Information Processing for the Chemotaxis of *Physarum polycephalum* by the Self-Organization of a Spatio-Temporal Pattern of Ca2+ Concentration

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Abstract

The development of a spatio-temporal pattern of Ca2+ concentration in a plasmodium of *Physarum polycephalum* during chemotaxis was studied using fura-2. Whenever the cell displayed coordinated migration in one direction as a whole body, a spatio-temporal pattern was established along the longitudinal axis. In the cell, the Ca2+ concentration at the frontal site was higher than that at the rear site . It also oscillated with the period of a few minutes. When the plasmodium was stimulated with attractants at the rear site, the period of the Ca2+ concentration at the stimulated site was first shortened. It propagated toward the non-stimulated site. Then the Ca2+ gradient reversed resulting in the reversal of the migration direction of the plasmodium. On the other hand, when the plasmodium was stimulated with a repellent at the frontal site, the period of the Ca2+ oscillation decreased immediately. At the same time, Ca2+ concentration at the stimulated site decreased. This local change induced the change of the Ca2+ pattern in the whole cell, and as a result, the plasmodium reversed the migration direction. The possible role of the spatio-temporal pattern of Ca2+ concentration in the information processing for the chemotaxis of the plasmodium is discussed.

1. Introduction

The plasmodium of *Physarum polycephalum* is a giant unicellular organism that usually displays coordinated migration as a whole body. It has the chemotactic behavior. Even when a cell receives a local chemical stimulus, it can properly process information for the entire cell to behave in a well coordinated manner as a whole body. However, there is no specially differentiated organ for the information processing.

In this study, we observed both the change of spatio-temporal pattern of Ca2+ concentration and the migratory behavior of the plasmodium during information processing for the chemotaxis. Calcium ion is known to regulate the cytoskeleton of the plasmodium, which is related to the migration of the cell. Our present work showed that a steady spatio-temporal pattern of Ca2+ concentration always exists when the cell displays coordinated migration. By stimulation, a new steady and coherent pattern was self-organized and the cell began to migrate in a coordinated manner Therefore, the plasmodium seems to utilize a coherent and spatio-temporal pattern, which determines the migratory direction, for information processing.

2. Method

The system used to measure Ca2+ concentraion is composed of a fluorescence microscope, a photomultiplier tube and a recording instrument. A fura-2 microinfected plasmodium, which was about 2 cm long, was illuminated by ultraviolet light at 340, 360nm at 10 sec intervals. The Ca2+ concentration was quantitatively estimated from the ratio of the intensity of fluorescence at 340nm to that of 360nm. Chemical stimulation was applied by exchanging a part of the agar gel plate,which contained 10mM glucose (attractant) or 50mM KCl (repellent), under the plasmodium. The stimulation site will be referred to as the "S-site" and the non-stimulation site as the "NS-site".

3. Results

3.1 Spatio-Temporal Pattern of Ca2+ concentration during the coordinated migration of plasmodium

The plasmodium always had a spatial gradient of Ca2+ concentration, when it migrated in one direction. The concentration at the front was about 140nM higher than that at the rear. At both sites, the Ca2+ concentration constantly oscillated with periods of a few minutes.

3.2 Spatio-Temporal Pattern of Ca2+ Concentration After Stimulation with Attractant

When the rear part of the cell was stimulated with 10mM glucose, the period of Ca2+ oscillation at the S-site shortened at first. The change propagated to the NS-site immediately within 5 sec. Then the Ca2+ gradient was reversed and a steady Ca2+ gradient was established from 15 minutes after the stimulation (Figure 1). The reversal of the Ca2+ agreed with the migrating direction.

3.2 Spatio-Temporal Pattern of Ca2+ Concnetration After Stimulation with Repellent

When the frontal part of the migrating cell was stimulated by 50mM KCl, the period of Ca2+ oscillation at the S-site lengthened, contrasting the case of the attractant stimulation. The Ca2+ concentration at the S-site also lowered with repellent stimulation. This change induced the change of the pattern in the whole cell, resulting in the reversal of the Ca2+ gradient throughout the cell. Then the migration direction was reversed.

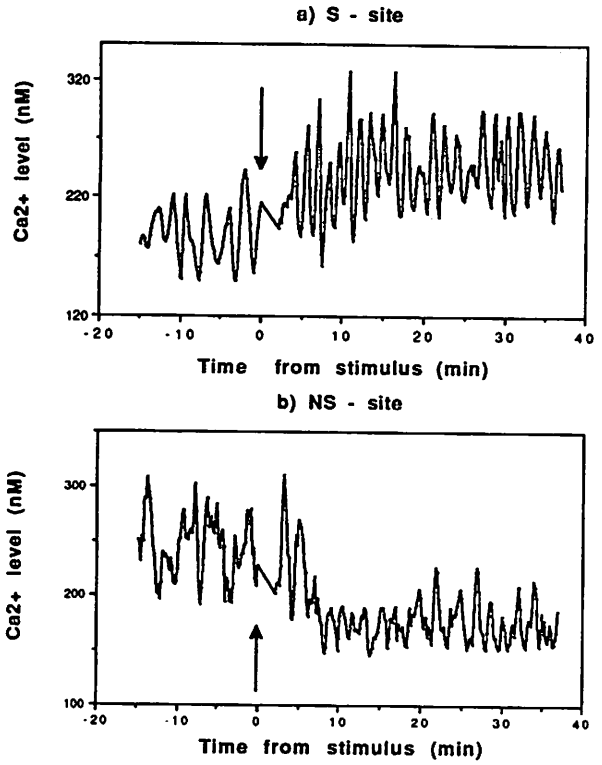

Figure 1. Examples of the developping temporal pattern of Ca2+ concentration at the S- and NS-sites when a plasmodium was stimulated with 10mM glucose. **a** S-site (stimulated site), **b** NS-site (non-stimulated site). Arrows indicates glucose application.

4. Discussion

When the plasmodium migrated in one direction, the steady Ca2+ gradient throughout the cell always existed along the longitudinal axis. The Ca2+ concentration also oscillated with the period of a few minutes. This spatio-temporal pattern of Ca2+ was changed during information processing for chemotaxis.

When the frontal part of the cell was stimulated with an attractant, the period of the Ca2+ oscillation at the S-site decreased and the Ca2+ concentration increased. The oscillation would entrain the Ca2+oscillation at the other site,the change of the period at the NS-site. The decrease in the period at the NS-site was accompanied with the decrease in Ca2+ concentration. As a result, the Ca2+ gradient in the plasmodium was reversed.

The repellent stimulation to the frontal area of the plasmodium caused a immediate increase in the period of Ca2+ oscillation at the S-site. The Ca2+ concentration at the S-site decreased. These changes induced a change in the Ca2+ pattern in the whole cell. As a result, the Ca2+ gradient was reversed.

Ca2+ gradient in the cell was reversed by both the stimulation to the rear site with the attractant and to the frontal site with the repellent. Stimulation causes changes in the frequency of the Ca2+ oscillation at the S-site. After that, a steady gradient of Ca2+ is generated. In this period, a spatial gradient in the phase of the oscillation throughout the cell is also observed; the phase gradient disappears after the cell begins to migrate. Nevertheless, the Ca2+ gradient remains unchanged. Therefore, in the information processing for the coordinated behavior, rhythmic phenomena could relate to the early stage, during which the plasmodium selects the best direction in which to migrate. In the following stage, the spatial Ca2+ gradient can generate the coordinated behavior and maintain the migratory direction of the cell.

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