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**Title:** Corpora non agunt nisi fixata : ligand receptor binding kinetics in G protein-coupled receptors

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Chapter 2

Structure-affinity Relationships and Structure-kinetic Relationships of 1,2-Diarylimidazol-4-carboxamide Derivatives as Human Cannabinoid 1 Receptor Antagonists

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About this chapter

Despite the plethora of human cannabinoid 1 (hCB₁) receptor antagonists active in vitro that have been synthesized as potential antiobesity drugs, the withdrawal from the market of rimonabant caused the termination of virtually all clinical programs of such antagonists. This was due to rimonabant’s class-related serious central nervous system side effects. A better understanding of the molecular mechanisms of hCB₁ antagonist action may, albeit retrospectively, shed some light on what went wrong. It is now emerging that drug target binding kinetics, next to traditional potency measures, may indeed contribute to a better understanding of drug action. Therefore, we now report on the synthesis and biological evaluation of a series of 1,2-diarylimidazol-4-carboxamide derivatives developed as hCB₁ receptor antagonists. These were evaluated in a radioligand displacement binding assay, a [35S]GTPγS binding assay, and in a competition association assay that enables the relatively fast kinetic screening of multiple compounds. The compounds show high affinities and a diverse range of kinetic profiles at the hCB₁ receptor, and their structure-kinetic relationships (SKR) were established. Using the recently resolved hCB₁ receptor crystal structures, we also performed a modelling study that sheds light on the crucial interactions for both the affinity and dissociation kinetics of this family of ligands. We provide evidence that, next to affinity, additional knowledge of binding kinetics is useful for selecting new hCB₁ receptor antagonists in the early phases of drug discovery.
Introduction

Within the endocannabinoid system (ECS) two human cannabinoid receptor subtypes have been identified: the human CB\(_1\) (hCB\(_1\)) receptor and the human CB\(_2\) (hCB\(_2\)) receptor.\(^1\) They are members of the rhodopsin-like class A G-protein-coupled receptors (GPCR), and are primarily activated by endogenous cannabinoids (endocannabinoids, ECs), including anandamide (or N-arachidonylethanolamine, AEA) and 2-arachidonoylglycerol (2-AG).\(^1\)\(^-\)\(^2\) The hCB\(_1\) and hCB\(_2\) receptors show 44% overall sequence homology, and display different pharmacological profiles.\(^3\) The hCB\(_1\) receptor is present in the central nervous system (CNS) and is widely distributed in the peripheral nervous system (PNS) and peripheral tissues,\(^2\)\(^-\)\(^4\) including heart, liver, lung, gastrointestinal tract, pancreas and adipose tissue.\(^5\)\(^-\)\(^6\) The presence of the hCB\(_1\) receptor within both the CNS and PNS mediates neurotransmitter release and controls various cognitive, motor, emotional and sensory functions. Furthermore, activation in the peripheral tissues contributes to energy balance and metabolic processes.\(^6\)\(^-\)\(^9\)

![Figure 1](image-url)

**Figure 1:** Structure of a) Rimonabant; b) Taranabant; c) Otenabant and d) the scaffold of 1,2-diarylimidazol-4-carboxamides as hCB\(_1\) receptor antagonists; the R\(^1\) substitution is defined as the “Left arm” of the scaffold while the R\(^2\) substitution defines the “Right arm” of the scaffold. The calculation of PSA values are reported in supporting information.
The broad presence of the hCB₁ receptor in a variety of complex physiological systems provides numerous opportunities for therapeutic intervention. In the particular case of obesity, the ECS, including the hCB₁ receptor, is overactive with increased levels of endocannabinoids in plasma, both in central and peripheral tissues. Therefore, blockade of the hCB₁ has been explored for the treatment of obesity. With this in mind, rimonabant (SR141716A, Figure 1a), a hCB₁ receptor inverse agonist, was developed by Sanofi-Aventis and introduced in Europe in 2006. However, it was quickly withdrawn from the market due to unacceptable psychiatric side effects. Many other hCB₁ receptor antagonists entered into clinical trials, such as taranabant (MK-0364, Figure 1b) and otenabant (CP945598, Figure 1c). However, they were not developed further due to similar psychiatric side effects, despite their diverse chemical structures.

