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Ultrastructural Studies of Calcium Location during the “Catch” Contraction of Clam Smooth Adductor Muscle Cells

Tomonori Tanaka, Hideki Ishida, Kohzoh Ohtsu
and Akira Matsuno*

*Department of Biological Science, Faculty of Life and Environmental Science,
Shimane University, Matsue 690, Japan*

ABSTRACT—Contraction of molluscan adductors has been classified into three states; 1) resting state, 2) contracted state, 3) prolonged “catch” state. Among these, the “catch” state is considered a peculiar state, which requires little expenditure of energy, but in which contraction can be maintained for long periods. It is not yet known whether “catch” muscle contraction is regulated by Ca, or where Ca translocates during resting state through “catch” state, if the muscle contraction is regulated by Ca. We attempted to observe Ca translocation in muscle cells during contraction by the K-pyroantimonate method. We fixed “catch” muscle cells for electron microscopy with fixative including K-pyroantimonate, and observed where electron-dense precipitates, in which Ca is concentrated, were located in the muscle cells in the three states of contraction. At the resting state, precipitate was located at cell peripheries, in positions such as at the inner surface of cell membranes and in sarcoplasmic reticular systems (SRs). In the contracted state, they were located within the cytoplasm. At the “catch” state, they were found in both the cytoplasm and at peripheries, although the number of precipitates in peripheral areas was small. Thus, we show that calcium translocates in the cells during resting-contraction-catch cycles of “catch” muscle contraction.

INTRODUCTION

Molluscan adductors and retractors can maintain tension for prolonged periods with little energy expenditure. These sustained contractions are called the “catch” contraction. In particular, retractor muscles and opaque portions in adductors of bivalves, which are composed of smooth muscle cells, show “catch” contraction (Lowy and Hanson, 1962; Lowy *et al.*, 1964). The “catch” contraction is characterized by three states of contraction; 1) resting state, 2) contracted state similar to that in general smooth muscle, 3) prolonged “catch” state.

Many structural and physiological studies have used molluscan “catch” muscles to study this particular contraction (Pfister and Ruegg, 1982; Ishii *et al.*, 1989a; Matsuno and Kuga, 1989; Matsuno *et al.*, 1993). Biochemical studies of “catch” muscles have focused mainly on paramyosin, because it is a major and characteristic protein in “catch” muscles (Szent-Gyorgyi *et al.*, 1971; Elliott and Bennett, 1984; Castellani *et al.*, 1983; Watabe *et al.*, 1990; Matsuno *et al.*, 1996). However, it is not yet clear in detail how “catch” muscle maintain prolonged contraction, and how the “catch” contraction is released.

Contraction of smooth muscle cell is regulated by calcium, as it is in cross striated muscle cells. Calcium in cross

striated muscle cells is stored in sarcoplasmic reticula (SR) when the cells are at resting state. When the cells are excited, calcium is dispersed from the SRs to the cytoplasm, and the cells come into contracted state. Similar calcium regulation has been recognized in contraction of smooth muscle cells (Twarog and Muneoka, 1972; Debbas *et al.*, 1975; McGuffee *et al.*, 1976; Suzuki, 1982). Several reports observed ultrastructural translocation of calcium during relaxation and contraction of smooth muscle cells, using conventional pyroantimonate methods (Suzuki and Sugi, 1978; Sugi *et al.*, 1982; Suzuki, 1982; Aguas, 1983). As the method is capable of detecting calcium in living cells, several studies have reported Ca-translocation in “catch” muscle (Ishii *et al.*, 1989a, b). A few reports have also examined Ca-translocation during the “catch” contraction (Atsumi *et al.*, 1974; Atsumi and Sugi, 1976). These reports suggested that calcium in the cytoplasm decreased during the “catch” contraction, and discussed the effects of decreasing calcium in cytoplasm. Quantitative Ca-translocation during contraction-catch-resting cycle of the “catch” contractions, however, remains obscure.

It is difficult to estimate calcium effects on “catch” state, because contraction of smooth muscle cells is generally attended by calcium influx through cell membranes from cell exteriors. Sugi and Daimon (1977) reported calcium translocation in smooth muscle using the pyroantimonate method. They fixed muscle cells with osmium fixative containing 2.5% potassium pyroantimonate, and could detect electron-dense

* Corresponding author: Tel. +81-852-32-6430;
FAX. +81-852-32-6449.

precipitate of intracellular cations. It may thus be possible to determine if calcium translocates during catch contraction using this method. We attempted to identify calcium translocation in "catch" muscle cells during a contraction-catch-resting muscle contraction cycle.

