International Journal of Advanced Biomedicine

http://dx.doi.org/10.18576/ab/090101

On Model of Processes in a System of Neurons

E. L. Pankratov[1,*]

[1] Nizhny Novgorod State Agrotechnical University, 97 Gagarin Avenue, Nizhny Novgorod, 603950, Russia.

Received: 25 Oct. 2024, Revised: 2 Nov. 2024, Accepted: 18 Dec. 2024.
Published online: 1 Jan 2025.

Abstract: In this paper we consider a model for description of processes in a system of neurons. The model gives a possibility to make an analysis of processes in the system of neurons in more common case in comparison with recently introduced models. We introduce an analytical approach to analyze the above process. Based on the model and approach we consider the possibility to control processes in the system of neurons.

Keywords: system of neurons; control on processes; analytical approach for analysis.

Introduction

One of the ways to study the patterns of information processing by the brain is to analyze the transmission of electrical impulses in it. The transmission of electrical impulses in the human brain is a complex oscillatory process that can be registered when electrodes are placed on the brain or on the surface of the scalp and is the result of combining and filtering elementary processes occurring in brain neurons [1-5]. The main aim of this work is to formulate a model for analyzing the transmission of electrical impulses in the brain. The model should be more common in comparison with the recently introduced model. The accompanying aim of this work is choosing an analytical approach for analyzing the formulated model, which gives a possibility to obtain solutions of the obtained in the above equations in so much common case as possible. Previous models for description of processes in neurons, which were considered in recently published works [4, 6-11], were considered stationary values of their parameters and usually (almost always) linear processes. The model, which was considered in the present paper, gives a possibility to take into account non-stationarity and non-linearity of the processes considered where it is necessary.

Method and results of solution

In the section we consider the following model for analyzing the transmission of electrical impulses in the brain

$$C_m \frac{\partial V_1(t)}{\partial t} = -g_{Na} m^3 h \left[V_1(t) - V_{Na}\right] - g_K n^4 \left[V_1(t) - V_{Na}\right] - g_l \left[V_1(t) - V_{Na}\right] + I_{1app}$$

$$C_m \frac{\partial V_2(t)}{\partial t} = -g_{Na} m^3 h \left[V_2(t) - V_{Na}\right] - g_K n^4 \left[V_2(t) - V_{Na}\right] - g_l \left[V_2(t) - V_{Na}\right] + I_{2app} + I_{syn}$$

$$\frac{\partial m(t)}{\partial t} = \frac{m_\infty - m(t)}{\tau_m},\ \frac{\partial h(t)}{\partial t} = \frac{h_\infty - h(t)}{\tau_h},\ \frac{\partial n(t)}{\partial t} = \frac{n_\infty - n(t)}{\tau_n}$$

(1)

where C_m are the specific membrane capacity; $I_{syn} = \frac{g_{syn}\left[V_2(t) - E_{syn}\right]}{1 + \exp\left\{-\left[V_1(t) - \Theta_{syn}\right]/k_{syn}\right\}}$ is the synaptic current; E_{syn} is the reversible synaptic potential; Θ_{syn} and k_{syn} are the shift and steepness of synaptic current; g_{syn} is the synaptic strength factor; $V_i(t)$ is the memprane potential (i =1 is for control neuron, i =2 for the control neuron); t is the current time; g_{Na}, g_K and g_L are the sodium, potassium and ohmic leakage currents; I_{app} is the current, which describes membrane depolarization; E_{Na}, E_K and E_L are the appropriate reversible potentials; e is the elementary charge. The instantaneous values of ion currents depend on the state of the gate variables: m (t) is an activation sodium variable with an equilibrium value m_∞ and a relaxation time τ_m, h (t) is the sodium inactivation variable with equilibrium value h_∞ and relaxation time τ_h, n (t) is the potassium activation variable with equilibrium value n_∞ and relaxation time τ_n. All variables, which were marked as functions of time, could be controlled by external influence on organism. It could be changing diet as a consequence of changing the type of food or by speed of obtaining of food. The above variables could be also changed by changing external parameters (air, physical activity, ...). The equilibrium values of the considerate variables and their relaxation times were determined by the following relations

