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2 **To be submitted to Journal of Food Science**

3 **JFS2005-0240-R1**

4 **Ca²⁺ Affects Physicochemical and Conformational Changes of**
5 **Threadfin Bream Myosin and Actin in a Setting Model**

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10 **Running head: Effect of Ca²⁺ on conformation of myosin**

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Abstracts

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The effect of Ca^{2+} on physicochemical and conformational changes of threadfin bream (TB) myosin and actin during setting at 25 and 40 °C was investigated. Ca^{2+} ion at 10-100 mM induced the unfolding of myosin and actin as evident by an increase of surface hydrophobicity (S_0 , ANS) at 40 °C. Total SH groups also decreased with an increased Ca^{2+} concentration, suggesting that Ca^{2+} promoted the formation of disulfide bonds during setting at 40 °C. Both hydrophobic interactions and disulfide linkages were involved in formation of myosin aggregates at 40 °C, and were enhanced by addition of 10-100 mM Ca^{2+} . Myosin Ca-ATPase activity decreased at $\text{Ca}^{2+} > 50$ mM, indicating conformational changes of myosin head. Circular dichroism spectra demonstrated that Ca^{2+} reduced the α -helical content of myosin and actin incubated at either 25 or 40 °C. Ca^{2+} induced conformational changes of TB myosin and actin incubated at 40 °C to a greater extent than at 25 °C.

Key words: Threadfin bream, myosin, actin, calcium, setting

Introduction

When fish muscle proteins are grounded with 2- 4 % salt and pre- incubated at 4- 40 °C for a period of time prior to heating, an increase in gel elasticity is observed. Such phenomenon is known as “setting” or “suwari” in Japanese (Lanier 2000). It has been generally accepted that setting is mainly attributed from the activity of endogenous transglutaminase (TGase), the Ca^{2+} -dependent enzyme (Kumazawa and others 1995; Benjakul and others 2004). The enzyme catalyzes an acyl transfer reaction between γ -carboxy amide groups of glutamyl residues in proteins as the acyl donor and variety of primary amines as the acyl acceptor (Folk 1980). The formation of ϵ -(γ -glutamyl) lysyl isopeptide bonds between glutamine (acyl donors) and lysine (acyl acceptor) resulted in a covalent cross-linking of muscle proteins.

Addition of Ca^{2+} has been reported to improve textural properties of Pacific whiting, threadfin bream, and Alaska pollock surimi (Lee and Park 1998; Yongsawatdigul and others 2002). Gel enhancing effect is more evident when sample is subjected to setting. It has been typically believed that Ca^{2+} improves gel-forming ability of fish proteins by activating fish endogenous TGase (Lanier 2000). However, Ca^{2+} is also known as a destabilizing salt in the Hofmeister series (Baldwin, 1996). Binding of Ca^{2+} to proteins prevents the salt exclusion, resulting in a decrease of preferential hydration and destabilized structure (Arakawa and Timasheff 1984). The effects of Ca^{2+} on structural changes of various proteins have been reported. Ca^{2+} solubilized rabbit myofibrillar proteins by salting-in effect (Taylor and Etherington 1991). Tertiary and secondary structure of α -crystallin decreased in the presence of Ca^{2+} (Valle and others 2002). Moreover, binding of Ca^{2+} to β -lactoglobulin induced partial unfolding which led

1 to an increased hydrophobicity during gelation (Jeyarajah and Allen 1994). Therefore,
2 Ca^{2+} could also have a direct effect on structure of muscle proteins, which could affect
3 gelation during setting. The role of Ca^{2+} on such conformation changes of fish protein
4 has not been thoroughly investigated.

5 Ogawa and others (1995) found that the unfolding of actomyosin as measured by
6 a decrease in α -helicity was a pre-requisite to initiate setting of actomyosin.
7 Hydrophobic interactions were also responsible for aggregate formation of cod and
8 herring myosin during setting at 40 °C (Gill and others 1992). In addition, formation of
9 disulfide bonds was noticed during setting of herring myofibrillar proteins (Chan and
10 others 1995). These studies suggested that other bondings, besides ϵ -(γ -glutamyl) lysyl
11 isopeptide bonds, were involved in setting. However, the effect of Ca^{2+} on hydrophobic
12 interactions and disulfide linkages of fish myosin and actin during setting have not been
13 elucidated.

