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The Biophysical Modeling of the Human Sight

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Abstract— *The eye has multiple roles in vision. It contributes to the formation of images of the outside world, adaptation to different light-intensities, transformation of light into electrochemical signals and then nerve impulses and to preliminary evaluation of visual information. For an object to be seen clearly the rays of light from each of its points have to be focused on the retina. When distant objects are viewed the image of near ones is indistinct and blurred, owing to the light rays being focused behind the retina, and diffused light circles being formed on it. The pupil is the aperture in the centre of the iris for the passage of light entering the eye. The pupil helps produce distinct images of objects on the retina. The retina is the internal membrane of the eye in which are located photoreceptors, rods and cones sensitive to light rays, and the nerve cells with their numerous processes that make up the nervous apparatus of the eye. We describe the biophysical model of the action potential. The minimum number of light quanta required to cause excitation in the eye in darkness is one. The trichromacy theories based on the assumption that the retina contains three types of colour-sensitive photoreceptors, or cones, is that most widely accepted*.

Keywords— *Eye, human sight, action potential, trichromacy theories, binocular sight*.

I. INTRODUCTION

The organ of visual reception, the eye, incorporates a receptor apparatus located in the retina and an optical system that focuses light rays and produces a clear, reduced, and inverted image of objects on the retina.

The sight plays an important part in the organism life. With the help of the sight organ humans perceive the external world. The sight provides over 90% of the information about the environment; this is why it has a considerable biophysical importance, not only in the differrentiation of luminosity, shape and colour of objects, but also in the space orientation, the maintenance of the equilibrium and the cortical tonus. [1]

The healthy human eye detects visible light, which is an electromagnetic, wave of wavelength between 400 and 750 nm. Visible light is bounded by the ultraviolet (10 nm – 400 nm) and the infrared ranges (750 nm – 1,5 μm).

Before falling on the retina light rays entering the eye pass through several refractive media, the anterior and posterior surfaces of the cornea, the crystalline lens, and the vitreous body. The direction of the passage of light rays depends on the refractive index and radius of curvature of the corneal surface, the crystalline lens and the vitreous body. The refractive power of the optical system is expressed in dioptres. [2]

A precondition for vision is that the eye projects the image of the object onto the retina. Light reaches the retina after undergoing refraction on the boundary surfaces of the cornea, aqueous humour, lens, and vitreous humour. [3] These surfaces can be characterized by a 60–65-dioptre optical system, which creates the real inverted image of the object on the bottom of the eye. The image of objects seen under a wider angle is larger, thus, nearby objects seem large and more details can be seen on them. By agreement, the distance of clear vision is 25 cm, which is the most comfortable reading distance for most people.

II. STRUCTURE

The optic analyser is made of eye (paired organ) or visual receptor, the optical way and the cortical integration corps of sight represented by the areas 17, 18 and 19 from the occipital lobe. The eye or the visual receptor is found in the neurocranium and it is made of the eyeball and the annex organs of the eyeball. The adequate excitant of the visual analyser is represented by the rays of light (electromagnetic rays, in case of humans with a wave length 750–400 mμ) which, reflecting on various objects, enter the eyeball. [4]

The eyeball is situated in the anterior and basal part of the orbit; and frontally it is protected by the two eyelids. The eyeball has a relatively spherical shape, with diameters of approximately 24 mm and weight of 6–8 g. Frontally it is more prominent, it corresponds to the cornea and its centre forms the previous pole of the eyeball. In opposition to it there is the posterior pole. The antero-posterior diameter which unites the two poles forms the anatomical axis of the eyeball, which is identical with the optic axis which passes through the refringent environments. [5]

The eyeball wall is formed of two concentric tunics. The external tunic is fibrous and it is formed of two unequal parts: behind, there is the sclerotic and in front there is the cornea. Inside the sclerotic there is the second eye membrane – the vascular membrane or choroid. It is rich in blood vessels and pigment. The presence of a big amount of pigment determines the dark colour of the vascular membrane, it gives the eye colour. [6]

The median vascular tunic presents three segments which are – from the back to the front: the choroid, the ciliary body and the iris. The ciliary muscle is formed of smooth muscular fibres. The circular fibres are innervated by the sympathetic. The ciliary processes are made of capillary agglomerations and secrete the aqueous humour. [7] The iris is a diaphragm in the front of the crystalline; in the middle, it has an orifice called pupil. The iris has the role of a diaphragm which allows the adjustment of the amount of light which comes to the retina.