$$m_\infty = \frac{\alpha_m}{\alpha_m + \beta_m},\ h_\infty = \frac{\alpha_h}{\alpha_h + \beta_h},\ n_\infty = \frac{\alpha_n}{\alpha_n + \beta_n}, \qquad (2)$$

$$\tau_m = \frac{1}{\alpha_m + \beta_m},\ \tau_h = \frac{1}{\alpha_h + \beta_h},\ \tau_n = \frac{1}{\alpha_n + \beta_n}, \qquad (3)$$

$$\alpha_{mi} = \frac{a_{mi}\left(b_{mi} - V_i\right)}{\exp\left[a_{mi}\left(b_{mi} - V_i\right)\right] - 1},\ \alpha_{hi} = -a_{hi} e V_i,$$

[*] Corresponding author E-mail: elp2004@mail.ru

$$\alpha_{ni}=\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}, \tag{4}$$

$$\beta_{mi}=-c_{mi}eV_i,\quad \beta_{hi}=\frac{1}{\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]-1},$$
$$\beta_{ni}=-c_{ni}eV_i. \tag{5}$$

Solutions of the third, fourth and fifth equations of the system (1) were determined in the framework of the appropriate standard procedure for the ordinary differential equations [6]. These solutions could be written in the following form

$$m_i(t)=\exp\left\{c_{mi}eV_i-\frac{a_{mi}\left(b_{mi}-V_i\right)}{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1}\right\}\Bigg(\int\limits_0^t\exp\left\{\frac{a_{mi}\left(b_{mi}-V_i\right)}{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1}-c_{mi}eV_i\right\}\times$$
$$\times\frac{a_{mi}\left(b_{mi}-V_i\right)}{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1}d\tau-\int\limits_0^\infty\frac{a_{mi}\left(b_{mi}-V_i\right)}{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1}\exp\left\{\frac{a_{mi}\left(b_{mi}-V_i\right)}{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1}-c_{mi}eV_i\right\}d\tau+$$
$$+\frac{a_{mi}\left(b_{mi}-V_i\right)}{a_{mi}\left(b_{mi}-V_i\right)-c_{mi}eV_i\left\{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1\right\}}\exp\left\{\frac{a_{mi}\left(b_{mi}-V_i\right)}{\exp\left[a_{mi}\left(b_{mi}-V_i\right)\right]-1}-c_{mi}eV_i\right\}\Bigg)$$

,

$$h_i(t)=\exp\left\{\frac{1-a_{hi}eV_i\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]+a_{hi}eV_i}{\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]-1}\right\}\Bigg(\int\limits_0^t\exp\left\{\frac{1-a_{hi}eV_i\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]+a_{hi}eV_i}{\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]-1}\right\}\times$$
$$\times a_{hi}eV_id\tau+\frac{1-a_{hi}eV_i\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]+a_{hi}eV_i}{\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]-1}\exp\left\{\frac{1-a_{hi}eV_i\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]+a_{hi}eV_i}{\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]-1}\right\}-$$
$$-\int\limits_0^\infty a_{hi}eV_i\exp\left\{\frac{1-a_{hi}eV_i\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]+a_{hi}eV_i}{\exp\left[c_{hi}\left(d_{hi}-V_i\right)\right]-1}\right\}d\tau\Bigg),$$

$$n_i(t)=\exp\left\{c_{ni}eV_i-\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}\right\}\Bigg(\int\limits_0^t\exp\left\{\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}-c_{ni}eV_i\right\}\times$$
$$\times\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}d\tau-\int\limits_0^\infty\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}\exp\left\{\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}-c_{ni}eV_i\right\}d\tau+$$
$$+\frac{a_{ni}\left(b_{ni}-V_i\right)}{a_{ni}\left(b_{ni}-V_i\right)-c_{ni}eV_i\left\{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1\right\}}\exp\left\{\frac{a_{ni}\left(b_{ni}-V_i\right)}{\exp\left[a_{ni}\left(b_{ni}-V_i\right)\right]-1}-c_{ni}eV_i\right\}\Bigg).$$