14 Threadfin bream (*Nemipterus spp.*) is the second largest resource used for surimi
15 production, after Alaska pollock. Thailand is one of the major threadfin bream surimi
16 producers in the world with an approximate annual production of over 80,000 metric
17 tons. Despite of its large production quantity and value, scientific information related to
18 setting phenomenon is still limited. Understanding the role of Ca^{2+} ion on
19 conformational changes of myosin and actin would be critical knowledge for improving
20 textural properties of surimi gels from threadfin bream and other warm water species.
21 Therefore, our objectives were to investigate the effects of CaCl_2 on physicochemical and
22 conformational changes of threadfin bream myosin and actin during incubated at 25 and
23 40 °C, typical setting temperatures of fish proteins.

Materials and Methods

Fish sample

Threadfin breams (TB) (*Nemipterus bleekeri*) were caught off the Gulf of Thailand at Rayong province. Fish were immediately transported to a Suranaree University of Technology laboratory in polystyrene boxes packed with ice. Fish were manually eviscerated upon arrival and kept on ice. Myosin preparation was carried out 24 h after catch.

Myosin Preparation

Myosin was purified according to the method of Martone and others (1986) with slight modifications. All steps were performed at 0-4 °C to minimize proteolysis and protein denaturation. TB mince was added with 10 volumes of buffer A (0.10 M KCl, 1 mM phenylmethanesulfonyl fluoride (PMSF), 0.02 % NaN₃ and 20 mM Tris-HCl, pH7.5) and homogenized at 15,000 rpm for 2 min in a homogenizer (AM-8, Nihonseiki Kaisha, Ltd., Tokyo, Japan). The homogenate was stirred for 10 min and centrifuged at 1,000×g (Sorvall RC-5C Plus, Dupont, Del., USA) for 10 min. The pellet was collected and washed with the same buffer twice. The washed pellet was subsequently extracted with 5 volumes of buffer B (0.45 mM KCl, 5 mM β-mercaptoethanol (BME), 0.2 M Mg (CH₃COO)₂, 1 mM ethylene glycol bis (β-aminoethyl ether) N,N,N',N'- tetraacetic acid (EGTA), and 20 mM Tris-maleate, pH, 6.8). Adenosine 5'-triphosphate (ATP) was added to a final concentration of 15 mM. The mixture was kept for 1 h with stirring on ice and then centrifuged at 10,000×g for 15 min. Pellets were collected for actin preparation. Twenty five volumes of 1 mM NaHCO₃ was slowly added to the

1 supernatant and kept on ice for 30 min. The precipitate was recovered by centrifugation
2 at 12,000×g for 15 min. The pellet was resuspended with 5 volumes of buffer C (0.50 M
3 KCl, 5 mM BME, and 20 mM Tris-HCl, pH7.5) and homogenized for 30 s. The solution
4 was kept on ice for 10 min and MgCl₂ was added to a final concentration of 10 mM.
5 Myosin was obtained by ammonium precipitation at 40-50 % saturation. The myosin
6 pellet was kept at -40 °C and used throughout the study. The purity of extracted myosin
7 was estimated using sodium dodecylsulfate polyacrylamide gel electrophoresis (SDS-
8 PAGE) with densitometric analysis (Lab works Version 4.0,UVB Ltd., New York, USA).
9 Before used, myosin pellet was dissolved in 0.6 M NaCl, 20 mM Tris-maleate, pH 7.0
10 and dialyzed against 100 volumes of the same solution. Dialyzed myosin was clarified by
11 centrifugation at 10,000×g for 15 min and used as myosin solution. Protein
12 concentrations were determined by Lowry and others (1951).

13

14 **Actin Preparation**

15 Actin pellet was added with buffer D (0.80 M KCl, 5 mM BME, 20 mM Tris-
16 HCl, pH 7.5) and stirred for 30 min before centrifugation at 10,000×g for 15 min. The
17 pellet was collected and added with 5 volumes of 2 mM NaHCO₃. The mixture was
18 stirred on ice for 1 h and centrifuged at 75,000×g for 1 h. The supernatant was used as
19 actin preparation. Actin was dialyzed against 0.6 M NaCl, 20 mM Tris-maleate, pH 7.0.
20 Dialyzed actin solution was concentrated by ultrafiltration using molecular weight-cut-
21 off 10,000 Da membrane (Viva flow 50, Vivascience Sartorius AG, Goettingen,
22 Germany). Purity of actin was estimated using SDS-PAGE and densitometric analysis.

