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DYNAMICAL MODELLING OF HUMAN CONES UPON ERG FLASH RESPONSES

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Abstract

The paper shows a new dynamical model of the human cone receptors of the eye that is based on the action potential changes of the receptors caused by coloured light stimuli. Flash electroretinograms of subjects having normal color vision were taken for light stimuli having different spectral characteristics. The different ERG answers led us to separate the individual answers of the three different human cones of the eye. Light flashes of the measurement were explained as switching on and off of an input signal for the unknown system of the eye, while the output of the system on this signal is given by the ERG curve itself.

Knowing the in- and outputs of the cone system, the transfer functions and the transfer systems were identified.

Keywords: flash ERG, color vision, action potential.

1. Introduction

The human eye consists of two main types of light sensitive receptors: rods and cones. Rods work basically under low illumination (scotopic) and can differentiate between lighter and darker sensations while cones are active under higher illumination (photopic) as daylight e.g. and are able to recognize colours. Three different types of cones can be found in the human eye: long wavelength sensitive *L* cones, medium wavelength sensitive *M* cones and short wavelength sensitive *S* cones. The sensitivities of the cones are overlapped [*Fig. 1*].

The separation of the receptors could not be achieved till the recent and famous measurement of STOCKMAN, SHARPE et al. [1], [2]

The measured sensitivity characteristics describe the long term effects of the color vision such as sensation of colours of surfaces and illuminations, but do not describe the short term effects, such as the Benham effect e.g.. The first set of effects arises in a stationary status of the eye when the reversible equilibrium of the breakdown and convalescence of the light sensitive photopigment is achieved, but the effects of the second set are dependent on the time. The aim of the work was to identify the time dependent function of the cone working.

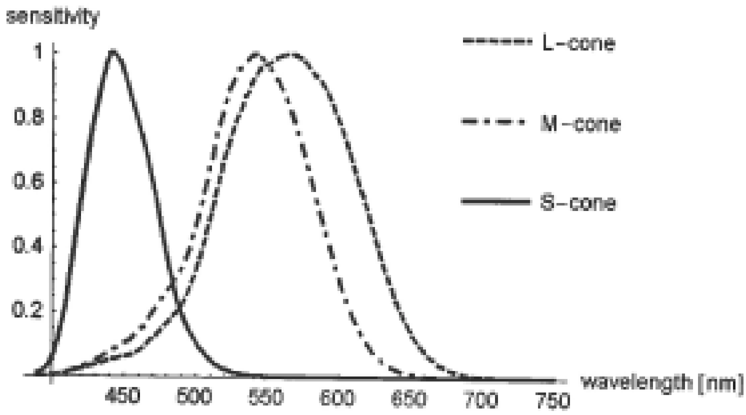

Fig. 1. Spectral sensitivities of the three cone receptors [1], [2]

Electroretinography is a well known clinical experimental method which records the changes of the action potential of the light sensitive neurons on light stimuli within very small time period.

The ERG is a series of small voltage changes measured across the globe when a light stimulus is presented to the eye. In the intact human subject an electrode system has been arrived at that allows the examination of the ERG with minimum patient discomfort. This system utilizes a contact lens electrode making electrical contact with the cornea. It also involves an indifferent electrode, frequently on the forehead or on the ear. The net effect of this detector arrangement is the measurement of the voltage across the globe [3].

The method was first described by HOLMGREN in 1865 [4]. All vertebrates and many higher invertebrates exhibit the ERG and it was demonstrated quite early that the measured change was entirely caused by the retina itself [5], [6] containing the effects of both the rod and cone systems [7].

Although the ERG potentials show remarkably higher sensitivity for ophthalmic diseases [8], they also can be used for investigation of the separated cone system [9]. Many results studied the effects of the anomalous color vision on the ERG [10], [11] and also several studies derived stationary spectral sensitivity characterizations of the three types of cones based on ERG data [12].

To achieve the aim of the work flash ERG answers were needed for various colored light stimuli. KRAVKOV published ERG answers for red and green light stimuli [13] and GRANIT published answers for red, green and blue light flashes [14] in case of subjects having normal color vision. Unfortunately, these results could not be used for modelling because the required additional information about the measurements was not published (time length, intensity and spectral radiation of the applied flash). So ERG measurements were undertaken at the II. Clinic of Ophthalmology, Semmelweis University of Medical Sciences.

