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OPTOELECTRONIC APPROACH OF DROSOPHILA VISION

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The biological information extracted from various excitable tissues can be obtained by intracellular as well as by extra-cellular recordings, the latest one being easier and non-invasive method with many applications in medicine testing. Electrophysiological recording of the eye excitability is analyzed in the following computational study dedicated to the diagnosis of the type of dynamics governing the compound eye of the superior invertebrates. The *Drosophila Melanogaster* representing a well consecrated biological model the optoelectronic transduction phenomena inside of its visual system have been investigated by means of the electroretinographic signal recording and analysis. The overlapping of linear and non-linear dynamical trend was evidenced following the application of several computational tests.

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1.Introduction

The optical signal absorbed in the rhodopsine molecules is internalized at the level of visual photoreceptors is further processed in the form of electric pulses along the optical pathway, the visual perception being the dominant modality of getting information from the surrounding medium for most animal species [1-3]. The result of the optoelectronic transduction not only by intracellular measurement but also by non-invasive investigations can be studied. So, the corneal projections of some retinian biopotentials can be recorded at the eye surface using adequate electronic device able to capture an electrical signal i.e. the electroretinograms – ERG. The study of the ERG in the biological model which is the fruitfly, *Drosophila Melanogaster* (having a very developed visual system and high genetic plasticity) is able to provide experimental data upon the visual system dynamics that could be then generalized (in some respects) for the human eye [4-6]. The utilization of the compound eye (characteristic to diurnal nonvertebrates such as the superior insects – best represented by the fruitfly *Drosophila melanogaster*) for the alternative study of the vertebrate and human eye is strongly sustained by several general considerations:

-characterized by an intermediate grade of complexity, the organization of the dipteran (flies) visual system is somewhat parallel to that of the vertebrate visual analyzer while its set of neurons is more limited and easier to identify;

- *D. melanogaster* has numerous mutants (many with *visual system peculiarities*);

- the photoreceptor cells are not tightly compacted as in the vertebrate retina allowing easier electrophysiological investigation at intracellular level;

- there are numerous types of K+ ion channels in the photoreceptors membranes that are important for the elucidation of transport phenomena through the membranes of many types of excitable cells. In the next the computational study on the dynamics of the optoelectronic transduction in intermittent light illumination by means of the ERG signal is carried out.

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2. Material and method

ERG recording. Experimental data have been recorded using specialized electronic installation. The ERG signals for intermittent illumination (white light, 10 Hz flickering frequency) were recorded. Two levels of the light intensity have been tested: relatively high intensity (10^{-5} $mWcm^{-1}$) and respectively small intensity light (10^{-7} $mWcm^{-1}$) – as measured with a Tektronix photometer.

Biological material. Drosophila Melanogaster individuals belonging to the white eyed mutant *white* have been grown in standard conditions and slightly anesthetized before the application of the eye electrodes.

The computational tests based on the Fourier and wavelet transformations as well as on Hurst exponent, portrait in the state space and correlation function have been applied using specialized software commercially av ailable. The strategy we followed in our analysis was mainly that proposed by Sprott and Rowlands [7]:

The graph of the studied data series $f(t)$ is first visualized and numerically smoothed if appropriate, though some loss of intrinsic information may be expected together with the noise reduction;

Further, the Fourier spectrum is to be studied in the linear-log representation (Log P versus frequency; Nyquist frequency may be considered, i.e. the inverse of the distance between two consecutive points). For different mathematical representations of studied signals, different definitions of the Fourier transformation should be used; considering the intrinsic periodicity of ERG signals when intermittent excitation is applied the next formula have been chosen as

$$f(t) = \sum_{-\infty}^{\infty} a_n \exp(i\omega_n t) \quad , \quad a_n = (\omega/2\pi)\int_0^{2\pi/\omega} f(t)\exp(-i\omega t)dt\,, \tag{1}$$

