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Mutation of an EF-hand Ca\(^{2+}\)-binding motif in phospholipase C of *Dictyostelium discoideum*: inhibition of activity but no effect on Ca\(^{2+}\)-dependence

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Phosphoinositide-specific phospholipase C (PLC) is dependent on Ca\(^{2+}\) ions for substrate hydrolysis. The role of an EF-hand Ca\(^{2+}\)-binding motif in Ca\(^{2+}\)-dependent PLC activity was investigated by site-directed mutagenesis of the *Dictyostelium discoideum* PLC enzyme. Amino acid residues with oxygen-containing side chains at co-ordinates \(x, y, z, -x, -y, -z\) of the putative Ca\(^{2+}\)-binding-loop sequence were replaced by isoleucine (\(x\)), valine (\(y\)) or alanine (\(z, -x, -y, -z\)). The mutated proteins were expressed in a *Dictyostelium* cell line with a disrupted plc gene displaying no endogenous PLC activity, and PLC activity was measured in cell lysates at different Ca\(^{2+}\) concentrations. Replacement of aspartate at position \(x\), which is considered to play an essential role in Ca\(^{2+}\) binding, had little effect on Ca\(^{2+}\) affinity and maximal enzyme activity. A mutant with substitutions at both aspartate residues in position \(x\) and \(y\) also showed no decrease in Ca\(^{2+}\) affinity, whereas the maximal PLC activity was reduced by 60%. Introduction of additional mutations in the EF-hand revealed that the Ca\(^{2+}\) concentration giving half-maximal activity was unaltered, but PLC activity levels at saturating Ca\(^{2+}\) concentrations were markedly decreased. The results demonstrate that, although the EF-hand domain is required for enzyme activity, it is not the site that regulates the Ca\(^{2+}\)-dependence of the PLC reaction.

INTRODUCTION

The enzyme phosphoinositide-specific phospholipase C (PLC) generates Ins\((1,4,5)P_3\) and diacylglycerol by hydrolysis of PtdIns(4,5)\(P_2\). Ins\((1,4,5)P_3\) and diacylglycerol are important roles in Ca\(^{2+}\) mobilization by releasing Ca\(^{2+}\) from internal stores [1,2], and diacylglycerol is the physiological activator of protein kinase C [3]. Besides its function as a producer of these classical second messenger proteins, PLC may play a role in remodelling of the cytoskeleton through regulation of the PtdIns(4,5)\(P_3\) interaction with actin-binding proteins such as profilin and gelsolin [4,5].

On the basis of sequence conservation, the mammalian PLC isoforms are classified into three distinct families, \(\beta, \gamma, \delta\), which are regulated by separate mechanisms. Members of the PLC-\(\beta\) family are activated by G-protein-linked receptors [6,7], and PLC-\(\gamma\) isoforms are activated by tyrosine kinase-linked receptors (see ref. [8]). The mechanisms involved in PLC-\(\delta\) activation have not been resolved so far. A RhoGAP protein has been identified which associates with and activates PLC-\(\gamma\), suggesting a mechanism in which the small G-protein Rho is involved in PLC-\(\delta\) regulation [9].

Lower eukaryotes provide systems in which to study the function of PLC by analysing mutants. In *Drosophila* the *norpA* gene, which encodes a protein similar to bovine retinal PLC-\(\beta\), appears to be involved in phototransduction [10]. The microorganisms *Saccharomyces cerevisiae* and *Dictyostelium discoideum* contain a PLC-\(\delta\)-like gene [11,12]. In *S. cerevisiae* deletion of the PLC gene resulted in retarded cell growth [13]. Deletion of the PLC gene in the slime mould *D. discoideum* resulted in cells containing no detectable PLC activity, yet growth and development were unaffected [14]. Ins\((1,4,5)P_3\) levels were only slightly lower in the plc\(^{-}\) mutant compared with wild-type cells, which suggests that there are alternative pathways for generating Ins\((1,4,5)P_3\) besides PLC [15].