MATERIALS AND METHODS

The materials used for this study were posterior adductors of giant clams (*Meretrix lusoria*), collected near the Oki Marine Biological Station of Shimane University. Posterior adductors were removed with a diamond cutter, together with shell at both ends. A cross-striated portion was then carefully removed from the adductor preparation, and the remaining shell attached at both ends was cut into small squares. These preparations were used for physiological experiments and electron microscopy.

Physiological experiment

One end of the prepared adductor muscle was connected to a transducer arm, and the other end hooked to the bottom of a small chamber in which experimental solutions could be exchanged. The chamber was filled with artificial sea water to wash the muscle. The adductor muscle came into resting state during the 30 min washing period. The muscle was then washed twice with Ca-free artificial sea water, and submerged into in Ca-free artificial sea water containing 10^{-2} M acetylcholine. The muscle began to contract in the acetylcholine solution within 30 sec, and reached full contraction 3 min after contraction began (contracted state). After full contraction, the muscle was washed with Ca-free artificial sea water, and left for 5-10 min (catch state). The muscle was then washed again with Ca-free artificial sea water and submerged in 10^{-2} M 5-hydroxytryptamine (5HT). The muscle began to relax within 2 min, and reached full resting state after 5 min (resting state). Thus, we obtained preparations at three states of contraction.

Electron microscopy

Adductors at the three states described above were immediately fixed for electron microscopic observation. Adductors at each state were fixed with 1% osmium-tetroxide and 2% potassium-pyrosulfate in Ca-free artificial sea water, by exchanging the solution in the chamber after the physiological experiment. After 90 min fixation, the adductors were cut into small pieces, and fixed again with osmium-tetroxide/potassium-pyrosulfate solution for 30 min. Fixative without potassium-pyrosulfate was also applied to control specimens at each state. The specimens were next dehydrated by a series of ethanol solutions (70, 80, 90, 100%), and embedded in Epoxy resin, followed by emerging agent QY-1. Embedded and hardened specimens were cut into thin sections and examined in an electron microscope. Some sections were observed after staining with aqueous uranyl acetate, followed by a lead nitrate solution to clarify the cell components.

RESULTS

Bivalve adductors are generally not suitable for physiological experiments of "catch" mechanism, because of difficulties in preparation. However, our preparation technique was successful, and we could prepare adductors which showed typical "catch" contraction similar to that of anterior byssus retractor muscle of mussels (ABRM). Thus, our preparations show the three states of muscle contraction; contracted, "catch" and resting states (Fig. 1).

The sensitivity of Potassium-pyrosulfate in detecting

calcium ion between 0.1 mM to 0.8 mM of concentration was first tested (Fig. 2). The results show it to be sensitive at a range of calcium concentration, producing insoluble and opaque calcium precipitates between 0.1 mM to 0.8 mM concentration in 540 nm of wavelength light. As it is well known that muscle cells come into contracted state at 10 mM calcium concentration, calcium in SRs at resting state and in cytoplasm at contracted state would be detected by our experiment.

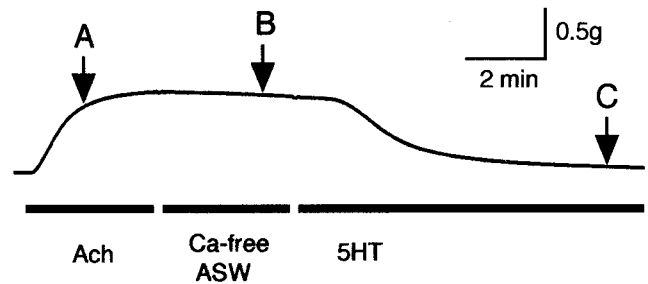


Fig. 1. Time-dependent tension of a "catch" muscle during the contraction-catch-resting cycle. Points of fixation: A, contracted state; B, catch; C, resting.