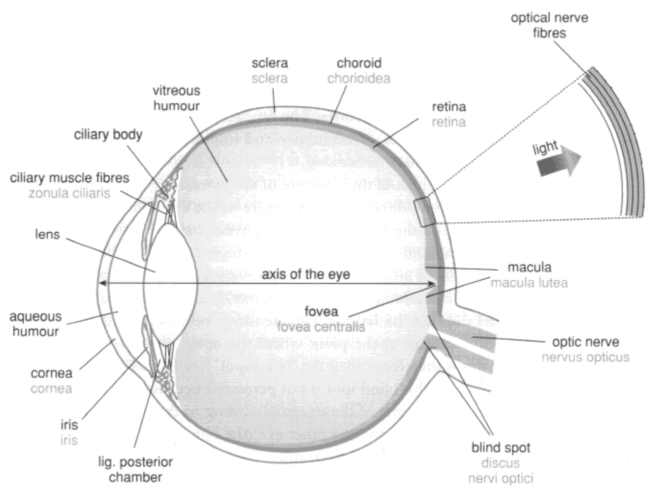

Figure 1. The schematic structure of the human eye-ball.

Behind the iris there is a biconvex transparent lens – the lens. The back parts of the lens, in comparison with the frontal one, is much more convex. The substance composing the lens is a semi-liquid. The lens is found in a fine transparent capsule, fixed with the help of some special ligaments on the ciliary body. In the lens there are no vessels and the feeding is ensured through a special liquid which fills the eye chamber. [8] Between the margins of the lens and the cornea there is such a space – the eye's posterior chamber. In the chambers there is liquid – the aqueous humour. All the internal cavity of the eye is filled entirely with a transparent gelatinous mass – the vitreous body. The vitreous body and the lens have the refraction capacity.

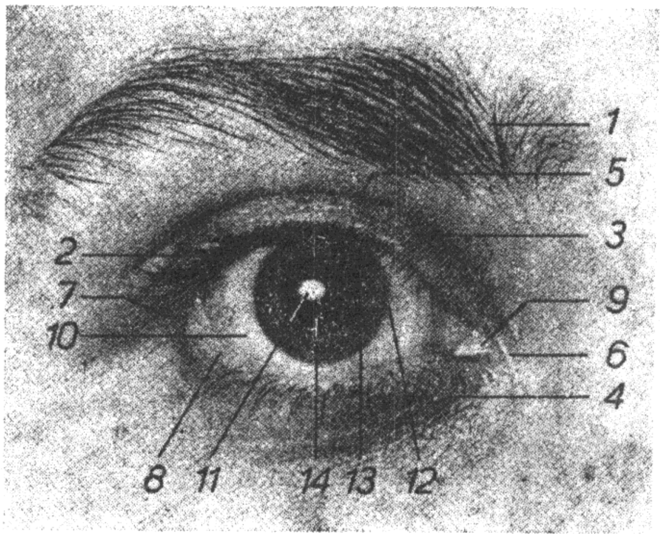

Figure 2. Parts of the eye and its surroundings
1. eyebrow; 2. eyelashes; 3. upper eyelid; 4. lower eyelid; 5. epicanthic fold; 6. inner canthus; 7. outer canthus; 8. eyelid margin; 9. lacrimal caruncle; 10. white of eye and blood vessels; 11. vitreous cornea; 12. limbus separating cornea and sclera; 13. iris; 14. pupil