Structural requirements of PLC-\(\beta, \gamma, \delta\) for enzyme activity have been identified using bacterial and mammalian expression systems. The domains A and B, containing conserved amino acids found in all PLC isoforms, are essential for enzyme activity and are thought to form the catalytic core [16,17]. In PLC-\(\gamma\) the region between the conserved A and B domains contains the src homology (SH) domains SH2 involved in the PLC-tyrosine kinase interaction, and an SH3 domain which targets the enzyme to cytoskeletal components [18]. In PLC-\(\beta\) the N-terminal domain is required for activation by G-protein \(\beta\)-\(\gamma\)-subunits, and the large C-terminal domain after the conserved B domain is required for activation by \(\alpha\)-subunits [19–21]. The N-terminal domain in PLC-\(\delta\), containing a pleckstrin homology (PH) domain, has been shown to form a high-affinity binding site for PtdIns\((4,5)P_2\) [22].

Ca\(^{2+}\) is an important regulator of PLC, yet little is known about the mechanism by which Ca\(^{2+}\) stimulates PLC activity. The sequences of several PLC isoforms predict an EF-hand motif, a domain found in many Ca\(^{2+}\)-modulated proteins [23,24]. The EF-hand motif consists of 29 amino acids arranged in a helix-loop-helix conformation, with Ca\(^{2+}\) binding in the loop region [25]. In this study we investigated the role of the putative Ca\(^{2+}\)-binding domain for Ca\(^{2+}\)-dependent PLC activity, by introducing point mutations into the EF-hand of *Dictyostelium* PLC. The altered proteins were expressed in a *Dictyostelium* mutant strain with a disrupted plc gene containing no endogenous PLC activity. The results show that there is no difference in Ca\(^{2+}\) dependence between PLC with a complete EF-hand and mutated PLC proteins, but that the maximal enzyme activity is affected by the mutations.

EXPERIMENTAL

Generation of plc\(^{-}\) cells

A vector was constructed for disruption of the endogenous DdPLC gene by homologous recombination using *ura*
complementation. A 3.7 kb Clal fragment from pDU3B1 [26] encoding the Dictyostelium UMP synthase gene was ligated between two internal Clal sites in a DdPLC cDNA construct to create the plasmid pUraPLCko (see Figure 1a). As in the previously reported G418-resistant plc- cell line HD10, a selection marker for a double-crossover event by homologous recombination, the tRNA<sub>His</sub>(UAA) suppressor gene, was included with no adverse effects [14].

A uracil auxotroph D. discoideum strain DH1 (a gift from P. N. Devreotes, The Johns Hopkins University, Baltimore, MD, U.S.A.) was grown axenically in minimal (FM) medium [27] supplemented with uracil (100 µg/ml). DH1 cells were transformed with pUraPLCko by electroporation [28] and grown in minimal medium (without added uracil) until colonies appeared. Transformants were clonally selected on agar plates with Klebsiella aerogenes, and then the clones were grown in minimal medium. Southern blotting on genomic DNA from DH1 and transformants using probes specific for the conserved A and B domains of DdPLC was performed as described [14]. One plc- clone, named DH1.19, was selected and used for further experiments.

**Point mutation of the EF-hand**

A cDNA fragment consisting of the coding region and 3' untranslated region of DdPLC (described in ref. [14]) was incorporated into the bacterial expression plasmid pBlueScript SK(−) (Stratagene) to yield pPLC-blue. Mutation of DdPLC at amino acid position 490, and positions 490 + 492 (in positions x, or x + y of the Ca<sup>2+</sup>-binding-loop sequence, see Figure 3b), were performed by site-directed mutagenesis using pPLC-blue as template [29]. The primer used for mutation of the EF-hand had the sequence 5'-CTCAACTGATATCAATG(A/T)TGATGATGGT-3' (bases 1746–1773 of DdPLC). The altered nucleotides are in bold. Clones carrying mutations could be detected by screening for the presence of an additional EcoRV restriction site in DdPLC. Clones encoding one or two mutations in the EF-hand were selected by sequence analysis [30]. Construction of a plasmid for expression of full-length DdPLC cDNA in Dictyostelium using the BS18 vector, pPLC-BS18, has been described previously [12]. A 1.4 kb NcoI–HindIII fragment of DdPLC cDNA containing the mutations in pPLC-blue was inserted and isolated into NcoI–HindIII-digested pPLC-BS18. The mutated DdPLC sequences cloned into BS18 were named pEF1 with one mutation in the EF-hand, and pEF2 with two mutations in the EF-hand.

