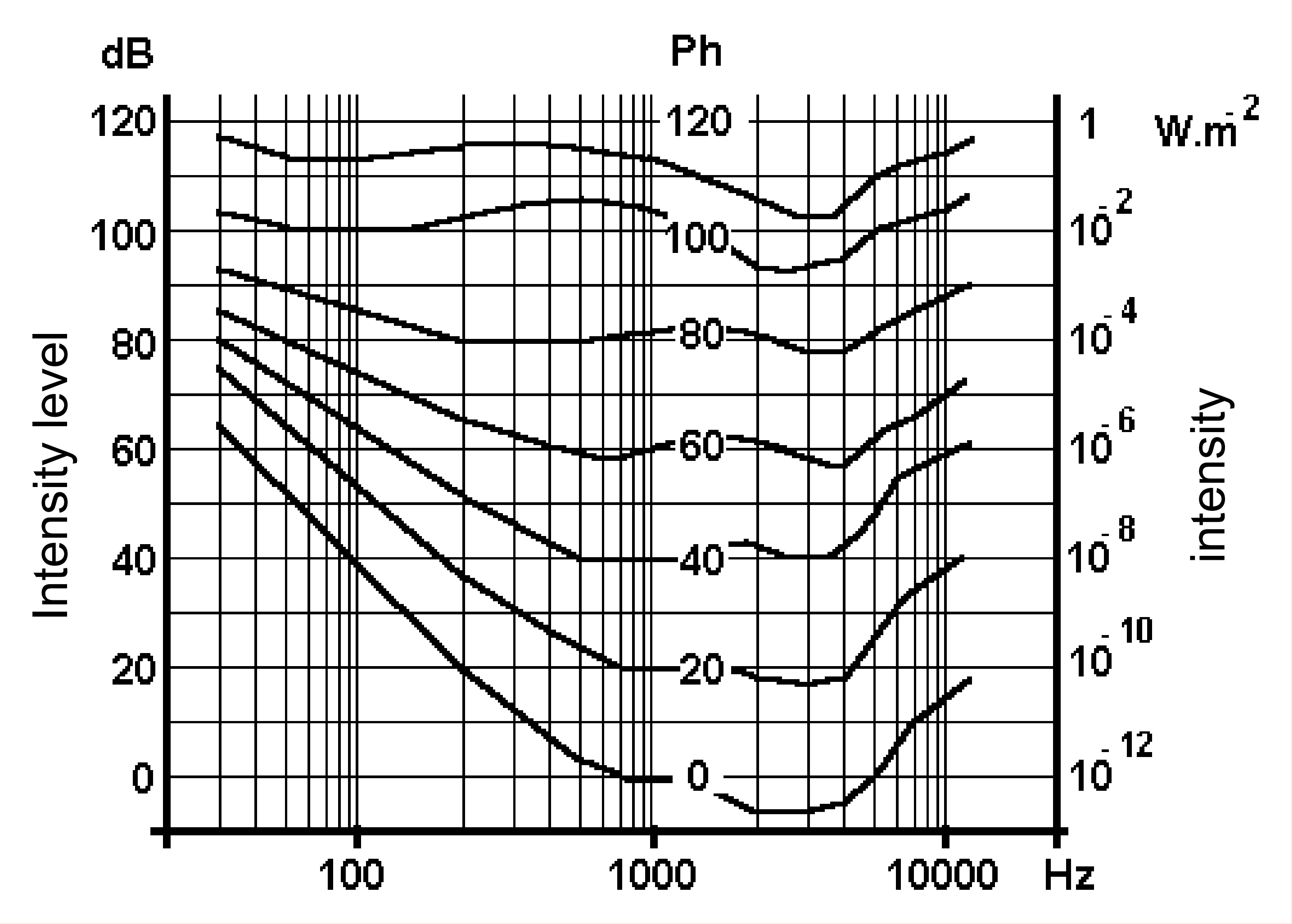
$$\mathbf{L = 10.\log(I/I_0) \quad [dB]}$$

- **Reference intensity of sound** (threshold intensity of 1 kHz tone) $\boldsymbol{I_0 = 10^{-12}\ W.m^{-2}}$ (reference acoustic pressure $p_0 = 2.10^{-5}$ Pa).

Loudness, hearing field

- **Loudness** is subjectively felt intensity approx. proportional to the logarithm of the physical intensity change of sound stimulus. The ear is most sensitive for frequencies of 1-5 kHz. The **loudness level** is expressed in **phones** (Ph). 1 phone corresponds with intensity level of 1 dB for the reference tone (1 kHz). For the other tones, the loudness level differs from the intensity level. **1 Ph is the smallest difference in loudness, which can be resolved by ear**. For 1 kHz tone, an increase of loudness by 1 Ph needs an increase of physical intensity by 26%.
- The unit of loudness is **son**. 1 son corresponds (when hearing by both ears) with the hearing sensation evoked by reference tone of 40 dB.
- Loudness is a threshold quantity.
- When connecting in a graph the threshold intensities of audible frequencies, we obtain the **zero loudness line (zero isophone).** For any frequency, it is possible to find an intensity at which the hearing sensation changes in pain - **pain threshold** line in a graph. The field of intensity levels between hearing threshold and pain threshold in frequency range of 16 - 20 000 Hz is the hearing field.

Hearing field



Loudness level of some sounds

Sort of sound	Loudness level [Ph]
whispering	10 - 20
Forest silence	20 - 30
Normal speech	40 - 60
Traffic noise	60 - 90
Pneumatic drill	100 - 110
Jet propulsion	120 - 130



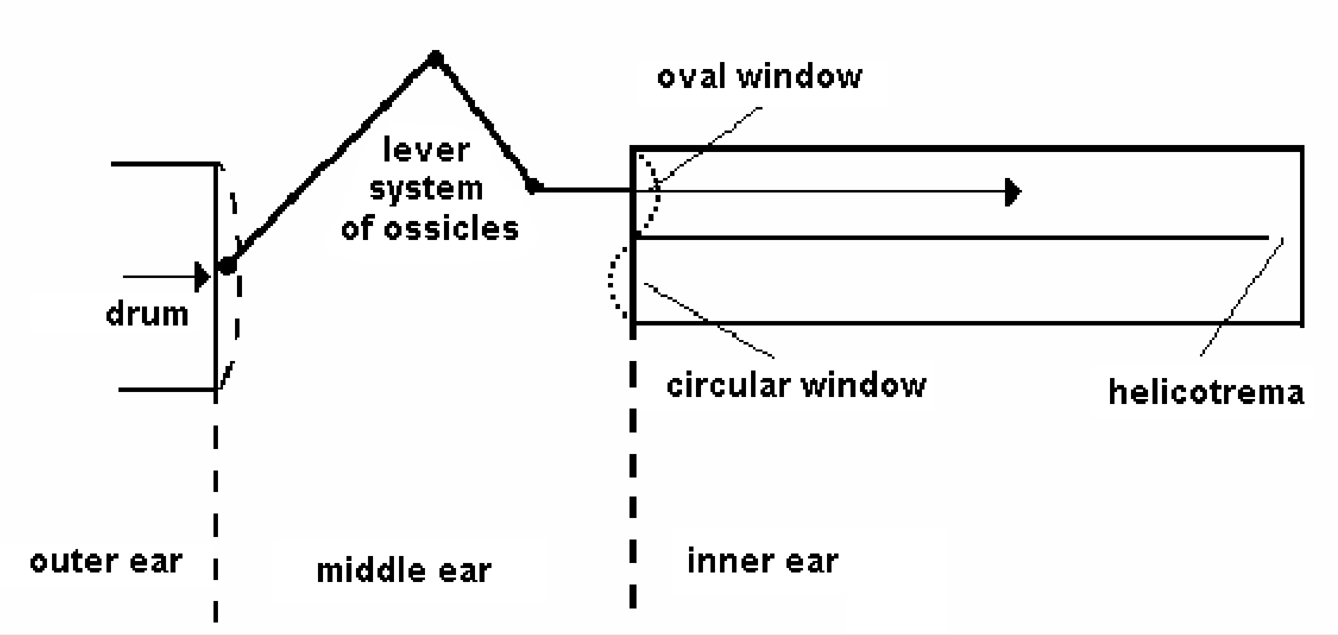



Biophysical function of the ear

The ear consists of outer, middle and inner ear.

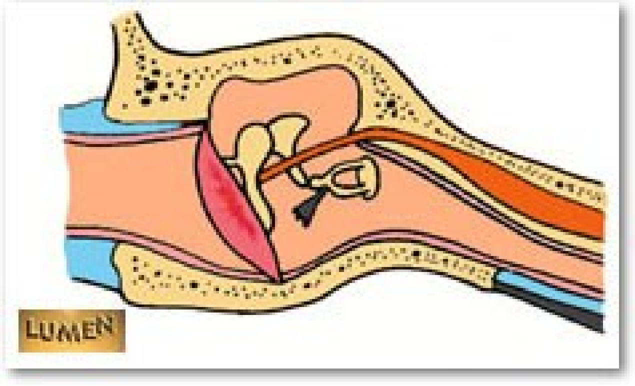
- Transmission of sounds into inner ear is done by outer and middle ear.
- Outer ear: auricle (ear pinna) and external auditory canal. Optimally audible sounds come frontally under the angle of about 15° measured away the ear axis.
- **Auditory canal is a resonator.** It amplifies the frequencies 2-6 kHz with maximum in range of 3-4 kHz, (+12 dB). The canal closure impairs the hearing by 40 - 60 dB.
- Middle ear consists of the ear-drum (~ 60 mm^2) and the ossicles – *maleus (hammer)*, *incus (anvil)* and *stapes (stirrup)*. *Manubrium malei* is connected with drum, *stapes* with *foramen ovale* (3 mm^2). **Eustachian tube** equalises the pressures on both sides of the drum.
- A **large difference of acoustic impedance of the air** (3.9 $kPa.s.m^{-1}$) **and the liquid in inner ear** (15 700 $kPa.s.m^{-1}$) **would lead to large intensity loss** (about 30 dB). It is compensated by the ratio of mentioned areas and by the change of amplitude and pressure of acoustic waves (sound waves of the same intensity have large amplitudes and low pressure in the air, small amplitudes and high pressure in a liquid). Transmission of acoustic oscillations from the drum to the smaller area of oval foramen **increases pressure 20x**.

Lever system of ossicles.



Maleus and incus form an unequal lever (force increases 1.3-times). So-called **piston transmission.**

Protection against strong sounds:
Elastic connection of ossicles and reflexes of muscles (*mm. stapedius, tensor tympani*) can attenuate strong sounds by 15 dB.