The first and the second equations of the system (1) with account solutions of the third, the fourth and the fifth equations have no analytically exact solution. In this situation the first and the second equations will be solved by method of averaging of function corrections [7-9]. In the framework of the approach to determine the first-order approximations of the required functions we replace them in the right sides of the considered equations on their not yet known average values $V_i(t)\to\alpha_{i1}$. At the same time due to cumbersomeness of the obtained relations we consider exponential functions in the considered equations in the linear approximation on their arguments. Integration of the obtained relations on time gives a possibility to obtain the required first-order approximations of the considered functions in the following form

$$V_{11}(t)=\int\limits_0^t\Big[I_{1app}-g_{Na}\left(c_{m1}e\alpha_{11}-1\right)^3\left(c_{h1}e\alpha_{11}-1\right)\left(\alpha_{11}-V_{Na}\right)-g_K\left(c_{n1}e\alpha_{11}-1\right)^4\left(\alpha_{11}-V_{Na}\right)-$$
$$-g_l\left(\alpha_{11}-V_{Na}\right)\Big]d\tau-\int\limits_0^\infty\frac{1}{C_m}\Big[I_{1app}-g_{Na}\left(c_{m1}e\alpha_{11}-1\right)^3a_{m1}\left(b_{m1}-\alpha_{11}\right)\left(\alpha_{11}-V_{Na}\right)-g_Ka_{n1}\times$$
$$\times\left(b_{n1}-\alpha_{11}\right)^4\left(\alpha_{11}-V_{Na}\right)-g_l\left(\alpha_{11}-V_{Na}\right)\Big]\frac{1}{C_m}d\tau \tag{2}$$

$$V_{21}(t)=\int\limits_0^t\frac{1}{C_m}\Big[I_{2app}+I_{syn}-g_{Na}\left(c_{m2}e\alpha_{21}-1\right)^3\left(c_{h2}e\alpha_{21}-1\right)\left(\alpha_{21}-V_{Na}\right)-g_K\left(c_{n2}e\alpha_{21}-1\right)^4\times$$
$$\times\left(\alpha_{21}-V_{Na}\right)-g_l\left(\alpha_{21}-V_{Na}\right)\Big]d\tau-\int\limits_0^\infty\frac{1}{C_m}\Big[I_{1app}-g_{Na}\left(c_{m2}e\alpha_{21}-1\right)^3a_{m2}\left(b_{m2}-\alpha_{21}\right)\left(\alpha_{21}-V_{Na}\right)-$$
$$-g_Ka_{n2}\left(b_{n2}-\alpha_{21}\right)^4\left(\alpha_{21}-V_{Na}\right)-g_l\left(\alpha_{21}-V_{Na}\right)\Big]d\tau$$

Average values α_{i1} were determined by using the standard relation [7-9]. The relation to our case could be written in the following form

$$\alpha_{i1}=\lim_{\Theta\to\infty}\frac{1}{\Theta}\int\limits_0^\Theta V_{i1}(t)\,dt. \tag{3}$$

Substitution of relations (2) into relations (3) and future transformations give a possibility to obtain the following relations to determine the required average values α_{i1}

$$\alpha_{11}=-e\int\limits_0^\infty\frac{g_{Na}c_{m1}}{C_m}d\tau-e\int\limits_0^\infty\frac{g_{Na}c_{h1}}{C_m}d\tau+\Bigg[e^2\int\limits_0^\infty\frac{g_{Na}^2c_{m1}c_{h1}}{C_m^2}d\tau+e^2\int\limits_0^\infty\frac{g_{Na}g_Kc_{m1}c_{h1}}{C_m^2}d\tau+$$
$$+e^2\int\limits_0^\infty\frac{g_{Na}g_lc_{h1}}{C_m^2}d\tau-\int\limits_0^\infty\frac{I_{1app}V_{Na}}{C_m^2}d\tau-\int\limits_0^\infty g_{Na}I_{1app}\frac{a_{m1}b_{m1}}{C_m^2}d\tau-\int\limits_0^\infty g_{Na}I_{1app}\frac{a_{h1}b_{h1}}{C_m^2}d\tau-$$
$$-\int\limits_0^\infty g_KI_{1app}\frac{a_{n1}b_{n1}}{C_m^2}d\tau-\int\limits_0^\infty\frac{g_lI_{1app}}{C_m^2}d\tau\Bigg]^{1/2} \tag{4}$$

