Efficient resolution of profen ethyl ester racemates by engineered Yarrowia lipolytica Lip2p lipase
Doriane Gerard, Marc Gueroult, Leticia Casas-Godoy, Jean-Stephane Condoret, Isabelle Andre, Alain Marty, Sophie Duquesne

To cite this version:

HAL Id: hal-01708480
https://hal.univ-reims.fr/hal-01708480
Submitted on 28 May 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author’s version published in: http://oatao.univ-toulouse.fr/20457

Official URL: http://doi.org/10.1016/j.tetasy.2017.01.014

To cite this version: Gerard, Doriane and Guérourlt, Marc and Casas-Godoy, Leticia and Condoret, Jean-Stéphane and André, Isabelle and Marty, Alain and Duquesne, Sophie Efficient resolution of profen ethyl ester racemates by engineered Yarrowia lipolytica Lip2p lipase. (2017) Tetrahedron: Asymmetry, 28 (3). 433-441. ISSN 0957-4166

Any correspondence concerning this service should be sent to the repository administrator: tech-oatao@listes-diff.inp-toulouse.fr
Efficient resolution of profen ethyl ester racemates by engineered
Yarrowia lipolytica Lip2p lipase

Doriane Gérard a,b,c, Marc Guéroult a, Leticia Casas-Godoy a, Jean-Stéphane Condoret b,c, Isabelle André a, Alain Marty a,* Sophie Duquesne a,*

a LISBP, Université de Toulouse, CNRS, INRA, INSA, Toulouse, France
b University of Toulouse, INPT, UPS Laboratoire de Génie Chimique, Toulouse, France
c CNRS, UMR 5503, F-31062 Toulouse, France

A B S T R A C T

Enzyme-catalyzed enantiomer discrimination is still a great challenge for the development of industrial pharmaceutical processes. For the resolution of ibuprofen, naproxen and ketoprofen racemates, three major anti-inflammatory drugs, only lipases from Candida rugosa present a high selectivity if solvent and surfactant use is discarded. However, their catalytic activities are too low. In the present work, we demonstrate that the lipase Lip2p from the yeast Yarrowia lipolytica has a higher catalytic activity than C. rugosa lipases to hydrolyze the ethyl esters of ibuprofen, naproxen and ketoprofen, but its selectivity is not sufficient [E = 52 (S); 11 (S) and 1.5 (R) respectively]. The enantioselectivity was further improved by site-directed mutagenesis, targeted at the substrate binding site and guided by molecular modelling studies. By investigating the binding modes of the (R) and (S)-enantiomers in the active site, two amino acid residues located in the hydrophobic substrate binding site of the lipase, namely residues 232 and 235, were identified as crucial for enantiomer discrimination and enzyme activity. The (S) enantioselectivity of Lip2p towards ethyl ibuprofen esters was rendered infinite (E >> 300) by replacing V232 by an A or C residue. Substitution of V235 by C, M, S, or T amino acids led to a great increase in the (S)-enantioselectivity (E >> 300) towards naproxen ethyl ester. Finally, the variant V232F enabled the efficient kinetic resolution of ethyl ketoprofen ester enantiomers [(R)-enantipreference; E >> 300]. In addition to the increase in selectivity, a remarkable increase in velocity by 2.6, 2.7 and 2.5 times, respectively, was found for ibuprofen, naproxen and ketoprofen ethyl esters.

1. Introduction

α-Substituted aryl and alkyl carboxylic acids are important intermediates encountered in the synthetic pathways of numerous drugs, such as prostaglandin, prostacyclin, semi-synthetic penicillin and thiazolium salts. Among them, derivatives of 2-arylpropionic acids, 2-(6-methoxy-2-naphthyl)propionic acid, commonly known as ibuprofen, 2-(6-methoxy-2-naphthyl)propionic acid, also called naproxen, and 2-(3-benzoylphenyl)propionic acid, commonly named ketoprofen are regularly used as non-steroid anti-inflammatory drugs (NAIDs) in the treatment of headaches, rheumatoid arthritis, cephalalgia or muscular cells. All of these molecules have a stereogenic centre at the α-position of the carboxylic function, leading to the co-existence of two enantiomers. In most cases, only one enantiomer has the required biological activity. For instance, the (S)-enantiomer of ibuprofen is 160 times more active than its (R)-counterpart.2,3 Similarly, the (S)-enantiomer of naproxen is 28 times more active than the (R)-form.3 The anti-inflammatory properties of ketoprofen are principally due to the (S)-enantiomer, whereas the (R)-enantiomer has side effects.2 The use of only the active enantiomer is thus often privileged whenever it can be obtained in a pure form. Therefore, a major challenge consists of separating these enantiomers to obtain a pure biologically active substance. Classical methods used to obtain pure enantiomers, such as chemical asymmetric synthesis, stereoselective crystallization or chiral chromatography, are usually expensive. The use of highly enantioselective enzymes (enantioselectivity value, E, ratio of reaction rates for both enantiomers higher than 200) is thus an appealing alternative to separate such enantiomers.