23

1 **Turbidity measurement**

2 Myosin (3 mg/mL) and actin (1.5 mg/mL) solutions were solubilized in 0.6 M
3 NaCl, 20 mM Tris-maleate, pH 7.0 containing 0, 10, 30, 50 and 100 mM CaCl₂.
4 Turbidity at 25 and 40 °C were monitored at 350 nm using UV/VIS 916
5 spectrophotometer (GBC Scientific Equipment, Ltd., Victoria, Australia.) equipped with
6 a circulating water bath set at either 25 or 40 °C. Turbidity changes at 25 and 40 °C were
7 monitored at each time interval for 4 and 2 h, respectively.

8

9 **Aggregation of TB myosin and actin**

10 Myosin (3.2 mg/mL) and actin (1 mg/mL) solutions containing 0-100 mM CaCl₂
11 were incubated at either 25 or 40 °C for 4 and 2 h, respectively. Subsequently, samples
12 were centrifuged at 84000×g for 1 h (XL-100 Ultracentrifuge, Beckman instruments, Inc.,
13 California, USA) to precipitate large aggregates. Protein concentrations in supernatants
14 were determined by dye binding method due to interference of CaCl₂ with Lowry method
15 (Bradford 1986). Bovine serum albumin (BSA) was used as a standard. Remaining
16 proteins (%) was expressed as a ratio of protein remained in the supernatant at any CaCl₂
17 concentrations to that of sample without CaCl₂ at 4 °C.

18

19 **Surface hydrophobicity (S₀)**

20 Changes of S₀ were monitored using 1-anilino-8-naphthalenesulfonate (ANS)
21 according to the method of Li-Chan and others (1985) with slight modifications. Myosin
22 and actin were diluted to various protein concentrations: 0, 0.125, 0.25, 0.5 and 1 mg/mL
23 in the presence of 0-100 mM CaCl₂ and incubated at either 25 or 40 °C for 4 and 2 h,

1 respectively. To 2.0 mL of diluted myosin and actin, 10 μ L of 10 mM ANS dissolved in
2 20 mM Tris-maleate (pH 7.0) was added. Fluorescence intensity (FI) was measured
3 using a RF-1501 spectrofluorophotometer (Shimadzu, Kyoto, Japan) at an excitation
4 wavelength of 374 nm and an emission wavelength of 485 nm. Blanks were prepared
5 without protein solution. The regression slope between FI and protein concentrations (%)
6 was calculated as S_0 ANS.

7

8 **Total sulfhydryl groups (SHs)**

9 Total SH groups of myosin and actin were determined using 5,5'-dithiobis(2-
10 nitrobenzoic acid), (DTNB). Myosin (3 mg/mL) and actin (1 mg/mL) solutions
11 containing 0, 10, 30, 50 and 100 mM CaCl_2 were incubated at 25 and 40 $^\circ\text{C}$ for 4 and 2 h,
12 respectively. Then, 1.5 mL of 0.2 M Tris-HCl (pH 6.8) containing 8 M urea, 2 % SDS
13 and 10 mM EDTA was added. Subsequently, 0.2 mL of 0.1% DTNB solution were
14 added to all samples before incubated at 40 $^\circ\text{C}$ for 15 min and absorbance at 412 nm was
15 measured. Total SH content was calculated using molar extinction of $13600 \text{ M}^{-1} \text{ cm}^{-1}$ for
16 myosin (Ellman, 1959). Molar extinction of actin used for the calculation was 12508 M^{-1}
17 cm^{-1} , which was obtained using standard L-cysteine. Blanks were performed without
18 protein solution.

19

20 **Ca-ATPase activity**

21 Ca-ATPase activity of myosin was estimated using the method described by
22 MacDonald and others (1994). The reaction was carried out at 1.5 mg of myosin, 17 mM
23 Tris-maleate, pH 7.0 at 0-200 mM CaCl_2 concentrations. The mixtures were incubated at

1 25 °C for 5 min. ATP was added to final concentration of 0.67 mM and samples were
2 incubated for 10 min. To stop the reaction, chilled TCA was added to final concentration
3 of 5 % and samples were centrifuged at 3,000×g for 10 min. The supernatant was
4 collected for inorganic phosphate (Pi) determination using KH_2PO_4 as a standard. Ca-
5 ATPase activity was expressed as $\mu\text{mole of Pi/mg protein/min}$ at 25 °C.

