Reactivity versus steric effects in fluorinated ketones as esterase inhibitors: a quantum mechanical and molecular dynamics study

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Abstract  Carboxylesterases (CEs) are a family of ubiquitous enzymes with broad substrate specificity, and their inhibition may have important implications in pharmaceutical and agrochemical fields. One of the most potent inhibitors both for mammalian and insect CEs are trifluoromethyl ketones (TFMKs), but the mechanism of action of these chemicals is not completely understood. This study examines the balance between reactivity versus steric effects in modulating the activity against human carboxylesterase 1. The intrinsic reactivity of the ketone moiety is determined from quantum mechanical computations, which combine gas phase B3LYP calculations with hydration free energies estimated with the IEF/MST model. In addition, docking and molecular dynamics simulations are used to explore the binding mode of the inhibitors along the deep gorge that delineates the binding site. The results point out that the activity largely depends on the nature of the fluorinated ketone, since the activity is modulated by the balance between the intrinsic electrophilicity of the carbonyl carbon atom and the ratio between keto and hydrate forms. However, the results also suggest that the correct alignment of the alkyl chain in the binding site can exert a large influence on the inhibitory activity, as this effect seems to override the intrinsic reactivity features of the fluorinated ketone. Overall, the results sustain a subtle balance between reactivity and steric effects in modulating the inhibitory activity of TFMK inhibitors.

Keywords  Fluorinated ketones · Esterase · Quantum mechanical computations · Molecular dynamics · Structure-based drug design

Introduction

Carboxylesterases (CEs; EC 3.1.1.1) include a heterogeneous group of isozymes that hydrolyze a wide range of aliphatic and aromatic esters, amides and thioesters [1, 2]. They comprise a multigene family that covers key hydrolytic enzymes with extremely broad substrate specificity [3, 4]. In addition, CEs are important in pest resistance since they participate in detoxification processes...
of carbamate and organophosphate insecticides, and insect strains resistant to these compounds have shown high levels of CEIs [5, 6]. Therefore, the development of new CE inhibitors may lead to drugs with therapeutic and/or agrochemical interest [7, 8]. Esterases are important also in the degradation of a large variety of insect pheromones and hormones, and thus are involved in many chemical and biochemical processes.

An important group of chemicals that promote CE inhibition are fluorinated ketones, which inhibit a variety of esterases such as acetylcholinesterase [9], juvenile hormone esterase (JHE) [10] and human liver microsomal CEIs [11, 12], as well as enzymes such as chymotrypsin and trypsin [13, 14] and enzymes that metabolize chemical mediators including fatty acid amide hydrolase and diacyl glycerol [15, 16]. Trifluoromethyl ketones (TFMKs) also reversibly inhibit pheromone-degrading esterases in male olfactory tissues [17–19]. Therefore, these compounds represent a potential approach for the disruption of pheromone communication as a new strategy for pest control [20, 21]. Nevertheless, further research is required to increase the clinical and agricultural application of these compounds [22].

TFMKs behave as transition-state analogues, since the enzyme inhibition involves formation of a tetrahedral adduct between the serine residue present at the active site and the highly electronegative carbonyl moiety [23, 24]. Support for this mechanism of action comes from X-ray crystallographic structures of the covalent complex of porcine pancreatic elastase and a peptidyl α,α-difluoro-β-ketoamide [25], and of the JHE from the tobacco hornworm Manduca sexta with 3-octyl-1,1,1-trifluoropropan-2-one [26]. Structure-activity relationship studies indicate that the potency of TFMK inhibitors is modulated by lipophilicity, with the optimal activity being associated with intermediate lipophilicity values (3<log P<5), molar refractivity and the degree of fluorination [12, 27]. These findings agree with the high hydrophobicity of the gorge that leads to the catalytic site in CEIs, and suggest a direct influence of substituents attached to the ketone moiety on the chemical reactivity toward formation of the tetrahedral adduct with the enzyme. The inhibitory potency has also been related to the degree of ketone hydration [28], so that inhibitors that favor the tetrahedral geometry of the hydrate (gem-diol) should stabilize the enzyme-inhibitor complex, thereby resulting in more potent inhibitors. Finally, it has also been suggested that in β-thiosubstituted TFMKs one of the hydroxy groups in the gem-diol might form an intramolecular hydrogen bond with the sulfur atom, and that the strength of such hydrogen bond shows a good correlation with the inhibitory potency of β-substituted TFMKs involving several groups (O, S, SO and SO2) [29].

In order to gain further insight into the precise nature of the molecular determinants that mediate the CE inhibitory activity of TFMKs, this work examines the contribution of both reactivity and steric properties of a series of TFMK inhibitors. The activity of the compounds has been determined experimentally against human carboxylesterase 1 (hCE1). The reactivity properties of the fluorinated ketone moieties are examined by means of density functional computations in conjunction with continuum solvation computations, paying particular attention to the balance between keto and hydrate forms of the ketone moiety. Moreover, the effect of the alkyl chain in TFMKs on the inhibitory potency is investigated by combining docking calculations with molecular simulations. The results are then used to discuss the relationship between the molecular structure of TFMKs and the hCE1 inhibitory potency.