2. Methods

Measuring instrument is a Tomey PS-400 portable electroretinograph in mode of flash ERG. The light source of the instrument is a xenon arc lamp with 20 Joule energy of radiation. The instrument is very compact and did not allow spectral radiance measurement of the light source, so the theoretical spectral radiation characterization of the xenon arc lamps was used for further computations [*Fig.2*]. The duration of the applied flashes was 0.2 s.

Measurements were performed following the standard clinical procedure. Using contact electrode and topical anesthesia on the patients, measurements were made by ophthalmologists.

Beside the white stimulus of the light source red, green and cyan flashes were examined. Coloured stimuli were realized applying colourful filters having spectral transmissions shown in *Fig. 3*.

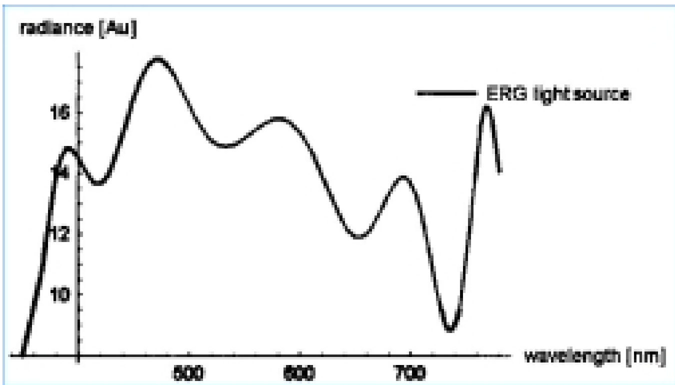

Fig. 2. Spectral radiance of the applied light source

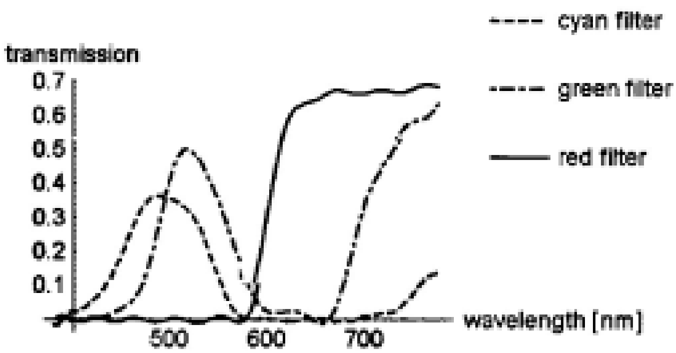

Fig. 3. Spectral transmissions of the applied filters

Eleven subjects with normal color vision were measured. Color vision ability was tested with Ishihara pseudoisochromatic plates and MFKI Led anomaloscope.

3. Results and Conclusions

The potential answer curves of the subjects with normal color vision were the same type though the characteristic parameters of the curves varied in a large range. For this reason the average of the eleven responses was used for modelling at every color.

Averages of the answer potentials of subjects with normal color vision are shown in *Fig. 4*. (The curves do not show responsible results in the first 0.05 sec period because of interpolation problems and the inertia of the measuring instrument):