Mutations of DdPLC at amino acid positions 490 + 492 + 501 and 490 + 492 + 494 + 498 + 501 (in positions x, y, −z or x, y, z, −x, −z of the Ca<sup>2+</sup>-binding-loop sequence, see Figure 3b) were performed by PCR [31] using pEF2 as template. Primers used were: PLC5'D, 5'-GTTCACTGTCATGACCCGACCTGCAAGAATATATCAGCACCTGCAATGAA-3' (bases 1537–1553 of DdPLC); PLC5'EF, 5'-GATCGGTG CGATTGTTGG (A/C)TATTATCATGATGAATATATCAGCACCTGCAATGAA-3' (bases 1765–1800 of DdPLC); PLC3'EF, 5'-ATCATGTCCTTAAATCCTGATGGTGG (A/C)TATTATCATGATGAATATATCAGCACCTGCAATGAA-3' (bases 1759–1799 of non-coding DdPLC); and TNS5BS3', 5'-ACTTGGATCTTCATCGG-3' (non-coding strand terminator sequence of BS18 vector). The orientation of the primers is indicated schematically in Figure 3(b). In the first step PCR was performed with primers PLC5'EF and TNS5BS3'. The amplified fragment of 1 kb was digested with NdeI–HindIII and inserted into NdeI–HindIII-digested pEF2, yielding construct pEF(min), which lacks an internal DdPLC fragment of 200 bp. A second PCR was performed with primers PLC5'D and PLC3'EF resulting in a 200 bp product which was digested with Ndel and ligated into compatible pUC21 vector. Sequence analysis revealed a product with five mutations in the EF-hand region, as expected, and an extra product with three mutations (at positions x, y, −z; the +z position was not mutated). The 200 bp products carrying three or five mutations were ligated into the Ndel site of pEF(min), and the orientation of the inserts was determined by DNA sequencing. Inserts generated by PCR were sequenced completely. The mutated DdPLC sequences cloned into BS18 were named pEF3 carrying three mutations in the EF-hand and pEF5 carrying five mutations in the EF-hand.

The urge plc- mutant DH1.19 was transformed with plasmids pPLC-BS18, pEF1, pEF2, pEF3 and pEF5. Transformants were selected and cloned in HLF medium [32] containing G418 at 10 µg/ml. The PLC proteins generated by cells expressing constructs with one, two, three or five mutations in the EF-hand of DdPLC were designated DdPLC-1(x), DdPLC-2(x,y), DdPLC-3(x,y,−z) and DdPLC-5(x,y, z, −x, −z) respectively.

**PLC assay**

To prepare cell suspensions for PLC assays, exponentially growing cells were harvested by centrifugation at 300 g and resuspended at a density of 5 × 10<sup>7</sup> cells/ml in 40 mM Hepes/NaOH buffer, pH 6.5. Samples of cells were lysed by rapid elution through Nucleopore polycarbonate filters (pore size 3 µm). PLC activity in lysates was measured as described previously [33], with at least two independently derived clones for each mutant DdPLC construct. The Ca<sup>2+</sup>-dependence of PLC activity was assayed in the presence of Ca<sup>2+</sup>/EGTA buffers, containing different concentrations of added CaCl<sub>2</sub> stock solutions. EGTA was added to the cells before lysis, and the final concentration of EGTA was fixed at 5.36 mM for all experiments. Free Ca<sup>2+</sup> concentrations were calculated as described by Barfati [34], solely taking the added EGTA and CaCl<sub>2</sub> solutions into account. As the reactions were performed in crude cell lysates, it should be noted that components interfering with the Ca<sup>2+</sup>/EGTA buffer could be present. However, as all experiments were performed under the same conditions, the effects observed in this study would not depend on the difference between calculated free Ca<sup>2+</sup> concentration and the actual final concentration of free Ca<sup>2+</sup> in the reaction.