* Corresponding authors at: Laboratoire d’Ingénierie des Systèmes Biologiques et Procédés, Institut National des Sciences Appliquées, 135 Avenue de Rangueil, 31077 Toulouse Cedex 4, France. Tel.: +33 (0)5 61 55 94 39; fax: +33 (0)5 61 55 94 00. E-mail addresses: alain.marty@insa-toulouse.fr (A. Marty), sophie.duquesne@insa-toulouse.fr (S. Duquesne).
Several enzymatic routes have been explored for obtaining enantiopure profens and profenols, such as use of alcohol dehydrogenases, arylmalonate decarboxylases, ene reductases and nitrilases, either based on the kinetic resolution of racemates or asymmetric protonation of prochiral precursors.

In the case of 2-arylpropionic acids, lipases have been shown to be good candidates to catalyze the kinetic resolution of (RS)-racemates, either by hydrolysis of an ester or by esterification of the acid form. Several lipases from various origins (plant and microbial) have already been reported for the resolution of ibuprofen, naproxen and ketoprofen esters or the corresponding acids.

Lipases from Rhizomucor miehei, Carica papaya or evolved Candida antarctica lipase were previously tested for the resolution of (RS)-ibuprofen racemate by either hydrolysis or esterification reactions. However, all three of them led to low enantioselectivity ($E < 200$). The lipase from C. rugosa (formerly C. cylindracea) was shown to be the best enzyme to discriminate (RS) ibuprofen racemate. The best result, considering the enantioselective hydrolysis of ibuprofen racemate using free enzyme, presents an enantioselectivity of 247. Nevertheless, this high $E$ value was obtained by the addition of N,N-dimethylformamide, which is highly toxic.

C. rugosa, Carica papaya and R. miehei free lipases were also studied for the hydrolysis of naproxen ester racemate. Among them, lipases from C. rugosa were found to be the most enantioselective enzymes for this reaction ($E = 397$). Lysozymophilipase and carboxylesterase were also studied for the resolution of the naproxen ester; the carboxylesterase NP produced by Bacillus subtilis gave a high enantioselectivity ($E = 500$), nevertheless, this high enantioselectivity was obtained by the addition of formaldehyde, which is highly toxic.

Lipases from Thermogota maritima, Aspergillus niger, Aspergillus terreus, Fusarium oxysporum, Mucor javanicus, Trichosporon laibacchii, Pseudomonas cepacia, Carica papaya, B. subtilis and from C. rugosa were previously tested for the resolution of (RS)-ketoprofen racemate. However, all of them led to poor enantioselectivity ($E < 200$). In order to improve upon the enantioselectivity of the lipase from C. rugosa ($E = 27$), various strategies were employed, such as enzyme immobilization or two step acetone treatment but only an enantioselectivity of 153 was reached.

The enantioselectivity of Serratia marcescens lipase was improved (from 63 to 1084) by the addition of a surfactant, Brij 92. Similarly, the enantioselectivity of Pseudomonas sp. KCTC10122BP lipase and Acinetobacter lipase were found to be superior to 200 (absolute and 752, respectively) but with use of triton X-100. However, addition of a surfactant generally leads to a complexification of the purification process, and to high production costs.

Variants of C. antarctica lipase CalB, and of the recently metagenome-isolated esterase Est25 enabled an enantioselectivity higher than 200, but very low concentrations of the substrate were used. It appears that the lipases from C. rugosa are good candidates for the resolution of the three substrates considered. Despite their significant enantioselectivity, the catalytic efficiencies of the lipases from C. rugosa are relatively low, almost one order of magnitude lower than that of Lip2p lipase from the oleaginous yeast Y. lipolytica during the resolution of 2-bromophenyl acetic acid ester.

Herein we tried to identify new enzymes able to highly discriminate between the (R)- and (S)-enantiomers of ibuprofen, naproxen and ketoprofen ethyl esters, and with high catalytic efficiency. The Y. lipolytica Lip2p lipase was reported to catalyze the resolution of ibuprofen racemate with a low enantioselectivity ($E = 56$). Moreover, variants of this lipase have been shown to have a high catalytic efficiency and enantioselectivity for the resolution of (RS)-2-bromophenyl acetic acid ester racemate. Enzyme variants with increased or totally inverted enantioselectivity, concomitant with a remarkable increase in velocity, were also obtained.