Methods

Chemicals

Compounds 1 and 5 were prepared as already reported by us [30, 31], and the synthesis of compounds 2 [12] and 3 [32] has been already described. Compounds 6 and 7 were obtained from n-decanal and n-octanamide, respectively (manuscript in preparation). Difluoromethyl ketone 8 was prepared as previously described [33] and 2-dodecanone (9) was commercially available from Acros Organics (Geel, Belgium). Compound 10 was prepared by reaction of the corresponding thiol with 4-chloro-1,1,1-trifluoro-2-butanone (manuscript in preparation). Compounds 11–13 were taken from ref [28]. TFMKs 14, 16 and 17 were prepared by trans-metallation reaction of the corresponding iododerivatives with tert-BuLi followed by treatment with ethyl trifluoroacetate [31]. Compound 15 was synthesized from 1-octadecene with trifluoroacetaldehyde ethyl hemiacetal in the presence of a Lewis acid followed by Dess-Martin oxidation [34] of the resulting trifluoromethyl carbinal (submitted for publication). Finally, methylketone 18 was obtained by methyl lithium addition to the corresponding carboxylic acid [35].

Synthesis of 1,1,1-trifluoro-3-octyloxypropan-2-one (4)

BF₃·Et₂O (5.5 μL, 0.044 mmol) was slowly added to a stirred solution of 1-octanol (400 mg, 3.07 mmol) and 1,1,1-trifluoroepoxypropane (280 mg, 2.5 mmol) in CH₂Cl₂ (1 mL). The reaction mixture was stirred at 40-45 °C for 16 h. The reaction mixture was partitioned between CH₂Cl₂ (10 mL) and H₂O (10 mL). The organic solution was washed with H₂O (2 x 10 mL), dried (MgSO₄), filtered and evaporated to afford a yellow oil, which was purified by column chromatography on silica gel eluting with hexane:
ether 9:1. The corresponding trifluoromethyl carbinol (386 mg, 63%) was thus obtained as colorless oil. A 15% w/w Dess-Martin reagent in CH₂Cl₂ (24 mL, 3.68 g, 1.05 mmol) was then added to a solution of the carbinol (188 mg, 0.77 mmol) in CH₂Cl₂ (0.2 mL). The reaction mixture was stirred at room temperature for 19 h. The resultant cloudy solution was diluted with Et₂O (10 mL), washed with 10% w/v aq. Na₂S₂O₃ (10 mL), NaHCO₃ saturated solution, and brine, and dried over MgSO₄. After filtration and concentration, the residual oil was purified by flash column chromatography eluting with hexane-ether 85:15 to afford compound 4 (146 mg, 78%) as colorless oil.

Biological data

Assays were performed in 96-well polystyrene microtiter flat bottom microplates (Maxisorp, Labclinics, Barcelona, Spain) at 32 °C using a 0.4 mM solution of p-nitrophenyl acetate (PNPA) in acetonitrile as substrate. Stock solutions of the possible inhibitors were prepared in ethanol from which 2 μL were used. For the assays, 50 μL of the enzyme in sodium phosphate buffer (containing 10 μg of hCE1) with the inhibitor was incubated for 15 min, and then 10 μL of the substrate solution was added for a final concentration of 0.4 mM. Each solution was diluted with sodium phosphate buffer (pH 7.8, 100 mM) to a final volume of 200 μL. The rate of PNPA hydrolysis was monitored every 30 s for 5 min in a Spectramax Plus plate reader (Molecular Devices, Sunnyvale, CA) at 405 nm (p-nitrophenol alcohol absorption). Each inhibitor concentration was tested in triplicate, and the assay was repeated three times along with positive (in the presence of enzyme but no inhibitor) and negative (no enzyme, no inhibitor) controls. Inhibitor concentrations were adjusted so that the linear region of the curve had at least four points above and below the IC₅₀. The IC₅₀ values were determined by regression analysis of at least eight points in the linear region of the curve. For the specific case of compounds 14-18, the experimental procedure described by Nishi et al. was adopted [36].

Quantum mechanical computations

Theoretical calculations were performed for model compounds built up by replacing the alkyl chain of TFMKs by an ethyl group (Fig. 1) in order to explore the reactivity properties of the carbonyl moiety present in TFMKs. This choice is justified not only by the reduction in cost of the quantum mechanical computations, but also to establish the relationship between the reactive properties of the substituted ketone moiety and the inhibitory activity. The geometries of model compounds were fully optimized at the B3LYP/6-31G(d) level [37, 38]. The nature of the stationary points was verified by inspection of the vibrational frequencies, which were used to calculate zero point, thermal and entropic corrections within the framework of the harmonic oscillator-rigid rotor at 1 atm and 298 K. These corrections were added to the electronic energies to estimate the free energy differences (ΔGgas) in the gas phase.

