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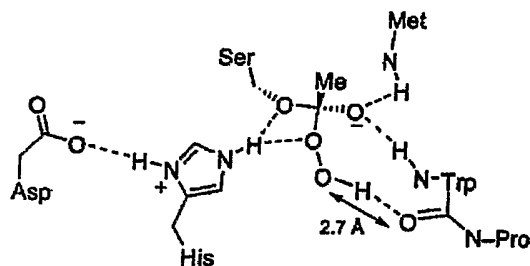
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(54) Title: INCREASING PERHYDROLASE ACTIVITY IN ESTERASES AND/OR LIPASES



(57) Abstract: The invention provides for methods of modifying n esterase or a lipase enzyme to introduce perhydrolase activity or to increase the already-existing perhydrolase activity. The invention also provides for methods of converting an polypeptide having predominantly esterase and/or lipase catalytic activity to a polypeptide having predominantly perhydrolase activity.

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INCREASING PERHYDROLASE ACTIVITY IN ESTERASES AND/OR LIPASES

TECHNICAL FIELD

This invention relates to enzymes, and more particularly to increasing
5 perhydrolase activity in esterases and/or lipases.

BACKGROUND

Catalytic promiscuity is the ability of the active site of one enzyme to catalyze
several chemical transformations. Understanding and controlling catalytic
10 promiscuity are key to understanding the evolution of new enzymatic activity and to
design new enzyme-catalyzed reactions for synthesis. The rationale presented here,
which was used to increase the perhydrolase activity in an esterase or a lipase, may be
used to design other enzymes with altered nucleophile selectivity and to catalyze
stereoselective oxidations.

15 SUMMARY

The invention provides for methods of modifying an esterase or a lipase
enzyme to introduce perhydrolase activity or to increase the already-existing
perhydrolase activity. The invention also provides for methods of converting an
polypeptide having predominantly esterase and/or lipase catalytic activity to a
20 polypeptide having predominantly perhydrolase activity.

In one aspect, the invention provides methods of increasing perhydrolase
activity in an esterase or lipase. Such methods generally include providing a nucleic
acid encoding the esterase or lipase, modifying one or more nucleotides in the codon
encoding the OXY+1 residue in the esterase or lipase to nucleotides that cause the
25 codon to encode an amino acid that can adopt a *cis*-configuration, and expressing the
modified nucleic acid to generate a modified polypeptide, wherein the modified
polypeptide has increased perhydrolase activity compared to the pre-modified esterase
or lipase. Such a method also can include screening the esterase or lipase for
perhydrolase activity and/or screening the modified polypeptide for perhydrolase
30 activity.

A representative amino acid that can adopt a *cis*-configuration is proline or a derivative of proline (e.g., hydroxyproline). A representative nucleic acid encoding an esterase has the sequence shown in SEQ ID NO:1, and a representative nucleic acid encoding a lipase has the sequence shown in SEQ ID NO:2. Generally, an esterase or lipase suitable for use in the invention is a bacterial esterase or lipase, a fungal esterase or lipase, a mammalian esterase or lipase, or a plant esterase or lipase.

In another aspect, the invention provides methods of introducing perhydrolase activity into an esterase or lipase. Such methods generally include providing a nucleic acid encoding the esterase or lipase, modifying one or more nucleotides in the codon encoding the OXY+1 residue in the esterase or lipase to nucleotides that cause the codon to encode an amino acid that can adopt a *cis*-configuration, and expressing the modified nucleic acid to generate a modified polypeptide, wherein the modified polypeptide has perhydrolase activity.

In still another aspect, the invention provides methods of converting a polypeptide having predominantly esterase and/or lipase activity to a polypeptide having predominantly perhydrolase activity. Such methods generally include providing a nucleic acid encoding the polypeptide having predominantly esterase and/or lipase activity, modifying one or more nucleotides in the codon encoding the OXY+1 residue in the polypeptide to nucleotides that cause the codon to encode an amino acid that can adopt a *cis*-configuration, and expressing the modified nucleic acid to generate a modified polypeptide, wherein the modified polypeptide has predominantly perhydrolase activity.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and

advantages of the invention will be apparent from the drawings and detailed description, and from the claims.

DESCRIPTION OF DRAWINGS

Figure 1 is a schematic showing the proposed molecular basis of perhydrolase activity in a *Pseudomonas fluorescens* esterase. The formation of the second tetrahedral intermediate (after hydrogen peroxide attack) can be facilitated and the intermediate subsequently stabilized by an important hydrogen bond in a Leu29Pro mutant.

Like reference symbols in the various drawings indicate like elements.

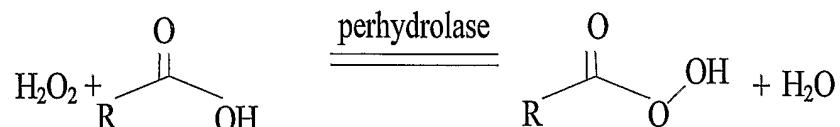
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DETAILED DESCRIPTION

The invention provides for methods of modifying an esterase or a lipase enzyme to introduce perhydrolase activity into the enzyme or to increase the already-existing perhydrolase activity. The invention also provides for methods of converting a polypeptide having predominantly esterase and/or lipase catalytic activity to a polypeptide having predominantly perhydrolase activity. It is shown herein that substituting a single amino acid in PFE was sufficient to shift the activity from hydrolysis to perhydrolysis in aqueous solution. The perhydrolase activity is similar to that of naturally occurring perhydrolases.

This disclosure provides methods for increasing the existing perhydrolase activity in an esterase or lipase, and methods for introducing novel perhydrolase activity into an esterase or lipase. This disclosure further provides methods of converting a polypeptide having predominantly esterase and/or lipase activity into a polypeptide having predominantly perhydrolase activity.

Perhydrolases, esterases, and lipases all contain a catalytic triad consisting of a Serine (Ser), a Glutamate (Glu) or Aspartate (Asp), and a Histidine (His). See, for example, Blow, 1990, *Nature*, 343:694-5. Perhydrolases (previously known as metal-free haloperoxidases) contain a Ser-His-Asp catalytic triad and catalyze the reversible formation of peracid from hydrogen peroxide and carboxylic acids [Eq. (1)].