The data were fitted to the equation:

\[
\text{PLC activity} = \frac{\text{PLC}_{\text{max}}}{1 + ([\text{Ca}^{2+}] / [\text{Ca}^{2+}]_{50})^h}
\]

where PL<sub>Cmax</sub> is the maximal PLC activity (in pmol of Ins[1,4,5]P<sub>3</sub> produced/min per µg), [Ca<sup>2+</sup>]<sub>50</sub> is the Ca<sup>2+</sup> concentration at which PLC activity is half-maximal, and h is the Hill coefficient.

**Western-blot analysis**

Cells were resuspended in 40 mM Hepes buffer, as described above for the PLC assay, and protein-separation sample buffer was added [35]. Samples for Western-blot analysis contained 40 µg of protein from total cell lysates for DH1 or the mutant preparations and 5 µg of protein from total cell lysates for analysis of the DdPLC EF-hand mutants. Samples were boiled before separation by SDS/PAGE [36], and transferred to nitrocellulose [37]. Blots were incubated with antiserum raised against recombinant DdPLC [14] and developed using the ECL detection kit (Amersham). Protein concentration was determined by a Bio-Rad protein assay with BSA as standard. G-protein β-subunit-specific antiserum [38] was used as an internal control to compare protein levels in the lanes of a blot.
RESULTS

Generation of plc− cells and rescue of Ca2+-dependent PLC activity

We have recently described a Dictyostelium mutant HD10, in which the endogenous PLC gene DdPLC had been disrupted [14]. As mutant HD10 was obtained by a transformation procedure using G418 selection, another plc− mutant was required for the present study to express altered proteins from the Dictyostelium expression vector BS18 (which confers G418-resistance).

A G418-sensitive plc− mutant was isolated by transforming the ura− strain DH1 with the plasmid pUraPLCko described in Figure 1(a). Transformants were selected for ura− complementation by growth in minimal medium. A number of independent clones was obtained, some of which had integrated the vector into the DdPLC locus as observed by Southern-blot analysis. The results for one clone which was used in further experiments, HD1.19, are presented in Figure 1. The Southern blot of genomic DNA demonstrated that a single crossover event had occurred in the DdPLC locus of HD1.19 cells. Disruption of the DdPLC gene resulted in a mutant containing no PLC protein when analysed by immunoblot using DdPLC-specific antiserum (Figure 1c), and no detectable PLC activity (see Figure 2). HD1.19 plc− cells showed a normal growth and developmental pattern compared with control cells, as was previously observed for HD10 plc− cells.

HD1.19 cells were transformed with plasmid BS18 containing the complete DdPLC cDNA sequence downstream from the actin-15 promoter. Figure 2 shows the PLC activity measured in cell lysates at different concentrations of free Ca2+. Expression of DdPLC in HD1.19 cells restored PLC activity to the plc− mutant. The PLC activity was dependent on the presence of Ca2+, showing no activity in the absence of added Ca2+ and reaching a maximum at approx. 5 μM free Ca2+. Studies on endogenous PLC activity in wild-type Dictyostelium lysates showed a dose–response curve for Ca2+ that was bell-shaped with a maximal activity of 0.1 pmol of Ins(1,4,5)P3 produced/min per μg of total protein [33]. In contrast, in cells expressing DdPLC from the strong actin-15 promoter, a maximum PLC activity level of 3 pmol of Ins(1,4,5)P3 produced/min per μg was reached which was sustained at high Ca2+ concentrations.

Mutation of the EF-hand

A search of the SWISS-PROT database revealed that mammalian PLC-γ1, PLC-δ1, S. cerevisiae PLC and D. discoideum PLC contain an EF-hand motif detected by the PROSITE EF-hand pattern [39]. In PLC-γ1, PLC-δ1 (containing two putative EF-
Figure 3  (a) Alignment of the Ca\(^{2+}\)-binding loop sequences of EF-hand III of rabbit skeletal-muscle troponin C (TnC-III) and bovine brain calmodulin (CaM-III), and the predicted EF-hands of rat PLC-γ1, PLC-γ1, S. cerevisiae PLC (ScPiP1) and D. discoideum PLC (DdPLC) and (b) point mutation of the EF-hand of DdPLC

