

COMPUTATIONAL APPROACH OF OPTOELECTRONIC TRANSDUCTION IN THE COMPOUND EYE

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There are presented the computational simulations of the optoelectronic effects in the biophysical processes involved by light absorption and the transmission of the membrane generated potential from the receptor cells to the neurons. The physical system is the compound eye of *Drosophila Melanogaster* flies. The experimental electroretinograms recorded at various frequencies between 8 and 60 Hz are well modelled by a system of two nonlinear, coupled oscillators. The understanding of the mechanisms of optoelectronic biological processes is a current topic of great scientific interest because of its potential applications.

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1. Introduction

The visual system has the role of light transduction into neural impulses directed to the control nervous system. The electroretinogram (ERG) represents the overlapping of the corneal projections of the action potentials generated in the photoreceptor cells and in the neurons from the first optic ganglion – the lamina. The physical parameters which are mainly responsible for the ERG signal amplitudes are the light intensity and wavelength. When the illumination is carried out intermittently, the flickering frequency is also influencing the amplitudes of the ERG signal. The computational study developed in the following is an application of the coupled oscillator model. The proposed system of equations is mainly modeling the biophysical process of membrane transmission of the potential generated by light absorption in the rhodopsin molecules from the receptor cells to the neurons from the lamina ganglion. The excitation of the lamina neurons causes the generation of a corresponding action potential; which is further transmitted to the next two ganglions and finally to the brain.

2. Materials and methods

Biological material. The analyzed *Drosophila Melanogaster* individuals belong to the "white" mutant (lacking the red pigment from the eye annex cells) that have been cultivated in large glass tubes on corn meal agarized medium until they were 8 days old. Each individual intended for the electrophysiological investigation was slightly anaesthetized within an adequate etherizer and then carefully fixed in melted paraffin except for the abdomen that remained free to assure normal respiration after paraffin solidification [1].

The optoelectronic transduction. The measure electrode was placed on the compound eye of the *Drosophila* individual while the reference electrode was slightly inserted into the thorax (to

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establish direct contact with the inside body electrolytic medium but avoiding damage of the physiological state). The electrodes were Ag-AgCl fine wires immersed in neutral glass micro-pipettes filled with Ringer type physiological solution having impedance of about $50\text{ M}\Omega$ [2]. The electric signal generated following light absorption in the eye is captured and further processed by an electronic module having the functions of impedance adapter and signal amplifier. The analog to digital converter assured the signal sampling at frequency of 5000 Hz and the display on a PC monitor. The light beam with the intensity of about 10^{-6} W/cm^2 (as measured with a Tektronix photometer) was provided by a slide projector source and conducted by a glass fiber cable to the proximity of the immobilized insect's eye. The illumination frequency could be varied between 5 and 100 Hz .

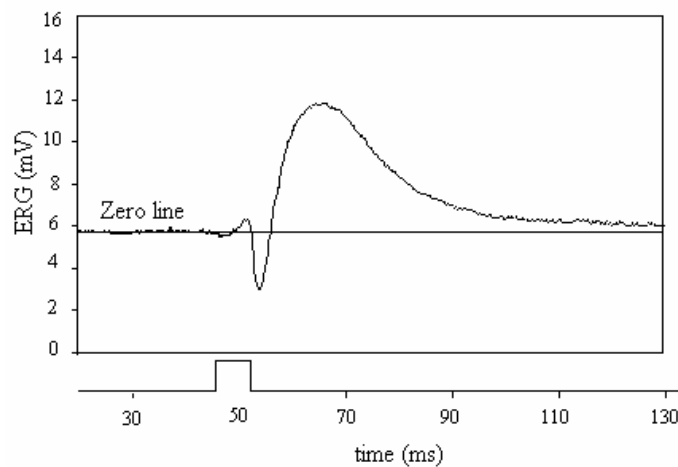


Fig. 1. The ERG signal corresponding to a single light stimulus (quasi rectangular as shown by the lower trace) during intermittent illumination. The hump above the zero line is generated mainly by the central photoreceptors while the peak below the zero line represents the hyperpolarization component reflecting the bioelectrogenesis in the lamina ganglion.

The depolarization component is provided mainly by the corneal projection of the receptor potential while the hyperpolarization component is given by the corneal projection of the action potential generated in the lamina neural cells.