Perhydrolysis presumably takes place with an esterase-like mechanism in which a carboxylic acid reacts with the active site serine to form an acyl enzyme intermediate, which then reacts with hydrogen peroxide to form a peracid. The change from water to hydrogen peroxide as a nucleophile could be considered a change in substrate selectivity, but the very different chemical reactivity of the products (carboxylic acid vs. peroxy-carboxylic acid) makes this an example of alternate catalytic activity. Recent X-ray structures of an aryl esterase from *Pseudomonas fluorescens* (PFE), which shows low perhydrolase activity, and a homologous perhydrolase from *P. fluorescens* (CPO-F) show very similar active sites and no obvious structural basis for esterase vs. perhydrolase activity. See, for example, Cheeseman et al., 2004, *Acta Crystallogr. Sect. D: Biol. Crystallogr.*, 60:1237-43.

Among the different types of esterase enzymes are those that act on carboxylic esters (EC 3.1.1). The consensus pattern for carboxyl-esterases is F-[GR]-G-x(4)-[LIVM]-x-[LIV]-x-G-x-S-[STAG]-G, wherein S is the active site residue (ProSite Documentation PDOC00112; for information regarding ProSite prefixes, see Sonhammer et al., 1997, *Protein*, 28:405-420 or expasy.org on the World Wide Web). See, also, Myers et al., 1988, *Mol. Biol. Evol.*, 5:113-9; Krejci et al., 1991, *PNAS USA*, 88:6647-51; and Drabløs & Petersen, 1997, *Methods in Enzymol.*, 284:28-61. The nucleic acid sequence of a representative esterase is shown in SEQ ID NO:1, and the encoded amino acid sequence is shown in SEQ ID NO:3. The sequences of additional representative esterases can be found, for example, at GenBank Accession Nos. X66104, L26319, M19677, J04167, M68491, and L24749.

Lipases are widely distributed in animals, plants, and prokaryotes. Triglyceride lipases (EC 3.1.1.3) are lipolytic enzymes that hydrolyse ester linkages of triglycerides. The consensus pattern of lipases is [LIV]-{KG}-[LIVFY]-[LIVMST]-G-[HYWV]-S-{YAG}-G-[GSTAC], wherein S is the active site residue (ProSite Documentation PDOC00110; for information regarding ProSite prefixes, see

Sonhammer et al., 1997, *Protein*, 28:405-420 or expasy.org on the World Wide Web). See, also, Persson et al., 1989, *Eur. J. Biochem.*, 179:39-45; and Drabløs & Petersen, 1997, *Methods in Enzymol.*, 284:28-61. The nucleic acid sequence of a representative lipase is shown in SEQ ID NO:2, and the encoded amino acid sequence is shown in
5 SEQ ID NO:4. The sequences of additional representative lipases can be found, for example, at GenBank Accession Nos. X61673, D50587, X17366, X54516, M35302 and M74010.

In order to increase the perhydrolase activity in an esterase or lipase, to introduce perhydrolase activity into an esterase or lipase, or to convert a polypeptide
10 having predominantly esterase and/or lipase activity to a polypeptide having predominantly perhydrolase activity, one or more nucleotides in the esterase or lipase are modified. Nucleic acids suitable for use as starting materials in the methods disclosed herein include nucleic acids encoding bacterial esterases or lipases, fungal esterases or lipases, mammalian esterases or lipases, or plant esterases or lipases.
15 Other enzymes that perform hydrolysis reactions may be suitable for modification by the methods of the invention.

Generally, nucleotides that encode the OXY+1 residue are identified in the esterase or lipase and modified to encode an amino acid that can adopt a *cis*-configuration. In addition to modifying the OXY+1 residue, nucleotides encoding
20 any one or more of the other 13 residues identified herein also can be modified in an esterase or lipase to increase or introduce perhydrolase activity.

The OXY+1 residue can be identified from 3-D modeling of the polypeptide. The loop regions containing the active site residues that form the catalytic Ser-His-Asp/Glu triad and a fourth, short loop that reaches near the active site can be
25 identified. This fourth, short loop usually comprises amino acids from the N-terminus of the polypeptide and contains the carbonyl oxygen involved in perhydrolase activity. The carbonyl oxygen is attached to the residue forming the oxyanion hole (referred to herein as the "OXY" residue). Modification of the first residue on the carboxy side of the oxyanion hole residue (referred to herein as the "OXY+1"
30 residue), alone and/or in combination with other mutations, imparts increased perhydrolase activity to the polypeptide.

Although not bound by any particular mechanism, it is suggested herein that a carbonyl group in the vicinity of the active site serves as a stabilizer for hydrogen peroxide attack on a putative acyl-enzyme intermediate, which ultimately results in an

increase in perhydrolase activity. Therefore, in addition to, or as an alternative to, modifying the OXY+1 residue as described above, modifications at one or more other residues (e.g., one or more of the remaining 13 residues identified herein) can be introduced into the polypeptide and the modified polypeptide modelled. The distance
5 between the O γ and the C=O is measured. As discussed below, a distance between the O γ and the C=O that is closer to 2.7 Å rather than 3.2 Å appears to provide stability to facilitate optimal perhydrolase activity. Although not bound by any particular mechanism, the distance between the catalytic serine O γ atom and the carbonyl oxygen (C=O) is an indication of hydrogen bond strength. Typically, this
10 distance is 2.8 ± 0.1 Å. A distance exceeding this value is considered a very weak to an absent hydrogen bond, which would provide little to no stability and cause sub-optimal perhydrolase activity.

A number of computer programs are available and known in the art for 3-D modeling of polypeptides. For example, InsightII (Accelrys, San Diego, CA) and
15 Sybyl (Tripos, St. Louis, MO). Standard protocols for energy minimization and computer modeling are known to those of skill in this art. See, for example, Leach, Molecular Modeling: Theory and Applications, 2nd Ed., Prentice Hall, 2001.