6 7 **Circular dichroism (CD)**

8 The effect of CaCl_2 on secondary structural changes of myosin and actin were
9 analyzed using CD measurement. Myosin and actin were dissolved in 0.6 M NaCl, 20
10 mM Tris-HCl, pH 7.0 due to strong UV absorption of Tris-maleate buffer. Myosin and
11 actin solutions (0.25 mg/mL) containing CaCl_2 (0-100 mM) were incubated at either 25
12 or 40 °C for 4 and 2 h, respectively. Samples were scanned at far UV (195-280 nm)
13 using a JASCO PS-150J spectropolarimeter (Jasco spectroscopic Co, Ltd., Tokyo, Japan)
14 equipped with a circulating water bath set at each respective incubating temperature. CD
15 spectra of samples without incubation were also measured at 4 °C. The instrument was
16 calibrated using (1S)-(+)-10-camphorsulfonic acid (CSA). The circular quartz cuvette
17 (0.02 cm path length) was used. Resolution was set at 1 nm, bandwidth was 2 nm,
18 sensitivity 50 mdeg, response 2 s and scanning speed was 50 nm/min. Molar mean
19 ellipticity $[\theta]$ and α -helical content from $[\theta]$ at 222 nm was calculated according to
20 Ogawa and others (1993).

21 22 **Results and Discussion**

23 **Effect of CaCl_2 on aggregation of myosin and actin**

1 Purity of myosin was estimated to be 90-91%. Four minor contaminated bands
2 with Mw of 43, 37, 34, and 27 kDa were observed in myosin (Figure 1). The 43 and 37
3 kDa bands were possibly actin and tropomyosin, respectively. TB actin showed
4 molecular weight of 43 kDa and exhibited high purity (>97%). Ca-ATPase activity of
5 purified myosin at 3.3 mM CaCl₂ was 0.220 μmole Pi/mg protein/min.

6 Low concentrations of CaCl₂ (0-50 mM) did not affect turbidity of myosin
7 solution incubated at 25 °C for 4 h, while 100 mM CaCl₂ increased turbidity of myosin at
8 25 °C (Figure 2a). Gill and others (1992) demonstrated that an increase in turbidity of
9 heated fish myosin solution was the direct result of formation of myosin aggregates.
10 Therefore, aggregation of TB myosin was enhanced at 25 °C in the presence of 100 mM
11 CaCl₂. Moreover, aggregation of TB myosin occurred to a greater extent at 40 °C than at
12 25 °C (Figure 2b). Turbidity of actin solution incubated at 25 °C sharply increased with
13 CaCl₂ concentration, especially at 50 and 100 mM CaCl₂ (Figure 2c). Aggregation of
14 actin dramatically increased when incubated in the presence of 10 mM CaCl₂ at 40 °C.
15 However, a further increase of CaCl₂ from 30 to 100 mM did not increase actin
16 aggregation (Figure 2d). Actin appeared to aggregate to a greater extent than myosin
17 even at lower protein concentration.

18 Large protein aggregates tend to precipitate under high centrifugal force. TB
19 myosin incubated at 25 °C did not form large aggregates that could be precipitated under
20 centrifugation at any studied levels of CaCl₂ (Figure 3a). In contrast, precipitation of
21 myosin was observed when incubated at 40 °C and the extent of aggregation appeared to
22 increase with CaCl₂ (10-100 mM). Based on turbidity results, TB myosin appeared to
23 form soluble aggregates at 25 °C, while large aggregates were formed at 40° C. Since

1 denaturation temperature (Td) of TB actomyosin was about 35 °C (Yongsawatdigul and
2 Park 2003), TB myosin subjected to 40 °C could unfold and re-associate to form
3 aggregates. Addition of 10-100 mM CaCl₂ further promoted myosin aggregation. These
4 myosin aggregates were unlikely to be resulted from the catalytic reaction of endogenous
5 TGase because the enzyme was mainly removed during extensive washing and
6 precipitation steps of myosin purification. This was evident by the absence of
7 nondisulfide covalent cross-links of myosin when incubated at either 25 or 40 °C to
8 induce endogenous TGase (data not shown).