The internal tunic is represented by the retina and it is the photosensitive membrane which realizes the reception and the transformation of the luminous stimuli in nervous influx. The retina is made of ten cellular layers. The deep layer, formed of pigment cells has protection and metabolic function, ensuring the synthesis of the photosensitive pigments. The second layer is made of the photosensitive cells – cones and rods. The cones, approximately 6 million/retina, predominate in the yellow spot (macula lutea) and represent entirely the fovea centralis, the area with maximum visual accuity. The photosensitive pigment is iodopsin. The cones have an important role in the day sight, in the perception of colours and shapes. The rods, approximately 130 million/retina are more numerous in the periphery and less in the yellow spot and miss from the fovea centralis. Their photosensitive pigment is rhodopsin. The rods ensure the sight in poor light and the night sight. [9]

The eye's defence mechanisms are the lids and the lachrymal secretion. The eyelids close as a reflex. By closing, they isolate the retina from the action of the light and the cornea and the sclerotic from toxic influences. Except for this, by blinking it is produces a uniform distribution of the lachrymal liquid on the entire eye surface, protecting the eye from drying. The tears are secreted by the lachrymal glands and are made 97,8% water, 1,4% organic substances and 0,8% of salts. The lachrymal liquid secreted covers uniformly the eye surface and maintains it moist. [10]

III. THE SIGHT'S PHYSICS

The human eye, with its various transparent humours, whose refraction index differs (approximately 1,33, for the cornea and eye humour and 1,42 for the lens) can be considered a biconvex lens with a dioptric capacity at rest of approximately 60D, of which 45 belong to the cornea and 15 to the lens. It refracts the rays which pass through it and gather them in a single point. This way a real, reversed and smaller image than the object is obtained. The eye's optic system represents a convergent refraction system. The refringent media are represented by: the transparent cornea, the aqueous humour, the lens and the vitreous body. As a consequence of the irregularity of the cornea or deformation of the lens astigmatism appears, the retinal images are unclear and the correction is made with cylindrical lenses. [11]

In order to see clearly an object, the rays which leave from the object must gather on the retina. The eye's adaptation for obtaining clear images of the objects which are found at various distances is called accommodation. The closest point to the eye at which we see clearly, with a maximal accommodation effort, is called proximal point. The closest point to the eye at which we see clearly, without accommodation effort is called remotum. Generally, in a normal eye, the proximal point is at 25 cm and the remotum point is at 6 m from the eye. In these cases the main focal point is at 17 mm behind the lens and the image of the objects placed at infinity is clear, without accommodation. When the image forms in front of the retina, we talk about myopia, which corrects with divergent lenses and when it is formed behind the retina it is called hypermetropia, which can be corrected with convergent lenses.

IV. Image Formation

The luminous rays from the visible spectrum arrived at the eyeball, cross the refringent environments of the dioptric system, then the retina, from the 10th layer to the 1st (from the multipolar neurons layer to the pigmentary state), from there they reach to the photoreceptor cells represented by the cones containing iodopsin and the rods containing rhodopsin. Through the decomposing of the photosensitive pigments – iodopsin to retinene and photopsin and rodopsin in retinen and scotopsin, the permeability of the photoreceptor cells is modified for ions and action potentials are triggered. [12] The rods are responsible for the scotopic sight, in diffuse light when the colours, the details and the shapes of the objects are not distinguished. It is the black and white vision. The rods have the excitability threshold lower than the cones, allowing the vision at a lower amount of light. The cones are responsible for the photopic, day vision, in intense light, necessary for the chromatic vision which allows the perception of colours.

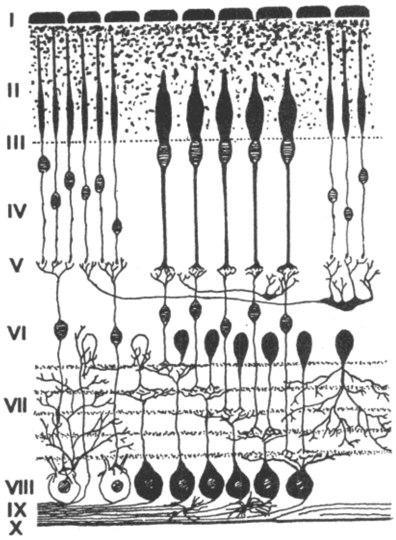

Figure 3. The structure of the retina
I.: Retinal pigment epithelium; II.: The layer of cones and rods; III.: External limiting membrane; IV.: Outer nuclear layer; V.: Outer plexiform layer; VI.: Inner nuclear layer; VII.: Inner plexiform layer; VIII.: Ganglion cell layer; IX.: Nerve fibre layer; X.: Inner limiting membrane.

