Calpastatin subdomains A and C are activators of calpain

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The inhibitory domains of calpastatin contain three highly conserved regions, A, B and C, of which A and C bind calpain in a strictly Ca\textsuperscript{2+}-dependent manner but have no inhibitory activity whereas region B inhibits calpain on its own. We synthesized the 19-mer oligopeptides corresponding to region A and C of human calpastatin domain I and tested their effect on human erythrocyte \( \mu \)-calpain and rat m-calpain. The two peptides significantly activate both calpains: the Ca\textsuperscript{2+} concentration required for half-maximal activity is lowered from 4.3 to 2.4 \( \mu \)M for \( \mu \)-calpain and from 250 to 140 \( \mu \)M for m-calpain. The EC\textsubscript{50} concentration of the peptides is 7.5 \( \mu \)M for \( \mu \)-calpain and 25 \( \mu \)M for m-calpain. It is noteworthy that at low Ca\textsuperscript{2+} concentrations (1-2 \( \mu \)M for \( \mu \)-calpain and 70-110 \( \mu \)M for m-calpain) both enzymes are activated about tenfold by the peptides. Based on these findings, it is suggested that calpastatin fragments may have a role in calpain activation \textit{in vivo}. Furthermore, these activators open new avenues to cell biological studies of calpain function and eventually may alleviate pathological states caused by calpain malfunction.
Introduction

Calpains represent a superfamily of proteases related by their homology in a papain-like protease domain (1,2). Several members of this family, such as the best studied typical forms, \( \mu \)- and \( m \)-calpain, are thought to be activated by a \( {\text{Ca}}^{2+} \) signal; their activation then leads to the limited proteolytic modification of a variety of substrate proteins. Recent X-ray crystallographic studies of rat (3) and human (4) \( m \)-calpain have revealed the structural background of the \( {\text{Ca}}^{2+} \)-dependence of calpain activity. Without \( {\text{Ca}}^{2+} \) the structure of the active site is distorted; large-scale conformational changes have to occur for the assembly of a catalytically competent active site. Although mechanistically clear, key aspects of the activation process \textit{in vivo} are still enigmatic as calpains require non-physiologically high \( {\text{Ca}}^{2+} \) concentrations \textit{in vitro}; \( \mu \)- and \( m \)-calpains reach half-maximal activation in the high \( \mu \text{M} \) to mM free \( {\text{Ca}}^{2+} \) concentration range (cf. (5)), hardly attainable under normal cellular conditions.

Several suggestions have been put forward how to close this gap. First, calpain undergoes autolytic activation with a concomitant sensitization to \( {\text{Ca}}^{2+} \) (5,6); this, of course, does not alleviate the initial high \( {\text{Ca}}^{2+} \) requirement. Second, phospholipids increase calcium sensitivity of calpain (7,8) and activation probably involves the translocation of the enzyme to the plasma membrane (9,10). Third, calpain might also be sensitized to \( {\text{Ca}}^{2+} \) by a specific activator protein that affects membrane localization and autolysis of the enzyme (11). Nuclear DNA, shown to promote calpain effect on transcription factors and other nuclear proteins, may be another positive effector (12). The above factors have been characterized to different extents and there is no consensus with respect to their contribution.

In this paper we raise the possibility of a further, rather unexpected way of calpain sensitization to \( {\text{Ca}}^{2+} \) by fragments of its endogenous inhibitor, calpastatin. Typical calpastatin molecules have five structural domains; the function of the N-terminal domain is not clear, the other four homologous domains are all capable of inhibiting a calpain molecule (13,14). The presence of \( {\text{Ca}}^{2+} \) is mandatory for calpain binding and inhibition by calpastatin (15-17) and calpastatin binding invariably occurs at a \( {\text{Ca}}^{2+} \) concentration significantly lower than that needed for enzyme activity (18). Each inhibitory domain contains three short conserved stretches of about 20 amino acids, termed subdomains A, B and C (cf. Fig. 1). In functional studies it was shown that subdomain B is responsible for inhibition (19-21), whereas subdomains A and C potentiate this inhibitory effect by binding to the calmodulin-like domains of the large and small
subunit, respectively, in a strictly Ca$^{2+}$-dependent manner (17,20-22). Subdomains A and C have no inhibitory effect on calpain (20-23).

