Evidence for the involvement of tyrosine-69 in the control of stereospecificity of porcine pancreatic phospholipase A₂

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Introduction

Phospholipase A₂ (PLA₂, EC 3.1.1.4) catalyses the hydrolysis of the fatty acid ester bond at the 2 position of 1,2-diacyl-sn-3-phosphoglycerides (l-α-phospholipids). The stereoisomeric 2,3-diacyl-sn-1-phosphoglycerides (D-α-phospholipids) bind with an equal affinity to the catalytic site but are not hydrolysed (Bosshart et al., 1972a). In mammals the enzyme occurs both extracellularly, serving digestive functions, and intracellularly, serving several regulatory functions. Phospholipase A₂ is also found in bee and snake venoms. The enzymes from mammalian pancreas and from snake venoms exhibit a high degree of homology (Volwerk and de Haas, 1982).

We have studied the role of Tyr-69 of porcine pancreatic phospholipase A₂ in catalysis and substrate binding, using site-directed mutagenesis. A mutant was constructed containing Phe at position 69. Kinetic characterization revealed that the Phe-69 mutant has retained enzymatic activity on monomeric and micellar substrates, and that the mutation has only minor effects on $k_{cat}$ and $K_m$. This shows that Tyr-69 plays no role in the true catalytic events during substrate hydrolysis. In contrast, the mutation has a profound influence on the stereospecificity of the enzyme. Whereas the wild-type phospholipase A₂ is only able to catalyse the degradation of sn-3-3 phospholipids, the Phe-69 mutant hydrolyses both the sn-3 isomers and, at a low (1-2%) rate, the sn-1 isomers. Despite the fact that the stereospecificity of the mutant phospholipase has been altered, Phe-69 phospholipase still requires Ca$^{2+}$ ions as a cofactor and also retains its specificity for the sn-2 ester bond.

Our data suggest that in porcine pancreatic phospholipase A₂ the hydroxyl group of Tyr-69 serves to fix and orient the phosphate group of phospholipid monomers by hydrogen bonding. Because no such interaction can occur between the Phe-69 side-chain and the phosphate moiety of the substrate monomer, the mutant enzyme loses part of its stereospecificity but not its positional specificity.

Key words: phospholipase A₂/site-directed mutagenesis/stereospecificity/substrate specificity/Tyr-69

Materials and methods

Construction of mutant phospholipase

Escherichia coli K-12 strain PC2494 [Δ(lac-pro), sup E, thi/F', tra D₄, pro A'B⁺, lac I', lacZΔM15, Phabagen collection, Utrecht] was used for plasmid constructions as a host for M13-derived vectors. HB2154 [ara, Δ(lac-pro), thi/F' pro A'B⁺, lac I', lac ZΔM25, mut L-::Tn10 (Carter et al., 1985)] was used as the recipient strain in the mutagenesis experiments.

Substitutions in the proPLA₂-cDNA (de Geus et al., 1987) were introduced by the gapped duplex procedure, using amber selection (Kramer et al., 1984). The proPLA₂-cDNA (de Geus et al., 1987) was provided with three unique restriction sites (SacII, KpnI and BglII) to facilitate the cloning of small PLA₂-cDNA fragments in future experiments. The applied mutations were silent except in the case of the SacII site, where the Ser$^V$-Ser$^VI$-Arg$^VIII$ sequence of the pro-peptide was changed into a Ser$^V$-Pro$^VI$-Arg$^VIII$ sequence, which slightly improved the processing rate of the pro-peptide by trypsin (data not shown).

The mutagenic oligonucleotides 5'-CATAGTGCACCTTTA 3' and 5'-CAGGAGTTACCTGAGTCC3' (KpnI) were used for site-directed mutagenesis. The BglII site was introduced by ligation of an adaptor consisting of the oligonucleotides 5'-AGCTTAGATCTCAT 3' and 5'-ACTCTTACAGCAGCTTTA 3' into the SacI-HindIII vector fragment of M13mp8 containing the proPLA₂-cDNA (de Geus et al., 1987). All oligonucleotides were synthesized on a Biosearch 6800 DNA synthesizer. The sites of mutation in the sequences of the oligonucleotides are underlined. The resulting proPLA₂-cDNA was sequenced by the dideoxy chain termination method (Sanger et al., 1977) and a BamHII-HindIII fragment containing the entire proPLA₂-cDNA was cloned into the expression vector described by de Geus et al. (1987). The new construction,
containing the three additional restriction sites, was designated pOK13. With the use of the proPLA2-cDNA described above, the Phe-69 mutation was applied with the oligonucleotide 5' GCTTCTGGTGGAAAAGATG3'. The cDNA encoding the mutant PLA2 species was sequenced, and a BstXI-BglIII fragment containing the mutation was ligated into expression vector pOK13. After transformation and expression in E.coli K-12 strain MC4100 (Silhavy et al., 1984) containing plasmid pCI857, the mutant phospholipase was obtained by tryptic cleavage of reoxidized fusion protein (de Geus et al., 1987) and purified by CM–cellulose chromatography at pH 5 and 6. Final purification to homogeneity was achieved on DEAE–cellulose at pH 8.0.