Hence, the receptors of the optical pathway are photosensitive cells with cones and rods. The 1st neuron is found in the bipolar cells from the retina and the 2nd neuron is also situated in the retina, but deeper, being represented by the multipolar cells. [12] The axons of the multipolar neurons coming from the internal field of the retina are crossed at the level of the optic chiasm, representing approximately 40% from the total of the neurons, after they reach the opposite optical duct. The axons coming from the external field of the retina do not cross and pass in the optic duct on the same side. The optic nerve contains fibres from a single eyeball, while the optic tract contains fibres from both eyes. The optic ducts reaches the metathalamus, where most of the fibres of the optical duct make a synapse with the 3rd neuron, whose axon propagates towards the cerebral cortex and ends in the occipital lobe, where the primary and secondary or associative area are found, representing the cortical segment of the analyzer. [14]

The visual cortex is organized for a maximum concentration of the afferent impulses, being made of vertical cell chains, which present maximum discharges for all the possible areas of the visual field. These cells are characterized by the fact that a chain of cells which discharges impulses is framed laterally by cellular chains in inhibition. More „simple” cells converge towards a „complex” cell where the analysis and integration of the stimuli is made and the visual sensation is elaborated. [15]

The visual sensation has three different components: a) the light sensation is the consequence of the afferents coming from all the photosensitive elements of the retina, as a consequence of the excitation of the receptors by the rays of the visible spectrum; b) the shape sensation, characterized by the perception of details, shapes, forms of various objects, is also due to the participation of all the receiving elements of the retina; c) the chromatic view is the most differentiated form of activity of the optic analyser. [16]

V. The Biophysical Modeling of the Action Potential

The slow variations of electrical potential registered as an electroretinogram are accompanied with the appearance of action potentials in the ganglion cells of the retina, where the fibres of the optic nerve take their origin. The eel was chosen because its optic nerve consists of a small number of relatively long fibres. The experiments proved that in the absence of a light stimulus, i. e. in darkness, action potentials occurred very seldom or not at all. Within 0.1–0.5 second of illuminating the eye frequent impulses arose, their frequency being very high in the first moment and then diminishing in spite of the continued stimulation. Termination of the light stimulus was immediately Followed by another short-lived outburst of impulses in the optic nerve. [17]

The mechanism of nerve transmission is as follows. As a result of the action potential at the presynaptic nerve end, the vesicles fuse with specific sites on the presynaptic membrane, thereby bringing the mediator into the synaptic cleft. From here, its molecules reach the postsynaptic membrane by diffusion and alter its conductivity to the sodium ion. The current of the postsynaptic membrane changes as a result of the current of sodium ions: this is the postsynaptic potential. Experience has shown that the postsynaptic potential is composed of small doses; this corresponds to the synaptic potential created by a vesicle. In terms of their function, synapses are of two types: stimulatory *and* inhibitory synapses. In the case of stimulatory synapses, the postsynaptic potential means depolarization, and in the case of inhibitors, hyperpolarization. [18]

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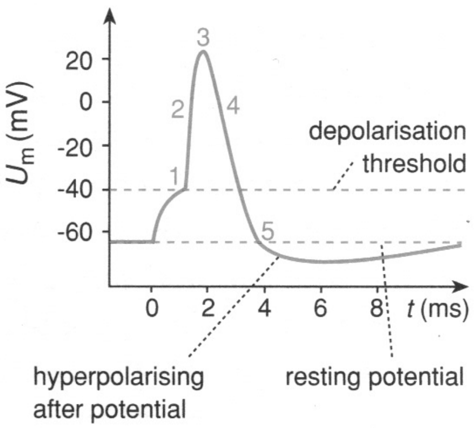