These observations allow for a very intriguing possibility, the activation of calpain by calpastatin fragments. Namely, as binding of calpastatin and its subdomains to calpain is facilitated by Ca$^{2+}$, thermodynamic necessity demands that the reverse be also true: calpastatin should facilitate Ca$^{2+}$ binding to calpain. In other words, calpastatin or its subdomains must lower the Ca$^{2+}$ demand of calpain. This is clearly seen with whole calpastatin, which binds at a Ca$^{2+}$ concentration significantly lower than that needed for calpain activity (18). In essence, calpastatin shifts the conformational equilibrium of calpain toward the active form; activation with whole calpastatin, of course, is not seen due to blocking of the active site by subdomain B. Subdomains A and C, on the other hand, lack this inhibitory potential. In earlier experiments they did not inhibit calpain at high Ca$^{2+}$ concentrations (20-23). Our result here show that they in fact potentiate Ca$^{2+}$ binding and thus activate the enzyme at sub-saturating Ca$^{2+}$ levels.

Experimental Procedures

Enzymes

Human erythrocyte µ-calpain was purchased from Calbiochem (cat # 208713). Rat m-calpain composed of a 80K large subunit and a 21K truncated small subunit was expressed in E. coli and purified via the C-terminal His-tag attached to its large subunit as given in (24). The enzymes were dialyzed against three changes of 10 mM HEPES, 150 mM NaCl, 1 mM EDTA, 2 mM benzamidine, 0.2 mM PMSF and 15 mM β-mercaptoethanol (calpain buffer) and stored at 4°C until use. On the day of use a small aliquot was taken out and reactivated with 15 mM β-mercaptoethanol for 1 hour prior to the experiments.

Peptides

The acetylated oligopeptide amides used in the present study correspond to subdomains A and C of human calpastatin inhibitory domain I (cf. Fig. 1 and (21)) and have the sequence as follows. A: SGKSGMDAALDDLIDTLGG, C: SKPIGPDDAIDALSSDFTS. The peptides were synthesised on 4-methylbenzhydrylamine resin by solid phase method using Boc technique. The side protection groups were as follows: Boc-Asp(cHex), Boc-Lys(2-Cl-Z), Boc-Ser(Bzl), Boc-Thr(Bzl). All Boc derivatives were obtained from Reanal, Hungary. The coupling was carried out by using 2 equivalents of protected amino acid derivative and 1.9 equivalents of O-
benzotriazol-1-yl-N,N,N',N'-tetramethyluronium hexafluorophosphate (dissolved in 1-methyl-2-pyrrolidone or in DMF), in the presence of N,N-diisopropylethylamine for 30 min. In case of positive ninhydrin assay the coupling was repeated until no free amino groups were detected. The Boc group was cleaved by 100% TFA for 1 x 1 min. After the cleavage the resin was washed with 5% N,N-diisopropylethylamine in DCM\(^1\) and with DCM. The N-terminal amino acetyl group was introduced by reacting the resin bound peptide with 10 equivalents of 4-nitrophenyl acetate.

The peptides were cleaved from the resin by liquid HF (20 ml) at –5ºC, in the presence of 2 ml anisole and 100 mg DTT for 1.5 hours. The peptides were purified by gel filtration in 30% acetic acid followed by RP-HPLC on a Vydac 5\(\mu\)m C18 column (250 x 4.6 mm) (Hesperia, CA, USA) using 0.045% TFA in water as eluent A, 0.036% TFA in acetonitrile as eluent B and linear gradient 30-55% B in 60 min and 20-52% B in 30 min for peptide A or 8.5-30% B in 100 min and 5-40% B in 30 min for peptide C. The homogeneity of peptide A was > 98% and of peptide C was > 92%.

The peptides were checked by amino acid analysis using a Beckman Model 6300 amino acid analyser and mass spectra were recorded on a Perkin Elmer Sciex API2000 triple quadrupole instrument (Toronto, Canada) equipped with TurboIonspray source. Both peptides were dissolved in calpain buffer at 5 mg/ml concentration and stored in aliquots at -20ºC until use.