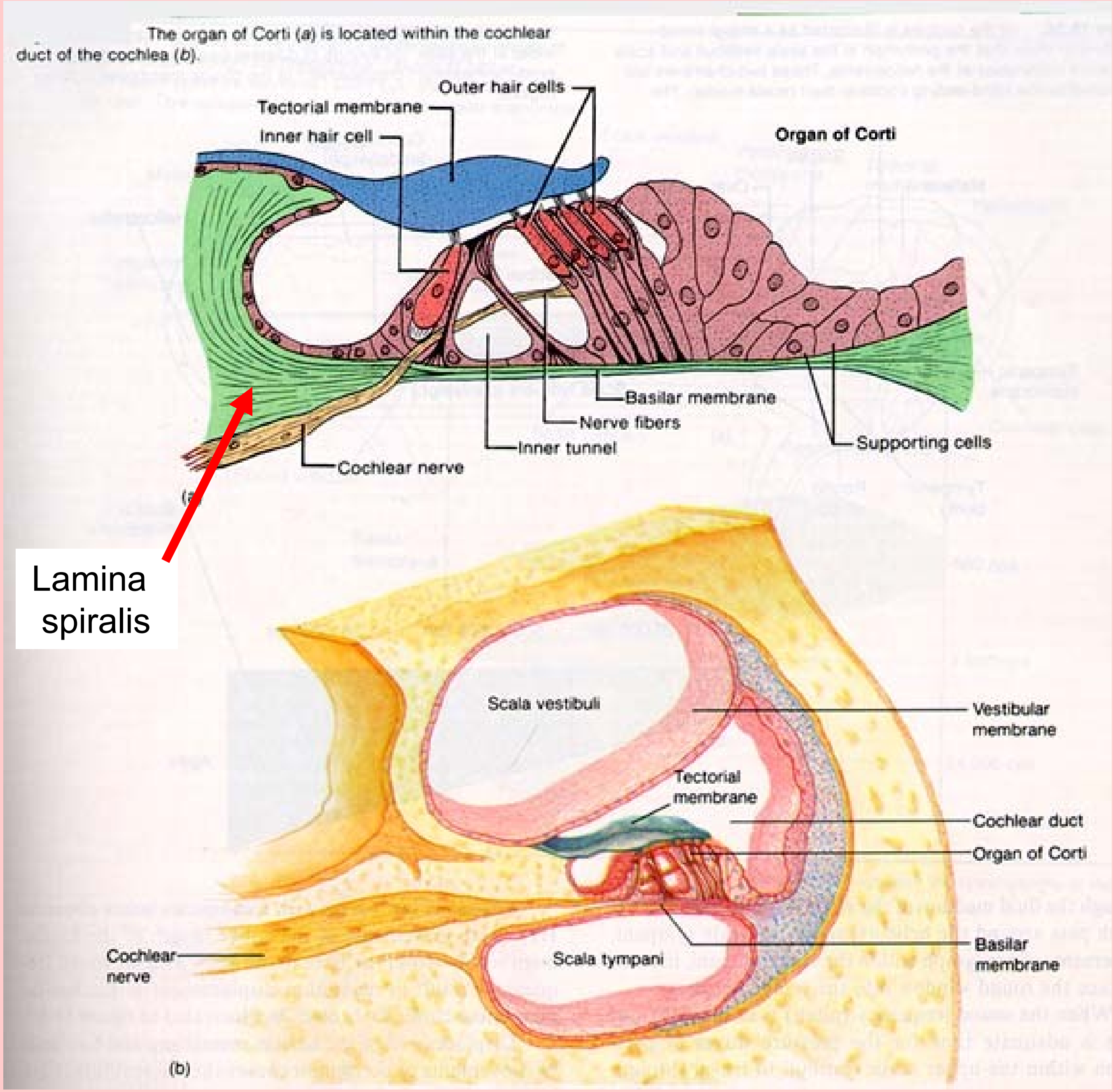


Mechanism of reception of acoustic signals

- The inner ear is inside the petrous bone and contains the receptors of auditory and vestibular analyser.
- The auditory part is formed by a spiral, 35 mm long bone canal ***- the cochlea*****.** The basis of cochlea is separated from the middle ear cavity by a septum with two foramina.
- The oval foramen is connected with stapes, the circular one is free.
- Cochlea is divided into two parts by longitudinal osseous *lamina spiralis* and elastic *membrana basilaris*. *Lamina spiralis* is broadest at the basis of cochlea, where the basilar membrane is narrowest, about 0.04 mm (0.5 mm at the top of cochlea).
- The *helicotrema* connects the space above (*scala vestibuli*) and below the basilar membrane (*scala tympani*).

Organ of Corti

•http://www.sfu.ca/~saunders/l33098/Ear.f/corti.html



Organ of Corti

- **Perilymph** - ionic composition like liquor, but it has 2x more proteins. **Endolymph -** protein content like liquor, but only 1/10 of Na+ ions and 30x more K+ ions - like intracellular liquid.

- **Sensory cells of Corti's organ: hair-cells (inner and outer).** In cochlea there are about 4000 inner and about 20000 outer hair-cells**.**

- **sensory hairs (cilia) -** stereocilia, deformed by tectorial membrane. Bending of hairs **towards** *lamina spiralis* leads to depolarisation, bending **away** *lamina spiralis* causes hyperpolarisation.

- About 95% neurons begin on inner cells (20 axons on one inner cell), about 5% neurons begin on outer cells - nerve-endings of 10 outer cells are connected in 1 axon. There are about 25 - 30 000 axons in auditory nerve.

Mechanism of sound perception: Békésy theory of travelling wave.

- Békésy theory of travelling wave: Sound brings the basilar membrane into oscillations, and the region of maximum oscillation shifts with increasing frequency from the top to the basis of cochlea.
- The receptor system in cochlea performs probably a preliminary frequency analysis. The further processing is done in cerebral auditory centres.
- **Sound comes to the receptors in three ways: air** (main), **bone** (the hearing threshold is by about 40 dB higher) and **through circular window** – small importance.

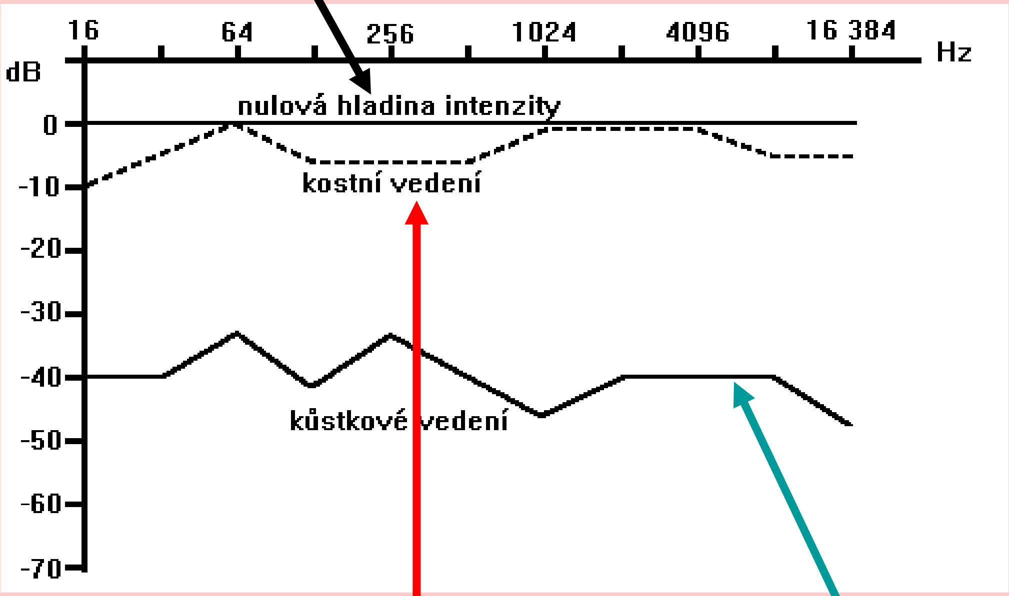
Electric phenomena in sound reception:

- Perilymph and endolymph differ in content of K^+ and Na^+. Endolymph content of K^+ is near to the intracellular content. The resting potential between endolymph and perilymph equals **+ 80 mV - endocochlear potential.**
- The big hair-cells of Corti's organ have a negative potential -80 mV against the periplymph. **The potential difference between the endolymph and hair-cells is about 160 mV.**
- The stimulation of Corti's organ leads to **cochlear microphone potential**, which can be measured directly on cochlea or in its close surroundings. At high frequencies, the maximum of microphone potential shifts to the basis of cochlea, what is in agreement with the theory of travelling wave.
- **Negative summation potential** is caused by stimulation of inner hair-cells of Corti's organ.
- The mechanism of the origin of final **action potential** led by auditory nerve is not yet fully explained. We suppose: The cochlear microphone potential and also the negative summation potential take place directly in action potential origin. This potential keeps the receptors in functional state.

Audiometry - hearing disorder examination

- **Audiometry** - see practical exercises. In practice, we obtain a **graph of loudness differences versus frequency** in comparison with normal hearing.
- **Bone conduction** is examined by tuning forks or **special oscillators** laid on *proc. mastoideus*.

Zero intensity level



finding: bone conduction normal, air conduction impaired

Two types of hearing disorders

- **1) Sound conduction disorder** - caused by cerumen (ear wax), Exudate or mucus in meatus, rigid drum, lowering of ossicular motility after inflammation. No full hearing loss is caused in this case - sound partly penetrates through bones into inner ear. The audiogram for air conduction is lowered in the whole range of audible frequencies, however the bone conduction is not damaged.

- **2) Perception or nerve conduction disorder.** Initially often limited to frequencies around 4000 Hz. It can be caused by long action of strong noise. Patient sound perception is distorted. Audiogram shows lowering of perception at these frequencies, bone conduction lowers as well. It increases with age.