Amino acids that can adopt a *cis*-configuration can be a natural or a non-natural amino acid. A non-limiting representative example of an amino acid that can adopt a
20 *cis*-configuration is proline or a proline derivative such as hydroxyproline. Other amino acids including aspartate, asparagine, alanine, phenylalanine, glutamate, glycine, serine, tyrosine, threonine, histidine, and tryptophan are able to adopt a *cis*-configuration. A review of *cis*-forming amino acid residues, can be found, for example, on the World Wide Web at [imb-](http://imb-jena.de/ImgLibDoc/cispep/non_proline/IMAGE_CISPEP2.html)
25 [jena.de/ImgLibDoc/cispep/non_proline/IMAGE_CISPEP2.html](http://imb-jena.de/ImgLibDoc/cispep/non_proline/IMAGE_CISPEP2.html).

One or more nucleotides encoding a particular amino acid residue in a polypeptide can be modified using a number of different methods known in the art. For example, site-directed mutagenesis can be used to modify one or more nucleotides such that those codons encode an amino acid residue that differs from the
30 corresponding residue encoded by the wild-type polypeptide. One of the most common methods of site-directed mutagenesis is oligonucleotide-directed mutagenesis. In oligonucleotide-directed mutagenesis, an oligonucleotide encoding the desired mutation(s) is annealed to one strand of the DNA of interest and serves as a primer for initiation of DNA synthesis. In this manner, the mutagenic

oligonucleotide is incorporated into the newly synthesized strand. See, for example, Lewis & Thompson, 1990, *Nucl. Acids Res.*, 18:3439; Bohnsack, 1996, *Meth. Mol. Biol.*, 57:1; Vavra & Brondyk, 1996, *Promega Notes*, 58:30; Deng & Nickoloff, 1992, *Anal. Biochem.*, 200:81; Kunkel, 1985, *Proc. Natl. Acad. Sci. USA*, 82:488; 5 Kunkel et al., 1987, *Meth. Enzymol.*, 154:367; Taylor et al., 1985, *Nucl. Acids Res.*, 13:8764; Nakamaye & Eckstein, 1986, *Nucl. Acids Res.*, 14:9679; Higuchi et al., 1988, *Nucl. Acids Res.*, 16:7351; Shimada, 1996, *Meth. Mol. Biol.*, 57:157; Ho et al., 1989, *Gene*, 77:51; Horton et al., 1989, *Gene*, 77:61; Sarkar & Sommer, 1990, *BioTechniques*, 8:404.

10 Other methods are used routinely in the art to modify the sequence of a protein or polypeptide. For example, polypeptides can be chemically synthesized to have the desired modified amino acid sequence. See, for example, Bang & Kent, 2005, *PNAS USA*, 102:5014-9 and references therein. In addition, nucleic acids can be generated (e.g., by PCR) and expressed to produce a modified or an unmodified polypeptide.

15 Methods for evaluating the catalytic activity of enzymes are used routinely in the art. Esterase activity, lipase activity, and/or perhydrolase activity of a modified or un-modified polypeptide can be evaluated using known methods. For example, esterase activity can be evaluated using the hydrolysis of *p*-nitrophenyl acetate (pNPAC); lipase activity can be evaluated using *p*-nitrophenyl palmitate (PNPP); and 20 perhydrolase activity can be evaluated using a monochlorodimedone (MCD) assay. See, for example, Hager et al., 1966, *J. Biol. Chem.*, 241:1769-77.

The modified enzymes made by the methods disclosed herein can be used, for example, in detergents. Modified enzymes that exhibit perhydrolase activity can be used, for example, in laundry detergents to remove fat stains from fabrics. Modified 25 enzymes that have perhydrolase activity also can be used in industrial sanitary and waste treatment applications. Industries such as textiles and pulp and paper are increasingly using peroxide in bleaching processes, and need an environmentally friendly process to de-toxify the waste resulting therefrom.

The modified enzymes made by the methods disclosed herein also can be used 30 to make derivatives of peracid (e.g., peroxy-carboxylic acid). Peroxycarboxylic acid in various formulations can disinfect, and eliminate biofilms and microbial contamination. See, for example, U.S. Publication No. 2002128312; PCT Publication No. WO 2003066107; PCT Publication No. WO 2001070030; and PCT Publication No. WO 9967213. For example, Fatemi & Frank (1999, *J. Food Protect.*, 62:761-5)

removed biofilms from food processing equipment within a minute using 160 parts per million peroxycarboxylic acids. Current chemical methods for making peroxycarboxylic acids usually involve very acidic, harsh conditions. An enzymatic method of making peroxycarboxylic acids would be beneficial to industry and to the environment.

Commercially useful lipases and esterases include, but are not limited to, *Candida antarctica* lipase B (CALB), *Humicola lanuginosa* lipase (HLL), *Pseudomonas cepacia* lipase (PCL), *Candida rugosa* lipase (CRL), Pig-liver esterase (PLE), *Mucor javanicus* lipase (MJL), *Mucor miehi* lipase (MML), and *Bacillus thermocateriualatus* esterase (BTE). Crystal structures have been determined for CALB (PDB ID: 1TCA), HLL (PDB ID: 1DT5), PCL (PDB ID: 1OIL), and CRL (PDB ID: 1GZ7).

Once it has been determined that a modified enzyme has perhydrolase activity, the enzyme can be evaluated at various pHs and/or temperatures for activity. Enzyme production can be established at industrially-relevant volumes using techniques known in the art (e.g., fermentation). For applications in which a modified enzyme is being used, for example, to de-toxify waste liquids, the modified enzyme can be attached to polymer beads and packed into columns for filtering the waste.

In accordance with the present invention, there may be employed conventional molecular biology, microbiology, biochemical, and recombinant DNA techniques within the skill of the art. Such techniques are explained fully in the literature. The invention will be further described in the following examples, which do not limit the scope of the invention described in the claims.

EXAMPLES

Example 1—Identification of Residues Important to Perhydrolase Activity

Previous experiments to convert PFE into a perhydrolase focused on three amino acids that differ between PFE and CPO-F (Met95, 4.5 Å from Ser94 Oγ to Met 95 Cα; Tyr69, 14 Å; and Thr122, 9.9 Å). Mutations at these sites did not significantly change perhydrolase activity. The Met95Thr mutation decreased esterase activity from 13.7 to 3.4 U mg⁻¹ and decreased perhydrolase activity to below the detection limit (< 0.02 U mg⁻¹). 1 U is equivalent to the consumption of 1 μmol of substrate min⁻¹. This decrease may be due to a shift in the backbone amide of residue

95, which forms part of the oxyanion hole. The esterase and perhydrolase activities of Tyr69Met and Thr122Pro are very similar to those for the wild-type protein (Table 1).