### Phospholipids

The 1,2-diacyl-sn-glycero-3-phosphocholines used in this study were obtained after reacylation of sn-glycerol-3-phosphocholine. Mixed acid lecithins were prepared by degradation of the parent compound with PLA2, followed by reacylation of the resulting lysophospholipid. The 1,2-diacyl-sn-glycero-3-sulphates were synthesized as described before (van Oort et al., 1985). The 2,3-diacyl isomers of lecithins and sulphates were isolated after extensive degradation of the racemic compounds with PLA2. Both isomers of the ether analogue 1-tetradecyl-2-hexadecanoyl-3-phosphocholine were prepared from the corresponding ‘diglycerides’ by standard procedures (Bonsen et al., 1972b). The β-lecithin 1-hexadecanoyl-3-tetradecanoyl-sn-glycero-2-phosphocholine was prepared from 1,3-ditetradecanoyl-sn-glycero-3-phosphocholine by degradation with PLA2 and reacylation of the resulting lysophospholipid with palmitoylchloride. DL-2-Nonanoylpropanediol-1-phosphocholine was synthesized by acylation of the mono-tritylated compound, followed by detritylation and phosphorylation with 2-chloro-2-oxo-1,3,2-dioxaphospholane (Chandrakumar and Hajdu, 1983). The triester was subsequently converted to the lecithin by treatment with trimethylamine. 1,2-Didodecanoyl-sn-glycero-3-phosphocholines was synthesized from 3-O-benzyl-sn-glycerol as described by Nifant'ev et al. (1978). The R<sub>p</sub> and S<sub>p</sub>-isomers were isolated by degradation with phospholipase A<sub>2</sub> and reacylation of the R<sub>p</sub>-lysophospholipid, essentially as described before (Bruzik et al., 1983).

### Phospholipase assays

The activities of phospholipases were determined qualitatively using TLC on silica gel plates developed in chloroform–methanol–water (65:25:4, by vol.) mixtures. Lipids (10–20 mg/ml) were solubilized in the presence of sodium deoxycholate (2.5 mol/mol phospholipid) in buffer (50 mM borate, 5 mM CaCl<sub>2</sub>, pH 8.0). Spots were visualized after spraying the plates with phosphorus-reagent (Dittmer and Lester, 1964) or spraying with 30% sulphuric acid and charring. For GLC analysis spots were visualized with I<sub>2</sub>-vapour and fatty acids were analysed as their methyl-esters on a Perkin–Elmer 8500 Gas Chromatograph.

Quantitative measurements were carried out with a titrimetric assay at pH 8 in the presence of 1 mM borate, 25 mM CaCl<sub>2</sub> and 100 mM NaCl at 25°C. The burette of the Radiometer ABU was filled with 10 mM sodium hydroxide. For substrates containing fatty acyl chains of >8 carbon atoms, sodium deoxycholate was included in the test at a 2.5-fold molar ratio to substrate. Routinely the activities were measured on an egg yolk suspension in the presence of deoxycholate (Nieuwenhuizen et al., 1974). Activities on monomeric racemic 1,2-dihexanoyldithiolenecithin were determined at pH 8 in the presence of 100 mM Tris, 100 mM NaCl and 100 mM CaCl<sub>2</sub>, as described previously (Volwerk et al., 1979).

### Direct binding of PLA<sub>2</sub> to monomers and micelles

The affinity of PLA<sub>2</sub> for monomers and micelles was determined by following the increase of tryptophan fluorescence upon addition of increasing concentrations of the non-hydrolysable substrate analogues n-dodecanoylphosphocholine (CMC 1.3 mM) for monomer binding and n-hexadecylphosphocholine (CMC 10 µM) for binding to micelles. Assays were performed in a buffer containing 100 mM NaAc, 50 mM CaCl<sub>2</sub> and 100 mM NaCl at pH 6.0. From saturation curves obtained with lipid monomers, a K<sub>d</sub>-value can directly be derived. The data concerning micelle binding were analysed in terms of the binding of the enzyme to a theoretical lipid particle consisting of N monomers with a dissociation constant K<sub>N</sub>. As has been discussed extensively by de Araujo et al. (1979), the N<sub>K</sub><sub>d</sub> value is the experimental concentration at which 50% of the enzyme is saturated with micelles.