The relative stabilities in solution were estimated by combining the free energy difference in the gas phase and the differences in solvation free energy (ΔGsol) determined by using the IEF/MST solvation model [39, 40], which relies on the integral equation formalism (IEF) of the polarizable continuum method [41, 42]. The IEF-MST model computes ΔGsol from the addition of electrostatic (ΔGelec), cavitation (ΔGcav) and van der Waals (ΔGvW) components. ΔGvW is determined from the interaction between the charge distribution of the solute and the electrostatic response of the solvent, which is treated by a set of point charges spread over the surface of the cavity that separates solute and solvent. ΔGcav is computed following Claverie-Pierotti’s scaled particle theory [43, 44]. Finally, ΔGelec is computed using a linear relationship to the solvent-exposed surface of each atom [40, 45].

IEF/MST computations were performed using the B3LYP/6-31G(d) optimized version of the MST(IEF) model [40]. Gas phase calculations were carried out using Gaussian-03 [46], and IEF/MST calculations were performed using a locally modified version of this program.

Molecular modeling

Docking calculations were used in conjunction with molecular dynamics simulations in order to examine the alignment of the alkyl chain along the gorge and its effect on the activity of selected TFMK inhibitors. To this end, the X-ray crystallographic structures of hCE1 complexed with palmitic acid (PDB entry 2DQY; solved at 3.0 Å resolution [47]) and benzoic acid (PDB entry 1YAJ; solved at 3.2 Å resolution [48]) were used in the docking study. The former was chosen due to the fact that the alkyl chain of palmitic acid delineates the gorge leading to the active site, whereas the latter was selected because the benzoic acid is found forming a covalently-bound tetrahedral intermediate with the catalytic serine Ser221 in subunits C, F and J (in the rest of subunits the benzoic acid is unbound in the catalytic site). Accordingly, these structures provide valuable information for the proper positioning of the covalent adduct formed by the TFMK derivatives investigated here with the hCE1 enzyme.

Docking studies were carried out using Gold 4.1 (CCDC, Cambridge) and the Goldscore scoring function [49-51]. The X-ray structure of hCE1 was used as a template for docking calculations after removal of ligands, ions and water molecules. The definition of the binding site...
to be considered for docking of TFMK inhibitors was made taking advantage of the known spatial arrangement of both palmitic acid and benzoic acid in the X-ray structures 2DQY and 1YAJ. The structure of each inhibitor was initially built up with the alkyl chain in an extended conformation using MOE (Chemical Computing Group, Montreal), and the geometry was subsequently refined by energy minimization using the MMFF94s [52] force field. This extended conformation seemed adequate as starting geometry, as the alkyl chain of palmitic acid is rather elongated in the complex with hCE1 (the distance from the carbon bearing the carboxyl group to the last methylene in the conformation found in 2DQY is 11.6 Å, which compares with a value of 16.4 Å for the same distance in a fully extended conformation). It is worth noting, however, that whereas the protein was kept rigid, Gold accounts for the conformational flexibility of the ligand around rotatable bonds during docking calculations. In order to explore the alignment of the inhibitor in a suitable orientation that mimics the covalently-bound tetrahedral intermediate arising from the nucleophilic attack of the hydroxyl group of Ser221 to the carbonyl unit of the TFMK inhibitor, a covalent bond was imposed between the oxygen atom of Ser221 and the carbonyl carbon atom in the inhibitor. In addition, a hydrogen bonding constraint was imposed to bias the orientation of the carbonyl oxygen in the tetrahedral intermediate toward the backbone NH units of Gly142 and Gly143. Thus, this constraint should account for the stabilization played by those residues upon formation of the tetrahedral adduct in the enzyme-substrate complex. Overall, the application of these constraints permits to enhance the conformational search in sampling the alignment of the alkyl chain in the binding site.

Refinement of the docked complexes was accomplished by means of molecular dynamics simulations using the parm99 force field of the Amber-9 package [53]. The general Amber force field (gaff; [54, 55]) was used to assign parameters for the covalently-bound adduct formed between the ketone moiety of the TFMK inhibitor and the hydroxyl group of Ser221. In order to refine the gaff parameters, the adduct was modeled by replacing the alkyl chain by an ethyl group and by adding acetyl and methyl groups to the N- and C-terminals of Ser221. The geometry of this model compound was subsequently optimized at the HF/6-31G(d) level, though the torsional angles of the backbone were kept frozen in order to avoid an unrealistic rearrangement in the molecular geometry of the peptide units. The optimized geometrical parameters were then used to refine the bond lengths and angles of the tetrahedral intermediate. Moreover, in order to improve the description of the charge distribution of the (Ser)-O-(C)-(TFMK) unit and to describe more accurately the hydrogen-bonding stabilization arising from the interaction with the NH units of Gly142 and Gly143, the partial atomic charges were slightly adjusted from the RESP charges [56] determined at the HF-6-31G(d) level (note that this level of theory was already adopted in the derivation of the gaff force field). The standard ionization state at neutral pH was taken for all the ionizable residues of the enzyme but His468, which was protonated. The complexes were then immersed in a pre-equilibrated box (ca. 109 Å3) containing the inhibitor-enzyme complex and around 17000 TIP3P [57] water molecules. Six Na+ ions were added using the CMIP strategy to neutralize the system [58], which was then energy minimized and equilibrated using a multistep protocol. First, the location of hydrogen atoms was energy minimized for 2000 steps of steepest descent. Next, the positions of water molecules and ions were relaxed for 2000 steps of steepest descent plus 5000 steps of conjugate gradient. Finally, the whole simulated system was refined via energy minimization by combining 2000 steps of steepest descent plus 8000 steps of conjugate gradient. At this point, the system was thermalized at 298 K by running four 25 ps molecular dynamics simulations where the temperature was increased from 100 to 150, 200, 250 and
298 K, respectively. Subsequently, a 10 ns MD simulation was carried out. The system was simulated in the NPT ensemble using periodic boundary conditions and Ewald sums for treating long-range electrostatic interactions (with the default Amber-9 parameters). The structural analysis was performed using in house software and standard codes (PTRAJ module) of Amber-9.

