Biochemical and Biophysical Research Communications 496 (2018) 661–666

Contents lists available at ScienceDirect

Biochemical and Biophysical Research Communications

journal homepage: www.elsevier.com/locate/ybbrc

Phenomena of synchronized response in biosystems and the possible mechanism

Jingjing Xu, Fan Yang, Danhong Han, Shengyong Xu*

Key Laboratory for the Physics & Chemistry of Nanodevices, Department of Electronics, Peking University, Beijing, 100871, PR China

ARTICLE INFO

Article history:
Received 5 January 2018
Received in revised form
14 January 2018
Accepted 18 January 2018
Available online 20 January 2018

Keywords:
Synchronized response
Electrical communication
Soliton-like electromagnetic wave
Membrane
Softmaterial waveguide

ABSTRACT

Phenomena of synchronized response is common among organs, tissues and cells in biosystems. We have analyzed and discussed three examples of synchronization in biosystems, including the direction-changing movement of paramecia, the prey behavior of flytraps, and the simultaneous discharge of electric eels. These phenomena and discussions support an electrical communication mechanism that in biosystems, the electrical signals are mainly soliton-like electromagnetic pulses, which are generated by the transient transmembrane ionic current through the ion channels and propagate along the dielectric membrane-based softmaterial waveguide network to complete synchronized responses. This transmission model implies that a uniform electrical communication mechanism might have been naturally developed in biosystem.

1. Introduction

A life system utilizes both electrical and chemical signals for communication. Molecules carrying chemical information move slowly in liquid environment of a life system. Therefore, for fast activities such as the motion of a body, electrical signals are usually the only choices for message carriers. Several theories have been developed to understand the electrical communication in a neural system. The Hodgkin and Huxley model has been well accepted for understanding the generation and transmission of electrical signals in nerve system [1,2]. The theory describe the transmission behavior of the electrical signal, referred to as “action potentials”, with a circuit model based on equivalent resistors (ion channels and the cytosol of the axon) and capacitor (lipid membrane). However, this model faces difficulty in explaining some phenomena such as “*saltatory propagation*” in myelinated axons, or crossover of two action potentials on one axon which appears missing the “*refractory period*”.

One decade ago, based on evidences of reversible heat changes, thickness and phase changes of the membrane observed during the action potential [3–6], Heimberg and Jackson describes the transmission of electrical signals in nerve systems in the form of mechanical dilatational waves, which are generated by transmembrane ion low induced heat. The waves propagate like electromechanical solitons and depend much on the presence of cooperative phase transitions in the membrane. The model is applied to explain the problem of refractory period, reversible release and reabsorption of heat, effect of anesthetics [7], as well as emergence of ion channel phenomena from thermodynamics of the membrane [8,9]. The model also carried out simulations showing that the minimum velocity of the solitons is close to the propagation velocity in unilamellar vesicles [3]. Recently, Xue and Xu stated that indeed it is soliton-like electromagnetic (EM) pulses rather than a mechanical wave that transmitting within the lipid membrane. The thin lipid bilayer membrane of an unmyelinated axon, or the thick sheath of a myelinated axon, together with intracellular and extracellular fluids, form a kind of “softmaterial waveguide” for efficient transmission of the EM pulses [10]. This hypothesis can be applied to explain various electrical communication phenomena in nerve system, as well as electrical communication phenomena in many other circumstances without nerve systems [10,11].

In addition to pulsed electric signals, indeed various weak photon emissions so called “biophotons”, have been detected since 1920's in bacteria, plants, animal cells, even in the nerve systems of human beings [12,13], and it has been suggested that biophotons play an important role in electrical communication of biosystems [14]. It is believed that this kind of biophotons could be guided along a filamentous mitochondrial network, where the

---

* Corresponding author.
E-mail address: xusy@pku.edu.cn (S. Xu).

https://doi.org/10.1016/j.bbrc.2018.01.118

microtubules acted as optical waveguides inside neurons [15].

Yet to date some important questions like synchronization remain open. How do the electrical signals activate a large number of cell organelles? How does electric communication work out in life systems without neurons, such as in a plant? And, how can billions of ion channels open simultaneously within 0.1–0.5 ms in an electric eel [16,17]? We show in the paper that these problems can be solved with conventional physics. By analyzing several systems where a large amount of effectors (e.g., proteins or cells) respond synchronously to a single source, including paramecium, flytrap and electric eel, we reveal a universal electrical communication model existing in biosystems with or without neurons and axons. In this communication model, soliton-like electromagnetic pulses serve as the message carriers, and the membrane-based softmaterial waveguide network serve as the transmission paths.