where *f* is the decomposed signal while a_n are the amplitudes of the Fourier transformation. Some standard cases are considered for the diagnosis of the system dynamics. A flat shape of the graph $\ln P(f(t))$, where $P(f)$ is spectral power (the square of the amplitude a_n of the harmonic component with frequency ω_n) indicates random fluctuations, several dominant peaks spectrum corresponds to quasi-periodic data, while coherent decrease of $\ln P(f)$ is the hallmark of hidden determinism (deterministic chaos), i.e. a more complex dynamics. Basically, the auto-correlation function, $\Psi(t) = \int_{-\infty}^{\infty} f(t+\tau)f(\tau)dt$, provides the same details about the system as the power spectrum but from a different point of view. While power spectrum is focused on the main frequencies, auto-correlation function informs about intrinsic connections between data. The value τ at which the auto-correlation function reaches $1/e, (e = 2{,}71...)$ of its initial value is the correlation time of the time series. The function $\Psi(t)$ decreases rapidly to zero for random data but also for some chaotic series formed by data that are not apparently correlated with each other. Nevertheless, there are chaotic data governed by strong connections and for them the auto-correlation function slowly decreases with time lag.

The Hurst exponent is proposed in the frame of the generalization of Einstein's finding that in the Brownian motion (random phenomena) the distance is proportional to the square root of the time duration; in this situation the Hurst exponent is up to 0.5 while for correlated time series it is considerable higher.

The wavelet transformation [9] offers the possibility to reconstruct the function of interest f(t) as a linear combination of soliton-like functions:

$$f(t) = \sum_{j,k} c_{jk} \Psi_{jk}(t) \tag{2}$$

The basical functions are obtained from a single soliton function (*mother wavelet* function) by translation and dilatation operations. Analogously to the Fourier transform coefficients, the wavelet transform coefficients are:

$$c_{jk} = [W_\Psi f]\left(1/2^j, k^{2/j}\right). \tag{3}$$

The projection of the wavelet transform in the (T, DT) plane (time and time scale or observation magnitude) is a two-dimensional picture with specific symmetry for chaotic, quasi-periodic, and random data. The stepwise Haar function was used as mother wavelet in this study:

$$\Psi(x) = \begin{cases} 1, \text{when} 0 \leq x < 1/2 \\ -1, \text{when} 1/2 < x \leq 1 \\ 0, \text{otherwise} \end{cases} \tag{4}$$

and: $\Psi_{jk}(x) \equiv \Psi(2^j x - k)$, where **j** is a non-negative integer and $0 \leq k \leq 2^j - 1$. So the analyzed function can be reconstructed as a superposition of rectangular signals, while the Fourier transformation is based on harmonic functions. The wavelet transformation represents a generalization in 3-D coordinates of the Fourier transformation: it maintains the time (rather than the frequency) as abscissa; the 2-D projection involves time as abscissa and the time scale as ordinate. The wavelet analysis was successfully utilized in investigations of other electrophysiological signals (heart rate fluctuations), for example by Bracic-Lotric et al. (2000) [10] and Kimura et al. (1998) [11], while the studies of Toledo et al. (1998, 2001)[12-13], Pichot et al. (2001)[14] can be mentioned as examples of applications to clinical problems.

The state-space portrait: In case of a dissipative system, the state space is an m-dimensional hyperspace formed by all system parameters, but the state-space portrait can be reconstructed using a single variable (measurable at equal time steps), x(t) [8] The first derivative versus the measured parameter is the most common representation (but the delay coordinates in the form $x(t)/x(t-1)$, are also convenient). The object shaped in the state space is able to provide information on the system *attractor* - the equilibrium states toward which the system may evolve starting from different initial conditions but following the same laws. The attractor appears as a complex object having the shape of a loop for a periodic system, a thorus for a quasi-periodic system, and a complicated object (yet with a discernible shape) for a more complex dynamics. The ERG dynamics investigation in the case of the human eye was carried out by Rilk (2003) [15].

3. Results and discussion

The structure of every type of ERG signal obtained for D. melanogaster eye using the optoelectronic device is in agreement with the literature data.