(a) The numbers indicate the position of the amino acid residues within the protein. The sequence positions in the Ca\(^{2+}\)-binding-loop domain are numbered 1–12, starting with the N-terminal residue. Ca\(^{2+}\) is co-ordinated directly by oxygen atoms provided by the side chains of residues at positions 1(x), 3(y), 5(z) and 12(–z). The side chain of the residue at position 9(–y) participates in Ca\(^{2+}\) ligation via its backbone carbonyl oxygen. The established nomenclature of an octahedral arrangement of the ligands is used, although the residue at –z (usually a glutamate) has been shown to use both its side-chain oxygens, resulting in seven oxygen ligands and a pentagonal bipyramidal Ca\(^{2+}\) co-ordination [44]. (b) The EF-hand in Dictyostelium PLC is located in the region between the conserved A and B domains. The amino acids that were mutated are boxed. The positions of the primers used in PCR are schematically indicated by horizontal arrows at the corresponding regions in the Figure. The positions of the restriction sites NcoI (N) and XmnI (H) are indicated by vertical arrows (the open arrow indicates the XmnI site generated by PCR, see the Experimental section).

Figure 4  Expression of normal and mutated DdPLC in Dictyostelium

Protein samples from plc cells expressing DdPLC (lane 1), DdPLC-1(x) (lane 2), DdPLC-2(y) (lane 3), DdPLC-3(x,y,–z) (lane 4) and DdPLC-5(x,y,–x,–z) (lane 5) were analysed by Western blot with DdPLC-specific antiserum (a). The blot was stripped and incubated with antiserum against the G-protein \(\beta\)-subunit, which is expressed constitutively in Dictyostelium cells [38], to compare the amount of protein loaded in each lane (b). Lanes 2 and 3 showed less intense staining with the \(\beta\)-subunit antiserum than lanes 1, 4 and 5, indicating that a lower amount of total protein was loaded in these lanes. Numbers on the left indicate migration positions of molecular-mass standards in kDa. The arrow shows the position of full-length PLC protein of approx. 97 kDa. In addition, samples contained a number of smaller products which probably represent cleaved PLC protein. The degradation products were detected when high levels of PLC proteins were analysed, explaining the higher amounts of smaller proteins in lanes 1, 4 and 5 than in lanes 2 and 3.
Mutation of an EF-hand motif in Dictyostelium phospholipase C

Figure 5  Effect of EF-hand mutations on PLC activity

Dictyostelium plc− cells were transformed with the expression vector BS18 containing unmutated and mutated DdPLC cDNA constructs. Data are expressed as percentage of the enzyme activity present in unmutated DdPLC at 0.1 mM free Ca\(^{2+}\). Each point represents triplicate determinations from a single experiment. The curve was obtained by fitting the data to a modified form of the Hill equation (see the Experimental section).

Table 1  Kinetic properties of normal and mutated Dictyostelium PLC

The data from Figure 5 and similar experiments were used to derive the pCa\(_{50}\) (pCa at which PLC activity is half-maximal), the PLC\(_{max}\) (maximal PLC activity) and the Hill coefficient (h) using the equation:

\[
\text{PLC activity} = \frac{\text{PLC}_{max}}{1 + (\text{Ca}^{2+}/\text{Ca}_{50}^{2+})^h}
\]

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<th></th>
<th>n</th>
<th>pCa(_{50})</th>
<th>h</th>
<th>PLC(_{max}) (pmol/min per (\mu)g)</th>
</tr>
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<tbody>
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<td>DdPLC</td>
<td>4</td>
<td>6.1 ± 0.3</td>
<td>1.0 ± 0.2</td>
<td>4.0 ± 1.7</td>
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<tr>
<td>DdPLC-1(x)</td>
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<td>1.5 ± 0.8</td>
<td>3.0 ± 1.1</td>
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<tr>
<td>DdPLC-2 (x,y)</td>
<td>6</td>
<td>6.3 ± 0.4</td>
<td>1.3 ± 0.7</td>
<td>1.7 ± 0.8</td>
</tr>
<tr>
<td>DdPLC-3 (x,y,−z)</td>
<td>6</td>
<td>6.3 ± 0.1</td>
<td>2.0 ± 0.4</td>
<td>0.6 ± 0.5</td>
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<tr>
<td>DdPLC-5 (x,y,z,−x,−z)</td>
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<td>6.3 ± 0.1</td>
<td>2.8 ± 1.2</td>
<td>0.3 ± 0.2</td>
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Effect of EF-hand mutations on PLC activity