9 Actin readily precipitated even at 4 °C without CaCl₂ (Figure 3b). The extent of
10 actin aggregation also increased with temperature. Similar to myosin, actin aggregation
11 was also enhanced by CaCl₂. The extent of aggregation monitored by ultracentrifugation
12 corresponded with changes of turbidity. Moreover, aggregation of actin was completely
13 attained when incubated at 10-100 mM CaCl₂ at 40 °C for 2 h (Figure 3b). These results
14 indicated that Ca²⁺ induced aggregation of TB myosin and actin when incubated at 40 °C
15 to a greater extent than at 25 °C.

16

17 **Effect of CaCl₂ on surface hydrophobicity (S₀ ANS) of myosin and actin**

18 S₀ ANS of myosin slightly increased with CaCl₂ concentration at all studied
19 temperatures (Figure 4a), indicating that Ca²⁺ promoted the unfolding of myosin. It was
20 noted that changes in S₀ ANS of myosin incubated at 25 °C for 4 h were similar to those
21 incubated at 40 °C, but higher than those at 4 °C (Figure 4a). It should be noted that TB
22 myosin only form soluble aggregates at 25 °C (Figure 3a). Incubation of myosin at 25 °C
23 was far below Td of tropical fish myosin, which has been reported to be 37- 43 °C (Sano

1 and others 1990). Limited unfolding of myosin at 25 °C would restrict intermolecular
2 entanglement via any interactions, resulting in formation of soluble aggregates, rather
3 than large aggregates.

4 At 40 °C, myosin molecules underwent partial unfolding due to thermal
5 denaturation. The partial unfolded molecules exposed the previously buried hydrophobic
6 groups to the aqueous environment, which subsequently re-associated via hydrophobic
7 interactions. As a result, large aggregate formation at 40 °C was evident (Figure 3a).
8 Hydrophobic interactions of unfolded molecules would reduce ANS-binding capacity.
9 This explained why S_0 ANS at 40 °C was comparable to that at 25 °C in spite of the
10 greater extent of unfolding occurred at 40 °C. Lanier (2000) suggested that hydrophobic
11 interactions participated in gelation during setting. Thus, Ca^{2+} ion induced the unfolding
12 of myosin, which could in turn enhance hydrophobic interactions among myosin
13 molecules during setting.

14 S_0 ANS of actin also increased with $CaCl_2$ concentration and exhibited higher
15 values than those of myosin at all temperature studied (4, 25 and 40 °C) (Figure 4b).
16 This may be partly due to the inactivation of actin by EGTA used in actin extraction
17 (Turoverov and others 1999). The inactivated actin tended to expose hydrophobic
18 clusters on the surface and showed high affinity to hydrophobic probes (Lehrer 1972).
19 Moreover, existence of large hydrophobic groups on the surface led to self-association of
20 actin monomers (Mazhul and others 2003). Thus, the greater extent of aggregation and
21 exposure of surface hydrophobicity was observed in actin. Transformation of native G-
22 actin to inactivated form resulted in partial unfolded structure, which was more prone to

1 denaturation. Our study showed that Ca^{2+} induced more open structure of inactivated
2 actin, leading to the aggregate formation via hydrophobic interactions.

