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Mode selection in electrical activities of myocardial cell exposed to electromagnetic radiation

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ABSTRACT

Based on the Fitzhugh–Nagumo neuron model, the effect of electromagnetic induction is considered and external electromagnetic radiation is imposed to detect the mode transition of electrical activities in a myocardial cell. Appropriate dynamical and functional responses can be observed in the sampled series for membrane potentials by setting different feedback modulation on the membrane potential in presence of electromagnetic radiation. The electromagnetic radiation is described by a periodical forcing on the magnetic flux, and it is found that the response frequency can keep pace with the frequency of external forcing. However, mismatch of frequency occurs by further increasing the frequency of external forcing, it could account for the information encoding of neuron. The dynamical response could be associated with the magnetization and polarization of the media, thus the outputs of membrane potential can become quiescent and/or bursting as well.

1. Introduction

Normal electrical activities in neurons and myocardial cells are much important for animals. As a result, the collapse of brain and heart can cause serious diseases and even death when the nervous system in invaded and injured. Many neuron models [1–10] have been set up to detect the mode transition of electrical activities in neurons. Within the view of nonlinear dynamics, appropriate parameters setting in system of ordinary differential equations(ODEs) and maps can be effective to generate time series for variables with similar rhythm as biological experimental results. As reported in Ref. [7], biological experiments are carried out that similar bifurcation behaviors can be observed from theoretical models in numerical way. Particularly, Lv and Ma [9] argued that the memory effect of neuron can be described by using magnet flux on the Hindmarsh–Rose and other neuron models. Among these neuron models, different modes of electrical activities such as quiescent state, spiking, bursting and even chaotic states can be reproduced in numerical way and bifurcation analysis [11–15] can be carried out for further discussion. It is confirmed that external stimuli can be effective to change the excitability of neuron and also the electrical activities. Furthermore, appropriate functional connection and loop could be helpful to enhance the self-adaption of neurons. For example, Ref. [8,14] found that electric and chemical autapse, which is a specific synapse connected to its body via closed loop, can modulate the electrical behaviors of neurons, and regulate the collective behaviors in network by inducing continuous pulses and wave fronts. Furthermore, Ren et al. [15] clarified the adaptive selection in response to external stimuli when autapse considered in neuronal circuit. Wang et al. [16] clarified that potential formation mechanism of autapse connection could be associated with injuried neurons. That is, neurons can give right response and mode selection [17,18], and the synchronization behaviors of neurons are dependent on the control parameters. Neuron model, which describes the main dynamical properties of excitable media, is often used to investigate the stochastic and coherence resonance [19–24] induced by different types of noise. When reliable neuron models are set and presented, for example, the modulation of astrocyte is considered [25,26], the collective behaviors such as synchronization and pattern selection [27–31] can be carried out on the network of neurons under different topological connections.

Indeed, the reliability of neuronal activities depends on the selection of neuron model which should be consistent with biological results. The original Hodgkin–Huxley neuron model mainly focus on the electrical activities and effect of ion channels on membrane potentials, the Hindmarsh–Rose neuron is thought as a simplified version from HH model, and it is available for bifurcation analysis in modes of electrical activities of neuron and neuronal network. In realistic neuronal system, the gliocyte and also astrocyte [32–34] has been confirmed to play important role in chang-

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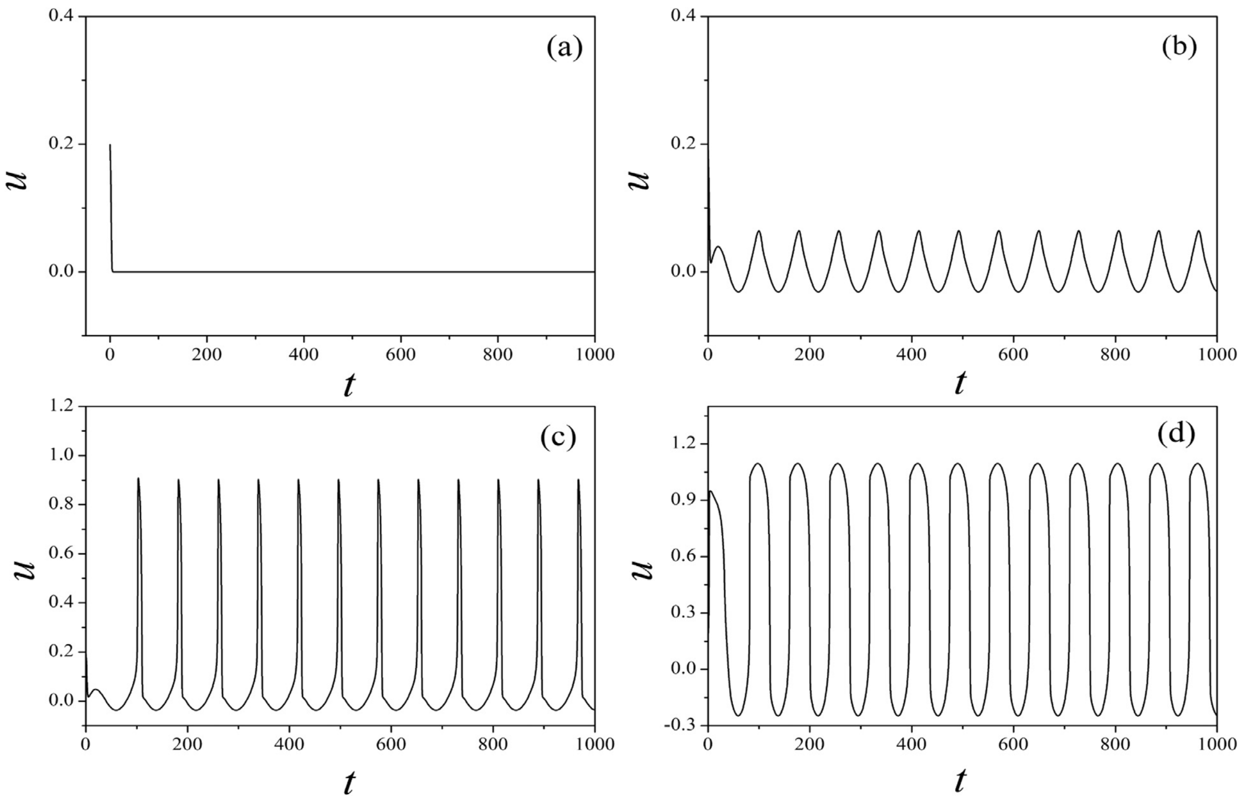

