INTRODUCTION

We previously substantiated the notion of the discrete wave mechanism of the integration of the activity of heterogeneous nervous elements as a universal mechanism of the functioning of nested polar brain structures [1–3]. This notion is based on the following assumptions:

1. Nervous structures at any organization level are cyclically acting natural devices that convert the energy of external signals into the energy of structural forces, which ensure the functioning of the devices.

2. The information control devices are polarized to form, firstly, a more differentiated, control part, which consists of opponent populations of heterogeneous elements (dipoles, in the simplest and most typical case), and secondly, an autonomous controlled object—an effector part.

3. In these parts, two systems of connections act: strong, address connections and collective connections, which are weak separately but act efficiently after synchronization of the action of a certain, critical number of elements.

4. During such a synchronization in the network of structural elements connected by collective connections, a cooperative process takes place: an action wave emerges and propagates.

5. This wave is solitary and discrete, since the process automatically ceases because of the synchronization of the refractory periods of structural elements (these refractory periods take place during each action; during these refractory periods, the structural forces are restored).

6. A set of such aperiodically emerging waves encodes the results of decoding (processing) the input signal into a control message to effector structures.

7. The signal decoding involves the suspension of the competition (due to the synchronization owing to strong connections) between populations of heterogeneous structural elements, which determines the initial conditions of the synchronization.

The real existence of the discrete wave mechanism was confirmed by studies performed on molecular structures [4] and simple polar cortical modules and also by observations of millisecond synchronization in rather complex polar brain structures, such as ocular dominance columns, reciprocally connected cortical zones of the opposite hemispheres, etc. [5].

The integration of the activity in the neuron is still less known, which is in part because of
methodological difficulties. That was the reason why we tried to test the universality of the discrete wave mechanism of the integration by modeling. One can prove that the nerve cell is an information control device where

1. the somatodendritic membrane is the control part polarized to form heterogeneous competing populations of synapses, and the axon hillock with the trigger zone is the autonomous controlled object—the effector part;

2. elements of the device—heterogeneous sets of receptors in the postsynaptic zones of the membrane—are connected by strong connections with the presynaptic membrane and by collective connections with one another and with the trigger zone of the axon hillock;

3. the activity of heterogeneous elements is integrated by means of synchronization, which generates a control message to the trigger zone of the axon hillock.

Under the assumption that collective connections are mediated by waves of conformational changes [4], let us study the wave interactions in terms of a model constructed with regard for the fact that conformational changes in membrane protein molecules are closely related to conformational changes in lipids.

Let the sequence of conformational changes in the lipid chain in the direction from the postsynaptic membrane to the axon hillock be regarded as a nerve impulse.

Thorough determination of the form and velocity of conformons and also the rules of their integration in the trigger zone of the axon hillock requires one to use quantum mechanics and to know the chemical composition of a lipid. We restrict our consideration to the classical approach and ignore the effect of the chemical composition of the lipid.

**BASIC POSTULATES OF THE MODEL**

1. Let us regard the lipid as a physical object that has
   
   a. a backbone, which is motionless relative to other lipids, and a mobile hydrocarbon tail, which is capable of vibrating about a certain equilibrium position in the plane that is parallel to the membrane surface; and
   
   b. a dipole moment, whose magnitude is invariable (i.e., the hydrocarbon tail undergo no such mechanical deformations as compression or tension).

2. Let the angle of displacement of the lipid dipole moment direction from the equilibrium lipid dipole moment direction be regarded as a characteristic of the lipid conformation.

Vibrations of the hydrocarbon tail of the lipid are caused by a force created by the dipole moments of neighboring lipids.

From the fundamental law of rotational motion, leaving out the cumbersome mathematical manipulations, as a first approximation we derive the equation of the dynamics of the system:

$$\frac{\partial^2\varphi}{\partial t^2} + \alpha \frac{\partial \varphi}{\partial t} + \omega^2 \varphi = -\varphi \left( a \frac{\partial^2}{\partial xy} + b \left( \frac{\partial^2}{\partial y^2} - \frac{\partial^2}{\partial x^2} \right) \right) \varphi = f(x, y, t). \quad (1)$$

Here, $\varphi(x, y, t)$ is the angle of displacement of the lipid dipole moment direction from the equilibrium lipid dipole moment direction; $\alpha$ is the attenuation coefficient; $\omega$ is the natural frequency of dipole vibrations; $a(x, y) = \cos(2\varphi_0)$; $b(x, y) = \sin(2\varphi_0)$; $\varphi_0$ is the angle that characterizes the equilibrium lipid dipole moment direction; $f(x, y, t)$ is the external force acting on the system; $\theta$ is the conformation velocity:

$$\dot{\theta} = \frac{q}{R} \left( \frac{L}{8\pi \varepsilon \varepsilon_0 m} \right)^{1/2};$$

$m$ is the weight of the hydrocarbon tail of the lipid; $L$ is the dipole arm; $R$ is the distance between dipoles; and $q$ is the charge.

The conformation velocity is 10–100 m/s (depending on the type of a lipid); i.e., this velocity is on the same order as the nerve impulse velocity.

Let us perform a further analysis in a case where $a$ and $b$ are constant. Changing the variables

$$x = \frac{c \varphi + j \theta}{1 + c^2}, \quad y = \frac{\varphi - j \theta c}{1 + c^2},$$

where $c = (4b^2 + a^2)^{1/2} - 2b$, we obtain the telegraph equation of the form

$$\frac{\partial^2 h}{\partial t^2} + \omega^2 h - \theta^2 \left( \frac{\partial^2}{\partial \varphi^2} + \frac{\partial^2}{\partial \theta^2} \right) h = f(\varphi, \theta, t) \exp \left( \frac{\alpha t}{2} \right). \quad (2)$$
these initial conditions and for the given external force, equation (1) has the following solutions: at $L > 0$, the solution is

$$\varphi(x, y, t) = \frac{1 + c^2}{4\pi \theta^2 \gamma} \exp \left( -\frac{\alpha(t - t_0)}{2} \right) \exp(-\omega L^{1/2}).$$

Analysis of the solutions obtained demonstrated that the leading edge of the conformational wave has the shape of an ellipse expanding at the velocity determined above.

The figure shows the dipole displacement amplitude versus $x$ plots of the cross sections of the conformational wave at moments of time $t_1$, $t_2$, and $t_3$, such that $t_1 < t_2 < t_3$. One can see that the conformational changes that have the oscillating character are spatially confined; i.e., there is a pronounced wave train (this was the reason why the mechanism was called the discrete wave mechanism).

This fact suggests that the spatial integration of the postsynaptic potentials in the trigger zone of the neuron can be regarded both as interference of waves constituting the wave train and as the synchronization of the entire wave trains propagating from each of the synaptic contacts.

With regard for the latter, we assume that training of nervous elements can be caused by establishment of a nonuniform lipid distribution over the membrane surface, which facilitates or hinders the conformation wave propagation to the trigger zone of the neuron.

The results obtained are consistent with the notion of the discrete wave mechanism of the integration of the activity in the nerve cell.

REFERENCES