*Calpain activity measurements*

Calpain activity was measured in a Jasco FP 777 spectrofluorometer at excitation and emission wavelengths of 380 and 460 nm in a 3 x 3 mm quartz cuvette. The reaction mixture in 50 \(\mu\)l calpain buffer contained 1 mM LY-AMC as substrate at various peptide- and Ca\(^{2+}\) concentrations as indicated. The actual free Ca\(^{2+}\) concentration was calculated from the total concentrations by using the stability constant \(\log K_{\text{app}} = 7.815\) for Ca\(^{2+}\)-EDTA. The reaction was started by the rapid mixing of the enzyme at a final concentration of 0.1 \(\mu\)M. The fluorescent trace recorded was transferred to a PC and evaluated by the MicroCal Origin data analysis software for determining the initial slope of fluorescence change; it was checked that this slope was proportional to enzyme amount/activity under the given conditions.

\(^{1}\) The abbreviations used are: DCM: dichloromethane; LY-AMC: N-succinyl-Leu-Tyr 7amido-4-methylcoumarin
Materials

The fluorescent substrate LY-AMC (cat. # S 1153) and all other chemicals were purchased from Sigma Chemical Co. The buffer was prepared with ion-exchanged distilled water.

Results

To see if oligopeptides A and C have an effect on µ-calpain activity, an intermediate Ca\(^{2+}\) concentration was used at which the enzyme activity could be conveniently measured but was significantly lower than that at saturating Ca\(^{2+}\) concentrations (13% at 2.4 µM free Ca\(^{2+}\)). At this Ca\(^{2+}\) level the enzyme was titrated with increasing concentrations of a mixture of peptides A + C. Fig. 2 shows that the oligopeptides increase calpain activity about 5-fold with an EC\(_{50}\) concentration around 7.5 µM. The concentration-dependence of activation has a slight sigmoidal shape, which hints at a cooperative effect between the two peptides. Subdomains A and C, when applied separately, also activate the enzyme (Fig. 2): under the conditions used both increase the activity about 2-3-fold, with a half maximal effect around 15 µM concentration.

Activation of calpain at sub-saturating Ca\(^{2+}\) concentration might result from the expected sensitization to Ca\(^{2+}\), from a net increase in maximal activity without affecting Ca\(^{2+}\) sensitivity, or both. To distinguish between these alternatives, the Ca\(^{2+}\)-dependence of µ-calpain in the absence of peptides and in the presence of peptides at saturating concentration (40 µM each) was measured (Fig. 3A). Activation is clearly due to a significant increase in Ca\(^{2+}\) sensitivity of the enzyme: the concentration of half-maximal activity shifts from 4.3 to 2.4 µM upon the addition of peptide mixture. The maximal activity at saturating Ca\(^{2+}\) concentrations, on the other hand, is unchanged within experimental error. With respect to the physiological activation of the enzyme, it is potentially very significant that an activation of about an order of magnitude is seen at low Ca\(^{2+}\) concentrations (Fig. 3B).

A similar set of experiments was carried out with m-calpain, i.e. with rat 80/21. Subdomains A and C exert a qualitatively similar activating effect: at 140 µM free Ca\(^{2+}\), where enzyme activity is 10% of that at saturating Ca\(^{2+}\) concentrations, the peptides cause an about 5-fold activation of the enzyme (Fig. 4). Half-maximal peptide concentration is somewhat higher (25 µM) and the course of activation has a more distinct sigmoidal shape than with µ-calpain. The peptides themselves activate the enzyme about 2-3-fold with a half-effective concentration of 55 µM. The activation again can be accounted for by an increase in the Ca\(^{2+}\)-sensitivity of the enzyme: the half-maximal Ca\(^{2+}\) concentration shifts from 250 to 140 µM at saturating (75 µM)
concentration of the peptides with no effect on maximal activity (Fig. 5A). At low \( \text{Ca}^{2+} \) concentrations the activation approaches one order of magnitude (Fig. 5B).