The concentration of free Ca\(^{2+}\) required to activate PLC in lysates from cells expressing unmutated DdPLC was compared with that in cells expressing EF-hand-mutated DdPLCs. The results of two representative experiments are shown in Figure 5, and in Table 1 the results of a number of experiments are summarized. The Ca\(^{2+}\)-activation experiments revealed that mutation of the EF-hand did not result in an altered affinity of PLC for Ca\(^{2+}\). Half-maximal PLC activity was observed at pCa values between 6.1 and 6.3. All PLC proteins reached their maximal activity at 5 \(\mu\)M free Ca\(^{2+}\); the rate of hydrolysis did not increase with higher concentrations of Ca\(^{2+}\). The Hill coefficient of unmutated DdPLC was approximately 1, but increased in the mutated proteins (see Table 1). This suggests that the EF-hand-mutated DdPLC proteins are activated by a positively cooperative process.

A striking difference was seen in the rate of PtdIns(4,5)P\(_2\) hydrolysis between DdPLC and mutated DdPLCs. The average ratios of PLC\(_{max}\) for DdPLC containing one, two, three or five mutations in the EF-hand relative to unmutated DdPLC were respectively 0.75, 0.4, 0.15 and 0.08. These values were obtained by comparing enzyme activities in total cell lysates, suggesting that a difference in maximal PLC activity might be due to a difference in expression level of the PLC protein in the cells. For DdPLC proteins with one or two mutations in the EF-hand, the lower PLC\(_{max}\) levels could partly be attributed to lower expression of the PLC protein. However, this is not the case for DdPLC with three or five mutations. Figure 4 shows an immunoblot analysis of the same cell preparations as were used for measuring PLC activities in Experiment 1 of Figure 5. The DdPLC proteins with three or five mutations in the EF-hand were expressed at higher levels than unmutated DdPLC, yet the rate of hydrolysis was decreased by 80–90%. The observed decrease in maximal PLC activity is therefore not due to a decrease in expression of the PLC proteins in the cells, but is caused by the mutations in the DdPLC protein. We conclude that increasing the number of mutations in the EF-hand of DdPLC results in a progressive decrease in maximal PLC activity, without affecting the affinity of the enzyme for Ca\(^{2+}\).

DISCUSSION

PtdIns(4,5)P\(_2\) hydrolysis catalysed by PLC is highly dependent on the presence of Ca\(^{2+}\) (for examples see refs.\([22,33,40]\)). Ca\(^{2+}\) could regulate PLC activity by binding directly to a Ca\(^{2+}\)-binding site in the PLC protein, by binding to an intermediate protein that regulates PLC activity, or by interacting with the substrate. Two different Ca\(^{2+}\)-binding sites have been predicted in PLC proteins. One has been proposed in mammalian PLC isoforms in a region with some homology to the Ca\(^{2+}\)-dependent phospholipid-binding domain of cytosolic phospholipase A\(_2\) and protein kinase C \([41]\). The Ca\(^{2+}\)-dependent phospholipid-binding domain of cytosolic phospholipase A\(_2\) has been demonstrated to be involved in Ca\(^{2+}\)-dependent translocation of the enzyme to the membrane. Dictyostelium PLC shows a similar homology to the consensus sequence of the Ca\(^{2+}\)-dependent phospholipid-binding domain at the C-terminus of DdPLC from residue 669 to 736. In Dictyostelium lysates PLC activity is associated with the membrane, but we have evidence that a Ca\(^{2+}\)-dependent translocation process is not involved in regulating DdPLC (A. L. Drayer and P. J. M. van Haastert, unpublished work). In addition, some PLC isoforms, including Dictyostelium PLC, contain a second Ca\(^{2+}\)-binding site in an EF-hand motif. The purpose of this study was to investigate the role of the EF-hand domain in Ca\(^{2+}\)-dependent PLC activity.