$$\alpha_{21}=-e\int\limits_0^\infty\frac{g_{Na}c_{m2}}{C_m}d\tau-e\int\limits_0^\infty\frac{g_{Na}c_{h2}}{C_m}d\tau+\Bigg[e^2\int\limits_0^\infty\frac{g_{Na}^2c_{m2}c_{h2}}{C_m^2}d\tau+e^2\int\limits_0^\infty\frac{g_{Na}g_Kc_{m2}c_{h2}}{C_m^2}d\tau+$$
$$+e^2\int\limits_0^\infty\frac{g_{Na}g_lc_{h2}}{C_m^2}d\tau-\int\limits_0^\infty\frac{I_{2app}V_{Na}}{C_m^2}d\tau-\int\limits_0^\infty g_{Na}I_{2app}\frac{a_{m2}b_{m2}}{C_m^2}d\tau-\int\limits_0^\infty g_{Na}I_{2app}\frac{a_{h2}b_{h2}}{C_m^2}d\tau-$$
$$-\int\limits_0^\infty g_KI_{2app}\frac{a_{n2}b_{n2}}{C_m^2}d\tau-\int\limits_0^\infty\frac{g_lI_{2app}}{C_m^2}d\tau-\int\limits_0^\infty\frac{I_{syn}V_{Na}}{C_m^2}d\tau-\int\limits_0^\infty g_{Na}I_{syn}\frac{a_{m2}b_{m2}}{C_m^2}d\tau-$$
$$-\int\limits_0^\infty g_{Na}I_{syn}\frac{a_{h2}b_{h2}}{C_m^2}d\tau-\int\limits_0^\infty g_KI_{syn}\frac{a_{n2}b_{n2}}{C_m^2}d\tau-\int\limits_0^\infty\frac{g_lI_{syn}}{C_m^2}d\tau\Bigg]^{1/2}$$

The second-order approximations of membrane potentials. We determine the considered potentials by using the following standard replacements $V_i(t)\to\alpha_{i2}+V_{i1}(t)$ [7-9] in the right sides of the first and the second equations of system (1). The replacement and integration on time of the obtained result gives a possibility to obtain the second-order approximations of the required potential in the final form

$$V_{12}(t)=\int\limits_0^t\frac{1}{C_m}\Big(I_{1app}-g_{Na}\left\{c_{m1}e\left[\alpha_{12}+V_{11}(t)\right]-1\right\}^3\left\{c_{h1}e\left[\alpha_{12}+V_{11}(t)\right]-1\right\}\left\{\left[\alpha_{12}+V_{11}(t)\right]-V_{Na}\right\}-$$

$$-\{g_K[\alpha_{12}+V_{11}(t)]\{c_{n1}e[\alpha_{12}+V_{11}(t)]-1\}-g_l\{[\alpha_{12}+V_{11}(t)]-V_{Na}\}\}\,d\tau-\int_0^{\infty}(-g_{Na}a_{m1}\times$$

$$\times\{c_{m1}e[\alpha_{12}+V_{11}(t)]-1\}^3\{b_{m1}-[\alpha_{12}+V_{11}(t)]\}\{[\alpha_{12}+V_{11}(t)]-V_{Na}\}-\{b_{n1}-[\alpha_{12}+V_{11}(t)]\}^4\times$$

$$\times g_K a_{n1}\{[\alpha_{12}+V_{11}(t)]-V_{Na}\}-g_l\{[\alpha_{12}+V_{11}(t)]-V_{Na}\}+I_{1app})\frac{d\tau}{C_m} \qquad (5)$$