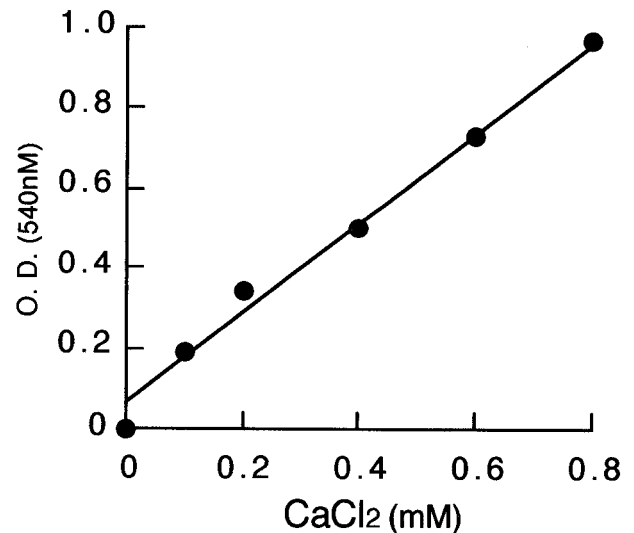


Fig. 2. Optical density of Ca-precipitate by pyrosulfate. This shows pyrosulfate can detect calcium down to 0.1 mM. Optical density (OD) was measured through a 540 nm wavelength filter.

Ultrastructure

General view of muscle cell

Clam adductor "Catch" muscle cells at resting state are oval in cross section, and are loosely connected to neighboring cells (Fig. 3). Cells bearing many myofilaments ran parallel to each other (Fig. 3). Enlarged views of cells revealed more details: small vesicles were observed at the periphery of the cells, and these vesicles were usually attached with cell membranes (Fig. 4). However, no ultrastructural differences among the cells at the three state were observed with respect