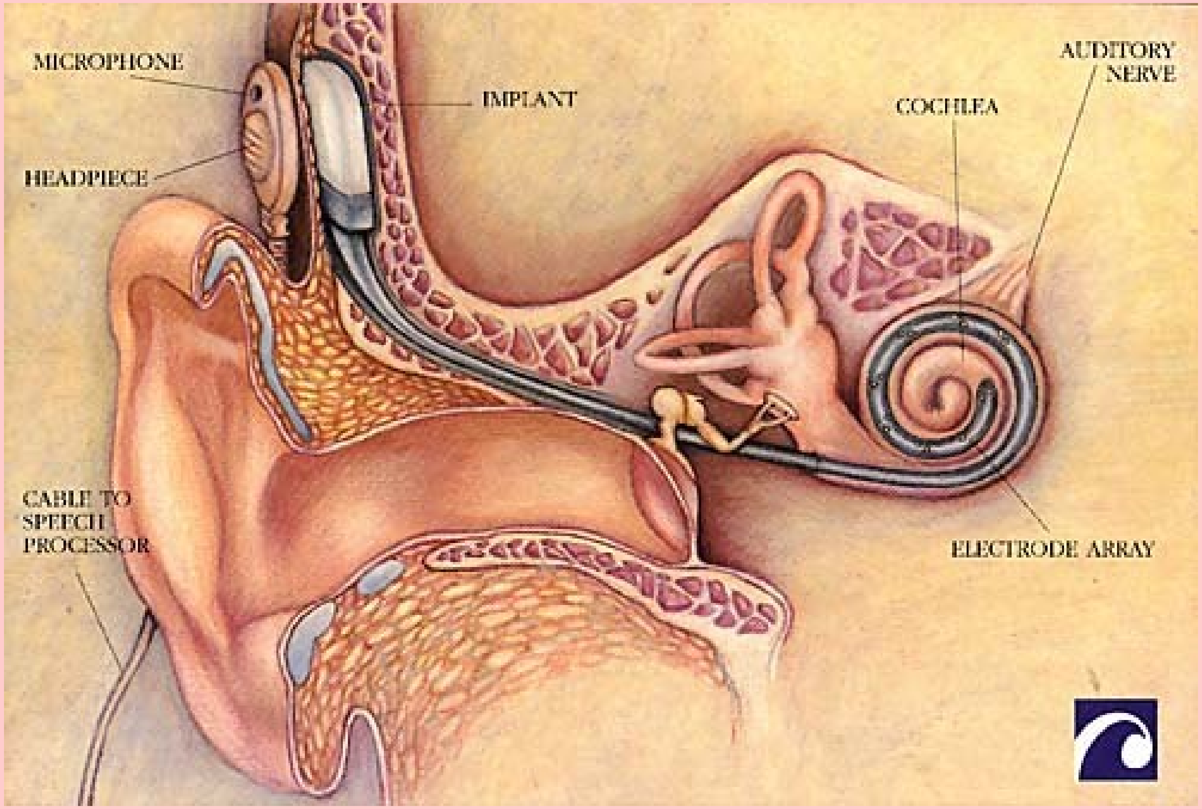
Hearing aid - correction of hearing disorders

Hearing aid: Consists of a microphone, amplifier, energy supply and a reproduction system (loudspeaker). It is an earphone with the end-piece inserted into meatus. For bone conduction, it is better to use a **vibrator** fixed to *proc. mastoideus*.

Purpose of hearing aids: amplification of frequencies at which hearing is lowered. Filtration. Hearing aids can be mounted into side-pieces of glasses.

Cochlear implant

•http://www.accessexcellence.org/AB/BA/biochip3.html



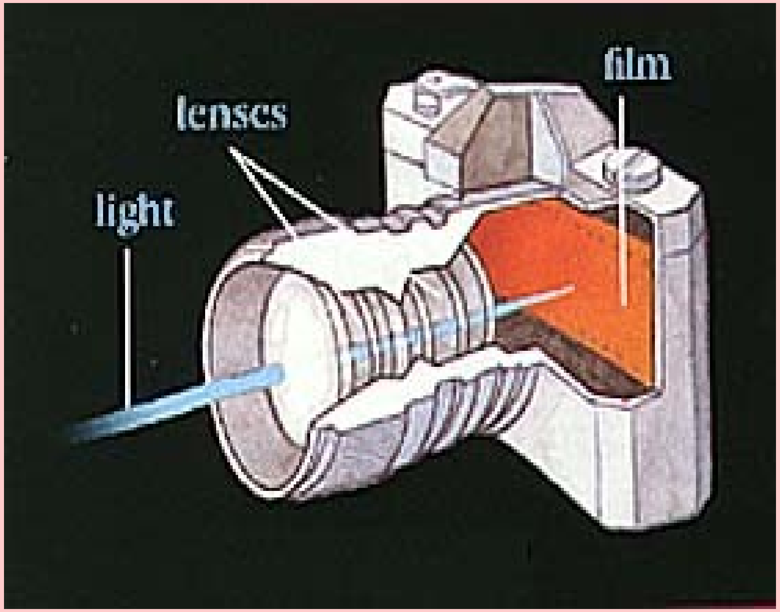
- This up to date method utilises the electronic cochlear implants, which can partly replace the Corti's organ, mainly in children which have functioning auditory nerve. It is an electrode system implanted into cochlea, which can stimulate the nerve, by impulses generated by a so-called speech-processor.

Anatomy of eye

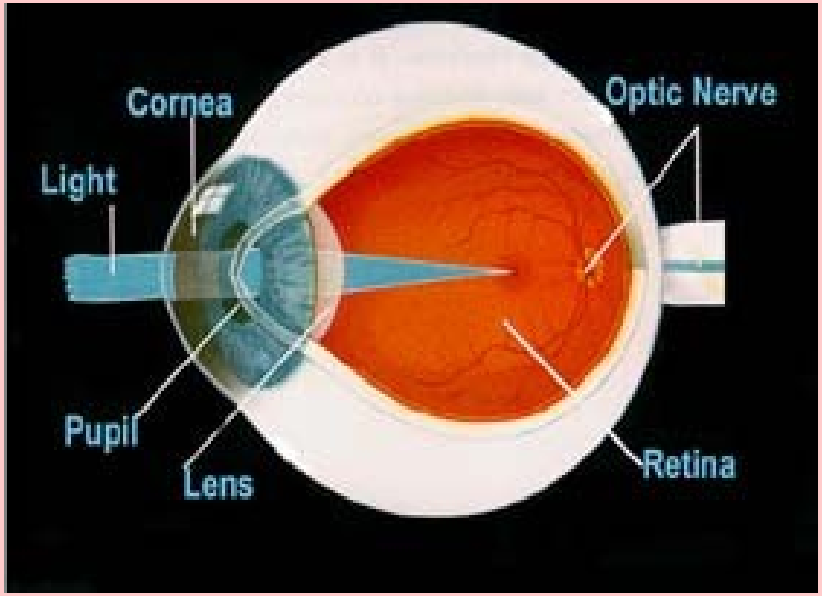
24

How Does The Human Eye Work?

The individual components of the eye work in a manner similar to a camera. Each part plays a vital role in providing clear vision.



The Camera



The Human Eye

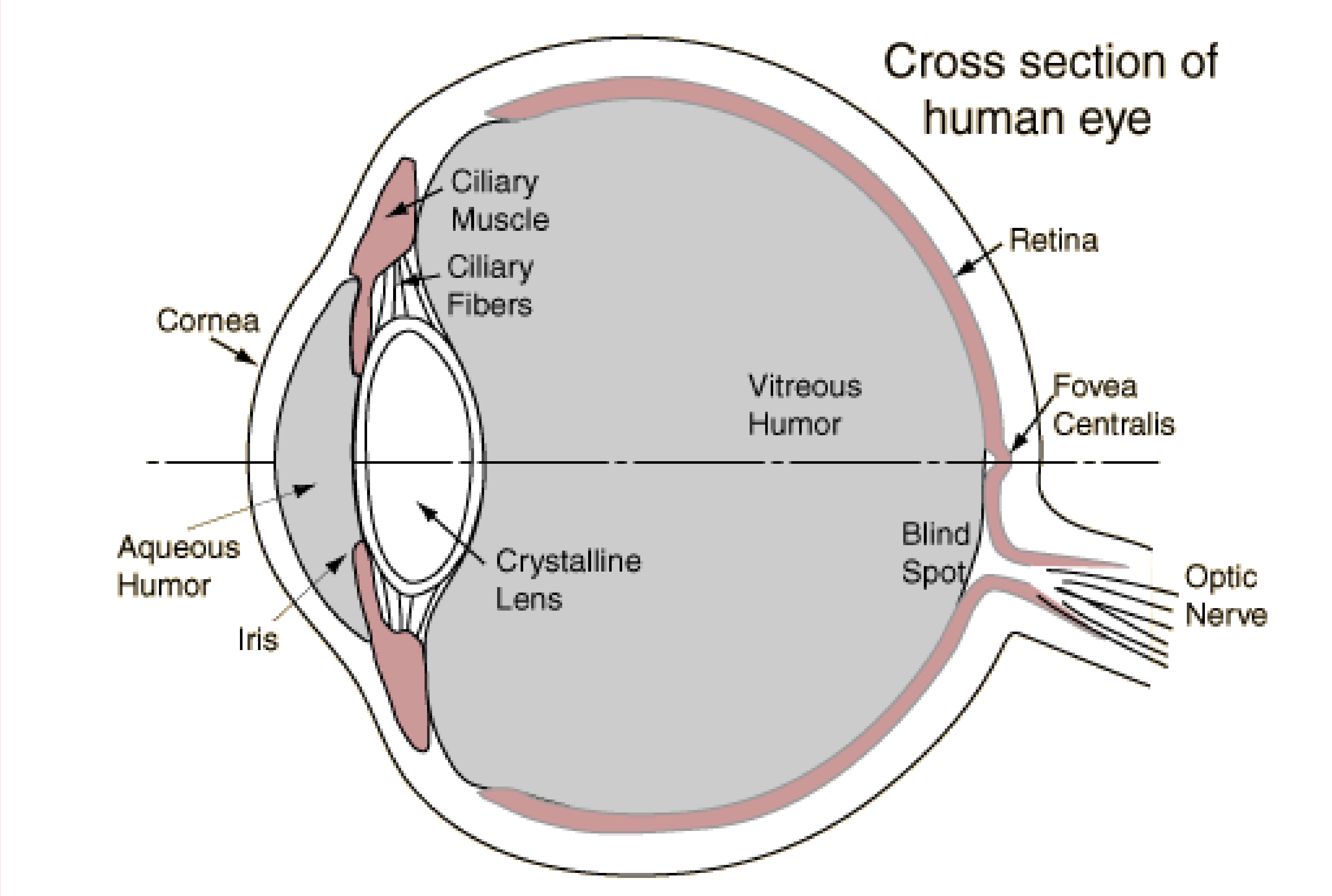
Visual analyser consists of three parts:

- **Eye –** the best investigated part from the biophysical point of view

- **Optic tracts –** channel which consists of nervous cells, through this channel the information registered and processed by the eye are given to the cerebrum

- **Visual centre** – the area of the cerebral cortex where is outwards picture perceived

Anatomy of the eyeball



27

Anatomy of the eyeball

The tough, outermost layer of the eye is called the **sclera**. It maintains the shape of the eye.

The front about sixth of this layer is clear and is called the **cornea**. All light must first pass through the cornea when it enters the eye. Attached to the sclera are the six_muscles that move the eye, called the **extraocular muscles**.

The **chorioid** (or uveal tract) is the second layer of the eye. It contains the blood vessels that supply blood to structures of the eye. The front part of the chorioid contains two structures:

•The **ciliary body** - the ciliary body is a muscular area that is attached to the lens. It contracts and relaxes to control the curvature of the lens for focusing.