The performances of the Y. lipolytica wild-type lipase is compared to wild-type lipases (CRL 1 and 4) from C. rugosa, which has been described in the literature as being one of the most efficient enzymes for the resolution of the considered racemates. In view of the results, the library of Lip2p variants from Y. lipolytica, previously built for the resolution of the (RS)-2-bromophenyl acetic acid ester racemate, was tested on the three molecules and molecular modelling was used to identify new targets for site-directed mutagenesis and to understand the role of amino acid changes on the selective recognition of the (R)-enantiomers of each racemate.

2. Results and discussion

2.1. Resolution of (RS)-ibuprofen naproxen and ketoprofen ethyl ester racemates using wild-type lipases

The reaction scheme of the enantioselective lipase-catalyzed hydrolysis of the racemic mixture of three different esters is presented in Figure 1. Wild-type Lip2p from Y. lipolytica was compared to C. rugosa lipases (CRL 1 and 4), the most efficient enzymes known to date for the resolution of ibuprofen, naproxen and ketoprofen racemates. CRL lipases were produced in recombinant form by a strain of Y. lipolytica as pure isofrom of CRL1 and CRL4.

All three lipases were produced using the Y. lipolytica strain JMY1212, in which the lipase encoding gene is introduced in the genome at the zeta docking platform, leading to good reproducibility of the enzyme expression and enabling a comparison of enzyme variant activities directly from the supernatant. In addition, this strain is deleted for the main extracellular protease (XPR2) and the main extracellular lipases (Lip2p, 7 and 8), which in turn enables for the supernatant to be obtained with high protein purity. It was checked that no activity with this strain was obtained whatever the used racemate (data not shown).

The protein contents of Y. lipolytica supernatant containing Lip2p, CRL 1 or CRL 4 were determined by SDS-PAGE (data not shown). Enzyme concentration was estimated as 5 times lower for CRL1 and CRL4 expressed in Y. lipolytica compared with Lip2p. The two enzymes of C. rugosa were then 10 times concentrated for comparison. Enzymes were then tested during the hydrolysis of ibuprofen, naproxen and ketoprofen ethyl esters (Table 1).

Our results confirmed that C. rugosa lipase CRL1 was an efficient enzyme with regards to the enantioselectivity to discriminate between the enantiomers of ibuprofen, naproxen and ketoprofen ethyl esters, with a total preference for the (S)-enantiomer. Nevertheless, whatever the racemate and even with a 10 times concentration of the supernatant, the rate of reaction was low. Despite sharing 81% of identity with CRL1, lipase CRL4 was only active on ketoprofen ethyl ester with a total preference for the (R)-enantiomer. This reverse enantioselectivity of CRL1 and CRL4 was already observed during the resolution of bromophenyl acetic acid ester racemates.

Wild-type Lip2p lipase from Y. lipolytica showed a clear preference for the (S)-enantiomer in the hydrolysis of ibuprofen ethyl ester racemate ($E = 52$, Table 1). This result is in agreement with the $E$ value of 56 obtained in previous studies of esterification of ibuprofen using immobilized Lip2p lipase. The positive influence of the para substitution of the phenyl group on the $E$ value of Lip2p lipase had already been observed for the transesterification of 2-bromo-phenyl acetic ethyl and 2-bromo-p-tolylacetic ethyl ester. The presence of a methyl group at the para-position of the phenyl group led to an improvement in the selectivity of Lip2p lipase.
The rate of hydrolysis of the (S)-enantiomer by Lip2p (E = 11). Moreover, the catalytic efficiency of Lip2p for the best recognized enantiomer of ibuprofen, naproxen and ketoprofen ethyl ester is one order of magnitude higher than the one obtained with CRL1. Only CRL4, during the ethyl ketoprofen ester resolution, possessed a catalytic efficiency in the same range to that observed with Lip2p.

### 2.2. Resolution of (RS)-ibuprofen ethyl ester racemate by Lip2p enzyme variants

With the aim of improving the enantioselectivity of the Lip2p lipase from Y. lipolytica for the resolution of the (RS)-ibuprofen ethyl ester racemate, a previously built library of enzyme variants was screened. This library of single enzyme variants results from a rational engineering strategy that consisted in applying site-directed mutagenesis to 5 amino acids (T88, V94, V285, V232 and D97) located in the substrate binding site. Among these Lip2p variants, position 232 was found to be crucial in terms of the activity and the enantioselectivity during the resolution of 2-bromophenyl acetic acid esters. In total, 25 single enzyme variants of Lip2p were tested for their ability to resolve the ibuprofen ethyl ester racemate (19 single variants at position 232 and enzyme variants D97A and V232D) located in the substrate binding site. Among these Lip2p variants, position 232 was found to be crucial in terms of the activity and the enantioselectivity during the resolution of 2-bromophenyl acetic acid esters was also tested. It was checked by SDS page gel protein that all of the variants tested are expressed at the same level than the wild-type enzyme (data not shown).