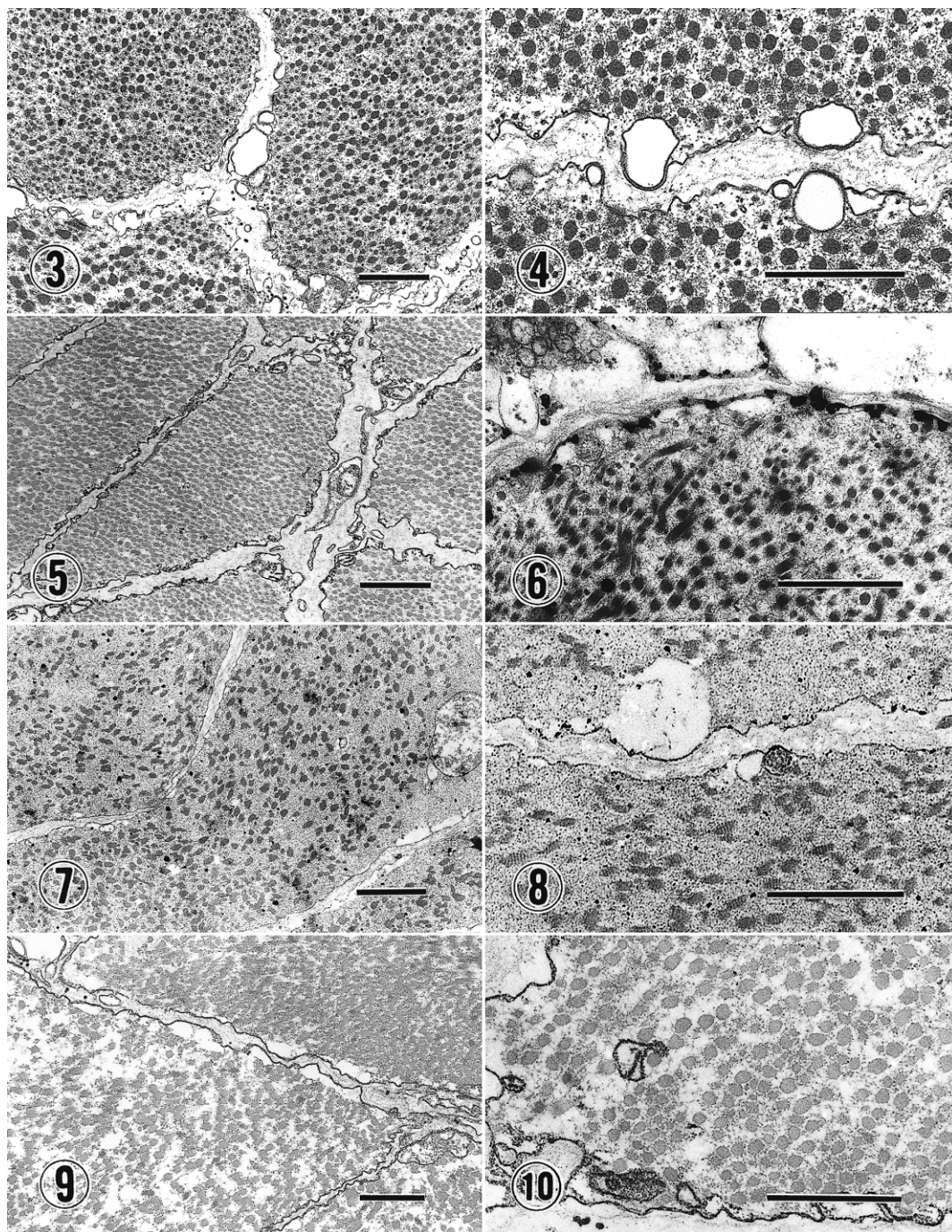


Fig. 3. Electron micrograph of cells in a control cross section at resting state, using fixative without K-pyroantimonate. Cells in the muscle are various diameters, and are connected to each other with thin connective tissue. $\times 6,100$. Scale bar, $2\ \mu\text{m}$.

Fig. 4. Enlarged views of muscle cells prepared as in Fig. 3. Myofilaments are evenly distributed and SRs are situated at cell peripheries. $\times 10,200$. Scale bar, $2\ \mu\text{m}$.

Fig. 5. Electron micrograph of muscle cells in a cross section at resting state. Cells were fixed with osmium and pyroantimonate. Precipitates occur at cell surfaces. $\times 9,600$. Scale bar, $2\ \mu\text{m}$.

Fig. 6. Enlarged views of resting state cells prepared as in Fig. 5. Precipitates are located at SRs and cell membranes. $\times 12,300$. Scale bar, $2\ \mu\text{m}$.

Fig. 7. Electron micrograph of muscle cells at contracted state. Precipitates are translocated throughout the cytoplasm, and precipitates at cell membranes have disappeared. $\times 11,500$. Scale bar, $2\ \mu\text{m}$.

Fig. 8. Enlarged view of muscle cells at contracted state. No precipitates occur at SRs and cell membranes. $\times 15,600$. Scale bar, $1\ \mu\text{m}$.

Fig. 9. Electron micrograph of muscle cells at "catch" state. Precipitates in the cytoplasm are decreased, but have not disappeared. $\times 8,700$. Scale bar, $2\ \mu\text{m}$.

Fig. 10. Enlarged views of cells at "catch" state. Precipitates at SRs and cell membranes are more abundant than in contracted state, but are fewer than in resting state. $\times 30,400$. Scale bar, $0.5\ \mu\text{m}$.

to diameter. The differences in diameter do not represent the degree of contraction in each state, but simply shows that the cells are large or small.

Resting state: The pyroantimonate precipitates at resting state of “catch” muscle cells were mainly located at cell peripheries (Fig. 5). Enlarged views showed the precipitates occurred mainly at the inner surface of the cell membrane and in the inner spaces of vesicles (SRs) associated with the cell membrane (Fig. 6). They were occasionally observed on the membranes of mitochondria (Fig. 5). The precipitates varied from about 20 nm to 150 nm in diameter. Larger precipitates were often concentrated in SRs or near the cell membranes (Fig. 6).

Contracted state: Pyroantimonate precipitates are dispersed evenly throughout the cytoplasm at contracted state, and are smaller than those in the resting state (Fig. 7). Enlarged views also showed that precipitates at SRs had disappeared, and those at cell membranes decreased in abundance (Fig. 8).

Catch state: Pyroantimonate precipitates were recognized at cell membranes, SRs and adjacent to mitochondria (Fig. 9), but those in cytoplasm had disappeared (Fig. 9). Beside these contrasts in precipitate location between the catch and contracted state, a clear difference can also be seen in precipitate size. Precipitates in the contracted state are larger than those of the “catch” state (Figs. 8 and 10).

Counting of Ca-precipitates

To confirm quantitative differences in translocation of precipitates in cells of each state, precipitates (50–130 nm in diameter) were counted from micrographs. We classified the locations of precipitates into three regions: cytoplasm, SRs and cell membranes. The results show pyroantimonate precipitates are located in characteristic areas in the cells at each

state (Fig. 11). At resting state, approximately 80% of the precipitates were located at cell membranes, with the rest evenly divided between SRs and cytoplasm. In contrast, at contracted state 93% were dispersed in the cytoplasm. At catch state, the percentage in the cytoplasm falls to 47%, with 42% at cell membranes, and 11% at SRs.