28

Anatomy of the eyeball

The **iris** - the iris is the coloured part of the eye. The colour of the iris is determined by the colour of the connective tissue and pigment cells. Less pigment makes the eyes blue; more pigment makes the eyes brown. The iris is an adjustable diaphragm around an opening called the **pupil**.

Inside the eyeball there are two fluid-filled sections separated by the lens. The larger, back section contains a clear, gel-like material called **vitreous humour**

The smaller, front section contains a clear, watery material called **aqueous humour**

The aqueous humour is divided into two sections called the anterior chamber (in front of the iris) and the posterior chamber (behind the iris). The aqueous humour is produced in the ciliary body

29

Anatomy of the eyeball

The iris has two muscles:

The *m. dilator pupillae* makes the iris smaller and therefore the pupil larger, allowing more light into the eye;

the *m. sphincter pupillae* makes the iris larger and the pupil smaller, allowing less light into the eye.

Pupil size can change from 2 millimetres to 8 millimetres.

This means that by changing the size of the pupil, the eye can change the amount of light that enters it by 30 times.

Anatomy of the eyeball

The transparent ***crystalline lens*** of the eye is located immediately behind the *iris*. It is a clear, bi-convex structure about 10 mm in diameter. The lens is kept in flattened state by tension of fibres of suspensory ligament. The lens changes shape because it is attached to muscles in the ciliary body, which act against the tension of ligament. When this **ciliary muscle** is

•**relaxed**, its diameter increases and the **lens is flattened**.

•**contracted**, its diameter is reduced, and the **lens becomes more spherical** (which is its natural state).

These changes enable the eye to adjust its focus between far objects and near objects.

The crystalline lens is composed of 4 layers, from the surface to the center: capsule, subcapsular epithelium, cortex, nucleus

Intraocular pressure

(production versus drainage of aqueous humour - dynamic balance)

2.66 kPa (20 mmHg)   0.3 kPa

Changes greater than 0.3 kPa are pathological

32

Optical properties of eye

33

Gullstrand model

The eye is approximated as an centred optical system with ability of automatic focussing, however, this model does not consider certain differences in curvature of the front and back surface of cornea as well as the diferences of refraction indices of the core and periphery of the crystalline lens.

Gullstrand´s model of the eye – basic parameters

Allvar Gullstrand
1852 – 1930
Nobel Award – 1911
Swedish ophthalmologist

- **Refraction Index:**
  cornea................................ 1.376
  aqueous humour............... 1.336
  lens... ....1.413
  vitreous humour……………. 1.336

- **Dioptric power:**
  cornea .... 42.7 D
  lens – inside eye................ 21.7 D
  eye (whole)....................... 60.5 D

- **Radius of curvature:**
  cornea .... 7.8 mm
  lens – outer wall....... .... 10.0 mm
  lens – inner wall.................... -6.0 mm

- **Focus location:**
  (measured from top of the cornea):
  front (object) focus.................... -14.99 mm
  back (image) focus .... 23.90 mm
  retinae location......................... 23.90 mm

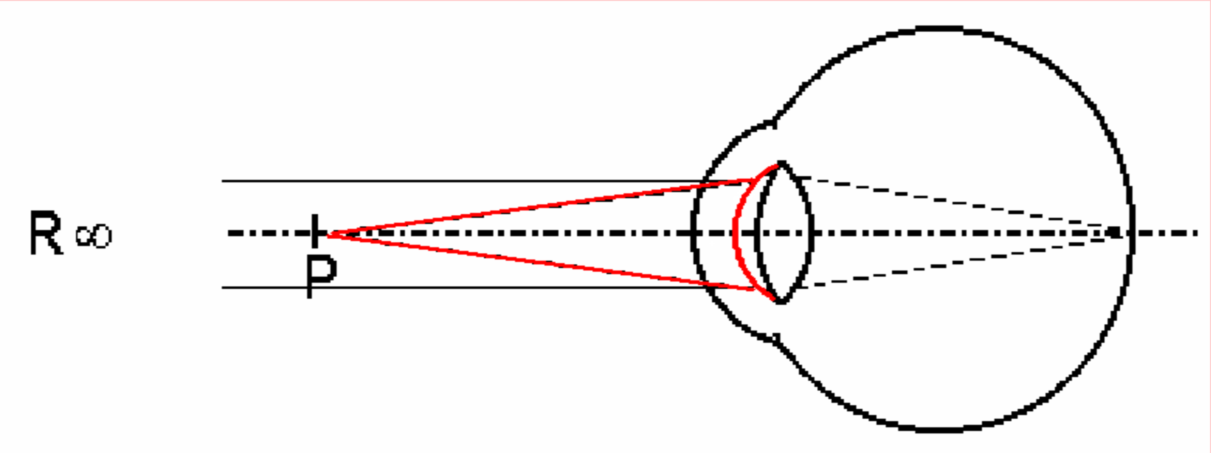
35

Accommodation

Accommodation is eye lens ability to change its dioptric power in dependence on distance of the observed object.

Accommodation – allowed by increasing curvature of outer lens wall (J.E.Purkyně)

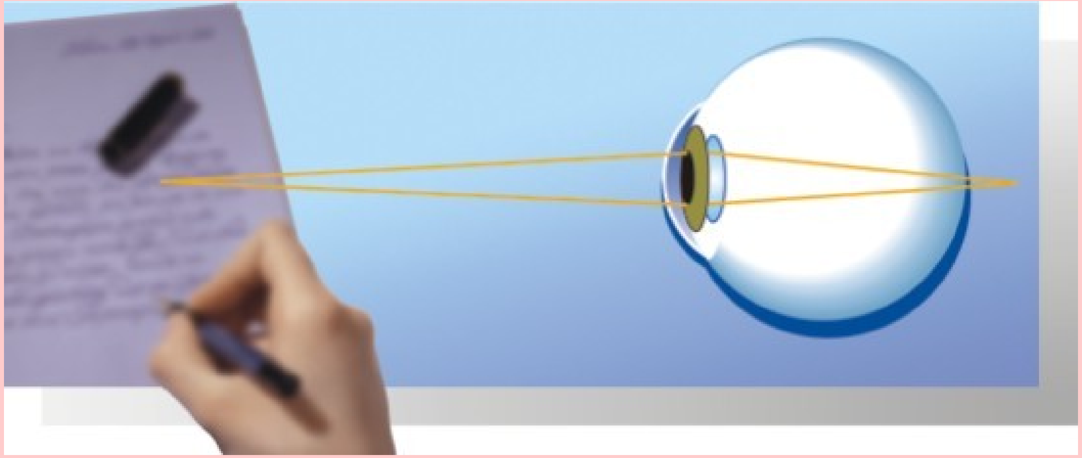
- **Far point** - *punctum remotum* (R) - farthest point of distinct vision without accommodation.
- **Near point** - *punctum proximum* (P) - nearest point of distinct vision with maximum accommodation.
- The **amplitude of accommodation** is defined as the difference of reciprocal values of the distances of the near a and far point, expressed in dioptres. In an emmetropic eye the reciprocal value equals to zero ($1/\infty = 0$), thus the amplitude of accommodation is given by the reciprocal value of the near point distance.



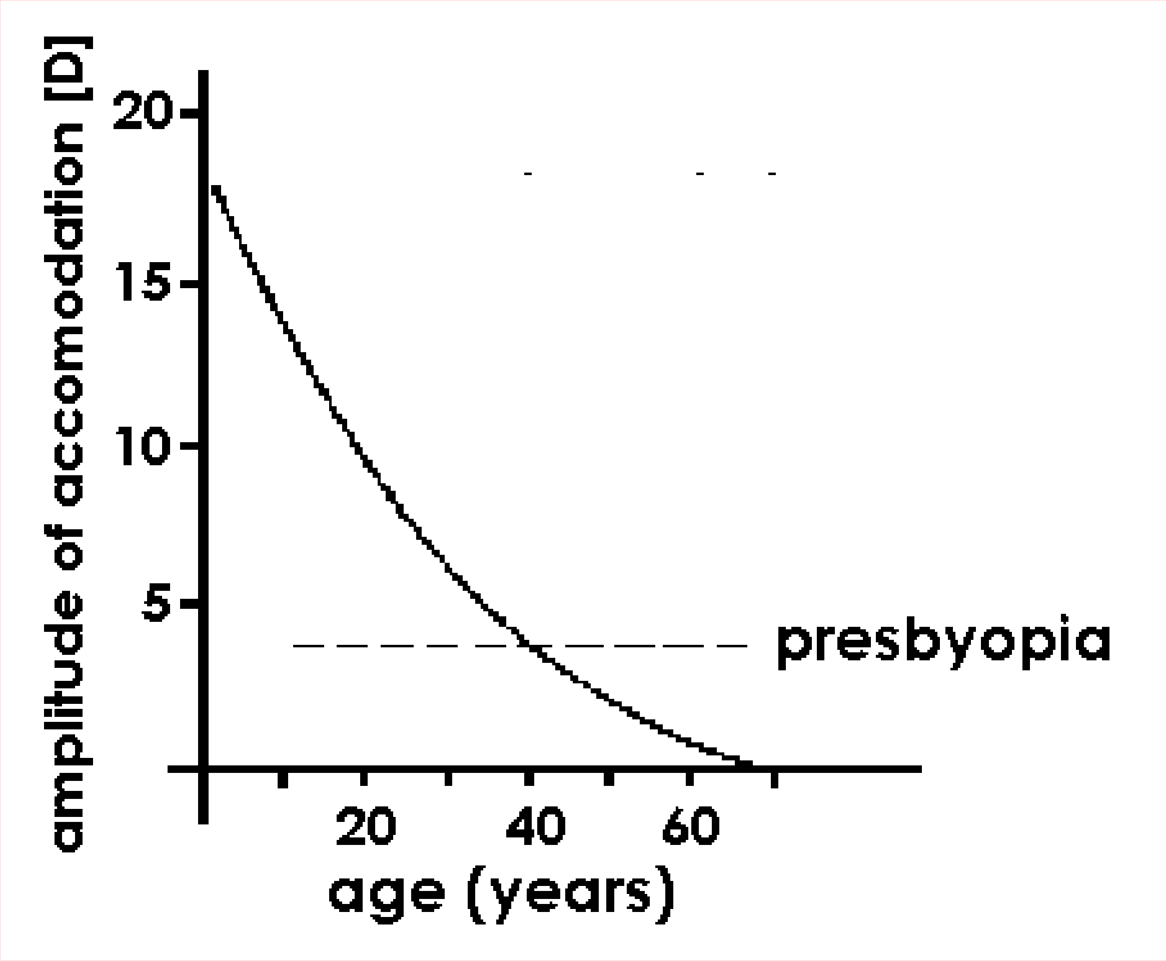
36

Presbyopia (“after 40” vision)
Old–age sight

After age 40, and most noticeably after age 45, the human eye is affected by ***presbyopia***, which results in greater difficulty maintaining a clear focus at a near distance with an eye which sees clearly at a far away distance. This is due to a lessening of flexibility of the crystalline lens, as well as to a weakening of the ciliary muscles which control lens focusing, both attributable to the aging process.