3. Results and modeling

The structure of the electroretinographic (ERG) signal corresponding to low frequency illumination (about 8 Hz) is presented in fig. 1. The light stimulus recording is displayed at the bottom of the figure. According to the data in literature, the ERG response is the result of some nervous impulses overlapping at the cornea level. They are generated in different visual cells (being of nervous origin as in the case of vertebrates), having different amplitudes, durations and phases at the moment of their superposition at the eye exterior membrane. The depolarization component is the projection of the depolarization generated mainly in the central photoreceptors while the hyperpolarization component is given mainly by the projections of the neural impulses generated in the lamina ganglion.

The role of the light processing in the visual system is to direct the information from the environment toward the brain, the light signal is converted into electric potential by the photoreceptor cells membranes and then transmitted to the neurons from the three optic ganglions interposed between retina and the brain: lamina, medulla and lobula. The energy of some the nervous impulses is dissipated in the other possible directions of propagation since all the body tissues are electrolytic conductors (inhomogeneous and anisotropic). Consequently, part of the electric signals generated in the photoreceptors and neural cells from the optical ganglions is projected backwards to the exterior of the eye (the cornea) being recorded in the form of the ERG

signal. Actually, the ERG is the superposition of the corneal projections of the electric potential generated in the membranes of the photoreceptor cells as well as in the membranes of the neural cells from the first optic ganglion, the lamina. There are two main types of photoreceptors: the peripheral photoreceptors that make synapses into the lamina neurons and the central photoreceptors that bypass the lamina and make synapses directly into the medulla neural cells (from where no projection can be recorded at the cornea level). The model based on two coupled oscillators is widely used in simulations of the dynamics on a variety of nonlinear systems such as plasmas [3,4,5], hetero-structures [6, 7] and neuroscience [8,9]. The Bonhoeffer-van der Pol (BVP) equation is considered as an important model for studying the dynamics in a nerve system [10-12]. In our investigation the neuron system is operating in the excitable mode, where an action potential is generated only as response to an outside stimulus. We propose a computational model to describe the observed dynamics consisting in the coupling between the mutual action of the membrane cell, acting as a photo-transduction gate and the neuron that directs the message further and responds with a feed-back that brings the system back to its stand-by situation. The first two equations represent a modified BVP system, where the term standing for the applied impulse is consisting of the output of a forced van der Pol (VDP) oscillator (the last two equations) modeling the response to the external light stimulus. The feed back coupling between the two systems is mimicked by the term qx_1 in the third equation. The driving of the VDP oscillator, $f(t)$ is a sequence of rectangular pulses. The frequency, amplitude and pulse duration can be fitted to the experimental values.

$$\frac{dx_1}{dt} = ax_2 + x_1 - mx_1^3 + x_3 \quad (1)$$

$$\frac{dx_2}{dt} = b - dx_1 - cx_2 \quad (2)$$

$$\frac{dx_3}{dt} = x_4 - qx_1 + f(t) \quad (3)$$

$$\frac{dx_4}{dt} = -n(x_3^2 - 1)x_4 - px_3 \quad (4)$$

Using numerical integration, we find oscillations with patterns very similar to periodic dynamics observed in the real system.

The variables in the differential equations are proportional to the electric membrane potential and the currents in the photoreceptors and in the neurons from the lamina ganglion. The values of the parameters were chosen to best fit the experimental recordings, but their correct physical meaning requires further, more detailed, experimental studies.

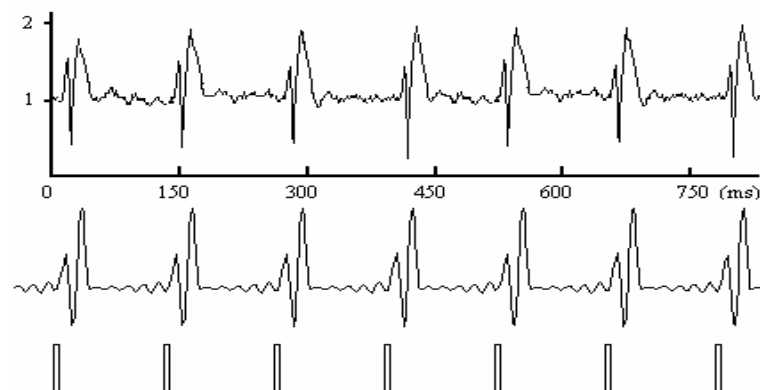


Fig. 2. ERG response for intermittent illumination with rectangular stimulus (lowest trace) at frequency of 8Hz. The experimental recording is shown by the upper trace and the modelled time series by the middle trace.

