The Base Neuronal Model of the Critical Physiological Mechanisms that Underlie the Electrical Signals Measured on the Scalp

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Abstract. *The article presents the basic neuronal model of the cortex, that in a great deal takes part in the creation of the EEG activity of the brain scanned from the surface of the scalp. The proposed submodel comes out from the real physiology and anatomy of the human brain and is the basic building stone of the complex thalamocortical model producing the resulting EEG activity of the brain. Another part of the article points to the deeper physiological - anatomical mechanisms, that are related to the creation of EEG activity of the brain.*

Keywords: EEG, cortex, basic neuronal model, brain

1. Introduction

Human brain is with no doubt one of the most complicated systems that mankind ever encountered. It integrates all somatic functions (metabolism, endocrinic regulations, immunity, cardiovascular and gastrointestinal systems, etc.), psychic functions (vigility, reactivness, sleep, memory, etc.) and its own systems. Electrical activity is probably generated by synchronous and synphasic activity of electrical impulses of many neurons in cortex and deep brain centres. This synchronicity is ensured partially by the cortex itself but mainly thalamus and to certain extent even septal nuclei and hippocampus. The rhythm generated by cortex is irregular and is expressed basicly in slow waves area whereas more regular thalamic rhythm is prominent in faster wave areas. Electrical activity is measurable by scanning the electroencephalogram (EEG) from the head surface, see Fig. 1.

2. Physiology

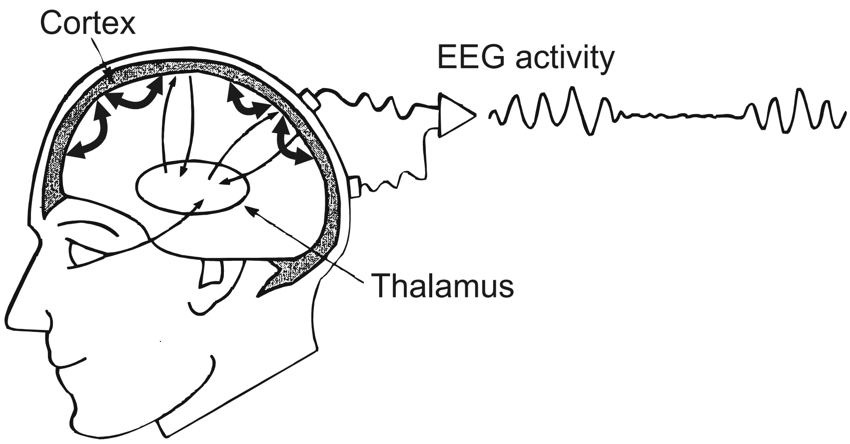

Fig. 1. Figure showing overall brain organization and the EEG activity. Cortical neurons cells interact locally with each other, and with many subcortical systems, each with complex delays and spatial dispersions.

Thalamocortical system with its cyclic activity produces alfa and beta activity. It seems that the basis to this activity is the circulating of excitements among the neurons of thalamic rythmic generators and neurons in the cortical columns (points in the crust) on the thalamocortical paths (thin arrows), see Fig. 1. The second system that connects the individual cortical areas is the subcortical associative and the commisure path (thick arrows). This system may be producing theta and delta activity. The basic cortex model of the neuron activity in the cortex will be discussed in another part of this article.

3. Basic Model

Action potentials from various neurons represented as neural fields Φ_e (excitatory activity), Φ_i (inhibitory activity) a Φ_s (subcortical activity), which incoming at the dendritic tree shown in Fig. 2 (a). The net effects $P_{e,i}$ on excitatory and inhibitory neurons are sums as

$$P_{(e,i)}(\vec{r},t) = N_{(e,i)e} s_e \phi_e(\vec{r},t) + N_{(e,i)i} s_i \phi_i(\vec{r},t) + N_{(e,i)s} s_s \phi_s(\vec{r},t), \tag{1}$$

where $N_{(x)y}$ is anatomical or structural in character and s_x is physiological or functional in nature. $N_{(x)y}$ is the mean number of connections from neurons of type $y = e, i, s$ on a neuron of type $x = e, i$ and s_x is the size of the impulse response associated with synapses of type $y = e, i, s$. The latter is the time integral of the perturbation on the transmembrane potential, as measured at the synapse.