Fig. 1. Sampled time series for membrane potential are calculated by setting different transmembrane currents at fixed parameters as $k_0 = -1$, $\omega = 0.08$, for (a) $I_0 = 0$, (b) $I_0 = 0.05$, (c) $I_0 = 0.06$, (d) $I_0 = 1$. The effect of electromagnetic induction is considered by setting $k_1 = 0.2$, $k_2 = 1.0$.

ing the membrane potential of neuron and electrical activities. On the other hand, autapse connection [35–38] to some interneurons could play important biological function for neurons, for example, appropriate time delay and feedback gain in autapse can calm down the excitatory neuron from bursting states, and inspire the quiescent neuron by applying positive type of time-delayed feedback along the loop. On the other hand, the autapse connection make neuron give appropriate response to external forcing thus the self-adaption to external stimuli is verified. Furthermore, distribution of autapse in neuronal network can trigger and develop continuous pulses or wave fronts to regulate the collective behaviors of neuron like a pacemaker [39–41].

According to the present description for neuron model, the transmembrane currents generated from sodium, potassium, calcium across the membrane of cell modulate the gradient difference of intracellular and extracellular ions contribute to the fluctuation of membrane potential of neuron. However, one important physical effect, named by electromagnetic induction, should be considered because electromagnetic field can be induced during the fluctuation of ion concentration. Furthermore, the effect of electromagnetic radiation can be detected and investigated when neuron or cell is exposed to electromagnetic field [42–44]. It is known that magnetic flux can describe the change and distribution of electromagnetic field. As a result, magnetic flux can be regarded as additive variable to describe the effect of electromagnetic induction. In this paper, magnetic flux is introduced into the two-variable Fitzhugh–Nagumo neuron model to propose a new model that the effect of electromagnetic induction and radiation on myocardial cell or neuron can be discussed in reasonable view. Furthermore, external electromagnetic radiation is imposed on the improved model to investigate the dynamical response of cell and mode transition in electrical activities and potential mechanism is discussed.

2. Model setting and description

An improved model is designed to reproduce the electrical activities of myocardial cell by introducing the additive magnetic flux variable, which can describe the dependence of magnetic field in the media during the fluctuation of membrane potentials for cell induced by changing the distribution of ion concentration of potassium, sodium, calcium and chloridion. For simplicity, magnetic flux is supplied as additive new variable on the well-known Fitzhugh–Nagumo neuron model [45], and the improved model is described by

$$\begin{cases} \frac{du}{dt} = -ku(u-a)(u-1.0) - uv + I_{st} + k_0\rho(\varphi)u \\ \frac{dv}{dt} = \left(\varepsilon + \frac{v\mu_1}{u+\mu_2}\right)[-v - ku(u-a-1.0)] \\ \frac{d\varphi}{dt} = k_1 u - k_2\varphi + \varphi_{ext} \end{cases} \tag{1}$$

$$\rho(\varphi) = \alpha + 3\beta\varphi^2 \tag{2}$$

where the variable u, v, φ describes the membrane potential, slow variable for current and magnetic flux across the membrane, respectively. I_{st} is the transmembrane current mapped from external forcing, k_0, k_1, k_2 is feedback gain, for example, k_0 bridges the coupling and modulation on membrane potential from magnetic flux or field, k_1 calculates the effect of electromagnetic induction induced by the transport of ions in the cell, k_2 describes the degree of polarization and magnetization, and also be thought as physical parameter adjusting the saturation of magnetic flux. The nonlinear term $-ku(u-a)(u-1.0)-uv$ denotes the sum of the transmembrane current of ions on space unit of the membrane patch, and the parameter k is dependent on the media. $k_0\rho(\varphi)u$ is the induction current induced by electromagnetic induction in the cell, φ_{ext} is the external electromagnetic radiation, for simplicity, a periodical type as $\varphi_{ext}=A\cos 2\pi ft$ will be considered, and the transmembrane