ERG response to intermittent illumination with rectangular stimulus has very similar structure with the simulation in condition of the same type of forcing. The agreement between experimental signals and the computed time series is good for the whole range of flickering frequencies considered, demonstrating the validity of the proposed model for the photoreceptor-neuron interaction.



Fig. 3. ERG response for intermittent illumination with rectangular stimulus (lowest trace) at frequency of 30 Hz. The experimental recording is shown by the upper trace and the modelled time series by the middle trace.

The observed differences are given by the variation of the lamina-on-transient component from an ERG signal to another when the flickering light frequency is exceeding a certain threshold value.

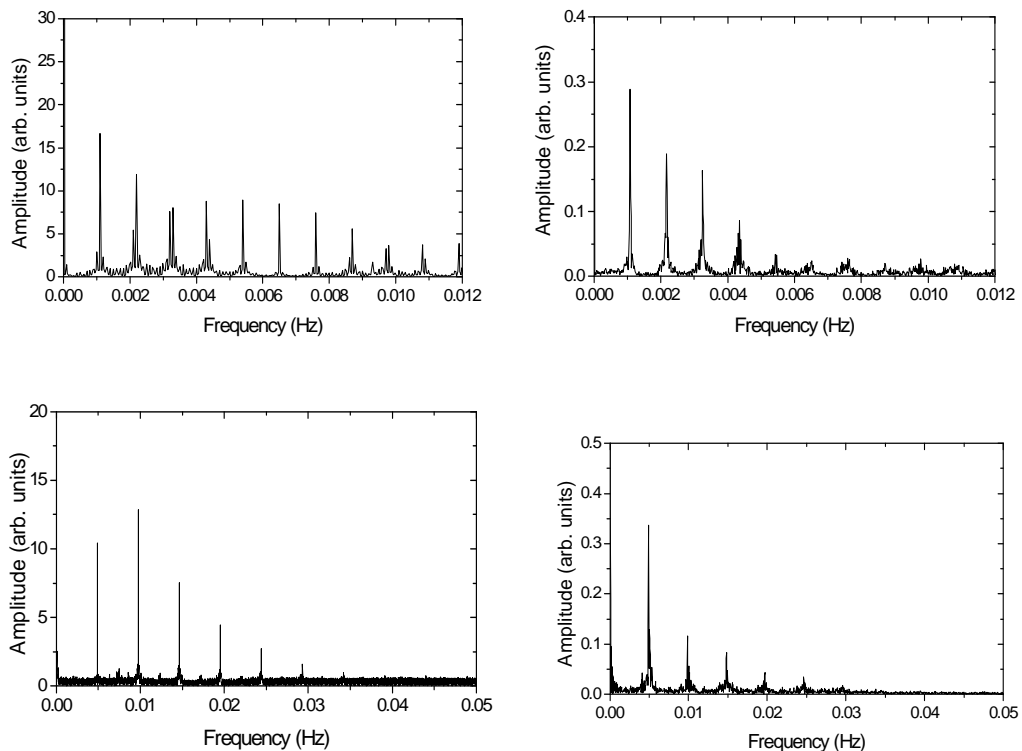


Fig. 4. FFT spectra: left - experimental; right - model for the data in Figs. 2 (top) and 3 (bottom).

This limitation can be observed also from the spectral analysis shown on Fig. 4. For the low frequency excitation (8 Hz), there is a detailed similarity between the experimental spectrum and the computed spectrum. For the higher frequency excitation, where the response of the eye is not totally the same from one pulse to the next, the agreement between the experimental and computed spectra is only approximate. It seems that the limitations of the proposed model are only related to this feature.

4. Conclusions

Electrophysiological investigations were carried out on the light signal transduction in the compound eye of the diurnal flying insect *Drosophila Melanogaster*. The recording of the corneal projection of the retinian and neural biopotentials was computationally simulated on the basis of a system of coupled nonlinear oscillators. The influence of the intermittent light frequency on the recorded signal amplitude was modeled in good agreement with the experimental data.

Acknowledgements

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