Decrement of accommodation ability in dependence on age



Retina – biological detector of the light

Retina - the light-sensing part of the eye.

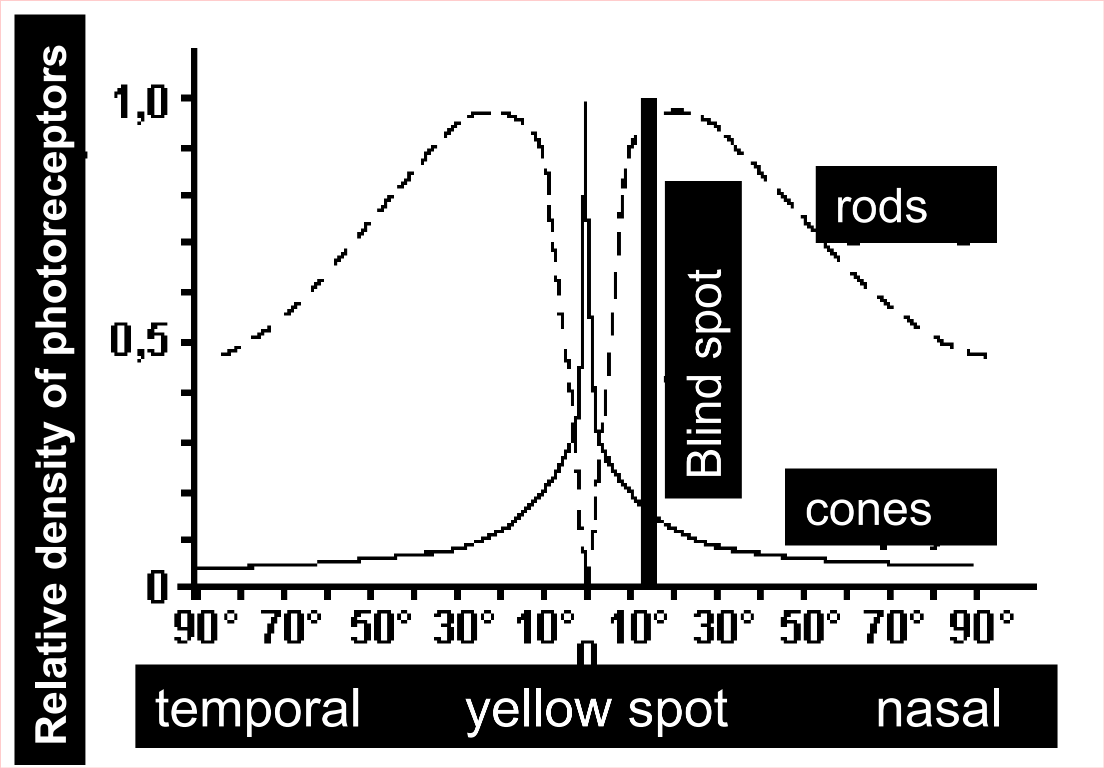
It contains **rod cells**, responsible for vision in low light, and **cone cells**, responsible for colour vision and detail. When light contacts these two types of cells, a series of complex chemical reactions occurs. The light-activated rhodopsin creates electrical impulses in the optic nerve. Generally, the outer segment of rods are long and thin, whereas the outer segment of cones are more cone-shaped.

In the back of the eye, in the centre of the retina, is the **macula lutea (yellow spot).** In the centre of the macula is an area called the **fovea centralis.** This area contains only cones and is responsible for seeing fine detail clearly.

39

Blind spot

Density of cones decreases from the yellow spot to the periphery of retina. The rods have maximum density in a circle around the yellow spot (20^{o} from this spot). The nerve fibres transmitting the stimulation of photoreceptors converge to a place positioned nasally from the yellow spot. This place with no photoreceptors is called **blind spot.**

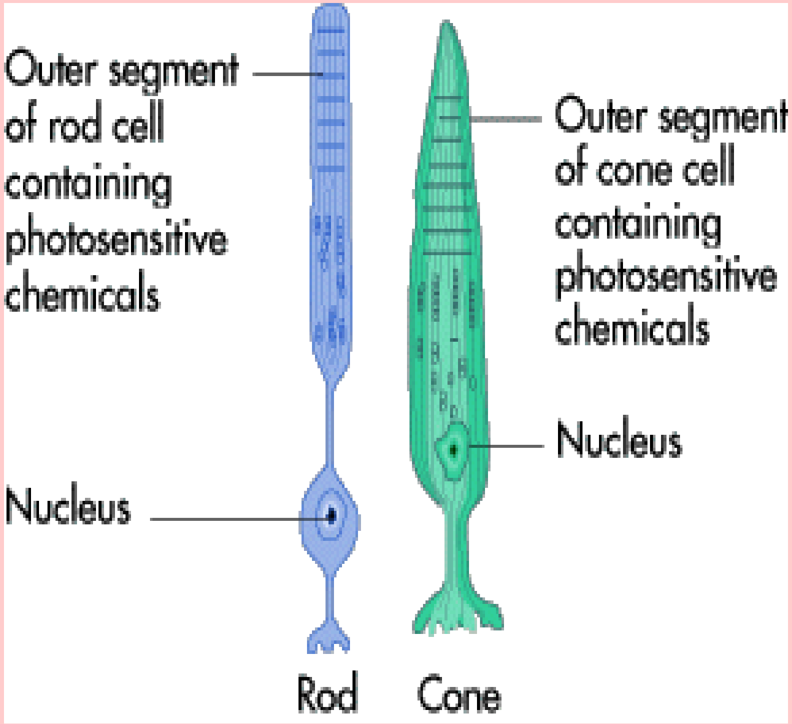


40

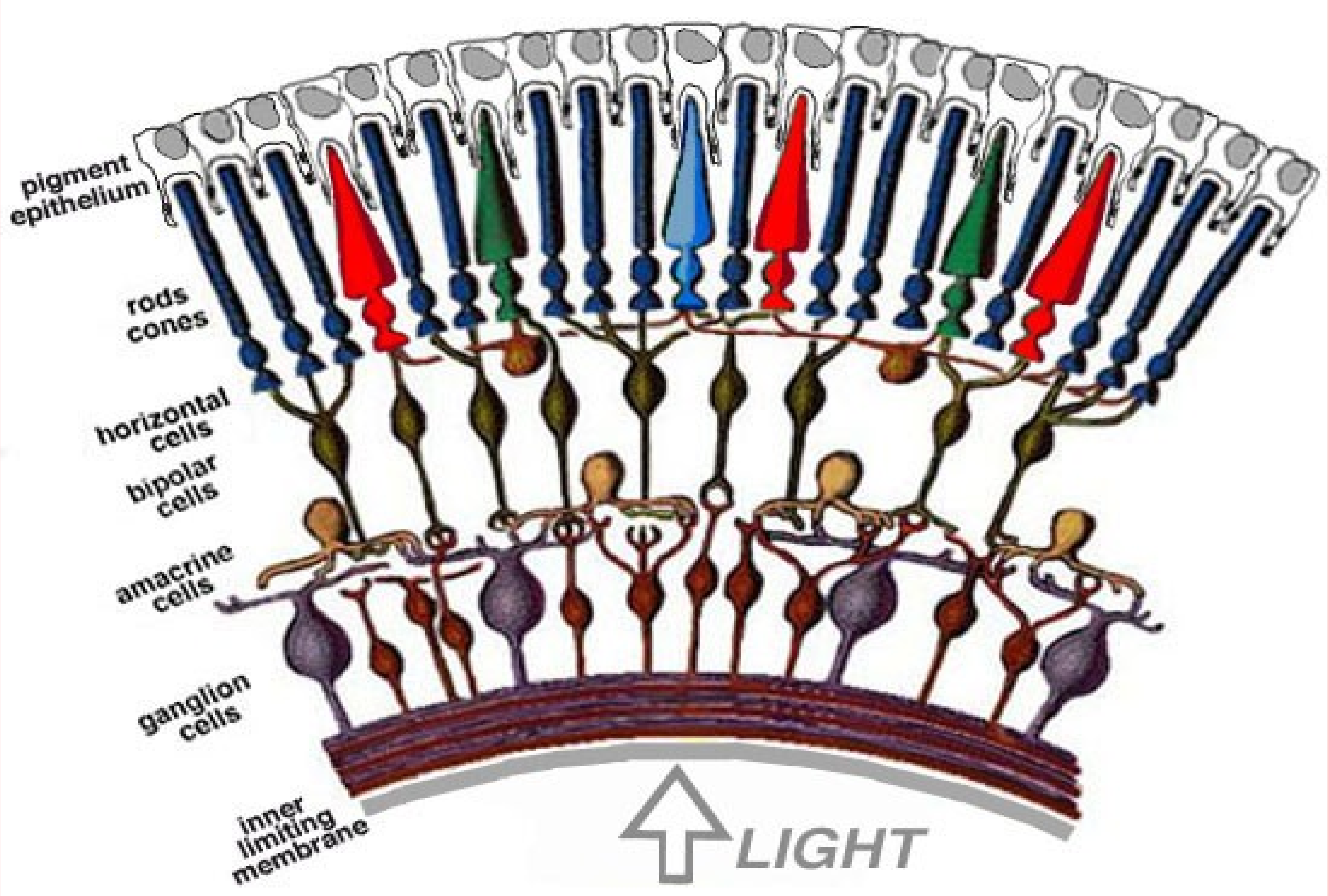
Rods and cones

The outer segment of a rod or a cone contains the photosensitive chemicals. In rods, this chemical is called **rhodopsin.** In cones, these chemicals are called **colour pigments**.

The retina contains 100 million rods and 7 million cones.



Structure of retina



Electrical phenomena in retina

The electrical activity of retina is closely connected with photochemical reactions taking place in photoreceptors after illumination.