Enzyme variant T88S and enzyme variants at position 94 present lower activity than the wild-type Lip2p and no change in selectivity. Enzyme variant V285A presents a similar behavior as the wild-type enzyme, whereas V285L and D97A variants are not more active. The double substituted enzyme variant D97A-V232F was not active on ethyl ibuprofen, whereas it displayed a total preference for the (S)-enantiomer of 2-bromophenyl-acetic octyl ester and 4.5 times enhancement of its activity.

As already observed during the kinetic resolution of 2-bromoarylactic acid esters, position 232 appears to be crucial for the discrimination between ibuprofen enantiomers. Indeed, three Lip2p variants with an amino acid change at this position 232 (V232A, V232C and V232D) present a higher enantioselectivity than the wild-type enzyme. All of them showed an improvement in enantioselectivity, from an E value of 52 for the wild-type enzyme to an E value higher than 200 for the enzyme variants; this was due towards the (S)-enantiomer with an E value of 28 against an E value of 3 in the absence of the methyl group. The presence of an isobutyl group at the para position of the phenyl group in ibuprofen ester seemed to have the same effect.

The steric hindrance of the naproxen ethyl ester in the Lip2p lipase active site is clearly more important than that of 2-bromophenyl-acetic and ibuprofen ethyl esters, due to the presence of the naphthalene group. As a consequence, the rate of hydrolysis of the (S)-enantiomer by wild-type Lip2p is 4 times lower than the one observed for the (S)-enantiomer of ethyl ketoprofen ester (Table 1). Conversely, the poorly-hydrolyzed (R)-enantiomer was slightly better recognized, leading to an enantioselectivity of 5 times lower (E = 11).

The rate of hydrolysis of the (S)-enantiomer of ethyl ketoprofen by wild-type Lip2p is 4 times lower than the one observed for the (S)-naproxen ethyl ester, and 16 times lower compared to the (S)-ibuprofen ethyl ester. The (R)-enantiomer of ethyl ketoprofen was the best recognized enantiomer by Lip2p (E = 1.5). Moreover, the catalytic efficiency of Lip2p for the best recognized enantiomer of ibuprofen, naproxen and ketoprofen ethyl ester is one order of magnitude higher than the one obtained with CRL1. Only CRL4, during the ethyl ketoprofen ester resolution, possessed a catalytic efficiency in the same range to that observed with Lip2p.

### Table 1

Comparison between activities and selectivities of Lip2p from Y. lipolytica and C. rugosa lipases for the hydrolysis of ethyl-ibuprofen, ethyl-naproxen and ethyl-ketoprofen. The hydrolysis was performed in a biphasic medium: 750 µL of decane containing 50 mM of ester racemate, 750 µL of enzyme supernatant (or the concentrate supernatant for CRL lipases), stirred at room temperature for 100 h.

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Activity</th>
<th>Enantioselectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRL1 10X</td>
<td>0.28</td>
<td>0</td>
</tr>
<tr>
<td>CRL4 10X</td>
<td>0</td>
<td>Nd</td>
</tr>
<tr>
<td>Lip2p 1X</td>
<td>1.56</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Nd = not determined.
to a better hydrolysis of the preferred (S)-enantiomer (2.2–2.6 times higher) concomitant to a lower hydrolysis of the poorly recognized (R)-enantiomer (Table 2). Enzyme variants V232A and V232C were no more able to recognize the (R)-enantiomer, whereas enzyme variant V232S exhibits only a lower recognition of the poorly recognized (R)-enantiomer (2.3 times lower than wild-type Lip2p). In addition to the gain in enantioselectivity, a remarkable increase in velocity was observed for the three variants (2.2–2.6 times increase). The best enzyme was the enzyme variant V232A (E ≥ 300 with an initial rate of hydrolysis of the (S)-enantiomer of 4.1 μmol h⁻¹ mL⁻¹).

During the resolution of 2-bromo-phenyl-acetyl octyl esters by Lip2p lipases, the best enzyme variant was found to be the V232S enzyme variant, with an E value ≥200.