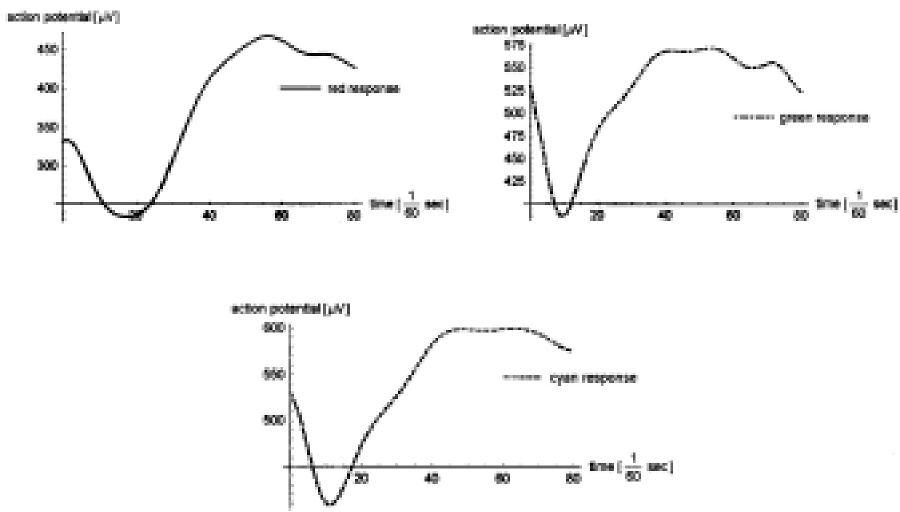

Fig. 4. Temporal ERG answers on the applied stimuli

4. Discussion

The separation of the individual cone dependent response potentials was processed by the functions shown in *Fig. 2* using the assumption of homogeneous linearity written in the matrix equation below:

$$\begin{pmatrix} l(t) \\ m(t) \\ s(t) \end{pmatrix} = \mathbf{T} \cdot \begin{pmatrix} r(t) \\ g(t) \\ c(t) \end{pmatrix},$$

where $r(t)$, $g(t)$ and $c(t)$ are the potential responses on red, green and cyan flashes and $l(t)$, $m(t)$ and $s(t)$ are the individual cone responses. Parameters of the transformation matrix are derived from the spectral sensitivity characteristics of the cones:

$$\mathbf{T}=\begin{pmatrix} \int_{350}^{780}\overline{L}(\lambda)\cdot S(\lambda)\cdot\tau_R(\lambda)\,\mathrm{d}\lambda & \int_{350}^{780}\overline{M}(\lambda)\cdot S(\lambda)\cdot\tau_R(\lambda)\,\mathrm{d}\lambda & \int_{350}^{780}\overline{S}(\lambda)\cdot S(\lambda)\cdot\tau_R(\lambda)\,\mathrm{d}\lambda \\ \int_{350}^{780}\overline{L}(\lambda)\cdot S(\lambda)\cdot\tau_G(\lambda)\,\mathrm{d}\lambda & \int_{350}^{780}\overline{M}(\lambda)\cdot S(\lambda)\cdot\tau_G(\lambda)\,\mathrm{d}\lambda & \int_{350}^{780}\overline{S}(\lambda)\cdot S(\lambda)\cdot\tau_G(\lambda)\,\mathrm{d}\lambda \\ \int_{350}^{780}\overline{L}(\lambda)\cdot S(\lambda)\cdot\tau_C(\lambda)\,\mathrm{d}\lambda & \int_{350}^{780}\overline{M}(\lambda)\cdot S(\lambda)\cdot\tau_C(\lambda)\,\mathrm{d}\lambda & \int_{350}^{780}\overline{S}(\lambda)\cdot S(\lambda)\cdot\tau_C(\lambda)\,\mathrm{d}\lambda \end{pmatrix}^{-1}$$

$$=\begin{pmatrix} 1.16207 & -0.07270 & 0.01668 \\ -0.97220 & 0.32268 & -0.07896 \\ 0.41354 & -0.59502 & 0.80047 \end{pmatrix},$$

where $\overline{L}(\lambda)$, $\overline{M}(\lambda)$, $\overline{S}(\lambda)$ are the spectral sensitivities, $S(\lambda)$ is the spectral radiance of the flash and $\tau_R(\lambda)$, $\tau_G(\lambda)$, $\tau_C(\lambda)$ are the spectral transmission of the coloured filters.

The determined $l(t)$, $m(t)$ and $s(t)$ cone response functions are shown in *Fig. 5*.

The obtained cone response functions should fulfil the following equation about the equality of the measured and approximated responses in case of white flash. The approximation can be derived from the individual cone responses and the spectral sensitivity of them.

$$w(t)=k\cdot\Bigg(l(t)\cdot\int_{350}^{780}\overline{L}(\lambda)\cdot S(\lambda)\cdot\tau_W(\lambda)\,\mathrm{d}\lambda+$$

$$+m(t)\cdot\int_{350}^{780}\overline{M}(\lambda)\cdot S(\lambda)\cdot\tau_W(\lambda)\,\mathrm{d}\lambda+s(t)\cdot\int_{350}^{780}\overline{S}(\lambda)\cdot S(\lambda)\cdot\tau_W(\lambda)\,\mathrm{d}\lambda\Bigg).$$

The duration of the applied flashes (0.2 sec) is long comparing to the transfer speed of the neural processes (the velocity of the currency of the sensation is in the range of 100 m/s). So the applied light stimulus was considered as a switching on and off with arbitrary defined amplitude of 1000 units instead of a Dirac δ impulse.