Since a direct structural comparison of PFE and CPO-F did not reveal how to increase perhydrolase activity, amino acid sequence alignments (ClustalW) of several hydrolases and perhydrolases were used to identify the essential residues for each activity. There were not enough aryl esterase sequences available in the databases so the set was expanded to serine hydrolases, which are still homologous. The sequences used were CPO-F from *P. fluorescens* (GenBank Accession No. AF031153); BPO-A1 from *Streptomyces aureofaciens* (GenBank Accession No. U01096); CPO-L from *Streptomyces lividans* (GenBank Accession No. U02635); CPO from *S. aureofaciens* (GenBank Accession No. AF031242); BPO-A2 from *S. aureofaciens* (GenBank Accession No. M84990); BPO from *Synechocystis* sp (GenBank Accession No. BAA10684); aryl esterase from *P. fluorescens* (GenBank Accession No. U12537); aryl esterase from *Bacillus cereus* (GenBank Accession No. AAP10065); esterase from *Pseudomonas putida* (GenBank Accession No. AAN69615); dihydrocoumarin hydrolase from *Actinobacter calcoaceticus* (GenBank Accession No. BAC55927); 2-hydroxy-6-oxohepta-2,4-dienoate hydrolase from *P. putida* (GenBank Accession No. P23133); and 2-hydroxymuconic semialdehyde hydrolase from *P. putida* (GenBank Accession No. P19076).

Comparison of these six esterase and six perhydrolase sequences identified fifteen amino acids common to most esterases and fifty-seven amino acids common to most perhydrolases. A Venn diagram (Rothman and Kirsch, 2003, *J. Mol. Biol.*, 327:593-608) was used to map residues conserved in esterases but not in perhydrolases, in esterases and perhydrolases, and in perhydrolases but not in esterases. PFE contains most of the amino acid residues common to esterases. PFE, however, has amino acid substitutions at fourteen positions out of the fifty-seven amino acids common to most perhydrolases. Perhydrolases generally contain the following residues at the indicated position. The residue in parentheses is the corresponding residue present in PFE. Thr4 (Val), Tyr13 (Phe), Val23 (Leu), Pro29 (Leu29), Leu76 (Ile), Glu99 (Asp), Lys114 (Gly), Lys127 (Gln), Asn131 (Tyr), Glu138 (Asp), Asp141 (Ala), Trp182 (Ile), Ile227 (Phe), and Gly248 (Asp).

It was hypothesized that an increase in perhydrolase activity and a decrease in esterase activity of an enzyme could be achieved by substituting one or several of the fourteen amino acid residues identified. It was further hypothesized that the residues

closer to the active site (in a three-dimensional configuration and not necessarily in the linear sequence) are more important for catalytic activity than residues more distal to the active site. Therefore, distances between the conserved residue's C α and the catalytic serine's O γ were measured (see below). Three amino acid residues were within a 12 Å sphere of the catalytic Ser94 O γ : proline at position 29 (Pro29), glutamic acid at position 99 (Glu99), and isoleucine at position 227 (Ile227).

Site-directed mutagenesis using complementary, mutagenic PCR-primers yielded the Leu29Pro, Asp99Glu, and Phe227Ile mutants of PFE. DNA sequencing confirmed the mutations and protein were expressed and purified as described (Cheeseman et al., 2004, *Acta Crystallogr. Sect. D: Biol. Crystallogr.*, 60:1237-1243).

Example 2—Methods of Evaluating Enzyme Activity

Activity assays were performed in quadruplicates on 96-well microtiter plates with a reaction volume of 100 μ l (90 μ l assay solution to 10 μ l enzyme in 5 mM BES pH 7.2). The path-length for light through the well was 0.29 cm.

The monochlorodimedon (MCD) assay (Hager et al., 1966, *J. Biol. Chem.*, 241:1769-1777) was used to detect peracid formation. Each reaction contained MCD (0.18 mM), H₂O₂ (90 mM), NaBr (90 mM) in acetate buffer (1 M, pH 5.5) at 25°C. The reaction was followed spectrophotometrically at 290 nm in UV-transparent microtiter plates (ϵ = 19.9 x 10³ M⁻¹cm⁻¹).

The *p*-nitrophenyl acetate (pNPAc) assay contained pNPAc (0.3 mM) and 8% acetonitrile as co-solvent in BES buffer (5 mM, pH 7.2). The reaction was monitored spectrophotometrically at 404 nm (ϵ = 11.4·10³ M⁻¹cm⁻¹). A pH-indicator assay was used to assay substrates without inherent light absorbing properties (Janes et al., 1998, *Chem. Eur. J.* 4:2324-2331). The reactions were carried out in BES buffer (5 mM, pH 7.2) containing *p*-nitrophenol. As hydrolysis progresses, protons add to the *p*-nitrophenolate and the course of reaction can be monitored as a decrease in absorbance at 404 nm (ϵ = 16.5·10³ M⁻¹cm⁻¹). This provides a good estimate of reaction rates, but is limited to substrates containing only one possible acid-functionality, as several would interfere with the pH indicator. Each reaction contained substrate (5 mM), as indicated in Table 3, and 8% acetonitrile as co-solvent.

Kinetic parameters for hydrolysis of pNPAc in wild-type and Leu29Pro were carried out with pNPAc at 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, and 10 mM under otherwise

identical conditions as for the pNPac-assay. Solubility problems limited higher substrate concentrations than 10 mM. Data points were fitted by non-linear regression using OriginPro 7.5 SR1 v7.5776 (OriginLab Corporation, Northampton, MA) with a hyperbola function of basic equation $y = P1 \cdot x / (P2 + x)$, where x is the substrate concentration (mM), $P1$ corresponds to V_{\max} ($\mu\text{mol min}^{-1} \text{mg}^{-1}$ or U/mg), and $P2$ corresponds to K_M (mM). R^2 -values for were 0.992 and 0.997 for wild-type and Leu29Pro, respectively.

An estimate of kinetic parameters was also obtained for hydrogen peroxide in wild-type and Leu29Pro. The hydrogen peroxide in wild-type was 5, 10, 20, 50, 100, and 200 mM; for Leu29Pro, the concentrations were 5, 10, 20, 35, 50, 121, 152, and 200 mM. Using the basic hyperbola function, $y = P1 \cdot x / (P2 + x)$, the R^2 -values were 0.974 and 0.976 for wild-type and Leu29Pro, respectively.