From molecular docking studies, it was assumed that the bulky bromine atom, facing V232 for the (S)-enantioselectivity. The size of this amino acid thus appeared to be crucial for the enantioselectivity. It is noteworthy that ibuprofen and 2-bromophenyl-acetic esters are rather similar in structure. The bromine atom present at the α-position of the carboxylic acid in 2-bromophenyl-acetic ester is replaced in ibuprofen by a methyl group, which presents similar steric hindrance. From our results, it appears that the size of the amino acid at position 232 is clearly more important than its polarity. Substitution of the valine present in the wild-type Lip2p lipase by smaller amino acid residues such as A, C or S enables a better recognition of the (S)-enantiomer and a poorer recognition of the (R)-enantiomer. However, enzyme variant V232G is no more active on ethyl ibuprofen whereas it was found to be more efficient and selective during the hydrolysis of 2-bromophenyl-acetic esters. As already observed with 2-bromophenyl-acetic octyl ester, the performance of the enzyme variant V232T is similar to that of the wild-type enzyme. Despite the low catalytic efficiency, enzyme variants V232L, V232I, V232F exhibited enantioselectivity inversion during 2-bromophenyl-acetic octyl ester resolution. Replacement of the valine by a bulkier amino acid such as L, I or F led to enzyme inactivation in the kinetic resolution of ibuprofen.

Using molecular modelling techniques, we constructed three-dimensional models of the covalent intermediates of Lip2p with the (RS)-enantiomers of ibuprofen ethyl ester (Fig. 2).

Docking studies revealed distinct binding conformations for the (RS)-enantiomers, which differed in the orientation of the aromatic ring, thus impacting the formation of hydrogen bonding interactions between ibuprofen ethyl ester and the oxyanion hole defined by L163 and T88. Only one hydrogen bond was found between the (R)-enantiomer of ibuprofen ethyl ester and oxyanion residues of wild-type Lip2p, whereas two hydrogen bonds were observed for the (S)-enantiomer (Fig. 3).

This could provide some explanation regarding the (S)-enantioselectivity of wild-type Lip2p toward kinetic resolution of the ibuprofen ethyl ester. Mutation of V232 by smaller amino acid residues such as A, C or S, provides more space to better accommodate the (S) enantiomer of ibuprofen ethyl ester in the catalytic site (Fig. 2B), with a slight reorientation of the aromatic ring that favors the formation of: (i) hydrogen bonding interactions between residues from the oxyanion hole and the carbonyl group from the ethyl ester (Fig. 3); and (ii) additional van der Waals interactions between I231 and the isobutyl group. Conversely, mutation of V232 did not alter binding mode of the (R)-enantiomer in comparison with that observed in wild-type enzyme.

2.3. Resolution of (RS)-naproxen ethyl ester racemate by Lip2p enzyme variants

The same strategy used for the resolution of ibuprofen ethyl ester racemate was applied for the resolution of naproxen ethyl ester racemate. The same library of 25 enzyme variants of Lip2p lipase from Y. lipolytica was tested. As previously observed for ibuprofen, an amino acid change at positions 88, 94, 97 and 285 had either a neutral or detrimental effect on the enzyme activity and selectivity. Changing V232 by smaller amino acid residues such as A, C or S did not improve either the activity or the selectivity of the enzyme. The hydrolysis rate of the preferred (S)-enantioselectivity of the enzyme during the naproxen ethyl esters hydrolysis (Table 3). Indeed, eight enzyme variants presented both an increase in activity and enantioselectivity.

The enantioselectivity was shown to increase due to a concomitant increase in the hydrolysis rate of the preferred (S)-enantioselectivity of the enzyme during the naproxen ethyl esters hydrolysis (Table 3). Indeed, eight enzyme variants presented both an increase in activity and enantioselectivity.

Moreover, to confirm that the (R)-enantioselectivity of the naproxen ethyl ester was absolutely not hydrolyzed by the Lip2p V235S variant, a first hydrolysis of the racemic mixture was conducted with this variant.

Table 2

| Wild-type V232 | 1.56 | 0.030 | 52 |
| V232A    | 4.07 | 0 | >300 |
| V232C    | 3.55 | 0 | >300 |
| V232S    | 3.44 | 0.013 | 263 |
and the organic phase was recovered after 60 h reaction. This organic phase, which was almost only composed of the (R)-enantiomer of the naproxen, was put into contact with fresh enzyme (Lip2p V235S). No hydrolysis of the (R)-enantiomer was observed over a period of 50 h.

Detailed analysis of molecular modelling results indicated that substitution of V235 by a small and polar amino acid residue such as S, T or C, favors the formation of an additional hydrogen bonding interaction between the amino acid side chain at position 235 and the oxygen of the methoxy group from the (S)-enantiomer (Fig. 4B), leading to an increase of the affinity for the (S)-enantiomer over the (R)-enantiomer and thus an enhanced enantioselectivity, as confirmed by experimental data.