Results and discussion

TFMK inhibitors

Two series of compounds were considered to investigate the relationship between the structure and the inhibitory potency of TFMKs. The first series includes 13 inhibitors that combine a short alkyl chain with a ketone moiety, which is the main source of chemical diversity due to factors such as the presence or absence of fluorine atoms in the terminal methyl group and chemical modifications in positions vicinal to the carbonyl group (compounds 1-13; Fig. 1). In contrast, the second series includes inhibitors that share the same trifluoromethyl ketone moiety, but differ in the nature of the long alkyl chain (compounds 14-17; Fig. 2). In the former case, it is reasonable to expect that the high flexibility of the short chain should not impede the proper alignment of the inhibitor in the catalytic site. Accordingly, the differences in inhibitory activity should mainly arise from the intrinsic reactivity of the ketone moiety, which in turn should influence the formation of the tetrahedral adduct with the catalytic serine. In the second case, the inhibitory potencies are expected to reflect differences in the proper arrangement of the long alkyl chain, particularly due to the presence of the double bond in positions β and γ (relative to the carbonyl group) in compounds 15 and 16, respectively, compared to the activity of 14.

Reactivity studies

The efficiency of TFMKs as inhibitors of CEs is related to the susceptibility of the ketone moiety to participate in the nucleophilic attack by the catalytic serine in the enzyme active site, thus leading to a tetrahedral adduct that mimics the transition state of the enzyme-substrate complex. Accordingly, in the absence of other factors that might prevent a correct positioning of the ketone moiety in the catalytic site, those inhibitors that favor the formation of the tetrahedral intermediate should a priori exhibit the largest biological effect. Under this rationale, we have examined the equilibrium between keto and hydrate species of model compounds 1-13 to gain insight into the reactivity properties of the ketone moiety. To this end, we have adopted the thermodynamic cycle shown in Fig. 3, which allows us to combine the intrinsic (gas phase) stability of the keto and hydrate species with the hydration preferences of the two species. For those compounds able to form an intramolecular hydrogen bond, a limited conformational search was also performed both in the gas phase and in aqueous solution in order to examine the relative stability of conformers with and without intramolecular hydrogen bonds in both phases.

The stability of the hydrate form in the gas phase ($\Delta G_{\text{gas}}$; Table 1) depends on the number of fluorine atoms positioned α to the carbonyl group. Thus, the structure with the lowest stability of the hydrate species corresponds to the non-fluorinated ketone 9 and introduction of three fluorine atoms in the terminal methyl group (5) stabilizes the hydrate form by 8.3 kcal mol$^{-1}$. This effect is also observed in the comparison of the relative stabilities for pairs of compounds 1 and 11, 3 and 12, and 4 and 13, where fluorination largely stabilizes the hydrate form compared to the keto species. Similarly, formation of an intramolecular hydrogen bond between one of the hydroxyl groups of the hydrate and the heteroatom in β position to the carbonyl group also enhances the stability of the hydrate, as noted in the comparison of thioether (1), sulfoxide (2), sulfone (3) or...
ether (4) derivatives with the unmodified compound 5. The stability of the hydrate species is, nevertheless, reduced by around 2-5 kcal mol\(^{-1}\) (\(\Delta G_{\text{sol}}\); Table 1) upon solvation in aqueous solution. This effect can be attributed to the weakening of the intramolecular hydrogen bond upon solvation in water. In contrast, the relative stability of the keto and hydrate forms is less affected for those compounds whose molecular structure does not permit the formation of such intramolecular hydrogen bond (compounds 5, 8, 9 and 10).

The preceding discussion points out that the balance between the hydrate and keto species depends on a subtle balance of different factors depending on the chemical nature of the groups introduced in the ketone moiety. The degree of fluorination of the methyl group vicinal to the carbonyl unit influences the electron density on the carbonyl carbon, which becomes more electrophilic and therefore more prone to hydration. Moreover, in many cases the amount of keto or hydrate forms may be very small, only detectable by very sensitive spectroscopic methods. On the basis of these considerations, we attempted to measure experimentally the ratio between keto and hydrate forms for few selected compounds using \(^{19}\)F NMR in chloroform solution (note that these assays were performed for compounds with \(R=\text{hexyl}\)). Under these conditions, the results indicate that hydration of the keto form follows the order sulfone (3; 100% hydrate)\(\geq\)sulfoxide (2; 90-96% hydrate)\(>\)ether (4; 78-80% hydrate)\(>\)thioether (1; 30-50% hydrate)\(>\)uns substi tuted TFMK (5; 0% hydrate)\(\equiv\)difluoromethyl ketone (8; 0% hydrate). Keeping in mind the different polarity of the solvent used in computations (Table 1) and in experimental measurements, one can conclude that there is satisfactory qualitative agreement between the theoretically predicted and experimentally determined preferences between the keto and hydrate forms of the studied compounds.