**Discussion**

The results presented unequivocally demonstrate that peptides corresponding to subdomains A and C of human calpastatin domain I markedly sensitize both \( \mu \)- and m calpain to \( \text{Ca}^{2+} \). At saturating peptide concentrations the peptides lower the \( \text{Ca}^{2+} \) concentration needed for half-maximal activity from 4.3 to 2.4 \( \mu \text{M} \) for \( \mu \)-calpain and from 250 to 140 \( \mu \text{M} \) for m-calpain. Perhaps more significantly, at low \( \text{Ca}^{2+} \) concentrations approaching the physiological range both \( \mu \)- and m-calpain are activated by an order of magnitude. The activation shows a sigmoidal concentration-dependence, which indicates cooperativity between binding of the two peptides. In structural terms this implies that the conformational change of the two subunits is functionally linked and occurs in a concerted manner. The peptide concentration needed for half-maximal effect is somewhat lower for \( \mu \)-calpain (7.5 \( \mu \text{M} \)) than m-calpain (25 \( \mu \text{M} \)), which might be due to the different sensitivity of isoforms, but may also reflect species difference as the peptides are derived from human calpastatin. Either way, this difference indicates that the development of isoform-specific activator peptides is conceivable. Overall, our observations have three important implications.

The first implication relates to the issue of the activation of calpains under physiological \( \text{Ca}^{2+} \) concentrations. As outlined in the Introduction, several factors may be involved in lowering the \( \text{Ca}^{2+} \) demand of calpains. Although this issue is not settled yet, it seems that phospholipids (7,8), nuclear DNA (12), a specific activator protein (11) and autolytic processing of calpain itself (5,6) may all contribute to shifting the \( \text{Ca}^{2+} \) need of calpain toward the physiological range. Our findings, perhaps paradoxically, bring calpastatin, the specific calpain inhibitor, into this picture. In principle, it is possible that calpastatin is fragmented in such a way *in vivo* that degrades its inhibitory subdomain (B) but leaves activator subdomains A and C more-or-less intact. Under such circumstances activation might override inhibition and calpastatin fragments stimulate calpain. Calpastatin is very sensitive to proteolysis *in vitro* (25) and is degraded by caspases (26) and calpain itself (27) *in vivo*. A significant difference in the sequence of calpastatin subdomains A, B and C suggests that the action of a protease with a trypsin-like specificity may result in such a fragmentation: subdomain B has several Lys and Arg residues...
making this part of calpastatin sensitive whereas subdomains A and C have only a single N-terminal Lys residue offering limited access to proteolysis.

The other condition for this mechanism to operate in vivo is that the intracellular concentration of calpastatin be high enough for the peptides to reach a level sufficient for activation. Quantitative considerations argue that in some tissues this condition is met. The physiological concentration of calpastatin varies in different tissues from about 0.035 µM to 4.4 µM (28,29); as calpastatin consists of four homologous inhibitory domains (cf. Fig. 1), each capable of inhibiting one calpain molecule in a Ca2+-dependent manner (13,14), the concentration of inhibitory domains—and the potential concentration of activator peptides—is four times higher, i.e. is in the range of 0.14 µM to 17.6 µM. Thus, in certain tissues specific fragmentation of calpastatin may produce the activator peptides in concentrations commensurable with the range used in our studies. Furthermore, two other considerations support this conclusion in a wider range. First, it seems that calpastatin concentrations at certain locations within the cell is markedly higher than the average values just mentioned. In an unstimulated cell calpastatin localizes in an aggregated state close to the cell nucleus (30), at local concentrations which significantly exceed the values calculated for homogeneous distribution. Second, macromolecular crowding caused by the extreme protein concentration in the cytoplasm favors interactions to such an extent that reaction rates and equilibrium constants of interactions may be orders of magnitude higher in vivo than under test-tube conditions (31). Owing to this mechanism, fragments corresponding to the same amount of calpastatin subdomains A and C may give a much higher effective concentration in the cell than in dilute solution in the test tube and activate calpain at concentrations significantly lower than the values reported in this work.

The second general implication of our work is related to previous efforts at characterizing the physiological function of calpains. It is known from knockout experiments that calpains play an essential role as deletion of the ubiquitous small subunit is lethal in mice (32). The role of various calpain forms has been extensively studied, almost invariably by the application of calpain inhibitors. From such studies we know that calpain(s) play a regulatory role in basic cellular processes such as the cell cycle (33), cell motility (34), cell spreading (35), apoptosis (36) and many more. The inhibitors, however, lack strict specificity: they may react with the proteosome, lysosomal proteinases, or even non-proteolytic enzymes (37,38). These findings have prompted the development of strictly specific calpain inhibitors (39) or the use of a cell-permeable variety of calpastatin subdomain B for cell biological studies. In general, the results
with calpain inhibitors can not always be unequivocally associated with the action of calpain. Thus, it is desirable to develop activators for calpain based on our observations with subdomains A and C. As these peptides are highly charged, both subdomains have to be fused with “carrier” peptides that make other substances membrane-permeable. The development of such constructs, which will probably complement the use of calpain inhibitors in further analysis of calpain function, is under way (patent pending).