The enzyme variants at the position V235 were tested for the resolution of ethyl ibuprofen; these enzyme variants have a low activity compared to the wild type Lip2p. For example, the enzyme variant V235S and V235C are 7 and 15 times less active than the wild type enzyme, respectively. The same negative result was obtained during the resolution of the (RS)-2-bromophenyl acetic acid ester racemate.
The two positions V232 and V235, were found to be crucial for selectivity. Enzyme variant V285L, D97A are not more active. V94A had lower activity than the wild-type Lip2p and no change in selectivity. Enzyme variant V285L, D97A are not more active. The two positions V232 and V235, were found to be crucial for both the activity and enantioselectivity of the enzyme towards ethyl ketoprofen. Substitution of the valine in position 232 present in the wild-type Lip2p by a smaller amino acid residue such as S (and to a lesser extent A) enables a better recognition of the (S)-enantionmer (6 times) and a poorer recognition of the (R)-enantionmer (3 times), resulting in an inversion of preferred enantionmer. The single enzyme variant V235A and mainly V235G present the same behavior with an inversion of the preferred enantionmer and a medium enantioselectivity. Nevertheless, the activity of the V235G variant is twice as high than the one obtained with variant V232S. The double enzyme variant V232S-V235G was constructed but the kinetics and enantioselectivity became lower than the wild-type lipase.

Regarding the enantioselective hydrolysis of ketoprofen ethyl ester, the best enzyme was the enzyme variant V232F which presents the same enantioselectivity while the rate is slightly higher for the monoenzyme variant (Table 4). The double mutation D97A-V232F was interesting in the case of the resolution of the 2-bromo-arylacetic acid ester, but in this case the double mutation is useless, since the monoenzyme variant V232F presents the same enantioselectivity while the rate is slightly higher for the monoenzyme variant (Table 4).

Table 3
Comparison of activity and selectivity of wild-type Lip2p and the best enzyme variants on position V235 during hydrolysis of (RS)-naproxen ethyl ester racemate. The hydrolysis was performed in a biphasic medium: 750 μL of decane containing 50 mM of ester racemate, 750 μL of enzyme supernatant (or the concentrate supernatant for CRL lipases), stirred at room temperature for 100 h.

<table>
<thead>
<tr>
<th></th>
<th>VS (μmol h⁻¹ mL⁻¹)</th>
<th>VR (μmol h⁻¹ mL⁻¹)</th>
<th>E (VS/VR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type V235</td>
<td>0.42</td>
<td>0.04</td>
<td>11</td>
</tr>
<tr>
<td>V235A</td>
<td>1.10</td>
<td>0.004</td>
<td>274</td>
</tr>
<tr>
<td>V235C</td>
<td>1.09</td>
<td>0</td>
<td>&gt;300</td>
</tr>
<tr>
<td>V235E</td>
<td>1.31</td>
<td>0.02</td>
<td>60</td>
</tr>
<tr>
<td>V235L</td>
<td>2.72</td>
<td>0.14</td>
<td>19</td>
</tr>
<tr>
<td>V235M</td>
<td>0.75</td>
<td>0</td>
<td>&gt;300</td>
</tr>
<tr>
<td>V235N</td>
<td>1.01</td>
<td>0.02</td>
<td>67</td>
</tr>
<tr>
<td>V235S</td>
<td>1.12</td>
<td>0</td>
<td>&gt;300</td>
</tr>
<tr>
<td>V235T</td>
<td>0.71</td>
<td>0</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

3. Conclusion

Herein we have identified new enzymes for the kinetic resolution of ibuprofen, naproxen and ketoprofen racemates, three molecules of interest for the pharmaceutical industry. Until now, only lipases from *C. rugosa* have been reported to be efficient for this purpose if we exclude solvent and surfactant use. However, if their enantioselectivity is high, their catalytic efficiency remains very low. Herein, the lipase Lip2p, efficiently extracellularly produced by the yeast *Y. lipolytica*, was shown to have reasonable selectivity and one order of magnitude higher activity than the lipase CRL1 from *C. rugosa* during hydrolysis of ibuprofen, naproxen and ketoprofen ethyl esters. The enantioselectivity of this Lip2p was improved by site-directed mutagenesis experiments targeted to the substrate binding site, guided by molecular modelling based on the molecular docking of the (R)- and (S)-enantiomers of the substrates in the active site. The nature of the amino acids at positions 232 and 235, localized in the hydrophobic substrate binding site, were identified as being crucial for the enantioselectivity of the resolution of these three racemates. The enantioselectivity of Lip2p towards ethyl ibuprofen was increased from 52 for the wild-type enzyme to an enantioselectivity higher than 300 for the variants V232A and V232C. Mutations of V235 to C, M, S, or T lead to a tremendous increase in enantioselectivity, from 11 to an E > 300 for the resolution of naproxen ethyl ester racemate. One variant of a lipase from *Y. lipolytica* with an infinite enantioselectivity was found (V232F) with an (R)-enantioselectivity for the resolution of ethyl ketoprofen ester racemate, while the wild-type lipase had a poor enantioselectivity of 1.5. In addition to the gain in selectivity, a remarkable increase in velocity was demonstrated (at least 2.5 times increase) for all substrates. These results demonstrate the high potential of rational engineering to create
In order to increase the activity, the medium:750 room temperature for 100 h allowed by Thin Layer Chromatography analysis (TLC) using hexane/.