Since the neural signals have a non-zero potential under non stimulated circumstances, the first step of the modelling was a zero level shift. The next step was the system identification. The mathematical model was built up knowing the systems and the type of their transfer functions. The last step was the identification of the transfer functions parameters using an iterative method.

The simplest system with minimum number of containers was identified in the model, which can describe the potential changes. *Fig. 5* shows, that the potential answers of the receptors are very similar to each other, so the same type of the transfer functions was identified for the three different cones. L and S cones can be described using a $P(-D)T_3$ system and M cone can be described using a

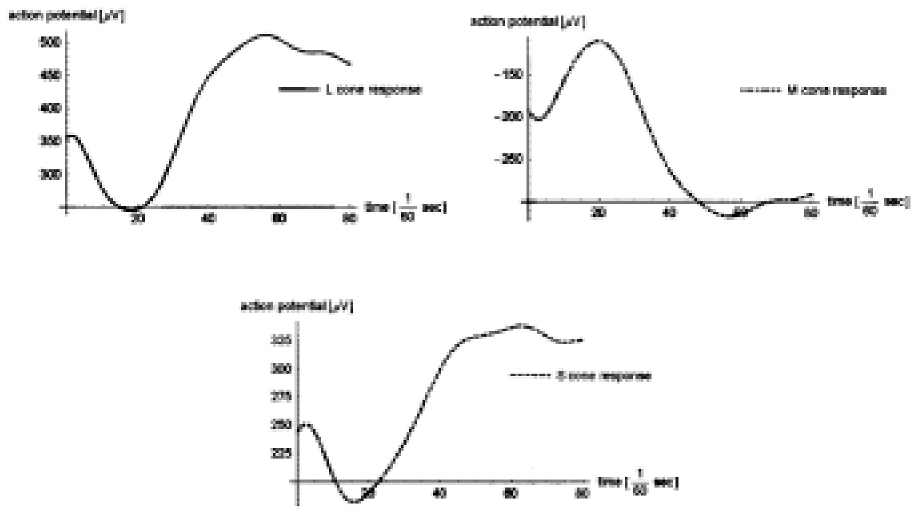

Fig. 5. Derived cone response functions

$-(P(-D)T_3)$ system. The transfer functions can be written in the following form:

$$F(s) = A\frac{1 - T_D s}{(1 + T_1 s)(1 + 2\xi T_2 s + T_2^2 s^2)} = \frac{V}{U},$$

so the signal flow:

$$\begin{aligned}
U_A(1 - T_D s) &= V\left[1 + s(T_1 + 2\xi T_2) + s^2(T_2^2 + 2\xi T_1 T_2) + s^3 T_2^2 T_1\right], \\
V T_2^2 T_1 s &= (UA - V) + s\left[-UAT_D - (T_1 + 2\xi T_2)V\right] \\
&\quad + s^2(-T_2^2 - 2\xi T_1 T_2)V, \\
V &= \frac{1}{T_2^2 T_1 s}\Big\{-(T_2^2 + 2\xi T_1 T_2)V \\
&\quad + \frac{1}{s}\left[-UAT_D - (T_1 + 2\xi T_2)V + \frac{1}{s}(UA - V)\right]\Big\}.
\end{aligned}$$

The transfer functions of the cones after the parameter identification are:

L cone

$$l(t) = 0.408455\frac{1 - 0.742888s}{(1 + 0.5s)\cdot(1 + 0.3333s + 0.0568182s^2)},$$