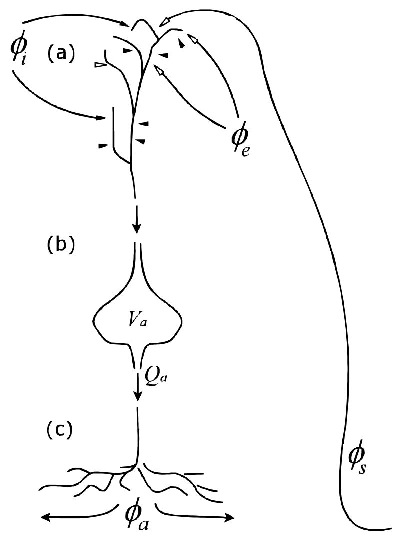

Fig. 2. Schematic showing the basic neuronal model , (a) synaptic connections at dendritic tree, where $\Phi_{e,i}$ represented neural field, (b) the somatic membrane potential $V_{a=e,i}$ at the cell body and neural impulse firing $Q_{a=e,i}$, (c) spread of action potentials as the field $\Phi_{a=e,i}$

The temporal spread and conduction delay within the dendritic tree of an individual neuron Fig. 2 (a), leading to the membrane potential $V_{e,i}$ at the cell body approximately obeys a convolution [2]

$$V_{e,i}(\vec{r},t) = \int_{-\infty}^{\infty} L(t-t')P_{e,i}(\vec{r},t')dt' = L(t) \otimes P_{e,i}(\vec{r},t'), \tag{2}$$

where $L(\tau)$ is the normalized dendritic impulse response function [3]. A suitable choice for $L(\tau)$ is

$$L(\tau) = \frac{\alpha\beta}{\beta-\alpha}(e^{-\alpha\tau} - e^{-\beta\tau}), \tag{3}$$

for u > 0, where α and β are positive constants. The Fourier transform of $L(\tau)$ used in the final transfer function is

$$L(\omega) = \frac{1}{\left(1 - \frac{i\omega}{\alpha}\right)\left(1 - \frac{i\omega}{\beta}\right)}, \tag{4}$$

where $\omega = 2\pi f$ is angular frequency. The mean firing rate $Q_{e,i}$ of neurons occurring at the cell body, see Fig. 2 (b) is assumed to vary according to a sigmoid function that relates firing rate to the average membrane potential $V_{e,i}$

$$Q_{e,i}(\vec{r},t) = \frac{Q_{e,i}^{\max}}{1 + \exp\left(-\frac{\pi}{\sqrt{3}}\left(\frac{V_{e,i}(\vec{r},t) - \theta_{e,i}}{\sigma_{e,i}}\right)\right)}, \tag{5}$$

where $\theta_{e,i}$ is the mean threshold activation for neurons of type *e, i* and $\sigma_{e,i}$ is standart deviation of this threshold for the neural population, and $Q_{e,i}^{\max}$ is the maximum attainable firing rate.

Action potentials propagate away from cell body along a branching the neural fields or pulse densities $\Phi_{e,i}$, see Fig. 2 (c). On average the potentials propagate at velocity v [5] with decreasing effect at greater distances due to decreasing terminal density. Propagation can be approximated by a damped wave equation representing average spread of the electrical wave generated from a population of neurons as

$$D_{e,i}\phi_{e,i}(\vec{r},t) = Q_{e,i}(\vec{r},t), \tag{6}$$

where $D_{e,i}$ is

$$D_{e,i} = \left[\frac{1}{\gamma_{e,i}^2}\frac{\partial^2}{\partial t^2} + \frac{2}{\gamma_{e,i}}\frac{\partial}{\partial t} + 1 - r_e^2\nabla^2\right], \tag{7}$$

where v is the axonal conduction velocity, $r_{e,i}$ are characteristics ranges of axons [4], and $\gamma_{e,i} = v/r_{e,i}$ is the damping rate.

4. Conclusions

The basic neronal model of the cortex that truly copies the true physiology and anatomy of the human brain was presented in the article. This submodel is the basic building stone of the whole thalamocortical model, which is being constructed at the moment at the Institute of Biomedical Engineering of the CTU in Prague.

The necessity of creating a complex analytical model can be various. Further EEG study from a different point of view - using the model to foretell the measured shape of EEG spectrum and the following utilization in the desing of data EEG compression, identifying neurophysiological abnormalities including attention deficit hyperactivity disorder (ADHD) etc.

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