Example 3—Enzyme Activity

The catalytic activity of the Leu29Pro mutant shifted from that of an esterase to that of a perhydrolase. Under the conditions used to assay the enzymatic activity, perhydrolase activity increased 28-fold from 0.24 to 6.8 U mg^{-1} based on bromination of monochlorodimedone (see Hager et al., 1966, *J. Biol. Chem.*, 241:1769-1777). The level of perhydrolase activity in the modified esterase was higher than that of a true perhydrolase from *Pseudomonas fluorescens*, but lower than that of the perhydrolases from *Pseudomonas putida* or from *P. pyrocinia*. In addition, the hydrolytic activity toward *p*-nitrophenyl acetate decreased 100-fold from 14 to 0.14 U mg^{-1} (Table 1).

Table 1. Rate of hydrolysis and perhydrolysis for PFE variants

PFE variant	Hydrolysis [U mg^{-1}] ^[a]	$\Delta\Delta G_{\text{mut-wt}}$ [kcal mol^{-1}] ^[b]	Perhydrolysis [U mg^{-1}] ^[c]	$\Delta\Delta G_{\text{mut-wt}}$ [kcal mol^{-1}] ^[b]
wild-type	14	0	0.24	0
Leu29Pro	0.14	2.7	6.8	-2.0
Tyr69Met	18	-0.17	0.30	-0.13
Met95Thr	3.4	0.83	<0.02	>1.5
Asp99Glu	8.6	0.28	0.12	0.44
Thr122Pro	15	-0.062	0.18	0.17
Phe227Ile	38	-0.60	0.23	0.050

[a] Hydrolase activity determined in 5 mM *N,N*-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid (BES) buffer (pH 7.2) and 25°C where 1 U corresponds to 1 μmol of *p*-nitrophenyl acetate hydrolyzed per minute;

- [b] The energy equivalent of the rate change compared to wild-type PFE: $\Delta\Delta G = -RT \cdot \ln(x)$, x -fold rate-change, $T = 300$ K and R is the gas constant, $1 \text{ kJ mol}^{-1} = 4.18 \text{ kcal mol}^{-1}$; and
- 5 [c] Perhydrolase activity determined in 1 M acetate buffer (pH 5.5) where 1 U corresponds to consumption of $1 \mu\text{mol}$ of monochlorodimedon per minute at 25°C . The error-limit is estimated to 20% in kinetic assays.

The Asp99Glu and Phe227Ile mutants showed no increase in perhydrolase
 10 activity. For Asp99Glu, both the perhydrolase activity and the hydrolysis activity were somewhat reduced compared to the wild-type (Table 1). The perhydrolase activity for Phe227Ile was statistically equivalent with the wild-type enzyme's perhydrolase activity, while the hydrolysis activity for Phe227Ile was close to three-fold higher than the hydrolysis activity of the wild-type enzyme (Table 1).

15 Kinetic characterizations of wild-type and Leu29Pro PFE showed that the major contributor to the observed rate-increase is a 50-fold increase in V_{\max} for perhydrolysis, from 0.22 to 11 U mg^{-1} in the wild-type and mutant enzymes, respectively. The Leu29Pro mutation also increased the K_M for hydrogen peroxide three-fold, from 17 mM to 58 mM . These values point to a 14-fold increased catalytic
 20 efficiency (V_{\max}/K_M) for perhydrolysis of acetic acid, from 13 to $180 \text{ U mg}^{-1} \text{ M}^{-1}$, corresponding to a lowered activation energy barrier of $1.6 \text{ kcal mol}^{-1}$ at 300 K . The Leu29Pro mutation also caused a 50-fold decrease in the V_{\max} for the hydrolysis of *p*-nitrophenyl acetate (pNPAc), while the K_M increased three-fold (Table 2), altogether changing the catalytic efficiency (V_{\max}/K_M) 165-fold corresponding to an elevated
 25 activation energy barrier for hydrolysis of $3.0 \text{ kcal mol}^{-1}$ at 300 K .

Table 2. Kinetic parameters for *p*-nitrophenyl acetate (pNPAc) and hydrogen peroxide

Enzyme	$V_{\max} [\text{U mg}^{-1}]$	$K_M [\text{mM}]$	$V_{\max}/K_M [\text{U mg}^{-1} \text{ M}^{-1}]$
Wild-type, pNPAc	143 ± 9	2.8 ± 0.4	51000
Leu29Pro, pNPAc	2.8 ± 1.1	8.9 ± 1.1	310
Wild-type, H_2O_2	0.22 ± 0.02	17 ± 4	13
Leu29Pro, H_2O_2	11 ± 1	58 ± 12	180

The hydrolytic activity of Leu29Pro toward un-activated esters decreased
 30 much less dramatically, from no change to an eight-fold decrease (Table 3). The rate-determining step for hydrolysis may differ between activated esters (such as pNPAc) and un-activated esters. For activated esters, the acylation is likely fast and deacylation becomes rate-determining. For un-activated esters, the acylation and

deacylation are more similar than for activated esters such as pNPAc. The difference between the rate of hydrolysis of activated and un-activated esters suggests that the Leu29Pro mutation slows down the hydrolysis of *p*-nitrophenyl acetate by slowing down the deacylation step.

5

Table 3. Rate of hydrolysis and relative rates for several ester substrates

Ester	wild-type [U mg ⁻¹] ^[a]	Leu29Pro [U mg ⁻¹] ^[a]	x-fold decrease ^[b]
<i>p</i> -nitrophenyl acetate ^[c]	14	0.50	100
ethyl butyrate	1.3	0.16	8.1
ethyl valerate	0.65	0.083	7.8
propyl propionate	0.91	0.18	5.1
butyl propionate	0.57	0.14	4.1
ethyl propionate	0.75	0.19	3.9
methyl propionate	0.38	0.33	1.2

10

[a] Specific activity of ester hydrolysis determined in 5 mM *N,N*-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid (BES) buffer (pH 7.2) containing 0.51 mM *p*-nitrophenol and 5 mM substrate at 25°C where 1 U corresponds to 1 μmol of protons generated from hydrolysis per minute; [b] The rate of hydrolysis in wild-type PFE divided by rate of hydrolysis in Leu29Pro PFE; and [c] Experimental value, [pNPAc] = 0.3 mM.