Figure 4. The action potential

The biophysical modeling of this graphic is next function:

$$f(U) = \begin{cases} \dfrac{2t(4-t)*(t-10)}{\frac{t}{6}+1} & 0 \le t \le 4 \ \text{[msec]} \\ \dfrac{4-t}{t^2-3t} & 4 \le t \le 10 \ \text{[msec]} \end{cases}$$

If two thin beams of light, both of subthreshold intensity, act within the limits of the same receptive field, there is a summation of receptor potentials, and impulses arise in the ganglion cell which are registered in the nerve fibre of the optic nerve.

However, if two thin beams of light of suprathreshold intensity, act on different receptive fields belonging to different ganglion cells, phenomena of inhibition are observed; the excitation of the one receptive field increases the stimulus threshold of the other. Thus the retinal neurones have the same properties (summation, inhibition) as are characteristic of the nerve centres. For that reason the retinal neurones are described as a peripheral part of the central nervous system.

VI. BINOCULAR SIGHT

The space grasped by sight is called visual field. A monocular visual field corresponds to each eye, which overlays partially with the visual field of the other eye. The visual field of each eye includes an angle of approximately 160° in horizontal plan and 145° in vertical plan. The common part of the two fields represents the binocular visual field. The isolated or combined action of the globular muscles makes possible the movement of the eyeball in all the directions. The innervation is given by the oculomotor nerve (III) for the muscles: upper right, medial, lower and inferior oblique; trochlear nerve (IV) for the upper oblique muscle and the abducens nerve (VI) for the lateral right muscle. [19]

Any object in the binocular visual field forms an image on the retina of each eye. These images merge on the cortex in a unique image. The cortical fusion process is possible only if the retina images are formed in corresponding points. This process of image fusion starts at the level of the optic chiasm where the crossing of the optic nerves takes place. Due to the particular crossing mode of the fibres of the optical nerve at the level of the optic chiasm, the left nasal hemiretina becomes corresponding with the right temporal hemiretina and viceversa.

Through the cortical retina and the differentiation of the impulses from the monocular and binocular sight fields, to which the proprioceptive impulses from the extrinsic muscles add up in the time of the convergence reflexes, is ensured the appreciation of the objects distances. Each eye sees the object under a different angle, generating the stereoscopic sight, in relief. The binocular sight confers the ability of the sight in depth. [20]

An important role has been assigned to the binocular sight in the perception of the depths and the stereoscopic sight. But this property is due to the relative dimensions of the objects, their shades and in the case of the objects in movement, their displacement compared to other objects.

In order to distinguish the shape precisely, a person must see clearly the limits, the details of the objects. The capacity to distinguish precisely the details of the object examined lays at the basis of the so called sight acuity. The visual acuity is determined by the shortest distance necessary between two points so that the eye perceives it differently. The shortest this distance is, the better the view. The greatest visual acuity is found in the yellow spot and the fovea centralis.

For the determination of the man's visual acuity a table (introduced in the ophthalmologic clinics by Kettesy) is placed on the wall 5 m away from the examined person. At the beginning the visual acuity of an eye is determined, then the other one. The sight span of both eyes is much wider than the sight of a single eye; the visual acuity increases. The sight acuity in a normal eye for the parallel lines is 0,15 mm and at an angle of 1'. The visual acuity depends on a big number of factors, amongst which the state of the ocular optic system, the retina's state and especially the cones, the intensity of the luminous system and the time of action etc.

We mention that if the frequency of the stimuli exceeds 40/s, the fusion of the images takes place, without perceiving discontinuity, due to the persistence of the images on the retina.

VII. CHROMATIC SIGHT

Between the 7 colours of the visible spectrum (red, orange, yellow, green, blue, navy, violet) there is great number of intermediary colours. The sensitivity of the retina photoreceptors is not equal for the entire range of radiation of the visible spectrum and it is higher for the 550 mμ wave length radiations. This is why the yellow colour is used for signalling. The maximum sensitivity was formed for the yellow colour because this is the fundamental Sun colour.

