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Transmission of blocked electric pulses in a cable neuron model by using an electric field

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ABSTRACT

Signal propagation can be blocked when the axon is injured or ion channels are blocked by certain drug, and thus signal communication between neurons can be interrupted. It is found that defects could be induced in the injured area of the axon, and the local heterogeneity can emit continuous pulses or wave fronts. In this paper, a weak electric field is imposed on the neuron to suppress the blocking of the defects on signal propagation. It is found that appropriate electric field can help signal propagate along the axon even the electric field is imposed on a local area. Its potential mechanism could be that the local electric field can suppress the wave emitting from the defects and thus the injured area can be bridged to transmit the blocked signals by adding gradient forcing along the axon.

1. Introduction

Neuronal system is made of a large number of neurons and astrocytes [1,2], and the electrical activities of neurons show complex dynamical behaviors. Based on the original Hodgkin-Huxley neuron model [3], and some simplified versions [4–7] have been proposed to describe the main dynamical properties of neuronal activities via bifurcation analysis [8–13] from the sampled series for membrane potentials. For example, Gu et al. [6,7] presented some discussion about multiple bifurcation of neuron model and experimental results were proposed for verification. Qin et al. [9] investigated the potential function of autapse on neuron and confirmed that autapse driving can excite the neuron and neuronal network. Karaoğlu et al. [10] gave a detailed Hopf bifurcation analysis of a recurrent neural network system with both discrete and distributed delays being considered. Yang and Duan et al. [12,13] studied the bifurcation-induced bursting state by adjusting the bifurcation parameters carefully. Indeed, oscillator-like models can give a feasible way to discern the phase transition in electrical activities of neurons. In fact, the mathematical Hindmarsh-Rose (HR) neuron model can be available for bifurcation analysis and energy consumption [14] during the mode transition induced by bifurcation parameters. For an isolate neuronal model, noise, external forcing current and time delay are often used to change the discharge mode, and dynamical properties in sampled membrane potentials can be discussed via bifurcation analysis [15]. On the other hand, the dynamical properties of neurons have also been investigated on some neuronal circuits [16–18]. Particularly, Babacan et al. [16] proposed a neuronal circuit composed of memristor, and the memory effect was described by generating spiking and bursting series. In fact, it is more important to study the signal transmission in neuron and between neurons. The biological neuronal system is made up of a large number of neurons; as a result, different types of functional and complex networks have been designed to study the signal transmission between neurons [19–21] and dynamical response in the collective behaviors [22–24]. For information encoding and signal transmission in an isolate neuron, the anatomical structure and its biological effect should be considered. For example, the effect of ion channels noise due to stochastic open and close in ion channels [25] is often discussed, furthermore, channel blocking is used to regulate the firing properties of neurons [26,27] and even the collective spiking activity of coupled neurons [28].

Appropriate noise and time delay can enhance the spatiotemporal regularity of neuronal activities in network. Propagation time delay is often considered due to finite propagation velocity of signals between coupled nodes. The intrinsic time delay, called as response delay, could be dependent on the geometry of neuron

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such as autapse connection. The autapse [29,30], a special synapse connected to the body of the cell, is described by applying time-delayed feedback current along a close loop on the membrane, and its biological function could be associated with self-adaption to external forcing. For example, autapse connection to neuron can benefit the neuron so that appropriate response could be triggered to external forcing signals [31]. Furthermore, appropriate distribution of autapse in network can generate "defects" [32] under negative feedback type, while positive feedback can generate a pacemaker with continuous pulse [33] or target wave, and the collective behavior, formation of spatial pattern in network of neurons can be regulated completely. Normal activities in neuronal system need cooperation between a set of neurons under appropriate coupling, and the collective behaviors of coupled neurons or network can be discussed on synchronization problems and pattern selection [34–42]. Signal or information flux is exchanged in the network during the course of patter formation, and self-sustained flow and scale-freeness could be helpful to regulate the collective behavior of the network [43–45]. For further review about the collective behaviors in neuronal network, readers can explore the survey [46–48] and reference therein.

Surely, most of the proposed neuronal models can discern the main dynamical properties of neuronal activities. Particularly, the energy model proposed by Wang et al. [49,50] could be important to discern the dependence of action potential, information encoding and signal propagation on energy metabolism and blood flow, for brief review can read Ref.[51]. However, these neuron models should be associated with realistic problems such as Parkinson's disease [52], slow-wave sleep [53], electrochemical effects of electric field on biological cells [54], drug on Ca^{2+} oscillations [55], effect of channel blocking and noise on signal processing [56,57]. External additive equivalent forcing current on the membrane potentials was used to model the effect of external electromagnetic field on neurons [58–60]. Rehan et al. [61] investigated the synchronization realization between multiple chaotic FitzHugh–Nagumo neurons with gap junctions under external electrical stimulation. Chizhov et al. [62] proposed a macroscopic approach towards realistic simulations of population activity of cortical neurons, based on the known refractory density equation and a new threshold model of neuronal firing. Gibson et al. [63] constructed a model of the steps leading from neural activity to increased blood flow in arterioles, in which astrocytes play a crucial role. Simões-de-Souza et al. [64] proposed a computer model of the olfactory epithelium was constructed consisting of a grid of olfactory receptor neurons (ORNs) connected by electrical synapses receiving simulated odor input, it is confirmed that propagating self-sustained activity waves might exist in the olfactory epithelium (OE). In the review [46], the author of this paper suggested that magnetic flux can be used to describe the electromagnetic induction [65,66] on the neuron even external electromagnetic field is applied, and the improved neuronal model can produce multiple electrical modes by changing single bifurcation parameter (the intensity of external field) [66].