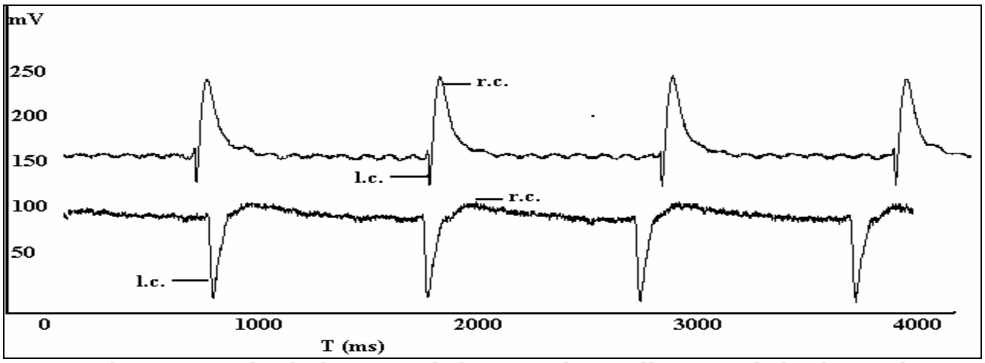

Fig. 1. The ERG signal in high intensity light (up) and in small intensity light (down).The notations are: r.c. for “receptor potential” and l.c. for ”lamina-on-transient”.

The main depolarization component, named the receptor potential, is generated mainly by the photoreceptor central cells while the hyperpolarization component, named lamina-on-transient is generated in the neural cells from the first optic ganglion (lamina) where only the peripheral photoreceptor cells make synapse (the central photoreceptors by pass the lamina optic ganglion making synapse in the second optic ganglion – medulla – but the electrical activity of this one is no longer projected toward the eye outside). In high intensity light the receptor potential is higher than the lamina-on-transient since the central photoreceptors are sensitive in high intensity light; in small intensity light the situation is reversed as the peripheral photoreceptors are specialized in high intensity light transduction. The periodic trend is obvious being tightly related to the intermittent illumination.

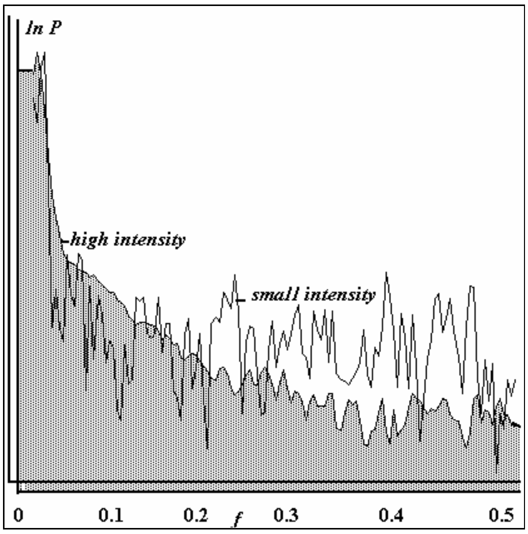

Fig. 2. Fourier spectra.

In fig. 2 the power spectra are presented. When passing from high to small intensity light the linear-logarithmic views of the power spectrum revealed larger areas with flat aspect instead of the decreasing tendency that suggest that for high intensity a chaotic component is visible but in small intensity the apparently randomic component is dominating the signal dynamics. The periodic dynamical trend is visible only for the smallest values of the abscissa variable (the frequency) where a distinct peak is present in both analyzed situations. The overlapping of periodic and randomic dynamical components in the case of the small intensity is suggested also by the comparison with the standard data series [7] provided for the qualitative interpretation by means of the wavelet transformation (fig. 3). Consequently the ERG signal corresponding to high intensity seems to be characterized by higher complexity (chaotic determinism dominating over the random fluctuations). However the Hurst exponent calculation, recommended when flat power spectrum appears, revealed high values (over 0.99) in both analyzed cases excluding the randomness hypothesis in the favor of relatively high correlated data.