$$V_{22}(t)=\int_0^t\Big(I_{2app}+I_{syn}-g_{Na}\{c_{m2}e[\alpha_{22}+V_{21}(t)]-1\}^3\{c_{h2}e[\alpha_{22}+V_{21}(t)]-1\}\{[\alpha_{22}+V_{21}(t)]-V_{Na}\}-$$

$$\times g_K[\alpha_{22}+V_{21}(t)]\{c_{n2}e[\alpha_{22}+V_{21}(t)]-1\}-g_l\{[\alpha_{22}+V_{21}(t)]-V_{Na}\}\Big)\frac{d\tau}{C_m}-\int_0^{\infty}(-g_{Na}a_{m2}\{b_{m2}-$$

$$-[\alpha_{22}+V_{21}(t)]\}\{c_{m2}e[\alpha_{22}+V_{21}(t)]-1\}^3 g_{Na}a_{m2}\{[\alpha_{22}+V_{21}(t)]-V_{Na}\}-\{b_{n2}-[\alpha_{12}+V_{21}(t)]\}^4\times$$

$$\times g_K a_{n2}\{[\alpha_{22}+V_{21}(t)]-V_{Na}\}-g_l\{[\alpha_{22}+V_{21}(t)]-V_{Na}\}+I_{2app}+I_{syn})\frac{1}{C_m}d\tau$$

Average values α_{i2} were calculated by using the following standard relation [7-9]

$$\alpha_{i2}=\lim_{\Theta\to\infty}\frac{1}{\Theta}\int_0^{\Theta}[V_{i2}(t)-V_{i1}(t)]\,dt\,. \qquad (6)$$

Substitution of relations (2) and (5) into relation (6) gives a possibility to obtain the following result

$$\alpha_{12}=-e\int_0^{\infty}\frac{g_{Na}c_{m1}}{C_m}d\tau-e\int_0^{\infty}\frac{g_{Na}c_{h1}}{C_m}d\tau+\Bigg[e^2\int_0^{\infty}\frac{g_{Na}^2c_{m1}c_{h1}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}g_Kc_{m1}c_{h1}}{C_m^2}d\tau+$$

$$+e^2\int_0^{\infty}\frac{g_{Na}g_lc_{h1}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}c_{m1}\alpha_{11}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}c_{h1}\alpha_{11}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}\alpha_{11}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}c_{m1}V_{11}(t)}{C_m^2}d\tau+$$

$$+e^2\int_0^{\infty}\frac{g_{Na}c_{h1}V_{11}(t)}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}V_{11}(t)}{C_m^2}d\tau-\int_0^{\infty}g_{Na}I_{1app}\frac{a_{m1}b_{m1}}{C_m^2}d\tau-\int_0^{\infty}g_{Na}I_{1app}\frac{a_{h1}b_{h1}}{C_m^2}d\tau-$$

$$-\int_0^{\infty}\frac{I_{1app}V_{Na}}{C_m^2}d\tau-\int_0^{\infty}g_KI_{1app}\frac{a_{n1}b_{n1}}{C_m^2}d\tau-\int_0^{\infty}\frac{g_lI_{1app}}{C_m^2}d\tau\Bigg]^{1/2} \qquad (7)$$

$$\alpha_{21}=-e\int_0^{\infty}\frac{g_{Na}c_{m2}}{C_m}d\tau-e\int_0^{\infty}\frac{g_{Na}c_{h2}}{C_m}d\tau+\Bigg[e^2\int_0^{\infty}\frac{g_{Na}^2c_{m2}c_{h2}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}g_Kc_{m2}c_{h2}}{C_m^2}d\tau+$$

$$+e^2\int_0^{\infty}\frac{g_{Na}g_lc_{h2}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}c_{m2}\alpha_{21}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}c_{h2}\alpha_{21}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}\alpha_{21}}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}c_{m2}V_{21}(t)}{C_m^2}d\tau+$$