### Results

#### Enzymatic activities of Phe-69 phospholipase

The enzymatic activities and binding properties of the mutant and the native enzyme were determined on monomeric 1,2-dihexanoyldithiolenecithin and with the substrate analogue n-dodecanoylphosphocholine. The activities and binding properties with substrates present in aggregates were determined with

| Table I. Enzymatic activity of native and Y69F PLA2 on monomeric substrate of dC6dithioPC and binding to the substrate analogue C12PN |
|------------------|------------------|------------------|------------------|
| Enzyme           | dC6dithioPC      | C12PN            |
|                  | k<sub>cat</sub> (s<sup>-1</sup>) | K<sub>m</sub> (mM) | k<sub>cat</sub>/K<sub>m</sub> (s<sup>-1</sup> M<sup>-1</sup>) |
| Native           | 0.7              | 0.8              | 900              | 0.3              |
| Y69F             | 1.4              | 1.0              | 1400             | 0.3              |

Monomeric substrate was rac 1,2-dihexanoyldithiolenecithin. C12PN stands for n-dodecanoylphosphocholine. The activity on 1,2-dioctanoyl-sn-glycero-3-phosphocholine (L-diC8-PC) was varied between 0.5 and 10 mM. C<sub>16PN</sub> stands for n-hexadecylphosphocholine. The activity on 1,2-dioctanoyl-sn-glycero-3-phosphocholine (L-diC8-GS) was measured at a fixed substrate concentration of 2 mM. Accuracy was ~10% for each given value. For details see Materials and methods.

| Table II. Enzymatic activity of native and Y69F PLA2 on micellar substrates and binding to the substrate analogue C16PN |
|------------------|------------------|------------------|
| Enzyme           | t-diC8-PC        | C16PN            |
|                  | V<sub>max</sub> (µmol min<sup>-1</sup> mg<sup>-1</sup>) | N/K<sub>d</sub> (µM) | Egg yolk activity (µmol min<sup>-1</sup> mg<sup>-1</sup>) |
| Native           | 2000             | 3.7              | 70               | 1470              |
| Y69F             | 440              | 9.5              | 240              | 305               |

The substrate concentration of 1,2-dioctanoyl-sn-glycero-3-phosphocholine (t-diC8-PC) was varied between 0.5 and 10 mM. C16PN stands for n-hexadecylphosphocholine. The activity on 1,2-dioctanoyl-sn-glycero-3-substrate (t-diC8-GS) was measured at a fixed substrate concentration of 2 mM. Accuracy was ~10% for each given value. For details see Materials and methods.
micelles of various substrates and substrate analogues. The results of these determinations are summarized in Tables I and II. It is clear that the mutation Y69F has only limited effects on the binding and the specificity constant for monomeric substrates. Thus Tyr-69 is not involved in the true catalytic steps. Using aggregated substrates either in the form of mixed micelles (egg yolk), as neutral lecithin micelles or as negatively charged micelles, it is evident that the mutant is a somewhat less effective catalyst than the wild-type enzyme. The apparent affinity of the mutant for aggregated lecithins was reduced with regard to that of the wild-type PLA₂. Direct binding experiments also showed the reduced affinity of this mutant PLA₂ for micelles of the non-hydrolysable substrate analogue n-hexadecylphosphorylcholine. These data stress the importance of Tyr-69, specifically its phenolic OH moiety, for productive interaction of the enzyme with micelles.

**Effect of substitution on stereo- and positional-specificity**

Phospholipases A₂ are highly stereo- and position-specific. Although the exact nature of the interaction between enzyme and substrate is unknown, it has been suggested (Renetseder et al., 1988) that the hydroxyl group of Tyr-69 is involved in phosphate binding. We therefore tested the mutant enzyme for its ability to hydrolyze lipids other than sn-3 phospholipids. In initial experiments, using TLC as a qualitative assay, we found in fact that the Y69F mutant behaved differently from the wild-type enzyme. The Y69F mutant appeared to be capable of catalysing the hydrolysis of several phospholipids that are not hydrolysed by the wild-type enzyme. This different behaviour on both isomers of didecanoyllecithin is illustrated in Figure 1.