DISCUSSION

Hauck and Achazi (1987) considered that a major cause of “catch” state was that thick filaments in the cell were attached to each other by fused paramyosin molecules during “catch” contraction. However, it is more probable that the contraction is based on cross-bridges between thick myosin and thin actin filaments (Bennett and Elliott, 1989), and the cycle of cross-bridges is delayed by phosphorylation of myosin molecules (Achazi, 1979; Cohen and Castellani, 1988).

On the other hand, it is important to remember that muscle contraction is regulated by calcium: that is, muscle contracts with activation of cross-bridges triggered by calcium, and come into resting state through the reverse process. At the resting state, calcium is restored to the SRs. Ishii *et al.* (1989a) measured free calcium concentration in cytoplasm at resting and contracted states of “catch” muscle using fluorescent calcium indicator fura-2. They concluded that high calcium concentration is not required for maintenance of “catch” tension, and that free calcium concentration is close to resting values during the “catch” state (Ishii *et al.*, 1989b).

The condition (free or bound) in which calcium occurs in cytoplasm during “catch” state is not yet clear. It is very difficult to measure calcium concentrations in muscle cells, because living cells change their physiological conditions dynamically. Accordingly, we measured calcium translocation using the K-pyroantimonate method. The method used was modified from that reported by Sugi and Daimon (1977). As shown in Fig. 1, 2% K-pyroantimonate can detect calcium as low concentration as 10^{-5} M. These results agree well with a previous report on K-pyroantimonate sensitivity (Wick and Hepler, 1982), and the method we used gives a reliable indication of where Ca is located in the cells. We did not analyze the electron-dense precipitates to verify that they do contain Ca, as this has already been established by previous x-ray microanalysis of similar precipitates (Sugi and Daimon, 1977; Sugi *et al.*, 1982).

Studies similar to ours have been reported from many kinds of muscle cells. This work suggests that Ca-pyroantimonate precipitates are located around the cytoplasm when the cells are at contracted state, and in the SRs when at resting state (Sugi and Daimon, 1977; Suzuki and Sugi, 1978; Sugi *et al.*, 1982; Suzuki, 1982). Some studies also report numbers of “catch” muscle cells using such methods (Atsumi *et al.*, 1974; Atsumi and Sugi, 1976), but few identify quantitative translocation of precipitates during “catch” contraction.

Our examination of the location of precipitates at resting and contracted states show similar translocation to that reported previously. However, our results show about half the

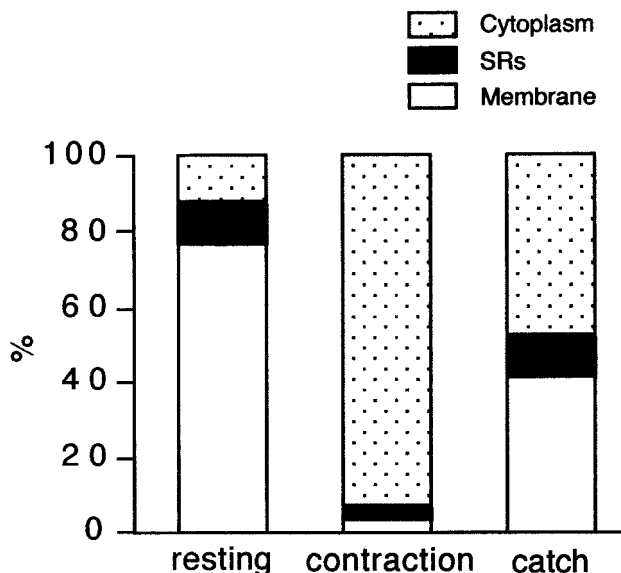


Fig. 11. Precipitate distribution in the cell at each state of contraction.

precipitates remain in the cytoplasm during "catch" contraction. Atsumi and Sugi (1976) observed decrease of myoplasmic free calcium during the "catch" state, and concluded that the "catch" contraction may be maintained under much lower myoplasmic free Ca ion concentration than active contraction. Our observations that less than 50% of precipitates remain in the cytoplasm during "catch" contraction differ from physiological reports using fluorescent fura-2, which apparently showed that free calcium in cytoplasm was close to resting values during the "catch" state (Ishii *et al.*, 1989a). This difference arises because Ishii *et al.* (1989a) measured only free calcium in the cytoplasm, and did not detect calcium bound with Ca-binding proteins such as myosin and calmoduline, whereas our measurements include both free and bound calcium. We suspect that bound calcium is more important than free calcium in maintaining the "catch" contraction, but it is not yet clear how and why the calcium functions during the "catch" contraction.

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