new biocatalysts with enhanced activity and selectivity, suitable for industrial applications.

4. Experimental

4.1. General

Peptone, tryptone, and yeast extract were purchased from Difco (Paris, France), oleic acid from Prolabo (Fontenay sous Bois, France). Racemic ibuprofen, racemic ketoprofen, (S)-naproxen and other chemicals were purchased from Sigma-Aldrich (Sigma-Aldrich, St. Louis, MO).

4.2. Racemization of (S)-naproxen

The protocol used for the racemization of the (S)-naproxen is described in earlier studies.\(^{31,32}\)

4.3. Synthesis of ibuprofen, naproxen and ketoprofen ethyl ester

The reaction (2.5 g of racemic ibuprofen, naproxen or ketoprofen) was mixed with ETOH (100 mL) ethanol and sulfuric acid (1 mL). The mixture was stirred at 65 °C overnight. Then calcium carbonate (2.5 g) was then added and the mixture was stirred again for 30 min. The precipitate was removed by filtration and the filtrate was dried under reduced pressure. The reaction was followed by Thin Layer Chromatography analysis (TLC) using hexane/isopropanol (99/1 v/v) as the eluent. \(^1\)H NMR spectra were recorded on a Bruker AC-200.1 (200.1 MHz) spectrometer and confirmed the purity of both esters.

4.4. Construction of Lip2p variants by site-directed mutagenesis

Variants at position 88, 94, 97, 232 and 285 were previously constructed\(^{54}\) and only the construction of variants targeting position 235 was performed in the current work. JMP8 plasmid carrying the wild-type LIP2 gene was previously described: \(^{55,56}\) Lip2 encoding the extracellular lipase Lip2p is under the transcriptional control of the strong promoter POX2 inducible by oleic acid also previously described. \(^{55}\) Mutagenesis in the LIP2 gene was performed using the QuikChange\(^\text{\textsuperscript{\textregistered}}\) site-directed mutagenesis kit (Stratagene). The following primers and their complementary reverse counterparts were used for systematic directed mutagenesis at position 235: 5'–CGTCCCCCTCAAXXXXXXXXCTGTGGG–3' with XXX being GCC for V235A, TGC for V235C, GAC for V235D, GAG for V235E, TTC for V235F, GGC for V235G, CAC for V235H, ATC for V235I, AAG for V235K, CTC for V235L, ATG for V235M, AAC for V235N, CCC for V235P, CAG for V235Q, CGA for V235R, TCC for V235S, ACC for V235T, TGG for V235W, TAC for V235Y. Escherichia coli DH5\(\alpha\) was used as the host to produce the different plasmids and sequences were controlled by sequencing (GATC, Konstanz, Germany). Plasmids were digested by NotI and used for the transformation of strain Y. lipolytica JMY1212\(^{57}\) by the lithium acetate method as described previously.\(^{58,59}\)

4.5. Production and activity of lipases

The production of lipases from Y. lipolytica and C. rugosa is described elsewhere.\(^{51,61}\) In order to increase the activity, the obtained lipases can be concentrated using centrifugal filter units (Amicon Ultra Centrifugal Filters, Merck Millipore).

4.6. Enzymatic hydrolysis of ibuprofen, naproxen and ketoprofen ethyl esters

In a 2 mL reactor (Eppendorf), 750 \(\mu\)L of culture supernatant (or the concentrate supernatant) containing the enzyme and 750 \(\mu\)L of racemic ethyl ibuprofen, naproxen or ketoprofen (50 \(\mu\)M in decane) were added. The reactors were stirred in a vortex Genie 2 (D. Dutcher, Brutam, France) at room temperature for 100 h. At regular time intervals, the progress of the reaction was monitored by analyzing the organic phase composition after phase separation by centrifugation (dilution 1, 10 and 30 in hexane for the ibuprofen, naproxen and ketoprofen ester, respectively).