In order to avoid the CNS side effects, peripherally acting hCB₁ receptor antagonists with physicochemical features that reduce brain penetration have been developed. Another approach has been the development of hCB₁ receptor neutral antagonists, because it has been postulated that the CNS side effects of rimonabant were due to its inverse agonism.

Drug target binding kinetic parameters are receiving increasing attention, alongside classical affinity (Kᵢ) and potency (IC₅₀) values, as has been discussed for several other class A GPCR. In particular the receptor-ligand residence time (RT) is emerging as an additional parameter to assess the therapeutic potential of drug candidates with respect to drug efficacy and safety. In the research field of GPCR, a number of structure-kinetic relationship (SKR) studies have been published, and the results suggest that the strategic combination of SKR with classic structure-affinity relationships (SAR) can improve the resulting decision process. By doing so, ligand-receptor interactions can be better understood, as together they not only comprise the equilibrium state of a ligand-receptor interaction but also its metastable intermediates and/or transition states. The binding kinetics
driven drug discovery approach for the hCB₁ receptor has been validated in some aspects already by its application in the development of allosteric modulators of the hCB₁ receptor.²⁸, ²⁹

In the current study we report the synthesis and evaluation of 1,2-diarylimidazol-4-carboxamide derivatives (Figure 1d), as human CB₁ receptor antagonists with more polar characteristics than rimonabant.³⁰, ³¹ Together with rimonabant they were evaluated in a radioligand displacement assay, a [³⁵S]GTPyS binding assay, and a dual-point competition association assay that enables the relatively fast kinetic screening of compounds.³² Selected compounds were progressed to a full competition association assay. The compounds show high affinities and a diverse range of kinetic profiles at the hCB₁ receptor, which allowed their structure-kinetic relationships (SKR) to be established. Their putative binding mode was analyzed using the recently resolved crystal structures of the hCB₁ receptor,³³, ³⁴ shedding light on key structural features of the receptor binding site that are involved in ligand recognition and dissociation. Thus we provide evidence that, in additional to affinity, knowledge of binding kinetics is useful for selecting new hCB₁ receptor antagonists in the early phases of drug discovery.

**Results and discussion**

**Chemistry.**

The synthesis of the 1,2-diarylimidazol-4-carboxamide scaffold commenced from commercially available 4-(benzyloxy)aniline 1, which was converted to the 2,4-dichlorobenzamidine 2 (Scheme 1). After a one-pot condensation and cyclization sequence, the core-imidazole 3 was obtained. Afterwards, either saponification of the ethyl ester or acidic hydrolysis of the benzyl ether of 3 led to intermediates 4 and 5, respectively. Subsequently, Mitsunobu reaction on intermediate 5 yielded mono- and tri-fluoropropyl ether derivatives 6a and 6b. After saponification of the ethyl esters of 6a and 6b, the corresponding carboxylic acids (7a and 7b) were transformed to acid chlorides and
reacted with piperidin-1-amine to yield the corresponding amides (8a and 8b). Alternatively, the rest of the series was produced from intermediate 4 by first introducing the piperidin-1-amide. Lewis acid-catalyzed cleavage of benzyl ether 9 followed by substitution of the released alcohol 10 with various alkyl halides gave the corresponding ethers 11a-11h, completing the “left arm” series of antagonists (Table 1).

Scheme 1. Synthesis of antagonists 8a, 8b and 11a-h.

Reagents and conditions: a) EtMgBr, 2,4-diClPhCN, THF, r.t., 20 h, 98%; b) i. EtO₂CC(O)CH(Br)CH₃, K₂CO₃, THF, r.t. 66 h, ii. AcOH, reflux, 1 h, 65%; c) HBr, AcOH, r.t., 15 h, 63%; d) R¹-OH, DEAD, Ph₃P, THF, Toluene, r.t., 15h, 77%; e) KOH, EtOH:THF:H₂O 2:2:1, 50 °C, 3.5 h, 95%; f) i. (COCl)₂, DMF cat., CH₂Cl₂, r.t., 90 min, ii. Piperidin-1-amine.HCl, pyridine, CH₂Cl₂, r.t., 2 h, 55% (2 steps); g) KOH, MeOH:H₂O 3:1, reflux, 2 h, 99%; h) i. (COCl)₂, DMF cat., CH₂Cl₂, reflux, 2 h, ii. Piperidin-1-amine, NET₃, CH₂Cl₂, 0 °C to r.t., 2 h, 74%; i) BBr₃, CH₂Cl₂, r.t., 1 h, 58%; j) R²-X, base, CH₂Cl₂. 56-90% Corresponding R² substitutions are listed in Table 1.