$$+e^2\int_0^{\infty}\frac{g_{Na}c_{h2}V_{21}(t)}{C_m^2}d\tau+e^2\int_0^{\infty}\frac{g_{Na}V_{11}(t)}{C_m^2}d\tau-\int_0^{\infty}\frac{I_{2app}V_{Na}}{C_m^2}d\tau-\int_0^{\infty}g_{Na}I_{2app}\frac{a_{m2}b_{m2}}{C_m^2}d\tau-$$

$$-\int_0^{\infty}g_{Na}I_{2app}\frac{a_{h2}b_{h2}}{C_m^2}d\tau-\int_0^{\infty}g_KI_{2app}\frac{a_{n2}b_{n2}}{C_m^2}d\tau-\int_0^{\infty}\frac{g_lI_{2app}}{C_m^2}d\tau-\int_0^{\infty}\frac{I_{syn}V_{Na}}{C_m^2}d\tau-\int_0^{\infty}g_{Na}I_{syn}\frac{a_{m2}b_{m2}}{C_m^2}d\tau-$$

$$-\int_0^{\infty}g_{Na}I_{syn}\frac{a_{h2}b_{h2}}{C_m^2}d\tau-\int_0^{\infty}g_KI_{syn}\frac{a_{n2}b_{n2}}{C_m^2}d\tau-\int_0^{\infty}\frac{g_lI_{syn}}{C_m^2}d\tau\Bigg]^{1/2}.$$

We analyzed changing in time the membrane potentials analytically as the second-order approximation in the framework of the method of averaging functional corrections. This approximation is usually sufficient to make a qualitative analysis and obtain some quantitative results. The results of analytical calculations were verified by comparing them with the results of numerical simulation. Using the obtained relationships, it was revealed that by changing the reversal synaptic potential, the shift and steepness of the synaptic current, as well as the current describing membrane depolarization, it is possible to both increase and decrease membrane potentials. Figure 1 shows typical dependences of the neural potential on leakage currents. Figure 2 shows typical dependences of the neural potential on time. The figure shows two pairs of curves: analytical results with numerical one. The results of analytical calculations turned out to be larger than the results of numerical calculations. Figure 3 shows typical dependences of the neural potential on activation variables.