In order to rationalize the hydration extent of compounds 1-13, the free energy difference between keto and hydrate species was compared with the partial charge of the carbonyl carbon, which was determined by using the atoms-in-molecules theory [60]. Figure 4 shows that there is a correlation between the free energy difference determined in aqueous solution and the charge of the carbonyl carbon (the only exception to this behavior is compound 6, which likely reflects the influence of the vicinal carbonyl group). Clearly, this trend can be realized from the influence exerted by the degree of fluorination in \(\alpha\) position and the substitution by electron-withdrawing groups at \(\beta\) position of the carbonyl group on the carbon charge, which becomes more electrophilic and therefore more prone to hydration.

The inhibitory potency determined experimentally for the TFMK inhibitors that incorporate the ketone moieties 1-13 is given in Table 2. In general, there is a close similarity between the experimental activities for the two series of compounds.

### Table 1

<table>
<thead>
<tr>
<th>Compound</th>
<th>(\Delta G_{\text{gas}}) (kcal mol(^{-1}))</th>
<th>(\Delta G_{\text{sol}}) (kcal mol(^{-1}))</th>
<th>Hydrate form (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-3.5</td>
<td>0.2</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>-3.2</td>
<td>-0.2</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>-3.6</td>
<td>-1.4</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>-4.0</td>
<td>-0.5</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>1.6</td>
<td>3.3</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>-6.2</td>
<td>-2.8</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>-3.1</td>
<td>-0.4</td>
<td>99</td>
</tr>
<tr>
<td>8</td>
<td>4.5</td>
<td>4.7</td>
<td>2</td>
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<td>9</td>
<td>9.9</td>
<td>10.5</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>2.5</td>
<td>44</td>
</tr>
<tr>
<td>11</td>
<td>4.3</td>
<td>9.4</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>2.9</td>
<td>6.3</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>1.6</td>
<td>6.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 4 Representation of the free energy difference in aqueous solution between keto and hydrate forms and the charge of the carbonyl carbon for compounds 1-13.
compounds reported in Table 2, which differ in the length of the short alkyl chain (R is hexyl in this work, and butyl in ref. [28]). Such an agreement supports the assumption that the differences in inhibitory potency are mainly due to the intrinsic reactivity properties of the ketone moiety of TFMKs.

Previous studies have examined the dependence on the inhibitory potency of TFMKs and the relative stability between ketone and hydrate species [28]. For a small series of six compounds, which includes sulfide (1, 11), sulfone (3, 12) and ether (4, 13) methyl ketone moieties and their trifluorinated derivatives, a linear dependence was found between the inhibitory activity against human carboxylesterase (from human liver microsomes) and the gas phase electronic energy difference between ketone and hydrate species [28]. Similar linear dependencies were also found with the gas phase free energy difference and with the relative stability estimated in aqueous solution using two solvation models [28]. These findings mainly reflect the activating effect due to the fluorination of the terminal methyl group in the ketone. Nevertheless, the linear dependence between the inhibitory activity and the energetic difference of keto and hydrate species is counterintuitive, as it would a priori suggest an enhancement in the inhibitory potency as the stability of the hydrate form is enlarged. In fact, the kinetic study reported for the trifluorinated sulfoxide derivative 2, whose predicted activity (pIC50=10.00) was much larger than the experimental value (pIC50=6.51), suggested that the dehydration of the gem-diol form was likely the rate-limiting step of binding to the enzyme.

In contrast to the preceding findings, comparison of the inhibitory potencies determined experimentally for compounds 1-13 with the free energy difference reported here for keto and hydrate species in aqueous solution reveals the existence of a parabolic dependence of the IC50 values.

### Table 2 Experimental data for the inhibitory potency\(^a\) of TFMK compounds 1-13

<table>
<thead>
<tr>
<th>Compound</th>
<th>(-\log IC_{50} (\pm SE))</th>
<th>(-\log IC_{50} (\pm SE))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.9 (0.04)</td>
<td>8.1</td>
</tr>
<tr>
<td>2</td>
<td>7.4 (0.04)</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>7.3 (0.04)</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>7.7 (0.02)</td>
<td>7.3</td>
</tr>
<tr>
<td>5</td>
<td>7.6 (0.06)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>5.9 (0.05)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6.1 (0.03)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6.5 (0.05)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>&lt;3</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>7.2 (0.1)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>4.6</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>4.3</td>
</tr>
</tbody>
</table>

\(^a\)IC\(_{50}\) is the inhibitor concentration (M) that reduces the esterase activity by 50%. SE: standard error
\(^b\)This work; R=hexyl
\(^c\)R=butyl; taken from ref. [28]

