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Taking control of initiated propagating wave in a neuronal network using magnetic radiation

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ABSTRACT

The effect of magnetic radiation is essential to be studied due to its favorable or unfavorable influences especially when it comes to biological systems. In this study, some effects of an external time-varying magnetic induction on the formation of spatiotemporal patterns in a model of excitable tissue are investigated. We have designed a two-dimensional neuronal network, in which the local dynamics of the neurons are governed by the four-variable magnetic Hindmarsh–Rose (HR) neuronal model. Besides, each neuron is set to be in chaotic regime. We have examined some values of the bifurcation parameters, namely the frequency and the amplitude of the external magnetic radiation. The resulting evolutionary spatiotemporal patterns have showed that an extremely low frequency provides the tissue more opportunity to support propagation process, while low frequency confines the evolution of the wave fronts. Moreover, higher amplitude of the sinusoidal radiation caused the wave propagation be impeded by an inherent obstacle that could limit the ultimate radius of the propagated wave. The resulting collective response of the designed neuronal network is represented in snapshots and the time series of a sampled neuron are plotted, as well.

1. Introduction

Neuronal network is the most significant processing mechanism in biological living systems. Nerve cells, also known as neurons, are the basic processing units in this complex system through which the network receives, processes and transmits the neural information. Though there exist various types of neurons specialized for particular tasks, they all operate more or less in the same way: an external stimulation can trigger continuous exchange of chemical ions across the membrane of the nerve cell through which an electrical pulse can be produced; this electrical response then passes through some special junctions between the neurons called synapses, by which the neurons communicate with neighboring cells and the information is transferred across the nervous system [1,2]. The functional and structural properties of neuronal network have been found to be consist of serious complexities, which do not rely only on the isolated neurons but the interactions between the nerve cells [3]. A solid idea to characterize the local transmission of accumulated signals in a network of

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interacting excitable neurons is exploring the process as a wave propagation mechanism in an excitable medium. The idea is strongly supported with evidence of abnormal patterns of wave propagation (e.g. spiral wave) in biological excitable media that arise in pathological conditions [4]. Many researches, therefore, have been conducted to study the mechanisms of wave generation and propagation in theoretical models of excitable tissues [5–7]. In particular, the effects of an induced energy on the propagation pattern have been investigated by means of mathematical models of wave front spreading in the neuronal network. Among various propagation patterns, target-like and spiral waves are of crucial importance for their property of being self-sustenance. Provoked by periodical excitation of a group of neurons in a limited area of an excitable media, target waves are equally spread to all the directions. Periodic excitation of source neurons may either arise from an external periodical driving force or stem from functional synchronization of oscillating neurons [8]. Spiral waves are another class of wave patterns known for their self-organizing vibration, which is a type of sustained periodic motion not induced by an external periodic force. Spiral seeds mainly emerge from breaking target waves or plane waves [9].

Due to their property of holding complex and rich dynamics, collective behaviors and communication mechanisms in biological system consisting of numerous interacting processing units are of particular importance. In fact, our perception of structure and function of biological systems and physiological processes in normal and pathological condition benefits from characterizing such collective behaviors [3,10]. Roughly speaking, collective behaviors are inferred from the properties of the individual components, tough cannot be simply anticipated from the dynamics of each individual agent [11]. Such collective responses and the emergence of particular spatiotemporal patterns have been previously studied by means of abstract representations of neuronal networks. For instance, Yao et al. focused on the effect of bounded noise on the formation or break up of the spatiotemporal patterns [12], Guo et al. [13] and Xu et al. [14] studied the role of field coupling on the collective behaviors in a neuronal network to see the pattern stability dependence on coupling intensity; Olmos detected the interactions of the spiral waves with obstacles and presented some properties for attachments of spirals to obstacles [15]; Perc discussed the effect of small-world connectivity on both spatial and temporal pattern in a network of coupled neurons [16]; Wang et al. investigated the effect of delay and rewiring probability on the information transmission in a neuronal network and also the effect of complex interaction structures have been recognized [2], etc.

In therapeutic context, the regulating role of an external current applying to the excitable tissue to control the behavior of medium received particular attention in simulation studies [8,17]. The studies have confirmed that, different currents can bring the network a variety of dynamical spatiotemporal demonstrations. Regarding the real systems and experimental studies, although the current stimulation is applied to lots of research issues [18–20], there are no formal safety guidelines for choosing the stimulus level in this method [21]. Besides, there have been reported some adverse effects using direct current stimulation especially with high amplitudes. For example, skin lesions like burns, mania or hypomania in patients with depression, or possibility of seizure induction [21] are some adverse effects reported in literature. Therefore, despite the beneficial opportunities provided by appliance of current stimulation including brain painless and non-invasive modulatory effect, still further safe approaches are needed to be investigated. It is beneficial turning to utilizing the functionalities and features of field induction. The effects of magnetic field stimulation have been noticed extensively in both theoretical and empirical studies [22–26]. A review of clinical studies on the effect of low frequency and extremely low frequency stimulation on the nervous system response is presented in [27]. In this paper, the effect of external magnetic radiation on the propagation of wave fronts in an excitable medium is investigated, which can function as a controlling parameter for neuronal electrical activity and even beat the effects of current stimulation. In fact, the propagating wave fronts can take place in the absence of external magnetic induction due to current stimulation effects. Given the simulation results, external magnetic induction with extremely low frequency also supports wave propagation, though within slight influences. However, a slight increase in the magnetic induction frequency noticeably restricts wave propagation especially in greater amplitudes.

Basically, the neuronal electrical activity relies on some precise and complex mechanisms. It is confirmed that, there exist some internal time-varying electromagnetic fields in the volume conductor consisting of excitable tissues caused by continuous exchange of ions across the membrane of the cells. These exchanges are based on the electrochemical gradient of the ions between the inside and the outside of the cell body [1]. Accordingly, some researchers suggest an improved model, in which the effect of magnetic flux is considered, so that more reliable demonstrations are obtained [17,25,28]. For the purpose of mathematical modeling, a good model should contain many physical and biological factors in order to get closer to the desired real system. Considering the mutual effects of electrical polarizations and the internal and external magnetic field, it is necessary to use a more reliable model for the neuronal studies. Therefore, in the present study, we use the four-variable magnetic Hindmarsh–Rose model, in which the effect of magnetic flux is considered.

It is confirmed that, the electrical activity of the neurons is seriously influenced by the time-varying electromagnetic field [29] that can also change the brain connections [24]. For example, a time-varying electromagnetic field applied to mirror neurons can modify their growth rate [13,30]. This process seems to need the information transference in a particular discipline which can exist in the form of wave propagation. Accordingly, the results of our study showed that the excitable network supports the wave propagation in presence of magnetic radiation under special circumstances. In this regard, more details are available in Section 3. Besides, as mentioned in [31,32], some cognition disorders seem to be correlated with presence of high intensity electromagnetic radiation. Moreover, the decline of learning and memory or decrease of antioxidant enzymes activities are reported to be attributed to electromagnetic radiation [33]. These disorders may be due to total lack or partial block of information transference in the form of wave propagation deficit. In accordance with this fact, the results of our study showed that high intensity magnetic induction restricts the evolution of wave propagation.