The cloning of PLC from the cellular slime mould \(D.\) discoideum and the isolation of mutants with a disrupted plc gene containing no PLC activity provided an ideal system for expression of mutated PLC proteins in their native environment. For the experiments described here, we constructed an independent Dictyostelium plc− mutant by disruption of the en-
dogenous DdPLC gene. This new plc- strain DH1.19 confirmed the results obtained for the plc- strain HD10 [14] that DdPLC accounts for all PLC activity in Dictyostelium and that plc- cells are not affected in growth or development. Expression of DdPLC in the plc- mutant from a highly active promoter resulted in cells expressing high levels of PLC protein and PLC activity. These cells to which PLC activity was restored showed a normal phenotype as was previously observed for wild-type cells overexpressing DdPLC [12].

In EF-hand Ca2+-binding sites, the Ca2+ ion is usually coordinated by seven ligands. We expected that removal of the coordinating oxygen atoms by site-directed mutagenesis would reduce the affinity of the enzyme reaction. In contrast, we observed that the Ca2+ concentration giving half-maximal activity was unaltered, whereas the maximal activity decreased markedly. We also observed that the Ca2+-activation curves were steeper for mutants with multiple mutations, as represented by the Hill coefficient. We tried to demonstrate direct binding of Ca2+ to unmutated DdPLC using purified recombinant DdPLC in a 45CaCl2 overlay assay [42]. After SDS/PAGE and blotting of proteins to nitrocellulose membranes we were unable to detect Ca2+ binding to DdPLC, although in our hands Ca2+-binding to α-actinin [43] was detected under these conditions (M. E. Meima and A. L. Drayer, unpublished work). It is therefore not resolved whether the reduced maximal PLC activity in the EF-hand-mutated proteins is caused by loss of Ca2+ binding to the EF-hand.

The first residue in the Ca2+-binding loop of an EF-hand is an invariant aspartate, which is considered to play an essential role in binding of the Ca2+ ion [44]. We expected that if the EF-hand of DdPLC is a true Ca2+-binding regulatory site, mutation of this first residue in the Ca2+-binding loop would have a profound effect on enzyme activity. Our Ca2+-activation data demonstrate that replacement of this aspartate with an amino acid without an oxygen-containing side chain had little effect on the Ca2+ affinity and maximal activity. Although the Ca2+-binding-loop sequence was completely altered by introducing additional mutations, the affinity for Ca2+ did not decrease. In contrast, PLC activity at saturating Ca2+ concentrations was affected by the mutations. The different mutated proteins showed a progressive reduction in maximal activity with increasing number of mutations, with 40% activity after two mutations, 15% activity after three mutations and 8% activity after five mutations.

Although the putative EF-hand Ca2+-binding site is required for PLC activity, the results clearly show that this site in Dictyostelium PLC does not regulate the Ca2+-dependence of the enzyme reaction. In Dictyostelium PLC, the EF-hand is situated between the conserved A and B domains in a region containing 12 acidic amino acid residues. This region between the putative catalytic domains also contains a high percentage of acidic residues in PLC-β and PLC-δ isoforms. Limited proteolysis of PLC-δ1 suggests that this hydrophilic region is exposed, forming a loop to connect the A and B domains in the catalytic core [17,22]. It is possible that the Ca2+-dependence of PLC resides in either the interaction between substrate and enzyme, for instance through the Ca2+-dependent phospholipid-binding domain, or the interaction between Ca2+ and the substrate, through formation of a Ca2+-PtdIns(4,5)P2 complex. The putative EF-hand domain could fulfill a more structural role to bring together the A and B domains of Dictyostelium PLC to form the correct active structure.

In summary, expression of Dictyostelium PLC mutants in their natural cellular context reveals that the putative EF-hand Ca2+-binding domain is essential for enzyme activity, but does not mediate the Ca2+-dependence of the PLC enzyme reaction.

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