M cone

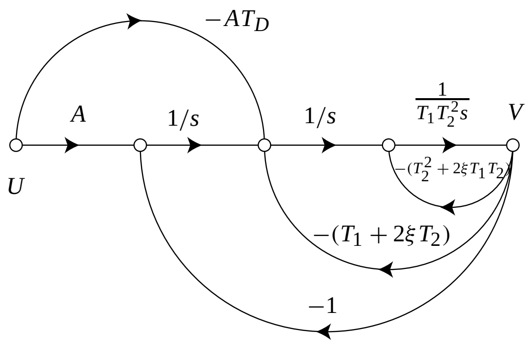

Fig. 6. The signal flow diagram of the $P(-D)T_3$ system

$$m(t) = -0.0413009\frac{1-6.5s}{(1+0.5s)\cdot(1+0.3333s+0.0568182s^2)},$$

S cone

$$s(t) = 0.245074\frac{1-0.742888s}{(1+0.5s)\cdot(1+0.3333s+0.0568182s^2)}.$$

The comparison of the obtained model results and the individual cone responses considering the zero level shifting is shown in *Figs.* *7.a*, *7.b*, *7.c*.

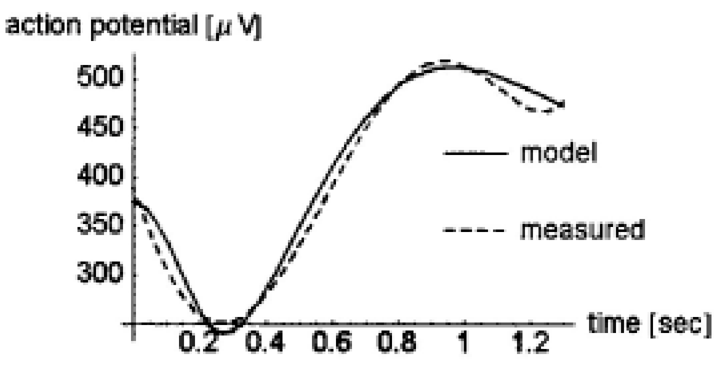

Fig. 7.a. Effectiveness of the model for the L-cone

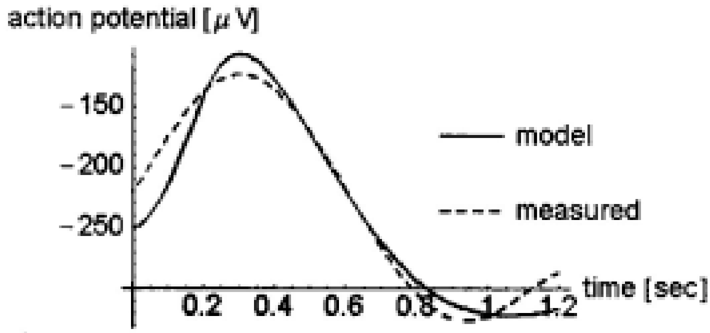

Fig. 7.b. Effectiveness of the model for the M-cone

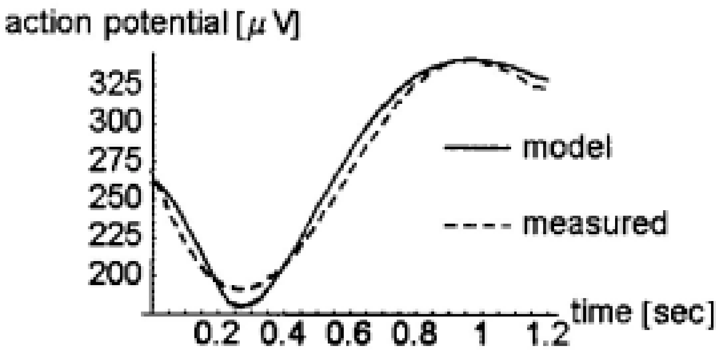

Fig. 7.c. Effectiveness of the model for the S-cone

5. Summary

A mathematical model of the temporal behaviour of the human cone receptors was developed. The model is based on experimental flash ERG data of subjects with normal color vision. Individual cone potential responses were separated from action potential responses on colored light stimuli.

The developed model is a first and simplified attempt to describe the human cone system and can be more sophisticated in the future. Although using more flexible ERG instrument and allowance of systems having more than three containers in the identification would result more precise model, the recent model already can serve as the basis of an electrical simulation of the temporal behavior of the retinal elements.

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