### Table 3 Experimental data for the inhibitory potency (IC\(_{50}\); nM)\(^a\) of TFMK compounds 14-18

<table>
<thead>
<tr>
<th>Compound</th>
<th>IC(_{50}) (± SE)</th>
</tr>
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<tbody>
<tr>
<td>14</td>
<td>14.0±2.0</td>
</tr>
<tr>
<td>15</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>16</td>
<td>11.8±0.7</td>
</tr>
<tr>
<td>17</td>
<td>9.9±0.9</td>
</tr>
<tr>
<td>18</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

\(^a\)IC\(_{50}\) is the inhibitor concentration (M) that reduces the esterase activity by 50%. SE: standard error

### Fig. 5
Comparison of the experimental IC\(_{50}\) values with the free energy difference between keto and hydrate species in aqueous solution

### Fig. 6
Detailed view of the orientations adopted by the alkyl chain of palmitic acid (in orange) in the three subunits of the complex with hCE1 (PDB entry 2DQY). The catalytic serine residue is shown in colored spheres
Fig. 7 Detailed view of the two main poses found in docking computations of compound 14. The plot also shows the catalytic residue His468, and the residues Gly142 and Gly143, which stabilize via hydrogen bonding the tetrahedral intermediate. In the yellow pose the trifuoromethyl group makes unfavorable contacts with the NH unit of Gly142 and the imidazole ring of His468. In the orange pose, however, no steric clash is observed between the trifuoromethyl group and the neighboring residues in the catalytic site.

(Fig. 5). Compared to the theoretical linear relationships reported in [28], the distinct functional dependence found in this study can be attributed to the inclusion of a larger, more diverse set of compounds. The parabolic relationship between inhibitory potencies and keto-hydrate relative stabilities can be understood from the balance between two opposite factors: the hydration of the keto species and its intrinsic reactivity against a serine residue of the enzyme. Thus, an increase in the electrophilicity of the carbonyl carbon should enhance the reactivity for the attack of the catalytic serine residue, but at the same time it also implies a displacement of the compound toward the hydrate form in aqueous solution. Accordingly, the activity of those ketone moieties poorly activated for a nucleophilic attack will be limited by the intrinsic reactivity, though they will tend to populate the keto species in solution. Likewise, those compounds containing a ketone moiety with enhanced reactivity toward a nucleophile will be moderate or even poor inhibitors because the concentration of the inhibitor will mainly populate the hydrate species, and the inhibitory activity will therefore be largely determined by the dehydration of the gem-diol form to generate the ketone species.

Overall, Fig. 5 allows us to reconcile the predictions made from theoretical calculations for the balance between keto and hydrate species of TFMK compounds with the experimental evidences reported in [28], which support the crucial role played by the degree of ketone hydration on the inhibitory potencies. Moreover, it can also be deduced that if the keto-hydrate conversion is sufficiently dynamic as to ensure the equilibrium between those species, increased incubation times would then result in enhanced inhibitory potencies, because dehydration of the gem-diol species would yield the ketone species, as found in previous experimental studies [12].

Modeling studies

The preceding results reflect the influence of the electronic properties exerted by substituents on the reactivity of the ketone moiety. In particular, the results point out the important role due to fluorination in enhancing the reactivity of the compounds relative to their non-fluorinated partners. This trend would suffice to justify the drastic reduction in the hCE1 inhibitory activity measured for compound 18 relative to TFMKs 14 and 17 (see Fig. 2 and Table 3). Such a reduction cannot be attributed to the different length of the alkyl chains (C18H35 in 14, and C16H31 in 17 and 18), since the terminal part of the long alkyl chain should be easily accommodated.
in the mouth of the gorge, as noted upon inspection of the
different orientations found for the terminal part of the chain
of palmitic acid (C15H31COOH) in the three subunits of the
X-ray crystallographic structure (PDB entry 2DQY; Fig. 6).
Rather, the enhanced inhibitory potency of compounds 14
(IC50=14 nM) and 17 (IC50=9.9 nM) compared to 18 (IC50>
1000 nM) can be explained by the enhanced reactivity of
TFMK associated with the presence of fluoride atoms in α
position to the carbonyl.

Surprisingly, the data in Table 3 also shows a drastic
reduction in the inhibitory potency of compound 15 (IC50>
1000 nM), which compares with the similar change in
activity observed for the non-fluorinated compound 18.
This unexpected trend cannot be realized from electronic
factors, as the trifluorinated methyl ketone moiety is
preserved in compound 15, which should therefore have
similar propensities for the nucleophilic attack by the
catalytic Ser221. Likewise, the weak inhibitory activity of
15 can hardly be attributed to the hydrophobicity of the
compound, as the length of the alkyl chain is identical in
compounds 14-16, which only differ in the number and
location of the double bonds present in the chain.
Inspection of the chemical structures of those compounds
suggests that the poor inhibitory potency of 15 could be
attributed to the precise location of the double bond
between β and γ positions in the alkyl chain, as the
inhibitory activity of compound 16 (IC50=11.8 nM), where
such a double bond involves carbon atoms γ and δ, nearly
matches the activity of 14 and 17. Therefore, it can be
hypothesized that the conformational restraints imposed by
the double bond could affect the proper alignment of the
TFMK inhibitor in the catalytic site, thus preventing the
formation of the tetrahedral intermediate with the catalytic
serine residue.

