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Synchronization with low power consumption of hardware models of cardiac cells

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Abstract

In a diffusively coupled system of mathematical models of cardiac cells, an acceleration phenomenon becomes apparent, with the period of the system becoming shorter than the periods of each isolated circuit. In order to investigate the energy or power consumption necessary to accelerate the oscillation of the coupled system, we propose an electronic circuit oscillator model for cardiac cells with the action potential presented by square waves with plateaus of different duration. When the durations of the plateaus of the isolated circuits were set at different values, while keeping the periods the same, the coupled system was accelerated. As a result the power consumption was reduced by the coupling. A requirement for the acceleration driven by the lowest power consumption was that the duty cycle of the coupled system be equal to 0.4. This duty cycle can be physiologically observed in living cardiac cell tissue. This suggests that cardiac cells are self-organized so as to accelerate through the coupling of cells while the total power consumption is reduced to the minimum state.

Keywords: Acceleration phenomenon; Plateau potential; Diffusive coupling; FitzHugh-Nagumo equation; Duty cycle

1. Introduction

Excitable or oscillatory electrical phenomena, shown by neurons and many other cells, are modeled by using nonlinear differential equations. These models, such as the Hodgkin–Huxley (HH) equations (Hodgkin and Huxley, 1952) and the FitzHugh-Nagumo (FHN) equations (FitzHugh, 1961) are often used as components in the network to analyze the dynamics, which are regarded as the main information carrier in biological systems. The coupled system described by the HH or FHN equations can be synchronized when the coupling is relatively strong. After synchronization, their period is changed. Meunier (1992) demonstrated a surprising phenomenon whereby the oscillation accelerated after coupling of the modified FHN equations. When two nonlinear FHN oscillators are coupled diffusively, they synchronize and their periods become shorter. It is the duration of the plateau after the sharp upstroke

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during the action potential that plays an important role in such acceleration phenomena. The acceleration phenomenon is highly efficient in the sense that the biological system can propagate the excitation in the short term. However, if the energy consumption required for coupling is higher, the biological system might not employ the acceleration phenomenon. One can ask the question of how much energy is needed to cause the acceleration phenomenon.

In general, a biological system is often in a self-organized state in which the total energy consumption is minimized. For example, it is said that many cardiac cells couple and pulsate with low energy consumption. Therefore, the energy consumption, which in electrical terms is defined as the integral of the power consumption, should also be considered as well as the synchronization and acceleration phenomena. It is difficult, however, to investigate physical quantities such as the energy or power consumption from mathematical models. These physical quantities disappear from abstract mathematical models because the variables in the equations are dimensionless. Actually, in the FHN equation, there are no variables such as voltage and current which can be used to calculate the power consumption.

Hardware models are very useful in discussing both the acceleration phenomenon and the power consumption simultaneously. However, many types of hardware model, such as those proposed by Gulrajani et al. (1977), Hoshimiya et al. (1979), Keener (1983), Sekine et al. (1999) and Maeda and Makino (2000), are dynamics-oriented models used to investigate biological information processing or the response characteristics to current stimuli. In this paper, we propose a new hardware model that replicates the electrical behavior of cardiac cells, chiefly to investigate the power consumption of a diffusively coupled system. The main purpose of this research is to find the acceleration phenomenon of the coupled system whilst reducing the power consumption. To this end, the average and the deviation of the duration of the plateau of the isolated circuit are used as control parameters. To evaluate the synchronization and acceleration phenomena with low power consumption of the hardware model, the duty cycle defined as the ratio of the duration of the plateau to the period is used. In this paper, we present that both the acceleration phenomenon and the reduction in power consumption can take place simultaneously in our coupled system, and there exists a unique minimum point for the power consumption. Furthermore, the duty cycle of the coupled system at the minimum point corresponds to the value observed in living cardiac cell tissue. We can surmise that it is possible that synchronization and acceleration with low power consumption may take place in the real cardiac system.

In Section 2, we introduce the hardware models for cardiac cells. The action potentials with plateaus are qualitatively reproduced in the hardware model. In Section 3, the average, $\overline{\tau}$, and the deviation, σ, of the duration of the plateau of the isolated circuit are defined as control parameters. Two ratios, ϕ and ψ, are defined to evaluate the acceleration phenomenon and the reduction in power consumption, respectively. In Section 4, the acceleration phenomenon reducing the power consumption is illustrated. We discuss these phenomena in Section 5, and finally summarize in Section 6.

2. Hardware models and their coupling

Hoshimiya et al. (1979) proposed that the dynamics of an excitable/oscillatory membrane be modeled in terms of electronic circuits. The circuit structure is a parallel connection of two sorts of current branches, physiologically corresponding to the sodium and potassium ionic currents. Its dynamics are basically the same as the FHN equation. Maeda and Makino (2000) obtained a burst generating hardware model by modifying the Hoshimiya hardware model. This modification is based on the general results of the diverse and common features in the nonlinear differential equations (Doi et al., 2001). Specifically, another current branch, associated with the plateau potential to generate bursting phases, was added in parallel to the Hoshimiya hardware model.

In order to construct a hardware model for cardiac cells (HMC), we improved the current branch that was added for the Maeda–Makino hardware model to regenerate the plateau potential without bursting. The circuit configuration is illustrated in Fig. 1. In Fig. 1, the labels “Inside” and “Outside” represent the inside and outside of the membrane, respectively. The membrane potential is measured as the voltage between the inside and outside with the outside earthed. Four dotted arrows correspond to the voltage-dependent inward sodium current, I_{in1}, with negative resistance