- **Early receptor potential**
- **Late receptor potential**

Electroretinography (ERG), recorded by means of two differential electrodes, measured voltage ranges from 100 to 400 μV

Colour Vision

Trichromates - have normal colour vision

Monochromates - have only one cone colour sensing system

Dichromates:

protanopia (difficult distinguishing between blue/green and red/green) – „ red blindness “

deuteranopia (difficult distinguishing between red/purple and green/purple) – „ green blindness “

tritanopia (difficult distinguishing between yellow/green and blue/green) – „ blue blindness “

44

Limits of vision

- **visual acuity:** given by angle of 1min. of arc (tested by Snellen's charts)
- **sensitivity (intensity) limit:** 2 – 3 photons in several ms
- **frequency:** 5 - 60 Hz depending on brightness
- **wavelength limit about:** 380 – 760 nm
- **limit of stereoscopic vision:** stereoscopic parallax difference smaller than 20 seconds of arc

Visual acuity

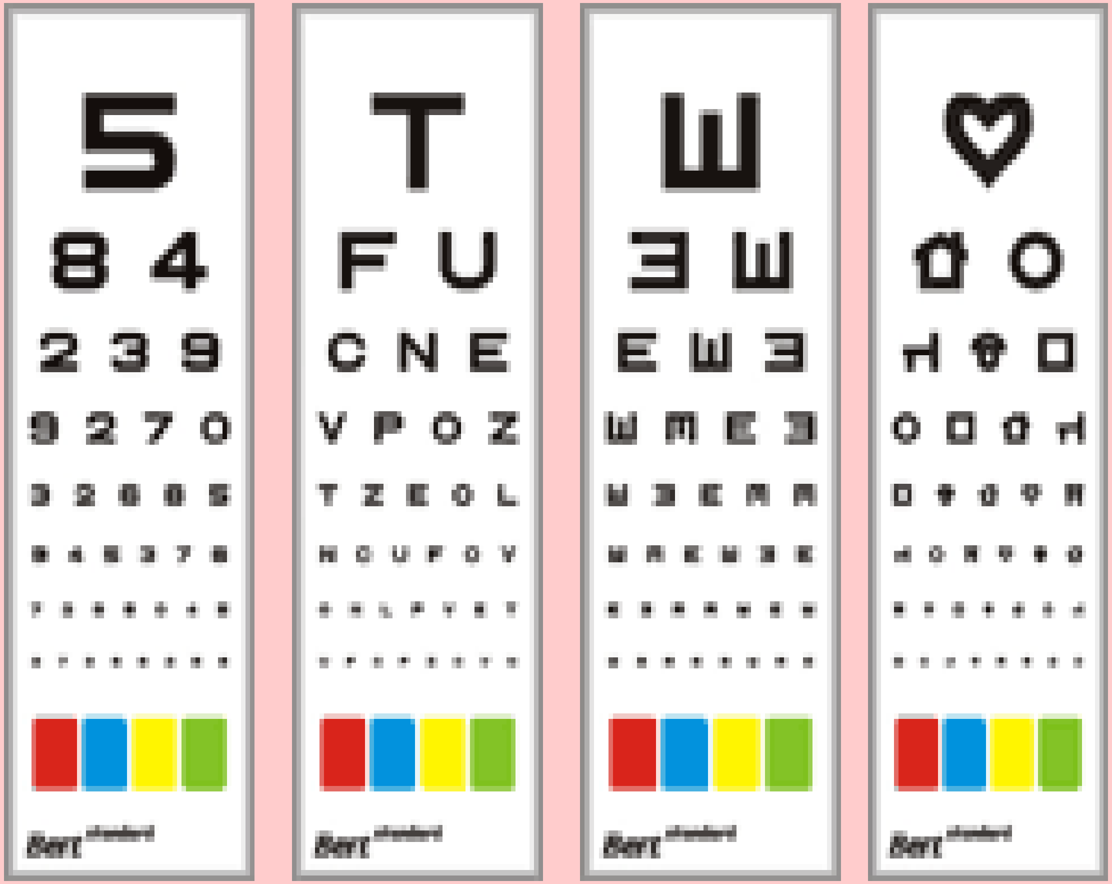
Definition: clarity and sharpness of vision (Latin “acuitas” = sharpness)

Often referred to as “Snellen” acuity. The **Snellen charts** used in its assessment are named after a 19th-century Dutch ophthalmologist Hermann Snellen (1834–1908) who created them as a test of visual acuity.

The optotypes are made for a viewing distance of 4, 5 and 6 m. Visual acuity is expressed by means of a fraction where the numerator is the viewing distance in m and the denominator the number of the row of correctly distinguishable symbols (e.g. acuity of 6/18 indicates visual acuity reduced to a third).

Someone with **6/6 vision** is just able to distinguish a symbol that subtends a visual angle of *5 minutes of arc* (written *5′*) at the eye.

Snellen charts



Ametropia - errors of eye optical system

Emmetropia: the normal (“emmetropic”) eye images in points and images are focused (projected) on the retina.

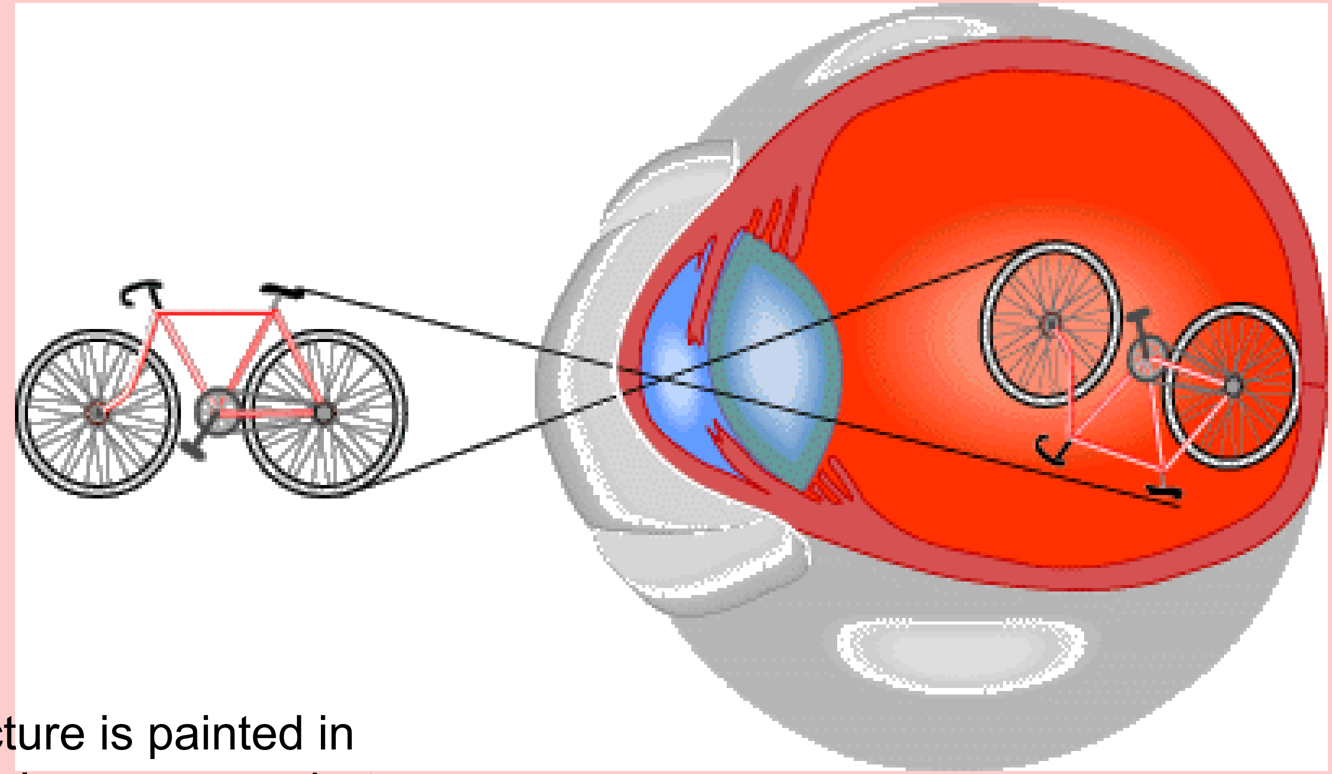
Ametropia: If the image focus is not situated on the retina or the eye does not image in points (the eye is “ametropic”).

we can distinguish two main ametropias:

- spherical (nearsightedness and farsightedness)
- aspherical (astigmatism)

Normal eye

Normally, our eye can project an image exactly on the retina:



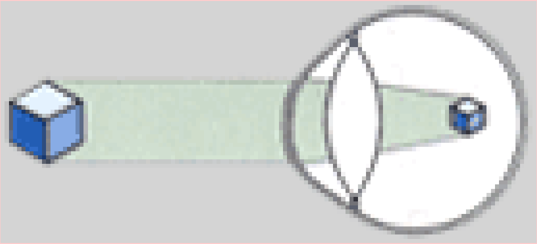
(this picture is painted in absolutely wrong way but otherwise it is nice)

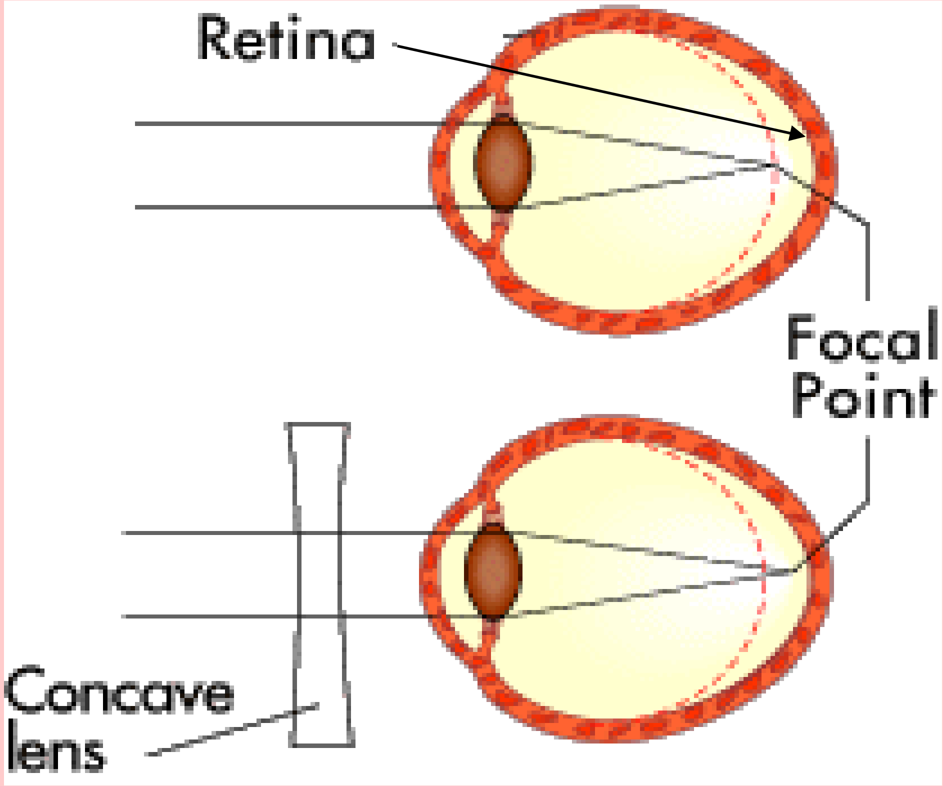
Spherical ametropia: Nearsightedness and farsightedness

Nearsightedness (myopia): see near objects well, and difficulty seeing faraway. Light rays coming from far distance are focused in front of the retina. This is caused by an eyeball that is too long, or a lens system that has too high dioptric power. Corrected with a **concave (diverging)** lens**.** This lens causes the light to diverge slightly before it reaches the eye.

