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Reverse resonance and stochastic resonance in intracellular calcium oscillations

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HIGHLIGHTS

- Reverse resonance exhibits in the function of RCV vs. time delay.
- Reverse resonance exhibits in the function of RCV vs. strength of noises as time delay increases.
- Both stochastic and reverse resonance are observed in the function of RCV vs. correlation time with varying strength of noises.

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ABSTRACT

The roles of time delay on the coherence resonance are investigated in the intracellular calcium oscillation system described by the processes of active and passive transport of intracellular Ca^{2+} driven by colored noises. From the numerical simulation of the reciprocal coefficient of variance of interspike intervals of calcium spikes by the method of second-order algorithm, the results indicate that: (i) The stochastic or reverse synchronization is induced by a certain value of time delay or correlation time; (ii) A phenomenon of reverse resonance can be obtained in the function of reciprocal coefficient of variance vs. time delay or vs. strength of noises as time delay increases; (iii) Both stochastic and reverse resonance are observed in the function of reciprocal coefficient of variance vs. correlation time with varying strength of noises.

1. Introduction

In many studies on intracellular calcium oscillation (ICO), there are a variety of channels showing calcium-induced calcium release and a variety of models to describe ICO as in Refs. [1–4]. Many interesting phenomena have been found such as stochastic backfiring [5], dispersion gap and localized spiral waves [6], stochastic resonance [7], coherence resonance [8,9], bistability solutions with hysteresis [10,11], calcium puffs [12], various spontaneous Ca^{2+} patterns [13], non-Gaussian noise-optimized ICO in cytosol [14] and so forth. This is an interesting topic which was intensively studied by Martin Falcke group [5,6,15–19], given that calcium is a ubiquitous second messenger, and experimentally measured calcium oscillations are inherently stochastic. Careful analysis of experimental data and comparison with mathematical models showed clearly that real ICO is non-Gaussian [19].

More importantly, Matjaž Perc group [20–25] has studied the effects of noise on the dynamics of calcium oscillations, from experimental data, shown directly that noise and other stochastic effects indeed play a central role [20,21]. In fact, stochasticity is the predominant mode of functioning in intracellular processes. For instance, in Ref. [22], which suggested

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that noise may be beneficial for the stability and robustness of calcium oscillations; in Ref. [23], noise could aid the detection of weak calcium signals within the cell; and in Ref. [25], noise could induce periodic calcium waves. Moreover, they have demonstrated that the effects of noise become lesser [24] when the cells are coupled. In a word, Matjaž Perc group mainly studied the effect of white noise on ICO system, rather than colored noise. However, colored noise is widespread in stochastic dynamical system inclusion biological cells, rather than ideally white noise.

In transmission processes, inclusion of time delay is natural due to finite transmission speed of matter, energy, and information. So many researchers have studied the effect of time delay in some stochastic biological systems [26–40]. In our research on ICO [11,41–43], in order to take into account of time delay in the processes of active and passive transport of intracellular Ca^{2+}, the role of colored noises on ICO system has been studied. We have found that noises can induce calcium spikes, so studying the regularity of spikes is significant in this paper.

In Section 2, considering colored noises and same time delay in the processes of active and passive transport of intracellular Ca^{2+}, the model for ICO is presented according to Ref. [43]. By means of the second-order algorithm for stochastic simulation colored noises [44] to simulate intracellular Ca^{2+} concentrations, the regularity of calcium spikes is studied in Section 3. Finally, conclusions are drawn in Section 4.

2. The model for ICO with colored noises and time delay

Taking into account same time delay τ in the processes of active and passive transport of Ca^{2+} in a real cell, the Langevin equations of ICO system read as follows according to Ref. [43]:

$$d_t x = A_1(x, y; x_\tau, y_\tau) + B_1(x, y; x_\tau, y_\tau)\epsilon(t), \tag{1}$$

$$d_t y = A_2(x, y; x_\tau) + B_2(x, y; x_\tau)\Gamma(t), \tag{2}$$

with

$$A_1(x, y; x_\tau, y_\tau) = v_0 + v_1\beta_0 - v_2 + v_{3\tau} + k_f y_\tau - kx, \tag{3}$$

$$A_2(x, y; x_\tau) = v_{2\tau} - v_3 - k_f y, \tag{4}$$

$$B_1(x, y; x_\tau, y_\tau) = \sqrt{v_1^2\beta_0^2 + 2v_1\beta_0\lambda W + W^2}, \tag{5}$$

$$B_2(x, y; x_\tau) = \sqrt{\frac{v_{2\tau} + v_3 + k_f y}{V}}, \tag{6}$$

$$W(x, y; x_\tau, y_\tau) = \sqrt{\frac{v_0 + v_1\beta_0 + v_2 + v_{3\tau} + k_f y_\tau + kx}{V}}, \tag{7}$$

and

$$v_2 = \frac{V_2 x^2}{x^2 + k_1^2}, \qquad v_3 = \frac{V_3 x^4 y^2}{(x^4 + k_2^4)(y^2 + k_3^2)}, \tag{8}$$

$$v_{2\tau} = \frac{V_2 x_\tau^2}{x_\tau^2 + k_1^2}, \qquad v_{3\tau} = \frac{V_3 x_\tau^4 y_\tau^2}{(x_\tau^4 + k_2^4)(y_\tau^2 + k_3^2)}. \tag{9}$$

Here, x and y denote concentration of free Ca^{2+} of cytosol and calcium store in a cell, respectively. The rates v_2 and v_3 refer, respectively, to pumping of Ca^{2+} into calcium store and to release of Ca^{2+} from store into cytosol in a process activated by cytosolic Ca^{2+}. $v_{2\tau}$ is v_2 with time delay. $v_{3\tau}$ is v_3 with time delay. $W = W(x, y; x_\tau, y_\tau)$, $x_\tau = x(t - \tau)$, $y_\tau = y(t - \tau)$. λ denotes the cross-correlation degree between internal and external noises before merger [11]. The values of parameters are set as in Ref. [8]: $v_0 = 1\ \mu M/s$, $v_1 = 7.3\ \mu M/s$, $\beta_0 = 0.287$, $k_f = 1/s$, $k = 10/s$, $V_2 = 65\ \mu M/s$, $V_3 = 500\ \mu M/s$, $k_1 = 1\ \mu M$, $k_2 = 0.9\ \mu M$, $k_3 = 2\ \mu M$, and $V = 1000$.

The noises $\epsilon(t)$ and $\Gamma(t)$ are considered as Gaussian colored noises with statistical properties:

$$\begin{aligned} &\langle\epsilon(t)\rangle = \langle\Gamma(t)\rangle = 0, \\ &\langle\epsilon(t)\epsilon(t')\rangle = D\lambda_1 \exp(-\lambda_1|t - t'|), \\ &\langle\Gamma(t)\Gamma(t')\rangle = D\lambda_1 \exp(-\lambda_1|t - t'|). \end{aligned} \tag{10}$$

Here, in order to study easily, suppose that noises $\epsilon(t)$ and $\Gamma(t)$ have same strength D and same correlation time τ_1, $\lambda_1 = 1/\tau_1$.

3. The regularity of calcium spikes

By means of the second-order algorithm for stochastic simulation colored noises in Ref. [44], one can stochastically simulate time evolution of intracellular Ca^{2+} concentration in cytosol $x(t)$ and calcium store $y(t)$, this algorithm has been