Example 4—Proposed Molecular Basis of New Perhydrolase Activity

15 Molecular modeling was used to identify the molecular basis of the increase in perhydrolase activity caused by the Leu29Pro mutation. Chain A of the crystal structure of the free PFE enzyme (PDB ID: 1VA4) was used as starting point for modeling experiments. Modeling was performed using the InsightII (Version 2000.1) software on a SGI UNIX workstation. The system was described by using the cvff
20 force field. Non-standard partial charges of the tetrahedral intermediate were calculated with the AM1 algorithm. A formal charge of -1 was assigned to the oxyanion oxygen of the tetrahedral intermediate. A distance dependent dielectric constant of unity was used in all calculations. The catalytic His224 was defined as protonated. Energy minimization procedures were as described previously (Raza et
25 al., 2001, *Prot. Sci.* 10:329-338). Leu29 in the wild-type structure was manually changed to *cis*-Pro before modeling in the tetrahedral intermediate. The tetrahedral intermediate of the deacylation step was manually modeled onto Ser94. Any water molecules near the active site were removed to make room for the substrate. After

energy minimization of the whole system hydrogen bond angles, and distances between heavy atoms participating as donors or acceptors, were measured.

After minimization, an overlay of the proline residue in Leu29Pro PFE on the proline residue in CPO-F (PDB ID: 1A8S) confirmed identical conformations.

- 5 Assuming that perhydrolysis takes place with an esterase-like mechanism, the second tetrahedral intermediate was modelled to represent the transition state for hydrogen peroxide attack on the acetyl-enzyme.

All modeled structures showed productive hydrogen bonds for catalytic triad residues and oxyanion-hole residues. In Leu29Pro PFE, a hydrogen bond was found
10 between the carbonyl oxygen of Trp28 and the peroxide hydroxyl-group, having a predicted O-O distance of 2.7 Å (O-H-O angle 133°). Similarly, this hydrogen bond length in CPO-F was 2.7 Å (O-H-O angle 127°). These distances are within the typical values for a hydrogen bond from a hydroxyl-group oxygen to a carbonyl-oxygen: 2.8 ± 0.1 Å (Schultz & Schirmer, *Principles of Protein Structure*, Springer-
15 Verlag, New York, 1984, p. 35). In contrast, the corresponding hydrogen bond in wild-type PFE is much weaker, having a predicted O-O distance of 3.2 Å (O-H-O angle 114°).

- Previous analysis of the CPO-F X-ray structure noted that Pro29 adopts a *cis*-peptide conformation, which may cause hydrogen peroxide to react instead of water.
20 See, for example, Hofmann et al., 1998, *J. Mol. Biol.*, 279:889-900. There, the perhydrolase activity of CPO-F was attributed to differences in nucleophilicity between hydrogen peroxide and water. The results reported herein suggest that a hydrogen bond between the carbonyl oxygen and the peroxide nucleophile is the molecular basis for the increased perhydrolase activity. A peroxide hydroxyl-
25 carbonyl hydrogen bond could favour the perhydrolase reaction by binding and orienting the hydrogen peroxide in a catalytically productive orientation. The energy equivalent of the rate-increase of perhydrolysis is $1.6 \text{ kcal mol}^{-1}$, which is consistent with a new hydrogen bond since a hydrogen bond between a neutral donor and neutral acceptor typically contributes $1\text{-}2 \text{ kcal mol}^{-1}$ to substrate selectivity (see, for example,
30 Fersht et al., 1985, *Nature*, 314:235-238; and Fersht, 1988, *Biochemistry*, 27:1577-1580).

To identify the molecular basis of the decreased hydrolytic activity of Leu29Pro toward *p*-nitrophenyl acetate, the first and second tetrahedral intermediates of hydrolysis were modeled. Modeling of the first tetrahedral intermediate of

hydrolysis of pNPAc showed no differences that could account for the large rate decrease. The pNP moiety does adopt different configurations in wild-type and Leu29Pro PFE, but neither structure encounters significant steric strain. See Figure 1.

Computer modeling of the second tetrahedral intermediate showed different
 5 hydrogen bonds of the water attacking the acetyl enzyme intermediate in wild-type PFE and in the Leu29Pro mutant. In wild-type PFE, a bridging water molecule hydrogen bonds to the carbonyl group of Trp28 and to the tetrahedral intermediate (O_i-O_w -distance: 2.5 Å, O_w-O_{Trp28} -distance: 2.6 Å, angles: 166° and 172°, respectively). However, in Leu29Pro, this carbonyl group has moved ~ 0.5 Å closer
 10 to the water forming the tetrahedral intermediate so a bridging water molecular no longer fits, but not close enough to form a direct hydrogen bond ($O-O$ -distance: 4.3 Å, $O-H-O$ -angle: 139°). Without being bound by any particular mechanism, this loss of a hydrogen bond in the tetrahedral intermediate is a likely origin of the lower hydrolytic activity of the Leu29Pro mutant because this change slowed the
 15 presumably rate-limiting deacylation step.

Example 5—Modeling and Mutagenesis of Other Esterases and Lipases

The tetrahedral intermediate of perhydrolysis was modeled into CALB to verify that the model presented herein is applicable to a variety of esterases and
 20 lipases.

Candia antarctica lipase B (CALB; PDB ID: 1TCA): The catalytic triad residues of CALB are Ser105, His224, and Asp187. Trp28 is the oxyanion hole residue (OXY) in PFE, which corresponds to Thr40 in CALB (6.0 Å between OXY and Ser105 O_γ). The residues surrounding the OXY residue (Thr40 is shown in bold
 25 and underlined) are VPGTGTT. Based on the methods described herein, increased perhydrolase activity is achieved by generating a modified polypeptide containing a Gly41Pro mutation. Modeling suggests that, in fact, Gly41Pro forms a stable tetrahedral intermediate during deacylation, implying a good perhydrolase activity.