4.7. Chromatography analysis

The HPLC device was equipped with a chiral column: Chiralcel OJ-H (25 cm × 4.6 mm) (Chiral technologies Europe, Daicel group).

---

**Table 4**

Comparison of activity and selectivity of wild-type Lip2p lipase from Y. lipolytica and its variants during hydrolysis of (R)-ketoprofen ethyl ester racemate. The hydrolysis was performed in a biphasic medium:750 \(\mu\)L of decane containing 50 mM of ester racemate, 750 \(\mu\)L of enzyme supernatant (or the concentrate supernatant for CRL lipases), stirred at room temperature for 100 h.

<table>
<thead>
<tr>
<th>Lipase</th>
<th>(\text{viS} (\text{(\mu)mol h}^{-1} \text{mL}^{-1}))</th>
<th>(\text{viR} (\text{(\mu)mol h}^{-1} \text{mL}^{-1}))</th>
<th>(E (\text{viS/viR})) or (E (\text{viR/viS}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type</td>
<td>0.11</td>
<td>0.16</td>
<td>1.5 (R)</td>
</tr>
<tr>
<td>V232A</td>
<td>0.11</td>
<td>0.04</td>
<td>2.91 (S)</td>
</tr>
<tr>
<td>V232F</td>
<td>0</td>
<td>0.40</td>
<td>&gt;300 (S)</td>
</tr>
<tr>
<td>V232S</td>
<td>0.7</td>
<td>0.05</td>
<td>14 (S)</td>
</tr>
<tr>
<td>V235A</td>
<td>1.6</td>
<td>0.13</td>
<td>12 (S)</td>
</tr>
<tr>
<td>V235G</td>
<td>1.17</td>
<td>0.07</td>
<td>16 (S)</td>
</tr>
<tr>
<td>D97A-V232F</td>
<td>0</td>
<td>0.36</td>
<td>&gt;300 (S)</td>
</tr>
</tbody>
</table>
connected to a UV detector (at 254 nm for the analysis of ibuprofen ethyl ester and 270 nm for the naproxen ethyl ester). A flow rate of 1.0 mL/min was used. The mobile phase was composed of a mixture n-hexane/isopropanol [98:2 v/v] for ibuprofen and naproxen ethyl ester analysis. Retention time: 4/4.5 min for the (S)– and (R)-enantiomers of ibuprofen ethyl ester and 20/22 min for the (S)- and (R)-enantiomers of naproxen ethyl ester. Ibuprofen formed during the reaction and remaining in the decane phase can be analyzed in the same conditions as ibuprofen ethyl ester, the retention time being 7/8 min for the (S)- and (R)-enantiomers of ibuprofen, respectively.

For the analysis of ketoprofen ethyl ester the mobile phase was composed only of hexane, with retention times of 12 and 13 min for the (S)- and (R)-enantiomers respectively.

4.8. Determination of enantioselectivity (E)

\[ E = \frac{v_S}{v_R} \]

or

\[ E = \frac{v_R}{v_S} \]

where \( v_S \) and \( R \) are the initial rates of hydrolysis of the (S)- and (R)-enantiomers respectively.

4.9. Molecular modelling studies

Since the only available crystallographic structure of Y. lipolytica Lip2p corresponds to a closed inactive conformation of the enzyme, we used an homology model of the open conformation to perform docking of the ligands in the catalytic site. Three-dimensional models of the covalent tetrahedral intermediates for each enantiomer (S)- and (R)-enantiomers of ibuprofen and naproxen ethyl esters, respectively, were built. Each enantiomer was placed in the active site so that it is covalently bonded to the catalytic serine (S162) and fulfills the hydrogen bonding interactions required for productive catalysis. Models of enzyme variants mutated at positions 232 or 235 were constructed from the model of wild type Lip2p by introducing site mutations using the mutator module in VMD. Each enzyme variant was then minimized using parm99sb-ildn force field in Gromacs software. The conformational docking of the enantiomers was carried out using Autodock program. The conformational space explored during docking was defined by a grid centered on Ser162 sidechain and spacing by 0.375 Å. Autodock parameters were set to the standard values for genetic algorithm and 200 docking poses were extracted. These poses were clustered based on their RMSD. One ligand conformation representative of the best cluster was placed in wild-type Lip2p or its enzyme variants and the whole system was minimized until the maximum force was less than 100 kJ mol\(^{-1}\). Visualization and analysis were done using VMD software.

Acknowledgments

We thank the Pôles de Recherche et d’Enseignement Supérieur de l’Université de Toulouse and the Région Midi-Pyrénées, France for PhD grant of Doriane Gerard. We also thank the ICEO facility, which is part of the Integrated Screening Platform of Toulouse (PICT, IBISA), for access to the analytical chromatography platform.

References