The synthesis of the “right arm” series of antagonists was started from intermediate 4 (Scheme 2). Using various amines and the aforementioned acid chloride introduction/amide formation sequence,
amides 12a-12h were obtained, as well as racemic (±) 20. Deprotection of the aromatic alcohol on 12a-12h and subsequent sulfonylation using 3,3,3-trifluoropropane-1-sulfonylchloride gave compounds 14a-14h.

Scheme 2. Synthesis of antagonists 14a-h, 19, (±)22, (±)25 and 28.

Reagents and conditions: a) i. SOCl₂, reflux; or (COCl)₂, DMF cat., CH₂Cl₂, r.t.; ii. R²-NH₂, NEt₃, CH₂Cl₂, 17-98% (2 steps); or 2-amino-5-trifluoromethylpyridine, Me₂Al, CH₂Cl₂, r.t. to 45 °C, 16 h, 64%; b) BF₃·OEt₂, Me₂S, CH₂Cl₂, r.t.; or HBr, AcOH, r.t. 20-97%; c) Et₃N, F₃CCCH₂CH₂SO₂Cl, CH₂Cl₂, -78 °C, 25-97%; d) i. TBDMSCl, Et₃N, CH₂Cl₂, r.t., 22 h; ii. Boc₂O, THF, r.t., 4 h, 70% (4 steps, a, b, d i. & ii.); iii. TBAF, THF, r.t., 90 min; iv. F₃CCCH₂CH₂SO₂Cl, Et₃N, CH₂Cl₂, -78 °C, 3 h; v. SOCl₂, MeOH, 0 °C to r.t., 1 h, 56% (3 steps, d iii., iv. & v.); e) i. (COCl)₂, DMF cat., CH₂Cl₂, r.t., 2 h, ii. ClCCCH₂OH, NETs, CH₂Cl₂, r.t., 3 h, 95% (2 steps, e, b); f) Zn, AcOH, 3 h; g) i. (COCl)₂, DMF cat., CH₂Cl₂, r.t., 2 h, ii. 4-amincyclohexanol, NaOH, H₂O:CH₂Cl₂ 2:1, r.t., 2 h, 54% (2 steps, f, g); h) CH₂O, NaBH₄, NaBH₄CN, CH₃CN, H₂O, AcOH, r.t., 48 h, 32%; i. (±) 23 R = Bn, (±) 24 R = H.

After deprotection of racemic (±) 20 however, it was found that direct substitution was not possible, therefore a series of protecting group manipulations was executed on (±) 21 to end up with (±) 22. Towards (±) 25, (±) 20 was first di-methylated and subsequently debenzylated and sulfonylated.
giving (±) 25. Exploring alternative synthesis routes, compound 19 was synthesized, with a few extra steps, by first esterifying 4 with 2,2,2-trichloroethanol, followed by deprotection of the aromatic alcohol. Sulfonylation of the released alcohol, saponification of the trichloroethylester, acid chloride formation and subsequent amide formation gave 19. To obtain trifluoromethylpyridine derivative 28, conventional methods as described for the industrial production of rimonabant were applied, starting with the direct amidation of ethyl ether 3 followed by debenzylation and sulfonylation.

**Biology.**

All 1,2-diarylimidazol-4-carboxamide derivatives were evaluated as antagonists in an *in vitro* [35S]GTPγS binding assay on HEK-293 cells membrane fractions overexpressing the human CB1 receptor. We also determined the functional activity of nine representative antagonists on the human CB2 receptor. The data in Table 1 and S1 shows that all compounds tested had higher functional activity for the human CB1 receptor over the human CB2 receptor, with approximately 110 to 570-fold selectivity.