To obtain quantitative data we repeated these experiments in the pH-stat. In order to minimize kinetic differences due to physico-chemical properties of aggregated lipids, we used sodium deoxycholate to get uniformly dispersed lecithins (Table III). The mutant Y69F hydrolysed D-lecithins and D-glycerosulphates at low rates but the difference with the wild-type enzyme is significant. Because the Y69F mutant still keeps its preference for l-phospholipids, the loss of stereospecificity is partial and not absolute. The fact that 1-tetradecyl-2-hexadecanoyl-sn-glycero-3-phosphocholine, containing an ether bond at sn-1, is hydrolysed by the Y69F mutant indicates that this mutant, although it has partially lost its stereospecificity, still retains its positional specificity for the secondary ester bond. This retention of positional specificity was confirmed with DL-2-nonanoyl-propanediol-1-phosphocholine, a phospholipid with only a secondary acyl ester bond. This compound is still being degraded by the wild-type enzyme, with retention of stereospecificity, since only the l-compound is hydrolysed. The positional specificity was further investigated on mixed-acid diacyl phospholipids. Incubation of 1-tetradecanoyl-2-hexadecanoyl-sn-glycero-3-phosphocholine with wild-type and mutant phospholipasas, and gas-chromatographic analysis of the liberated fatty acid (palmitic acid) and the resulting lysolecithin, showed that the products of hydrolysis of wild-type and mutant phospholipases were indistinguishable, in agreement with the known 2-specificity of PLA₂. The positional specificity was also verified with the β-lecithin 1-tetradecanoyl-3-tetradecanoyl-sn-glycero-2-phosphocholine as a substrate. Again no difference between wild-type and mutant phospholipase was observed, as from this lecithin only hexadecanoic acid was removed. To further investigate the interactions of Tyr-69 and Phe-69 in the wild-type and mutant enzymes respectively with the phosphate moiety of the substrate, we tested these enzymes on substrates modified at phosphorus. The Rₖ- and Sₖ-isomers of lecithins with a sulphur present on the phosphate (Bruzik et al., 1983) were synthesized, and incubated with wild-type and Phe-69 PLA₂. TLC analyses showed that the Rₖ-1,2-didecanoyl-sn-glycero-3-thiophosphocholine was hydrolysed rapidly by both the wild-type and the mutant enzymes, whereas the Sₖ-isomer was resistant to the action of the wild-type enzyme. The Phe-69 mutant, however, slowly degraded the Sₖ-isomer to completion. Since the mutant Y69F had lost part of its stereospecificity it was of interest to test whether this mutant still required Ca²⁺ as a cofactor. We assayed the Y69F PLA₂ in the presence of 5 mM EDTA and found that the hydrolysis of both D- and L-lecithins was completely blocked.

**Discussion**

Using chemically modified pancreatic PLA₂, Meyer et al. (1979) concluded that Tyr-69 in PLA₂ is involved in the binding of both monomeric substrates and aggregated substrates. The introduction of a large hydrophobic group like the dansyl group on amino Tyr-69 increased the affinity of the modified PLA₂ for lecithin analogues in the pH-state. TLC after overnight incubation, under conditions as described in the legend of Figure 1, did not show any hydrolysis of the substrate.

Table III. Enzymatic activity of native and Y69F PLA₂ measured on both sn-3 and sn-1 species of three different micellar substrates

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Native</th>
<th>Y69F</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-diC₁₂-GS⁻</td>
<td>66</td>
<td>51</td>
</tr>
<tr>
<td>D-diC₁₂-GS</td>
<td>-b</td>
<td>1</td>
</tr>
<tr>
<td>L-diC₁₀-PC⁺</td>
<td>106</td>
<td>28</td>
</tr>
<tr>
<td>D-diC₁₀-PC</td>
<td>-b</td>
<td>0.21</td>
</tr>
<tr>
<td>L-14,16-PC</td>
<td>46</td>
<td>17</td>
</tr>
<tr>
<td>D-14,16-PC</td>
<td>-b</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Activities were determined at pH 8.0 and 25°C in the presence of 25 mM CaCl₂, 100 mM NaCl and 1 mM borate and substrate concentrations of 1 mM. The lecithin analogues were assayed in the presence of 2.5 mM sodium deoxycholate. Accuracy was ± 10% for each given value.