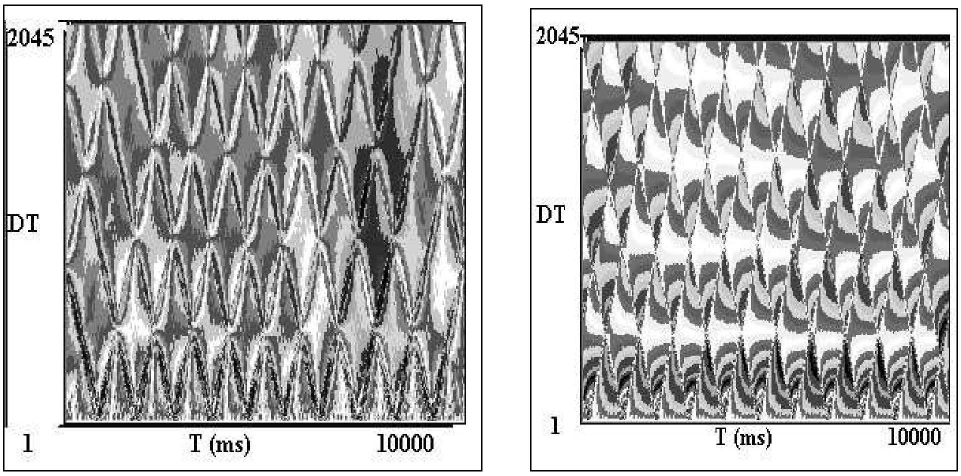

Fig. 3. The wavelet transformation of the ERG signal for small (left) and high (right) intensity light. The abscissa is the time (T) while the ordinate is the time-scale (DT).

The same indication upon the existence of considerable correlation in both ERG signals is provided by the correlation function which slowly decreases, in high intensity light the correlation time (41.33) being higher than in low intensity light (33.56) which corresponds to better correlation of the temporal data. As expected it is no possible to assess the dynamic behavior of the analyzed signal using only one or another of the computational tests mentioned above: it is necessary to corroborate the information provided by several such tests in order to conclude upon the dominating type of dynamics.

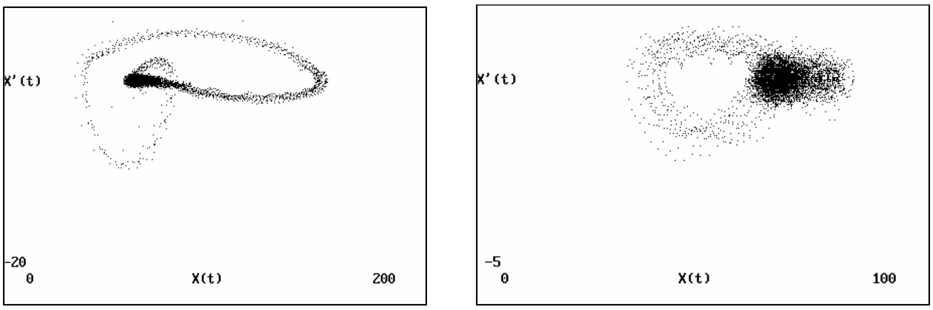

Fig. 4. The portrait in the state space for high (left) and respectively low intensity (right).

In the analysis of temporal data series the representation in the state space is almost ubiquitously used. So, in figure 4 the system attractor is presented for the ERG signal.

One can see that for high intensity light the attractor has a more distinguishable shape (a bi-lobed loop corresponding to the two-component structure of the ERG signal) slightly affected by certain fuzzyness (corresponding to the recording noise). This could be taken as a chaotic trend dominancy in high intensity light while for small light the fuzzy lobe of the attractor (intrinsic fluctuations overlapped upon the recording noise) is suggesting mostly randomic data. Considering all above results one might conclude that certain difference between the two signal dynamics can be revealed by the semi-quantitative tests proposed for the experimental data interpretation. We may assume that the compound eye of the *D. melanogaster* is able of normal electric transduction of the light stimuli within the intensity range utilized in the present experiment. The detected differences characterizing the type of dynamic behavior of the first segments of the visual system (photoreceptors and the first optic ganglion) are related to the different degrees of implication of different types of visual cells in the generation of ERG signal in the two studied situations. Taking into account that, when the hyperpolarization component, lamina-on-transient, is dominating the ERG structure, the involving of the neural cells is higher, then we could say that the predictability of the system behavior is affected by more randomness due to the neural cells. The recording noise contributes to this because the zero line fluctuations (fig. 1) are comparable with the depolarization component in the case of small intensity light. The high complexity of the ERG signal in intermittent light application reveals the non-linear response of the visual system – further computational investigation being intended in the next studies.

4. Conclusions

The computational investigation of eye electrical response to the periodic excitation evidenced distinct dynamical trends for high and small intensity light. The interpretation based on the power spectrum revealed dominant chaotic trend in the case of high intensity light. The wavelet transform revealed the periodic trend in both ERG signals as well as the randomic trend in the case of small intensity light. The same was suggested by the portrait in the state space. The Hurst exponent and the correlation time did not emphasize sufficiently the differences between the two signal types.

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