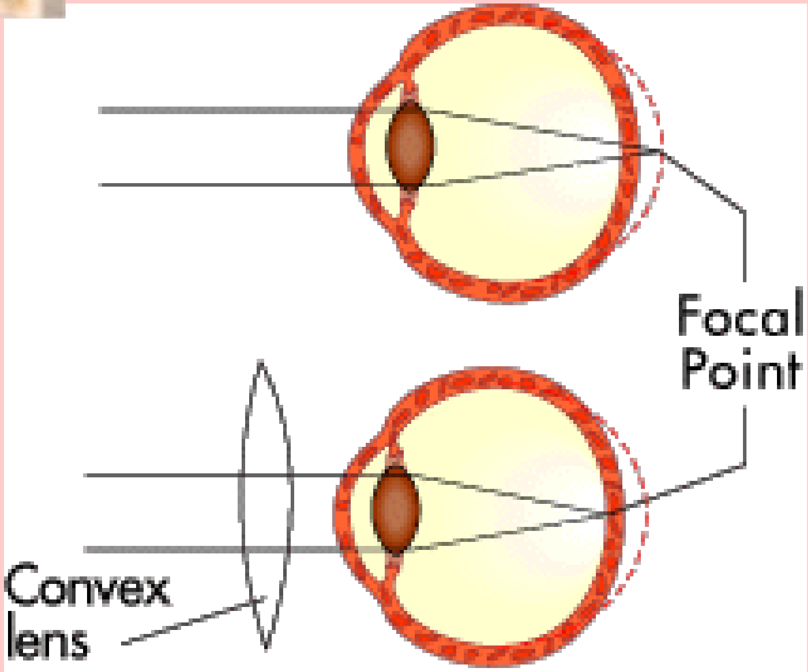
When **farsightedness (hyperopia):** see distant objects well but not near objects. Light rays are focused behind the retina. This is caused by an eyeball that is too short, or by a lens system that has too little dioptric power. Corrected with a **convex (converging)** lens.

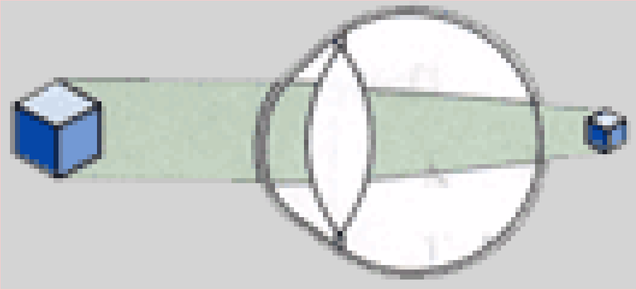
Nearsightedness (myopia)





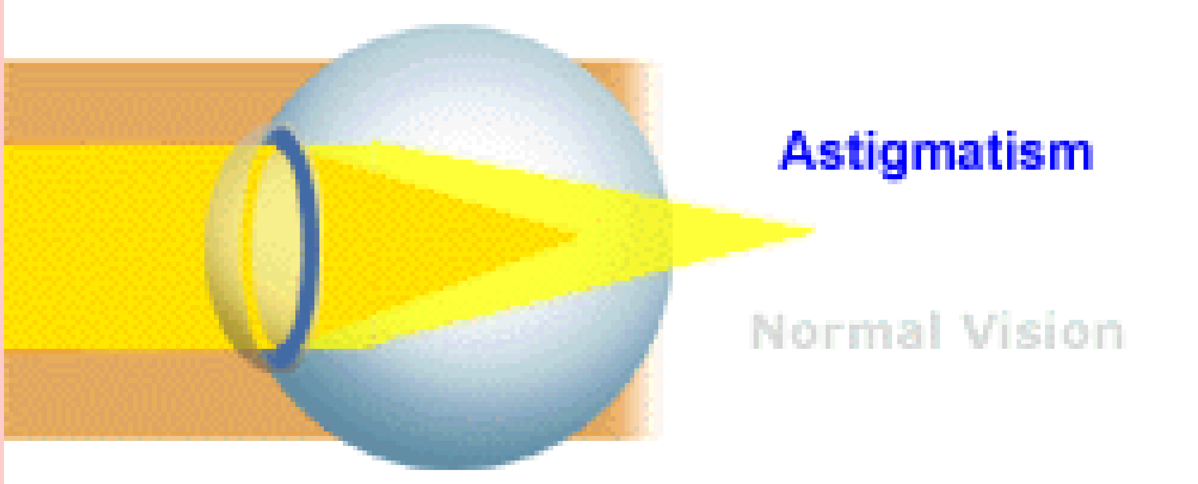
Farsightedness (hyperopia)



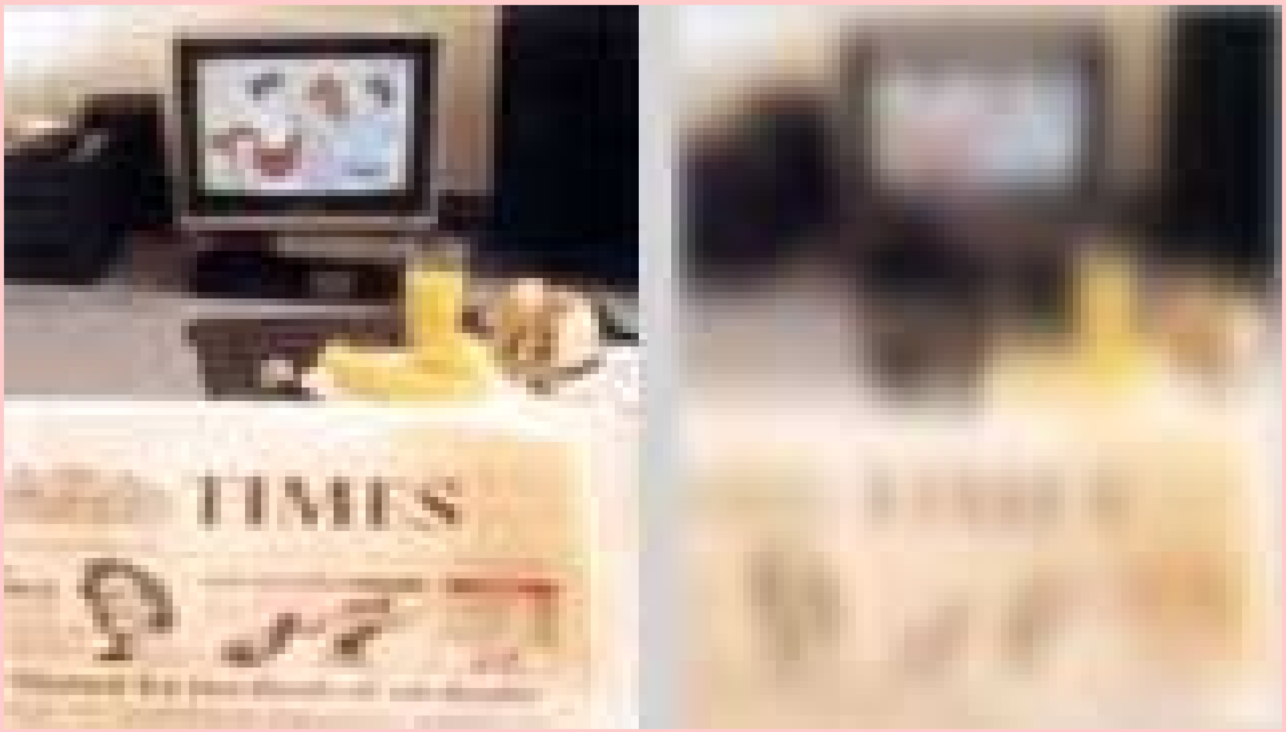


Aspherical ametropia (astigmatism)

Astigmatism occurs when the cornea or the lens, have a different curvature in different planes. This irregular shape prevents light from focusing properly on the retina. As a result, vision may be blurred at all distances.



Astigmatism

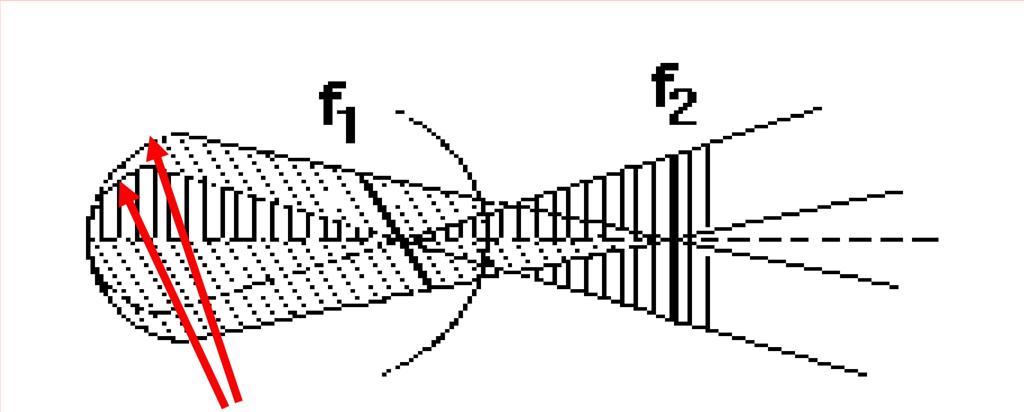


Astigmatism

Simple astigmatism: One of the focal lines does not lie on retina

Mixed astigmatism: Both focal lines are not on the retina – one in front, one behind.

Compound astigmatism: means the eye has characteristics of both astigmatism and nearsightedness / farsightedness. Both focal lines are in front or behind the retina.



Main meridians (characterised by biggest difference in curvature) of the eye can be seen – case of mixed astigmatism.