Our eye distinguishes approximately 200 intermediary colours and five million colour shades. The colours of the objects are perceived by us according to the objects capacity to absorb or reflect luminous waves of various lengths. If the objective absorbs a part of the luminous waves and reflects other, it will have the colour of the waves which are reflected by its surface. The reflection of the waves of the spectrum determined the feeling of the white colour and when the object absorbs all the colours, it will have the colour black, between black and white, there is grey, with various nuances. [21]

It is enough to chose, except for a main colour another colour so that through their mixing we obtain the white colour. These colours, which give white, by completing one another, got the name of complementary colours. The following pairs of colours are complementary colours: 1) red and greenish yellow; 2) orange and blue; 3) yellow and dark blue; 4) greenish yellow and violet; 5) green and red. By mixing any of these pairs, we obtain white. By mixing these colours in various proportional we obtain different shades of grey. The grey colour, obtained from any of the complementary colours pairs is not different by anything than the grey colour obtained from another pair and our eye does not notice the difference between them.

In the retina, the cones contain three types of sensitive pigments: in the red colour („red cones"), cones with pigment sensitive to the green colour („green cones") and cones with pigment sensitive to the blue colour („blue cones"). The equal stimulation of these three types of cones gives white. The stimulation of a single category of cones causes the feeling of the colour absorbed. The colours red, green and blue are fundamental colours. By mixing them in various proportions, we can obtain all the other colours of the spectrum, including white.

By the simultaneous or consecutive examination of the objects coloured in two different colours, the difference between them seems more intense than it really is. This phenomenon is called contrast. On the basis of the experimental determinations, the maximum contract appears between the yellow-black colours. [22]

There is a certain form of sight disturbance, when the person loses the perception of colours partially or totally. This disease is called daltonism. First of all, daltonists cannot see the colour red, because the „red cone" misses. Most frequently these defects are inherited, with a sex related recessive character, being the consequence of the genetic alteration of the X chromosome. Daltonism affects more men (4% of them), than women (0,5%).

The classification of the patients according to the chromatic sight is made in three big groups, that is:

1. Trichromatic – who has all the 3 cone types. This category includes both normal people and those with a decreased capacity to perceive colours because one of the cone types is weaker.
2. Dichromatic – they have only two types of cones this is why they cannot see one of the fundamental colours.
3. Monochromatic – they only have one type of cones and apparently they cannot perceive colours, their sight being in black and white with grey shades.

The lack of vitamin A from the diet determined sight disorders through the decrease of the photosensitive pigment synthesis.

The visual analyser allows the recognition of form, size, colour, luminosity, movement of objects and estimation of distances. In correlation with the acoustic, vestibular and kinaesthetic analysers, it achieves space orientation and balance.

VIII. The Sight's Pathology

This chapter has already discussed about some sight defects, such as: myopia, hypermetropia, astigmatism, daltonism etc.

Cataract is an eye disease characterized by the blooming of the lens or its capsule, which leads to a progressive visual discomfort. It can be corrected through surgery. The implantation of an artificial lens takes place under local anaesthesia. [23]

Glaucoma is an ocular complex of symptoms determined by the increase of the intraocular tension. It manifests essentially by the hypertonia of the eyeball, the reduction of the visual span; in certain forms it associates with corneal anaesthesia, a feeling of coloured circles under artificial light, with the gradual weakening of the sight.

Conjunctivitis is an acute or chronic inflammation of the conjunctive. The ocular conjunctive is the part which covers the anterior third of the eyeball from the retrotarsal fold to the edge of the cornea.

Retina displacement is the intraretinal separation in pathological conditions of the cones and rods layers of the retina from the pigment epithelium, which remain adherent to the choroid. [24]

The macular degeneration consists in a destruction of the central area of the retina. The macula is the area of the retina which is responsible for the precise sight. The macula can be damaged gradually and this is followed by an irreversible weakening of the sight. Numerous people need to correct their sight, most old people (over 50%) turn to glasses or contact lenses.

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