The third implication worth considering is related to the pathological role of calpain. Overactivation of calpain seems to be important in a range of disorders (37,40); more recent findings, however, point to the link of diminished activity and the development of pathological states. Positional cloning in patients with limb girdle muscular distrophy 2A linked the gene of calpain 3 (p94) with this disease (41). Later studies revealed that disease is associated with mutations in this gene, which invariably leads to a partial or complete loss of enzyme activity (42). In a similar approach, diabetes mellitus type 2, which accounts for about 90% of the incidence of diabetes, was linked to the gene of calpain 10 (43); a single-nucleotide polymorphism within one intron of the gene is associated with a significantly reduced mRNA level (44). Thus, the enzyme in this case is fully active, but it is expressed at a lower level. The two diseases, and possibly others, have in common a diminution in calpain activity; apparently, drugs that could boost activity might be beneficial.
Acknowledgments

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Figure legends

Fig. 1  **Alignment of human calpastatin inhibitory domains**

The four domains of human calpastatin inhibitory to calpain are shown aligned. Identity or strong similarity of residues extending to four (black) or three (gray) domains are marked by shading. Subdomains A, B and C, as defined in (21), are boxed.

Fig. 2  **Activation of human \( \mu \)-calpain by calpastatin subdomains A and C**

The activity of \( \mu \)-calpain was measured by a fluorescent peptide substrate, LY-AMC at 2.4 \( \mu \)M free Ca\(^{2+} \) concentration as given under Experimental Procedures. To the assay, either peptide A (○) or C (□), or both A and C (▲) was added at the concentrations indicated. The initial rate of substrate consumption was determined and plotted in percentage of the activity measured at saturating (2 mM) Ca\(^{2+} \) concentration. Data points represent the mean of 3 separate experiments.

Fig. 3  **Ca\(^{2+} \)-dependence of human \( \mu \)-calpain activation by calpastatin subdomains A and C**

A) The activity of \( \mu \)-calpain was measured by LY-AMC at the free Ca\(^{2+} \) concentrations indicated in the absence (△) or presence (▲) of 40 \( \mu \)M of peptides A and C. The initial rate of substrate consumption was determined and plotted in percentage of the activity measured at saturating (2 mM) Ca\(^{2+} \) concentration. Data points represent the mean ± s.d. for 3 or 4 separate measurements. Free Ca\(^{2+} \) concentration needed for half-maximal activation is shifted from 4.3 to 2.4 \( \mu \)M by the peptides. B) The extent of activation exerted by the peptides at various Ca\(^{2+} \) concentrations is calculated by dividing enzyme activity measured in the presence and absence of the peptides, taken from A.
Fig. 4  
**Activation of rat m-calpain by calpastatin subdomains A and C**

The activity of m-calpain was measured by a fluorescent peptide substrate, LY-AMC at 140 μM free Ca\(^{2+}\) concentration as given under Experimental Procedures. To the assay, peptide A (○) or C (□) or both A and C (▲) was added at the concentrations indicated. The initial rate of substrate consumption was determined and plotted in percentage of the activity measured at saturating (3 mM) Ca\(^{2+}\) concentration. Data points represent the mean for 2-3 separate experiments.

Fig. 5  
**Ca\(^{2+}\)**-dependence of rat m-calpain activation by calpastatin subdomains A and C

A) The activity of m-calpain was measured by LY-AMC at the free Ca\(^{2+}\) concentrations indicated in the absence (△) or presence (▲) of 75 μM peptide A and C. The initial rate of substrate consumption in percentage of the activity measured at saturating (3 mM) Ca\(^{2+}\) concentration is given. Free Ca\(^{2+}\) concentration needed for half-maximal activation shifted from 250 to 140 μM by the peptides. B) The extent of activation exerted by the peptides at various Ca\(^{2+}\) concentrations is calculated as given in Fig. 3B for μ-calpain.
References


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