To corroborate this hypothesis, docking calculations
were combined with molecular dynamics simulations in
order to examine the ability of the catalytic site to
accommodate the covalently bound adducts generated from
inhibitors 14-16. Inspection of the docked poses revealed
that the alkyl chain was generally suitably aligned along the
hydrophobic gorge. However, due to the pharmacophore
constraints imposed to the carbonyl group of the ketone in
docking computations (see Methods), two main orientations
were found for the terminal trifluorinated methyl group, as
noted in Fig. 7 for compound 14 (similar results were
obtained for 15 and 16; data not shown). In the two poses
the orientation of the trifluoromethyl ketone moiety permits
the correct positioning of the hydroxyl oxygen of Ser221
for the nucleophilic attack to the carbonyl carbon. More-
over, the hydroxyl unit in Ser221 is assisted by a hydrogen
bond with the imidazole ring of His468. Nevertheless, the
two poses differ in the orientation of the trifluoromethyl
unit in the binding site. In one case (shown in orange in
Fig. 7) no steric clash is observed between the trifluoro-
omethyl group and the neighboring residues in the catalytic
site. However, in the other case (shown in yellow in Fig. 7)
the trifluorinated methyl is positioned close to the NH unit
of Gly142 and the imidazole ring of His468, suggesting the
existence of unfavorable clashes. Accordingly, this latter
pose was not considered for further analysis in molecular
dynamics simulations.

The structural integrity of the most favored pose for the
tetrahedral adduct formed between inhibitors 14-16 and the
catalytic serine of hCE1 was examined by means of 10 ns molecular dynamics simulations. Inspection of the time evolution of the potential energy of the simulated systems supported the stability of the trajectories in the last 5 ns (see Fig. S1 in Supporting Information). The profile for the positional root-mean square deviation (RMSD) of the backbone atoms ranged from 1.8 to 2.0 Å and remained stable during the last 3 ns, thus reflecting a small relaxation of the overall protein skeleton compared to the X-ray crystallographic structure (see Fig. S1). The RMSD of the heavy atoms for the residues that delineate the walls of the catalytic site and the gorge was smaller (ranging from 1.3 to 1.8 Å) and remained stable along the last 4 ns of the trajectories (Fig. 8).

Though the preceding results point out that the overall stability of the trajectories was similar for the three hCE1-inhibitor complexes, careful inspection of the residues at the binding site reveals a significant difference in the conformation of His468. This residue plays a relevant functional role, as it contributes to enhance the nucleophilicity of Ser221 through the formation of a hydrogen bond, and in turn interacts with Glu354. Thus, inspection of the three subunits present in the X-ray crystallographic structure 2DQY indicates that the distances from O(Ser221) to N$_{ε}$(His468) vary between 2.9 and 3.2 Å, and the distances from N$_{δ}$(His468) to O(Glu354) range from 2.6 to 2.8 Å. Interestingly, the triad formed by Ser221, His468, and Glu354 is structurally stable along the trajectories run for the adducts generated from TFMKs 14 and 16 (see Fig. 9). Thus, the hydrogen bond between Ser221 and His468 remains stable along the whole trajectory (with an average distance close to 2.9 Å; see Fig. 10). In contrast, the structural arrangement of the catalytic triad is completely lost in the simulation run for inhibitor 15 (Fig. 9), as noted in the large interatomic distance between O(Ser221) and N$_{ε}$(His468) (> 6 Å; Fig. 10).

The structural alteration of the catalytic triad, which is found since the beginning of the production run, would imply the loss of the catalytic power. Accordingly, such structural alteration should reduce the nucleophilicity of the serine residue, thus limiting the efficiency of the chemical process leading to the formation of the tetrahedral intermediate between enzyme and inhibitor. Ultimately, this drastic structural change reflects the steric clash that arises between the side chain of His468 and the restricted conformation of the alkyl chain imposed by the presence of the double bond between positions β and γ for compound 15, which is nevertheless completely alleviated in 16.

Even though compounds 14-16 can be viewed as very close analogues sharing similar intrinsic reactivity properties in the ketone moiety, the positional isomerism of the double bond has a dramatic impact on the inhibitory potency. According to present results, the apparently minor structural change associated with the presence of the double bond in position β or γ is crucial, as it triggers a profound structural alteration in the catalytic triad upon formation of the tetrahedral intermediate with 15, while the adduct is properly accommodated upon positional isomerism of the double bond to position γ in 16.

**Final remarks**

Previous studies have indicated that an increased hydrophobicity correlates with inhibitor potency, so that compounds containing longer, more hydrophobic alkyl chains are more potent inhibitors of CEs [12, 27]. Clearly, this trend reflects the lipophilic nature of the gorge, as found in the X-ray
crystalllographic structure of hCE1, where the binding site is lined by residues such as Ala93, Leu97, Val146, Val254, Leu255, Leu299, Phe303, Leu304, Ile359, Leu363, and Met425. However, other factors are expected to play a decisive role on the inhibitory activity of TFMKs.