1l- and d-diC₁₂-GS: both stereo-isomers of 1,2-didecanoylglycero-sulphate; l- and d-diC₁₀-PC: both stereo-isomers of 1,2-didecanoylphosphocholine; l- and d-14,16-PC: both stereo-isomers of 1-tetradecyl-2-hexadecanoylphosphocholine.
micelles about 10-fold. In the present study we find that substitution of Tyr-69 by Phe reduces the affinity for micelles more than 3-fold. The side-chain of Tyr-69, specifically its substitution of Tyr-69 by Phe reduces the affinity for micelles about 10-fold. In the present study we find that the affinity for monomeric substrates once more underlines that the major role of Tyr-69 is not to increase affinity for the substrate but, rather, to orient the substrate in a specific way.

Interestingly, Renetser et al. (1986) observed that in the crystal structure of bovine PLA2 inhibited by p-bromophenacyl-bromide the Tyr-69 side-chain is pointing inward instead of outward. This notable change in the position of the phenolic OH resembles the 120° rotation observed for Tyr-248 in carboxypeptidase A (Rees and Lipscomb, 1982) upon binding of a substrate molecule. If the phenolic OH of Tyr-69 in PLA2 is actually hydrogen-bonded to a hydrogen bond acceptor in the substrate molecule then its energetic content must be low. The Y69F mutant binds monomeric substrate molecules and their analogues about equally efficiently as the wild-type enzyme. This low energy content may be explained by the fact that formation of the hydrogen bond between the phenolic OH and the putative acceptor requires removal of bound water molecules from both acceptor and donor groups. Small changes in binding energy have also been observed for the interaction between hydrogen-bridged partners in trysoyl-tRNA synthetase (Wells and Fersht, 1985).

Likewise in carboxypeptidase A, mutation of Tyr-248 to Phe hardly affects the K_m for ester substrates (Gardell et al., 1985). The fact that the mutation Y69F does not significantly change the affinity for monomeric substrates once more underlines that this affinity is dictated mainly by hydrophobic interactions with the acyl chains of the substrate: the enzyme binds monomers of dioctanoyllecithins ~100 times more tightly than dibutyryllecithin molecules (Verheij et al., 1981). The data presented here imply that the major role of Tyr-69 is not to increase affinity for the monomeric substrate but, rather, to orient the substrate in a specific way.

The question remains which group in the substrate molecule acts as the hydrogen bond acceptor for the phenolic OH of Tyr-69. The phosphate group and the hydrogen atom at the 2-position are required for the maintenance of stereospecificity. The third possibility, the specific interaction of Tyr-69 with the phosphate (or sulphate) group of the substrate, seems more likely.

Using synthetic phospholipids, de Haas et al. (1968) showed that PLA2 has high stereo- and positional-specificity. It was concluded that stereospecificity, fulfilling the three-point interaction as defined by Ogston (1948), must reside in fixation of the susceptible ester bond, the 2-acyl chain and the phosphate group. Since no three-dimensional structure of an enzyme–substrate or enzyme–inhibitor complex has been determined yet, the exact position and orientation of the acyl chains and the phosphate group of the substrate relative to the enzyme’s active site and the bound Ca²⁺ ion remains obscure. It has been proposed, however, that the liganded Ca²⁺ ion has two functions: polarization of the carbonyl of the scissile ester bond and fixation of the phosphate moiety (Verheij et al., 1980). Mutant Y69F still has an absolute requirement for Ca²⁺ ions, but has lost part of its stereospecificity. This suggests that the hydroxyl of Tyr-69 is more important than the Ca²⁺ ion in the fixation and orientation of the phosphate moiety. Thus the major role of Ca²⁺ seems to be the polarization of the scissile ester bond.

In wild-type porcine PLA2 the phosphate group most likely interacts with the phenolic hydroxyl of Tyr-69. Replacement of tyrosine by phenylalanine results in a partial loss of stereospecificity at C2 and at phosphorations. To the best of our knowledge this is the first report of the alteration of stereospecificity of an enzyme by protein engineering. Considering the possible orientation of the substrate in the active site, it is plausible that during hydrolysis of substrates with the D-configuration the position of the phosphate group and the hydrogen atom at the 2-position are interchanged as compared to their position during hydrolysis of L-phospholipids. Such an interchange of positions would explain that the mutant PLA2 has lost part of its stereospecificity but has retained its positional specificity. The fact that the Y69F mutant hydrolyses D-phospholipids ~50–100 times more slowly than L-phospholipids indicates that such a reverse orientation of the phosphate moiety might be less favourable than the correct orientation. Because PLA2 is obviously not perfectly shaped for the hydrolysis of D-phospholipids, it would be attractive to optimize the binding pocket for the phosphate of these phospholipids by protein engineering. A rational approach for
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such an enterprise will, in our opinion, require the determination of the three-dimensional structure of an enzyme—substrate (anologue) complex.

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References


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