3 4 **Effect of CaCl_2 on total SH groups of myosin and actin**

5 Total SH groups of myosin and actin in the absence of CaCl_2 at 4 °C were $\approx 6 \times$
6 10^{-5} and 5×10^{-5} mole /g protein, respectively. When myosin was incubated at 40 °C
7 for 2 h, total SH groups decreased to $\approx 4.8 \times 10^{-5}$ mole /g protein as a result of thermal
8 denaturation. In the presence of Ca^{2+} ion, SH groups of myosin incubated at all studied
9 conditions continuously decreased as CaCl_2 concentration increased (Figure 5a). A
10 marked decrease in SH group was observed when incubated at 40 °C for 2 h. The similar
11 trend was also observed in actin (Figure 5b). These results indicated that Ca^{2+} induced
12 the formation of disulfide linkages of both myosin and actin when incubated at 40 °C.
13 The unfolding of myosin and actin induced by CaCl_2 resulted in an exposure of free SH
14 groups, which subsequently underwent disulfide interchanges. Similar effect of CaCl_2 on
15 the formation of disulfide linkages and hydrophobic interactions were also found in α -
16 crystallin molecules (Valle and others 2002). It should be noted that the extent of
17 disulfide bond formation at 40 °C was greater than that at 25 °C (Figure 5a). It was,
18 therefore, speculated that disulfide bond might be partly responsible for aggregation of
19 myosin set at 40 °C. Addition of CaCl_2 to fish protein paste induced hydrophobic
20 interactions and disulfide linkages of myosin and actin at 40 °C to a greater extent than at
21 25 °C. Besides ϵ -(γ -glutamyl) lysyl isopeptide bonds catalyzed by Ca^{2+} - dependent
22 endogenous TGase, hydrophobic interactions and disulfide linkages could be involved
23 during setting of fish protein.

1 When Ca^{2+} ion was not added, setting phenomenon at 25 °C was not observed in
2 surimi made from tropical fish (Kamath and others 1992; Klesk and others 2000). The
3 existing explanation was that tropical fish exhibited higher thermal stability that limited
4 the exposure of reactive groups on myosin molecule for TGase catalytic reaction.
5 However, Yongsawatdigul and others (2002) reported the setting of TB surimi at 25 °C
6 when 0.1% CaCl_2 (≈ 10 mM) was added. Our study revealed that addition of Ca^{2+} ion
7 (≥ 10 mM) increased more exposure of hydrophobic amino groups and more disulfide
8 linkages of myosin and actin, which subsequently contributed to setting phenomenon of
9 TB at 25 °C.

10

11 **Effect of CaCl_2 on Ca-ATPase activity of myosin**

12 Ca-ATPase activity of myosin slightly increased and reached the maximum at 50
13 mM CaCl_2 (Table 1). Further increase of CaCl_2 concentration dramatically reduced Ca-
14 ATPase activity. Ca-ATPase activity at 200 mM CaCl_2 was about 36 % of that at 50 mM
15 CaCl_2 . High level of CaCl_2 (> 50 mM) induced conformational changes of globular head
16 of myosin, resulting in a decrease of Ca-ATPase activity. The exposure of hydrophobic
17 and changes of total SH groups at $\text{CaCl}_2 < 50$ mM was likely to occur at myosin rod,
18 while both globular and rod portions underwent such changes at high CaCl_2 concentration
19 (> 50 mM).

20 Binding of Ca^{2+} to anionic sites on protein structure can induce the unfolding.
21 These binding interactions prevent salt exclusion from protein structure and decrease
22 preferential hydration of salts, resulting in salting-in and destabilization of protein
23 structure (Arakawa and Timasheff 1984). Myosin contained negative charges at pH 7

1 because pI of myosin is around 4.8-6.2 (Stefansson and Hultin 1994). Thus, the ionic
2 interactions between Ca^{2+} and negatively charged myosin might be responsible for
3 disturbance of native myosin molecules. Ca^{2+} also induced aggregation of β -
4 lactoglobulin (theoretical net charge, $Z = -8$) by selective binding to carboxylated anions
5 (Simons and others 2002). For myosin, most negative charges are located at myosin rod
6 ($Z = -34$ to -52) and followed by myosin light chains ($Z = -6$ to -27), while globular head
7 myosin has positive charges ($Z = 6$ to 16) (Bechet and Albis 1989). Therefore, Ca^{2+} was
8 more likely to bind to myosin rod than the globular head. For this reason, the rod portion
9 was more susceptible to conformational changes induced by Ca^{2+} ion.

11 **Effect of CaCl_2 on CD spectra of myosin and actin**

12 CD spectra in far UV region of myosin showed predominant α -helix structure
13 (Figure 6a). CaCl_2 promoted the loss of secondary structure of both myosin and actin
14 even at 4 °C (Figure 6a,b). The helical content of myosin at 4 °C without CaCl_2 was
15 71.2% and decreased to 51.4% in the presence of 100 mM CaCl_2 (Figure 7a). The helical
16 content of myosin incubated at 25 °C for 4 h was slightly decreased with increasing
17 CaCl_2 concentration. In contrast, CaCl_2 markedly decreased helical content of myosin
18 incubated at 40 °C for 2 h (Figure 7a). Both thermal energy and CaCl_2 synergistically
19 contributed to unfolding of myosin at 40 °C, leading to considerable loss of helical
20 structure. Ogawa and others (1995) reported that loss of helical structure of fish
21 actomyosin was a pre-requisite to initiate setting. Therefore, addition of CaCl_2
22 accompanied by incubating at 40 °C enhanced myosin unfolding, which subsequently

1 resulted in a higher degree of hydrophobic interactions and formation of disulfide
2 linkages.