Humicola lanuginosa lipase (HLL; PDB ID: 1DT5): The catalytic triad
 30 residues of HLL are Ser146, His258, and Asp201. As indicated above, Trp28 is the oxyanion hole residue (OXY) in PFE, which corresponds to Ser85 in HLL (6.3 Å between OXY and Ser146 O_γ). The residues surrounding the OXY residue (Ser85 is shown in bold and underlined) are FRGSRSIG. Based on the methods described

herein, increased perhydrolase activity is achieved by generating a modified polypeptide containing an Arg86Pro mutation.

Pseudomonas cepacia lipase (PCL; PDB ID: 1OIL): The catalytic triad residues of PCL are Ser87, His286, and Asp264. As indicated above, Trp28 is the oxyanion hole residue (OXY) in PFE, which corresponds to Leu17 in PCL (6.4 Å between OXY and Ser87 Oγ). The residues surrounding the OXY residue (Leu17 in shown in bold and underlined) are VHGLTGT. Based on the methods described herein, increased perhydrolase activity is achieved by generating a modified polypeptide containing a Thr18Pro mutation.

Candida rugosa lipase (CRL; PDB ID: 1GZ7): The catalytic triad residues of CRL are Ser209, His449, and Glu341. As indicated above, Trp28 is the oxyanionic hole residue in PFE, which corresponds to Gly124 in CRL (7.6 Å between OXY and Ser209 Oγ). The residues surrounding the OXY residue (Gly124 is shown in bold and underlined) are FGGGFGL. Because CRL has a GGGX motif, the loop conformation is slightly different than the previous lipases. Based on the methods described herein, increased perhydrolase activity is likely achieved by generating a modified polypeptide containing a Phe125Pro mutation. In the CRL open form (PDB ID: 1CRL), the distance between OXY and Ser209 Oγ is 6.7 Å.

Bacillus lipase: The catalytic triad residues of *Bacillus* lipase are Ser118 and His363, apparently without the third Asp/Glu residue. Based on the modeling, Asp322 is H-bonded to the amide of His363. The oxyanion hole residue (OXY) of *Bacillus* lipase is Phe21. Based on modeling, Thr22 is hydrogen bonded to His19, presumably to help stabilize the loop. Mutating Thr22Pro may twist the carbonyl oxygen of interest 180 deg to hydrogen bond a putative tetrahedral intermediate of perhydrolysis. The residues surrounding the OXY residue (Phe21 is shown in bold and underlined) are Leu18 His19 Gly20 **Phe21** Thr22 Gly23 Trp24. Based on the methods described herein, increased perhydrolase activity is likely achieved by generating a modified polypeptide containing a Thr22Pro mutation.

30 Example 6—Sequences

SEQ ID NO:1

GATCTGGACGTCCTCGGCCCCCGGCGCGCGGCGTCGAAGGTGAAGGGCTT
GAGGGCATCCTTGGCGTTCTGGGCGGCGTAGCTGTAAGTCTTGGCCATTTC
GTTACCTGTGTGATCTGACGGTAGAGGTCAGTGGACCAGCATAGACGCT
35 GAACCGTTCAACCGAGCACACCGGTACAAGCCCTTCGTCCGGTTTCACGC

AATAGTGCCTAGAGTCTTTCAGCCCCCTCAACCAGGAGTTTTTGCATGAG
 CACATTTGTTGCAAAAGACGGTACCCAGATCTATTTCAAGGACTGGGGCA
 GCGGTAAACCGGTGTTGTTTACGCCACGGTTGGCTACTGGATGCCGACATG
 TGGGAATACCAGATGGAGTACCTCAGCAGCCGCGGCTATCGCACCATCGC
 5 CTTTGACCGCCGCGGCTTTGGCCGCTCGGACCAACCCTGGACCGGCAACG
 ACTACGACACCTTCGCCGACGACATCGCCCAGTTGATCGAACACCTGGAC
 CTCAAGGAGGTGACCCTGGTGGGCTTCTCCATGGGCGGCGGCGATGTGGC
 CCGCTACATCGCCCGCCACGGCAGCGCACGGGTGGCCGGCCTGGTGCTGC
 TGGGCGCCGTCACCCCGCTGTTCCGCCAGAAGCCCGACTATCCCGAGGGT
 10 GTCCCGCTCGATGTGTTTCGAAGGTTCAAGACTGAGCTGCTGAAGGATCG
 CGCGCAGTTCATCAGCGATTTCAACGCACCGTTCTATGGCATCAACAAGG
 GCCAGGTGCTCTCCCAAGGCGTGACAGCCAGACCCTGCAAATCGCCCTG
 CTGGCCTCGCTCAAGGCCACGGTGGATTGCGTCACCGCGTTCGCCGAAAC
 CGACTTCCGCCCCGACATGGCCAAGATCGACGTACCCACCCTGGTGATCC
 15 ATGGCGATGGCGACCAGATCGTGCCGTTTCGAGACCACCGGCAAAGTGGCG
 GCGGAGTTGATCAAGGGCGCCGAAGTGAAGGTGTACAAGGACGCGCCCC
 ACGGGTTCGCGGTGACCCACGCCCAGCAGTTGAACGAAGACCTGTTGGCG
 TTCTTGAAACGCTGAGTTAATGTCTGCCTTTATCGGCCGGGCTTGCCCGGC
 CTTTTTTTTACGCGCTCGAATCTCGCGCGGTGCGCGGGCACGATCGTGCTG
 20 AACCGCCGCCCCCTCGCCACGGTCCCAACCCATACGTTTCATCGCTGCAG

SEQ ID NO:2

MSTFVAKDGTQIYFKDWGSGKPVLFSGHWLLDADMWEYQMEYLSSRGYRTI
 AFDRRGFGRSDQPWTGNDYDTFADDIAQLIEHLDLKEVTLVGFSMGGGDVA
 25 RYIARHGSARVAGLVLLGAVTPLFGQKPDYPQGVPLDVFAFRKTELLKDRAQ
 FISDFNAPFYGINKGQVVSQGVQTQTLQIALLASLKATVDCVTAFAETDFRPD
 MAKIDVPTLVIHGDGDQIVPFETTGVAAELIKGAELKVYKDAHPGFVTHA
 QQLNEDLLAFLKR