2. Electrical communication in different biosystems

2.1. Electrical communication in a paramecium

This electrical communication model is discussed in unicellular organisms possibly emerged 3.8–4 billion years ago [18], such as paramecium. A paramecium has as many as 5000–6000 cilia for swimming movement, by synchronously beating them forward or backward in water. When a paramecium touches a subject on its way swimming forward, it is able to reverse its swimming direction very quickly by changing the beating direction of all its cilia simultaneously [19,20]. Roger Eckert et al. found that it just needed 30 ms for all 5000–6200 cilia of a 200 μm long paramecium to reorient their beating direction [21]. This leads to a propagation speed of the signal about 6.8 mm/s from one end where an external stimuli is applied to the other end of the paramecium. Previous studies have shown that, when the impact occurs at the front side of a paramecium, it increases the permeability for Ca^{2+} and leads to an inward flow of Ca^{2+} at anterior membrane, thus initiating the "avoidance response". While an impact occurs at the caudal (posterior) surface, it evokes an increasing permeability of K^+ and causes an outward flow of K^+, thus enhancing the frequency of beating of all the cilia, which makes the paramecium swim faster to escape [19,20,22,23].

It is not likely that chemical signals carried by molecules play the role for realization of synchronized motion of the cilia over the whole paramecium. Not only because molecules diffuse slowly in liquid, but also it needs identical molecules reaching all cilia within a short time. Mechanical motion of the membrane presented by Thomas Heimberg et al. may be applied to understand the synchronized reaction of thousands of cilia. However, we believe that a paramecium has used electromagnetic pulses and softmaterial waveguide based on membranes to fulfill this processes.

In our model, when a paramecium runs into an obstacle, the receptors near the impact point sense the stimuli and generate electromagnetic pulses. The function of the receptors is similar to those mechanical sensors (e.g., tactile corpuscles) in advanced animals [24,25], where the sensor converts deformation in its proteins caused by the mechanical impact into transmembrane ion flows of Ca^{2+} and/or K^+. According to the Maxwell equations, these transient transmembrane ion flows introduce directly soliton-like EM pulses. Here, the membrane of a paramecium, together with intracellular and extracellular fluids, serves as the effective transmission path for the EM pulses. Then the EM pulses would propagate in the dielectric membrane layer at a speed more than one tenth of light speed to all over the paramecium to trigger the change of beating mode of the cilia [10,11]. It is the change of local electrical field near each cilia that triggers the change of its motion mode. The time of 30 ms mostly costs on the change of mechanical beating mode for the cilia. In this way, thousands of cilia reorient almost simultaneously their beating direction and frequency, as schematically illustrated as Fig. 1.

It has also been observed that there are many mechanosensitive channels on the somatic membrane of a paramecium, and voltage-gated channels on the ciliary membrane [21]. As a result, it is believed that the receptors for sensing impact are the mechanosensitive channels through which the transmembrane transient ionic current bring about EM pulses. And the conceivable effectors are the voltage-gated channels, which can be triggered open by a steep change in electric field, leading to a leak flow of Ca^{2+} ions which change the relative movement between microtubulins in cilia. In view of the microscale length of a paramecium, the EM pulses generated at the impact point are supposed to propagate all over the body through the membrane-based waveguide, similar to the cases in unmyelinated axons, where EM pulses generated by ion channels at one spot can trigger the opening of ion channels at neighbor spot located tens of microns away.

2.2. Electrical communication in a flytrap (*Dionaea muscipula*)

Plants are multicellular organisms without neural systems. However, electricity phenomenon in plants like *Mimosa pudica* and *Dionaea muscipula* were observed long ago [26,27]. It was reported that the transmission speed of electric signals in plant span a lot, while the highest speed was surprisingly comparable to that measured in myelinated axons [28].

Trapping action of a flytrap is performed by two leaves jointed at the leaf stalk position. Once any two of the six equivalent sensory hairs are triggered twice in less than 20–30 s or more times within 50 ms, the two leaves would close in 100–300 ms by the reaction of leaf stalk, completing a trapping performance [29–31]. The prey behavior of a flytrap need a fast reaction, where the signal speed from the receptors (under the sensory hairs) to the effectors (located in the leaf stalk) is in the order of 0.2 m/s or faster [28], comparable to that for action potentials propagating in unmyelinated axons.

We suggest that, similar to the case in a paramecium, the electrical signals occurred in plants are also in the form of EM pulses. In trapping action of a flytrap, the EM pulses are generated by the sensory receptors for mechanical shift at bottoms of the six equivalent hairs when triggered twice within 20–30 s [32,33]. Evidences have been observed showing that the sensory processes are strongly linked to transient transmembrane inflows of Ca^{2+} [34], which is probably the basic source for EM pulses in plants. The propagation of the EM pulses in plants relies on the membrane-based waveguide network. The main framework of this network is built up with cell membranes and plasmodesma, which connects extended membranes of two adjacent plant cells [28], as schematically illustrated in Fig. 2A. In addition, plasmodesma across sieve pore can connect the membrane of adjacent two sieve tube cells, therefore building up a continuous waveguide network along the sieve tube, as shown in Fig. 2B. Previous studies have recognized two forms for electric signal communication in plants [34–36]. Traps of flytraps and some lower plants possess a form of omni-directional propagation, which is similar to that of cardiac myocytes. More common electrical signals in higher plants are directionally propagated in vascular bundles along the plant axis. These two forms are probably corresponding to the two types of membrane network mentioned above respectively.

Due to the attenuation in intensity of the EM pulses transmitting in the softmaterial waveguide network and the long distance between receptors and effectors up to one centimeter or more, it needs ion channels serving as "relays" on the transmission path. Voltage-gated ionic channels observed in plants may play the role