3 Low helical content (28.73 %) was observed in actin at 4 °C (Figure 7b). Nagy et
4 al. (1972) reported that actin contained 30% α -helix structure, 10% of β -sheet and the
5 remaining residues did not appear to contribute to the optical activity (1972). α -Helical
6 content of actin decreased when incubated at 25 °C in the presence of 10 mM CaCl_2 .
7 However, further increase of CaCl_2 from 30 to 100 mM did not further decrease helical
8 content of actin. Moreover, α -helical structure of actin incubated at 40 °C for 2 h was
9 completely destroyed at 10 mM CaCl_2 . These results suggested that CaCl_2 at ≥ 10 mM
10 also induced the changes of secondary structure of actin.

11

12 **Conclusions**

13 Ca^{2+} ion induced conformational changes of TB myosin and actin leading to
14 partial unfolding and exposure of hydrophobic amino acids. The unfolded molecules
15 subsequently aggregated via hydrophobic interactions and disulfide linkages when
16 incubated at either 25 or 40 °C. Such interactions could be important in gel-forming of
17 TB during setting. Thus, CaCl_2 did not only enhance gelling properties of TB myosin
18 through activating endogenous TGase but also directly induce conformational changes of
19 myosin and actin, promoting hydrophobic interactions and disulfide linkages of “set” gel.

20

21 **Acknowledgements**

22

1 This research was financially supported by Thailand Research Fund (TRF) under
2 grant RSA/15/2545 and the Royal Golden Jubilee Scholarship. We would like to thank
3 Dr. Chartchai Kritanai of the Institute of Molecular Biology and Genetics at Mahidol
4 University, Salaya, Thailand, for his invaluable help on CD measurement and analysis.

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Figure legends

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Figure 1. SDS-PAGE patterns of TB myosin and actin. S= molecular weight standard, MI= TB mince, MY₁ and MY₂ = myosin from lot 1 and lot 2, respectively. AC₁ and AC₂ = actin from lot 1 and lot 2, respectively. MHC= myosin heavy chain, LC = myosin light chains.

Figure 2. Effect of CaCl₂ on turbidity of TB myosin and actin incubated at either 25 or 40 °C in 0.6 M NaCl, 20 mM Tris-maleate, pH 7.0: myosin at 25 °C (a), myosin at 40 °C (b), actin at 25 °C (c), and actin at 40 °C (d).

Figure 3. Remaining protein contents of TB myosin (a) and actin (b) at varied CaCl₂ concentration after centrifugation at 78,000 ×g for 1 h.

Figure 4. Effect of CaCl₂ on the changes in S₀ ANS of TB myosin (a) and actin (b) in 0.6 M NaCl, 20 mM Tris-maleate, pH 7.0.

Figure 5. Effect of CaCl₂ on the changes in total SH groups of TB myosin (a) and actin (b) in 0.6 M NaCl, 20 mM Tris-maleate, pH 7.0.

Figure 6. Effect of CaCl₂ on CD spectra of TB myosin (a) and actin (b) in 0.6 M NaCl, 20 mM Tris-HCl, pH 7.0 at 4 °C.

Figure 7. Effect of CaCl₂ on the changes in α-helical contents of TB myosin (a), and actin (b).

1

2 Table 1. Ca-ATPase activity of TB myosin determined at various CaCl₂ concentrations
3 at 25 °C.

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CaCl ₂ concentration (mM)	Ca-ATPase activity (μ mole Pi/mg protein/min)
0	0
3.3	0.274 ± 0.025
10	0.297 ± 0.013
30	0.313 ± 0.023
50	0.299 ± 0.010
100	0.229 ± 0.011
150	0.185 ± 0.020
200	0.106 ± 0.019

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