30 SEQ ID NO:3

ATGAAGCTACTCTCTCTGACCGGTGTGGCTGGTGTGCTTGCGACTTGCGTT
 GCAGCCACTCCTTTGGTGAAGCGTCTACCTTCCGGTTCGGACCCTGCCTTT
 TCGCAGCCCAAGTCGGTGCTCGATGCGGGTCTGACCTGCCAGGGTGCTTC
 GCCATCCTCGGTCTCCAAACCCATCCTTCTCGTCCCCGGAACCGGCACCAC
 35 AGGTCCACAGTCGTTTCGACTCGAACTGGATCCCCCTCTCAACGCAGTTGG
 GTTACACACCCTGCTGGATCTCACCCCGCCGTTTCATGCTCAACGACACCC
 AGGTCAACACGGAGTACATGGTCAACGCCATCACCGCGCTCTACGCTGGT
 TCGGGCAACAACAAGCTTCCCGTGCTTACCTGGTCCCAGGGTGGTCTGGTT
 GCACAGTGGGGTCTGACCTTCTTCCCCAGTATCAGGTCCAAGGTCGATCG
 40 ACTTATGGCCTTTGCGCCCGACTACAAGGGCACCGTCCTCGCCGGCCCTCT
 CGATGCACTCGCGGTTAGTGACCCCTCCGTATGGCAGCAAACCACCGGTT
 CGGCACTCACCACCGCACTCCGAAACGCAGGTGGTCTGACCCAGATCGTG
 CCCACCACCAACCTCTACTCGGCGACCGACGAGATCGTTCAGCCTCAGGT
 GTCCAACCTCGCCACTCGACTCATCCTACCTCTTCAACGGAAAGAACGTCCA
 45 GGCACAGGCCGTGTGTGGGCCGCTGTTTCGTATCGACCATGCAGGCTCGC
 TCACCTCGCAGTTCTCCTACGTCTCGGTGATCCGCCCTGCGCTCCACCA
 CGGGCCAGGCTCGTAGTGCACTATGGCATTACGGACTGCAACCCTCTT
 CCCGCCAATGATCTGACTCCCGAGCAAAGGTGCGCGGGCTGCGCTCCT
 GCGCGCCGGCAGCTGCAGCCATCGTGGCGGGTCCAAAGCAGAACTGCGAG

CCCGACCTCATGCCCTACGCCCCGCCCTTTGCAGTAGGCAAAAGGACCTG
CTCCGGCATCGTCACCCCCTGA

SEQ ID NO:4

5 LPSGSDPAFSQPKSVLDAGLTCQGASPSVSKPILLVPGTGTTGPQSFD SNWIP
LSTQLGYTPCWISPPPFMLNDTQVNTEYMVNAITALYAGSGNNKLPVLTWSQ
GGLVAQWGLTFFPSIRSKVDRLMAFAPDYKGTVLAGPLDALAVSAPSVWQQ
TTGSALTTALRNAGGLTQIVPTTNLYSATDEIVQPQVSNSPLDSSYLFNGKNV
10 QAQAVCGPLFVIDHAGSLTSQFSYVVGRSALRSTTGQARSADYGITDCNPLPA
NDLTPEQKVAAAALLAPAAAAIVAGPKQNCEPDLMPYARPFVAVGKRTCSGIV
TP

OTHER EMBODIMENTS

15 It is to be understood that while the invention has been described in
conjunction with the detailed description thereof, the foregoing description is intended
to illustrate and not limit the scope of the invention, which is defined by the scope of
the appended claims. Other aspects, advantages, and modifications are within the
scope of the following claims.

WHAT IS CLAIMED IS:

1. A method of increasing perhydrolase activity in an esterase or lipase,
5 comprising:
 providing a nucleic acid encoding the esterase or lipase;
 modifying one or more nucleotides in the codon encoding the OXY+1
residue in the esterase or lipase to nucleotides that cause said codon to encode an
amino acid that can adopt a *cis*-configuration; and
10 expressing the modified nucleic acid to generate a modified
polypeptide, wherein the modified polypeptide has increased perhydrolase activity
compared to the pre-modified esterase or lipase.
2. The method of claim 1, further comprising:
15 screening the esterase or lipase for perhydrolase activity.
3. The method of claim 1, further comprising:
 screening the modified polypeptide for perhydrolase activity.
- 20 4. The method of claim 1, wherein the amino acid that can adopt a *cis*-
configuration is proline or a derivative of proline.
5. The method of claim 4, wherein the proline derivative is
hydroxyproline.
25
6. The method of claim 1, wherein the nucleic acid encoding an esterase
has the sequence shown in SEQ ID NO:1.
7. The method of claim 1, wherein the nucleic acid encoding a lipase has
30 the sequence shown in SEQ ID NO:2.
8. The method of claim 1, wherein the esterase or lipase is a bacterial
esterase or lipase, a fungal esterase or lipase, a mammalian esterase or lipase, or a
plant esterase or lipase.

9. A method of introducing perhydrolase activity into an esterase or lipase, comprising:
- 5 providing a nucleic acid encoding the esterase or lipase;
modifying one or more nucleotides in the codon encoding the OXY+1
residue in the esterase or lipase to nucleotides that cause said codon to encode an
amino acid that can adopt a *cis*-configuration; and
expressing the modified nucleic acid to generate a modified
polypeptide, wherein the modified polypeptide has perhydrolase activity.
- 10
10. A method of converting a polypeptide having predominantly esterase and/or lipase activity to a polypeptide having predominantly perhydrolase activity, comprising:
- 15 providing a nucleic acid encoding the polypeptide having
predominantly esterase and/or lipase activity;
modifying one or more nucleotides in the codon encoding the OXY+1
residue in the polypeptide to nucleotides that cause said codon to encode an amino
acid that can adopt a *cis*-configuration; and
expressing the modified nucleic acid to generate a modified
20 polypeptide, wherein the modified polypeptide has predominantly perhydrolase
activity.

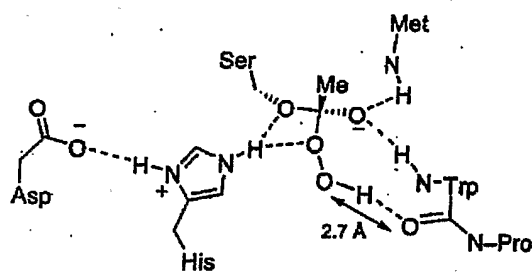


Figure 1