The results reported here allow us to stress the relevant role played by substituents present in the ketone moiety, which modulate the intrinsic reactivity against a nucleophilic attack, but also the balance between keto and hydrate species. Thus, the parabolic dependence found between the inhibitory potency and the relative stability between keto and hydrate forms of TFMKs strongly support the hypothesis that the inhibitory potency is related to the degree of ketone hydration, as noted in previous studies [28]. Such dependence suggests a direct implication of the electrophilicity of the carbonyl carbon atom of the ketone moiety in two counterbalancing effects: the susceptibility for the nucleophilic attack of the catalytic serine residue of the enzyme, and the degree of hydration of the ketone species.

In this context, present findings support the assumption of the keto species as the bioactive form of TFMK inhibitors [61] provided that the TFMK could fit properly in the catalytic cavity. The presence of apparently minor chemical modifications in positions close to the ketone moiety may thus have an unexpected effect on the inhibitory potency. This is the case of the positional isomerism associated with the displacement of the double bond from β to γ position in compounds 15 and 16, which gives rise to a drastic change in the inhibitory activity. In this case, the intrinsic reactivity properties of the trifluorinated methyl ketone moiety are overridden by the steric factors associated with accommodation of the inhibitor. In turn, these findings pave the way to take advantage of structural differences in the binding site in order to modulate the selectivity of this class of compounds toward different CEs.

Understanding the molecular determinants that modulate the interaction of TFMK inhibitors with CEs is necessary in order to develop compounds with improved pharmacological and agricultural properties. Based on the preceding findings and their implication for the mechanism of action of TFMKs, we feel that selectivity of inhibitors with a central pharmacophore of a polarized ketone for different target enzymes can be modulated through the inclusion of suitable substituents in the chemical structure that contains the ketone moiety. Finally, it is likely that general conclusions drawn from the interaction of TFMK inhibitors and CEs can be extended to the design of inhibitors of other targets such as fatty acid amid hydrolase [15] and diacyl glycerol [16].

Acknowledgments We are indebted to Dr. H. Huang for technical assistance. We also gratefully acknowledge the Spanish Ministerio de Ciencia e Innovación (MICINN; projects AGL2006-13489-C02-01/ AGR and SAF2008-05595) and the Generalitat de Catalunya (SGC2009 294 and 2009 SGR 871) for financial support. Partial support was provided by National Institute of Environmental Health Sciences R01 ES002710 and Superfund Research Program, P42 ES004699. JR acknowledges the Spanish Ministerio de Ciencia e Innovación for a FPI fellowship. BH is a George and Judy Marcus Senior Fellow of the American Asthma Association.

References

Supporting Information

Reactivity versus Steric Effects in Fluorinated Ketones as Esterase Inhibitors: A Quantum Mechanical and Molecular Dynamics Study

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Chemical characterization of compound 4 and is trifluoromethyl carbinol precursor

Trifluoromethyl carbinol. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 4.11 (m), 3.70-3.42 (m, 4H), 3.17 (b, 1H), 1.58 (t, $J = 6.8$ Hz), 1.4-1.2 (m, 10H), 0.87 (t, $J = 7.2$ Hz) ppm. $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ 124.18 (q$_{CF}$, $J = 280$ Hz), 69.27 (q$_{CCF}$, $J = 30.6$ Hz), 67.94, 31.77, 29.35, 29.32, 29.2, 25.91, 22.62, 14.04 ppm. $^{19}$F NMR (376.4 MHz, CDCl$_3$): $\delta$ -78.35 (d, $J = 6.3$ Hz) ppm. Elemental analysis: calculated for C$_{11}$H$_{21}$F$_3$O$_2$: C, 54.53; H, 8.74; F, 23.52; found: C, 54.35; H, 8.8; F, 23.71.

Compound 4. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 3.60 (t, $J = 7$ Hz, 2H), 3.62 (s, 2H), 3.52 (t, $J = 6.5$ Hz, 2H), 1.61 (m, 2H), 1.27 (b, 12H), 0.87 (t, $J = 7$ Hz, 3H) ppm. $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ 188.70 (q, $J = 34.4$ Hz, CO) 122.47 (q$_{CF}$, $J = 284$Hz), 115.28 (q$_{CF}$, $J = 290.6$), 92.33 (q$_{CCF}$, $J = 32.3$ Hz), 72.80, 69.62, 31.77, 29.40, 29.31, 29.18, 25.86, 22.63, 14.07 ppm. $^{19}$F NMR (282 MHz, CDCl$_3$): $\delta$ -78.48 (s, COCF$_3$), -85.88 (s, C(OH)$_2$CF$_3$) ppm. HRMS: calculated for C$_{11}$H$_{19}$F$_3$O$_2$ (M$^+$): 239.1252; found: 239.12590.
Figure S1. Time evolution of the (top) potential energy (kcal/mol) and (bottom) the positional root-mean square deviation (Å) of the backbone atoms along the 10 ns trajectories sampled for the hCE1 complexes with inhibitors 14 (black), 15 (green) and 16 (red).