Based on the oscillator-like neuronal model and even the autapse-driven Hodgkin–Huxley neuron model within channels being considered, more biological structure should be considered so that detailed description for signal transmission in isolate neuron can be discerned. For example, the signal propagation could be terminated when the axon was under badly injury. In this paper, based on a cable neuronal model, the blocking of signal propagation along axon will be investigated, and appropriate external electric field is imposed on the cell so that signals can be passed through the defects or injured area. The biological heterogeneity could be much complex, for simplicity, physical conductance diversity is generated to produce heterogeneity along the axon. It is found that local electric field can bridge the defects and normal signal propagation could be transmitted along the axon.

2. Model description and scheme

Positive potential is detected out of cell membrane of neuron while the inner of cell membrane could show negative potential. The channels embedded into the membrane can be switched to open state when appropriate external forcing current is imposed on the cell, thus an action potential is trigged to propagate signal along the axon. As a result, the discharge modes of electrical activities much depend on the external forcing so that appropriate mode for electrical activity could be selected adaptively. Depolarization occurs when the potential of membrane is changed that the negative inner membrane potential becomes decreased, otherwise, polarization emerges by applying appropriate electric forcing or field. It is thought that excitatory neuron can be cheered up to propagate signals in nervy system while inhibitory neuron can calm down the bursting synchronization to prevent possible occurrence of certain nervy disease. The cable neuron model included ion channels along x-coordinate is described as follows

$$\begin{cases} C\dfrac{dV}{dt} = -G_{Na}m^3h(V-V_{Na}) - G_kn^4(V-V_k) - G_l(V-V_l) \\ \qquad + I_{ext} + D\dfrac{d^2V}{dx^2} + \vec{E}_0\cdot\nabla VL(x) \\ \dfrac{dm}{dt} = \alpha_m(V)(1-m) - \beta_m(V)m \\ \dfrac{dh}{dt} = \alpha_h(V)(1-h) - \beta_h(V)h \\ \dfrac{dn}{dt} = \alpha_n(V)(1-n) - \beta_n(V)n \end{cases} \tag{1}$$

$$\begin{cases} \alpha_m(V) = \dfrac{0.1(V+40)}{1-\exp[-(V+40)/10]} \quad \beta_m(V) = 4\exp[-(V+65)/18] \\ ; \\ \alpha_h(V) = 0.07\exp[-(V+65)/20]; \quad \beta_h(V) = \dfrac{1}{1+\exp[-(V+35)/10]} \\ \alpha_n(V) = \dfrac{0.01(V+55)}{1-\exp[-(V+55)/10]}; \quad \beta_n(V) = 0.125\exp[-(V+65)/80] \end{cases} \tag{2}$$

where V describes the local membrane potential, G_{Na}, $G_{k,}$ G_l denotes the conductance associated with sodium, potassium channels and leakage current, respectively. V_{Na}, V_k, V_l represents the fixed reversal potentials, and m, n, h calculates the gate of channels, respectively. D is the diffusive intensity, C is the capacitance for membrane, $L(x)$ controls the area imposed on electric field, I_{ext} is the external forcing current. E_0 represents the intensity of external vector field, and term ∇V is the gradient potential along the axon. The parameter for this model is selected as $C=1\ \mu F/cm^2$, the maximal conductance $G_{Na}=120\ mS/cm^2$, $G_k=36\ mS/cm^2$, $G_l=0.3\ mS/cm^2$, $V_{Na=}50$ mV, $V_k=-77$ mV, $V_l=-54$ mV, $I_{ext}=20\ \mu A$, $D=1.06$. The effect of electric field along axon could be replaced by

$$\vec{E}_0\cdot\nabla V = E\cos\left(\vec{E}_0,\quad \nabla V\right)\frac{dV}{dx} \tag{3}$$

For simplicity, the effect of transverse electric field is left out, and the gradient effect along the axon is emphasized in this paper. In a mathematical view, the effect of electric field on signal propagation along axon could be equivalent with the term EdV/dx by selecting appropriate intensity of electric field if possible, axis of

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