How to correct astigmatism

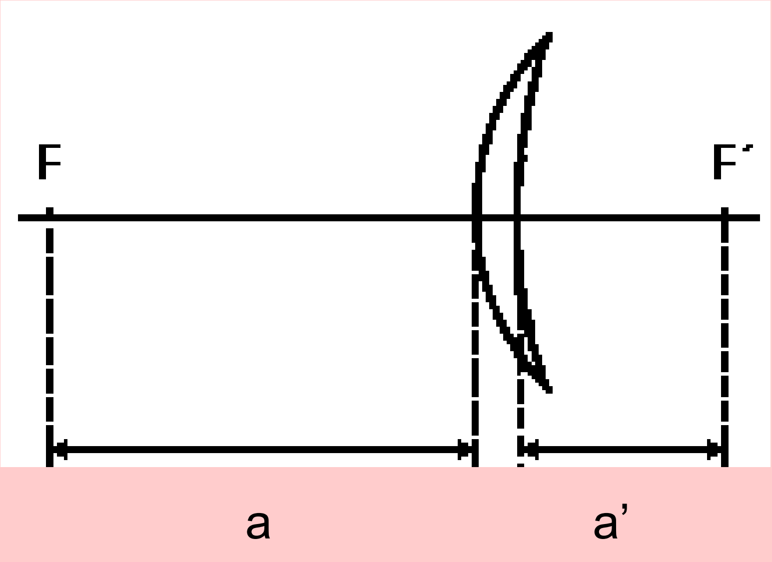
Simple astigmatism is corrected by a **cylindrical lens**, or *refractive surgery*.

Compound and mixed astigmatism are corrected by **toric lenses** (a toric refraction surface originates by a combination of cylindrical and spherical surfaces, i.e. has different radii of curvature in different planes).

Eyeglass lenses - back vertex power

- As opposed to other optical systems which are characterized by power, eyeglass lenses are characterised by their ‘back vertex’ power

  $A' = 1 / a'$



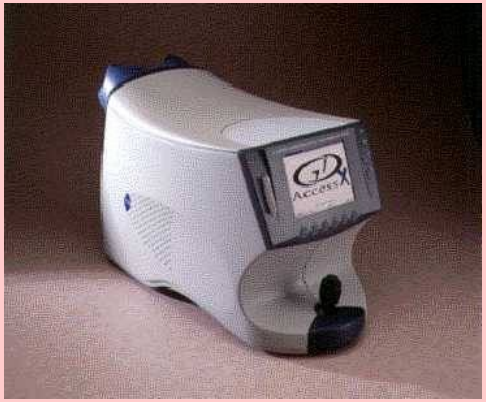
Contact lens

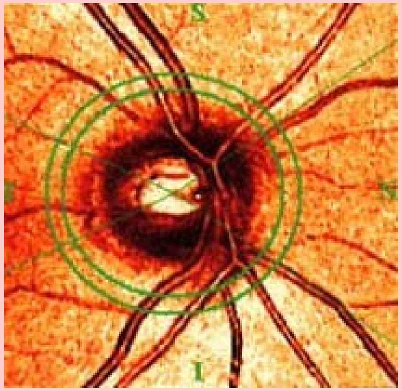
Contact lens made of hydrophilic gel (weak – Otto Wichterle invention) or hard contact lenses (RGP – Rigid Gas-Permeable)

Refractometer – objective examination of vision

Further devices for examination of vision

Perimetry the investigative method to assess the extent of visual field. Its essence is the ability of the eye to distinguish two stimuli in the field of vision. One stimulus is a light mark and the second the background surrounding the light mark. It is performed at the suspected loss of visual field, called scotoma.





The analyzer of nerve fibres layer - GDX (Glaucoma Diagnostics). Thickness of the layer of nerve fibres of the retina is measured using a laser scanning polarimetry. This technique uses birefringence of nerve fibres. Phase shift between ordinary and extraordinary beam after passing through a layer of retinal nerve fibre will be used to measure the thickness of peripapilar area. The device is equipped with a scanning unit with a light-emitting diode (wavelength 780 nm), which is associated with the computer transferring the degree of polarization in each image point to the thickness of nerve fibres using Fourier analysis.

Electroretinography (ERG)

Electroretinography

is a test to measure the electrical response of the eye's light-sensitive cells (rods and cones). Electrodes are placed on the cornea and the skin near the eye (monitored by unipolar leads), 100 – 400 microvolts.

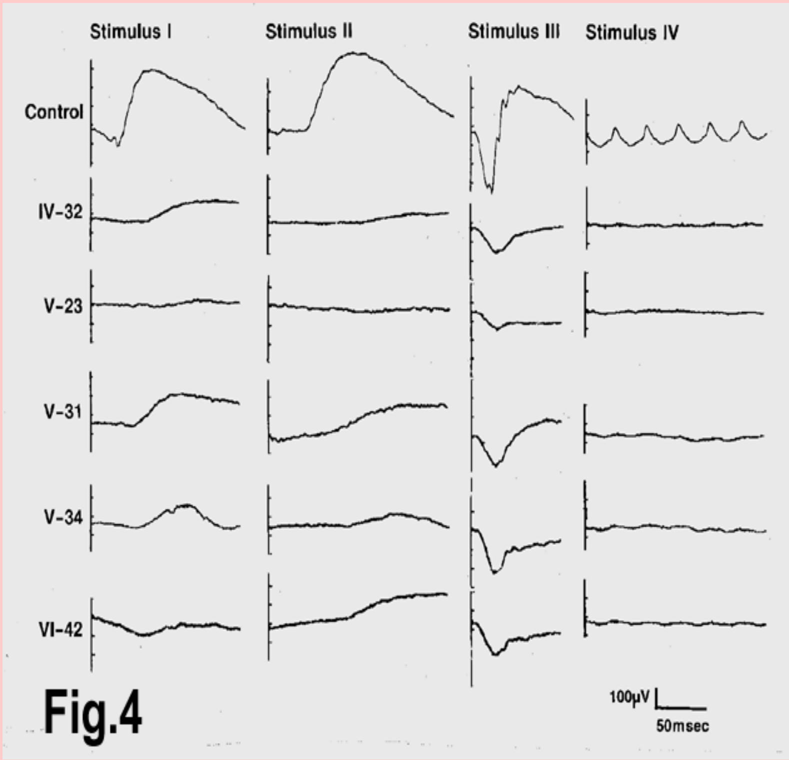
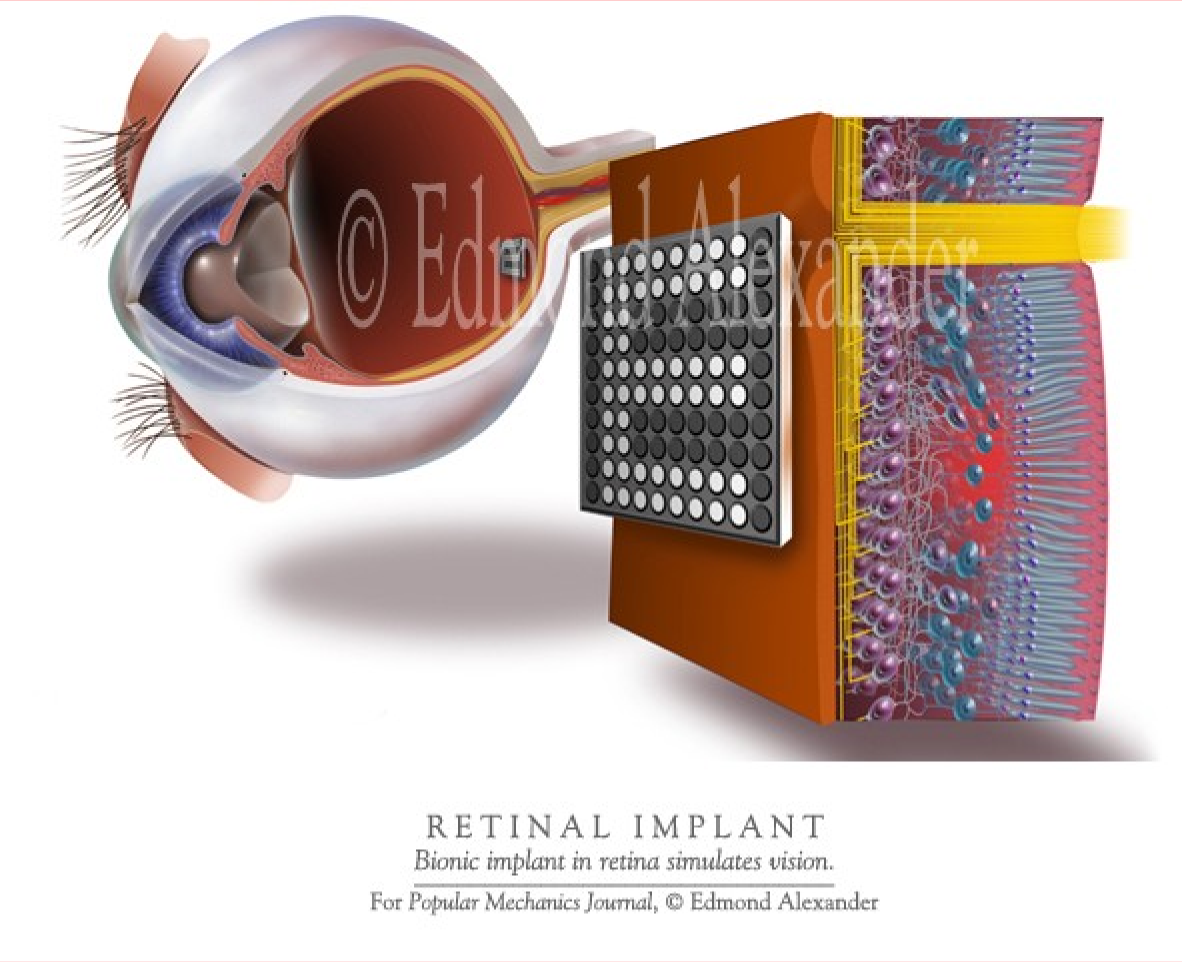
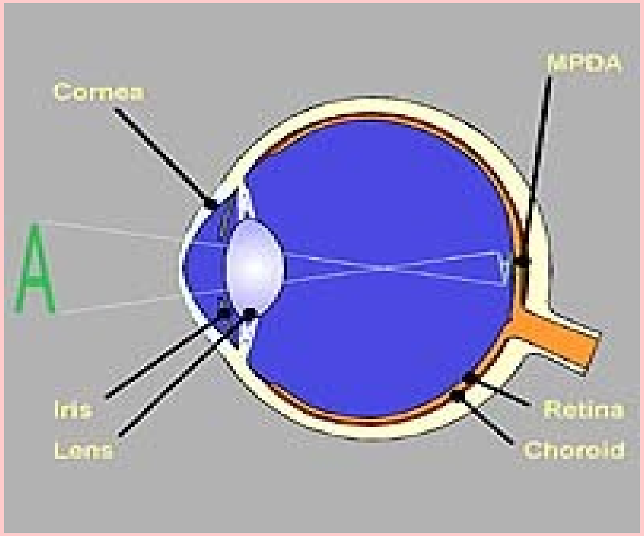


Fig.4

Retinal implant

www.nmi.de/deutsch/showprj.php3?id=3&typ=1





MPDA – micro-photo-diode-array

This device is in clinical testing. It should enable basic spatial orientation of blind people.