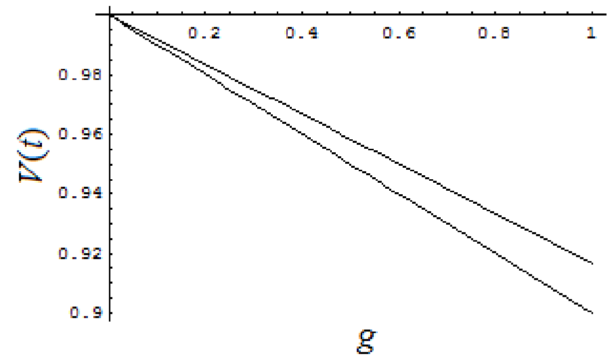

Fig. 1: Typical dependences of the neural potential on leakage currents

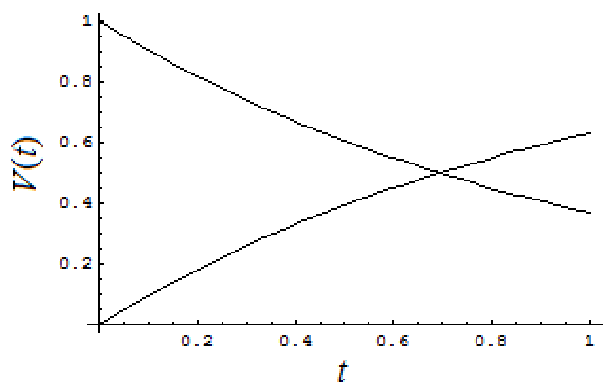

Fig. 2: Typical dependences of the neural potential on time

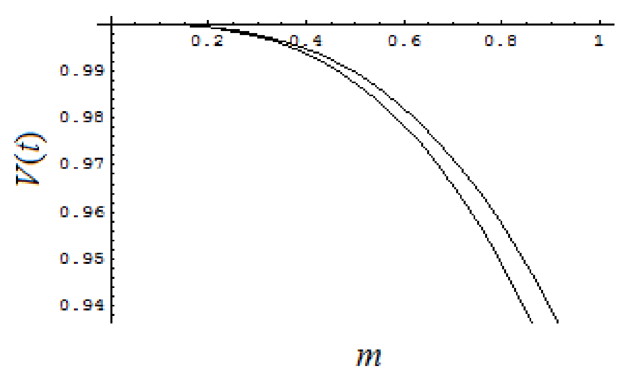

Fig. 3: shows typical dependences of the neural potential on activation variables

Conclusion

In this paper we present a model for the description of processes in a system of neurons. The model gives a possibility to make analysis processes in the system of neurons in more common cases in comparison with recently introduced models: the model gives a possibility to take into account variation of several parameters in time. We introduce an analytical approach to analyze the above process. Based on the model and approach we consider the possibility to control processes in the system of neurons.

References

[1] I. B. Starchenko, O.S. Borisova. Proceedings of the Southern Federal University. Technical science (Taganrog: Publishing House of the Taganrog Technical Institute of the Southern Federal University). Issue 5. P. 130-133 (2008).

[2] N. V. Zvezdochkina. Study of the electrical activity of the brain (Kazan: Kazan Federal University, 2014).

[3] L. M. Ortabaeva, N.M. Abdulaeva, M.M. Gabibov. Anatomy of the central nervous system (Makhachkala: Dagestan State University, 2017).

[4] A. E. Khomutov. Physiology of the central nervous system (Rostov-on-Don: Phenix, 2006).

[5] L. B. Dykhan. Introduction to the anatomy of the central nervous system (Taganrog: Southern Federal University, 2016).

[6] V. P. Volkov. Mathematical approach to differential diagnostics of malignant neuroleptic syndrome and febrile schizophrenia. Journal of neurology and psychiatry. Issue 4. P. 51-55 (2011).

[7] A. A. Kirpichenko, V.G. Obyedkov, A.N. Nesterovich. Dimensional model of schizophrenia: confirmatory factor analysis of symptoms. Bulletin of Voronezh state medical university. **Vol. 11** (2). P. 143-150 (2012).

[8] N. Rosjat, S. Popovych, S. Daun-Gruhn. A mathematical model of dysfunction of the thalamo-cortical loop in schizophrenia. Theoretical biology and medical modeling. **Vol. 11**. P. 45-66 (2014).

[9] T. V. Zhilyaeva, A.P. Bavrina, E.D. Kasyanov, A.S. Blagonravova, G.E. Mazo. Development of a mathematical model for predicting the risk of schizophrenia based on the assessment of the carriage of polymorphic alleles in 13 genetic loci affecting pterin metabolism. Genetics. **Vol. 59** (5). P. 573-583 (2023).

[10] A. V. Sergeeva, A.S. Blagonravova, G.E. Mazo, A.O. Kibitov. One-carbon metabolism disorders in schizophrenia: genetic and therapeutic aspects. Neurochemistry. **Vol. 36** (2). P. 91-100 (2019).

[11] T. V. Zhilyaeva, A.S. Blagonravova, G.E. Mazo. The effect of different forms of folates on cognitive functions in patients with chronic schizophrenia. Korsakov journal of neurology and psychiatry. **Vol. 120** (9). P. 87-92 (2020).

[12] G. Korn, T. Korn. *Mathematical Handbook for scientists and engineers*. *Definitions, theorems and formulas for reference and review*. Second edition (McGraw-Hill Book Company. New York, 1968).

[13] Yu. D. Sokolov. Applied mechanics. **Vol. 1** (1). P. 23-35 (1955).

[14] E. L. Pankratov, E.A. Bulaeva. International Journal of Modern Physics B. **Vol. 28** (27). P. 1450190-1--1450190-17 (2014).

[15] E. L. Pankratov, E.A. Bulaeva. Reviews in Theoretical Science. **Vol. 3** (4). P. 365-398 (2015).