Likewise they were also tested in a [3H]CP55940 radioligand displacement assay on membrane fractions of CHO cells overexpressing the recombinant human CB1 receptor. These results are reported in Tables 1 and 2. We found that, although using different cellular background and assay systems, there is a significant correlation (r² = 0.49, P = 0.0001) between the affinity (pKi) values from the radioligand binding assay and the potencies (pIC50) determined in the [35S]GTPyS binding assay (Figure 2). We subsequently determined the binding kinetics of the 1,2-diarylimidazol-4-carboxamide derivatives in a competition association assay with [3H]CP55940 as the probe after a validation step.
Figure 2: The correlation between the affinities/potencies of the CB$_1$ receptor antagonists measured in a radioligand binding assay (X-axis) and in a GTPyS binding assay (Y-axis) ($r^2 = 0.49$, $P = 0.0001$). Data taken from Tables 1 and 2.

Figure 3: Association and dissociation profile of $[^3H]$CP55940 (2.9 nM) at recombinant hCB$_1$ receptors stably expressed on CHO cell membranes at 30 °C. After 120 min of association, unlabeled rimonabant (10 µM) was added to initiate the dissociation. Association data was fitted in Prism 6 using one-phase exponential association ($n=3$, combined and normalized). Dissociation data was fitted using one-phase exponential decay ($n=4$, combined and normalized). Data are shown as mean ± SEM from at least three separate experiments each performed in duplicate.
Table 1. In vitro pharmacology data, including conventional antagonism, binding affinities and KRI values, for human CB1 receptor antagonists with various “left arm” R1 substitutions.

<table>
<thead>
<tr>
<th>Code</th>
<th>R1</th>
<th>([15S]GTP\gamma S) binding pIC\textsubscript{50} ± SD or SEM (mean IC\textsubscript{50} in nM)\textsuperscript{a}</th>
<th>pK\textsubscript{i} ± SEM (mean K\textsubscript{i} in nM)</th>
<th>KRI ± SEM (n1, n2) (n = 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8a</td>
<td>-CH\textsubscript{2}CH\textsubscript{2}CF\textsubscript{3}</td>
<td>8.3 ± 0.1 (5.6)\textsuperscript{d}</td>
<td>9.1 ± 0.2 (1.26)</td>
<td>0.90 (0.90;0.89)</td>
</tr>
<tr>
<td>8b</td>
<td>-CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}F</td>
<td>8.2 ± 0.01 (6.0)\textsuperscript{d}</td>
<td>10 ± 0.2 (0.34)</td>
<td>1.09 (1.34;0.84)</td>
</tr>
<tr>
<td>9</td>
<td>-CH\textsubscript{2}Ph</td>
<td>7.7 ± 0.1 (18)\textsuperscript{f}</td>
<td>8.2 ± 0.1 (6.28)</td>
<td>0.90 ± 0.20</td>
</tr>
<tr>
<td>11a</td>
<td>-CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CF\textsubscript{3}</td>
<td>8.9 ± 0.1 (1.2)</td>
<td>9.7 ± 0.1 (0.32)</td>
<td>0.80 (0.85;0.75)</td>
</tr>
<tr>
<td>11b</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{3}</td>
<td>8.7 ± 0.03 (1.8)\textsuperscript{d}</td>
<td>9.6 ± 0.1 (0.28)</td>
<td>0.59 ± 0.06</td>
</tr>
<tr>
<td>11c</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}F</td>
<td>8.5 ± 0.2 (3.1)\textsuperscript{d}</td>
<td>9.5 ± 0.2 (0.32)</td>
<td>0.88 (1.00;0.75)</td>
</tr>
<tr>
<td>11d</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CF\textsubscript{3}</td>
<td>9.0 ± 0.03 (1.1)</td>
<td>9.9 ± 0.1 (0.11)</td>
<td>1.02 (1.08;0.96)</td>
</tr>
<tr>
<td>11e</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{3}</td>
<td>8.9 ± 0.05 (1.3)\textsuperscript{d}</td>
<td>9.9 ± 0.1 (0.18)</td>
<td>0.77 ± 0.25</td>
</tr>
<tr>
<td>11f</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}CF\textsubscript{3}</td>
<td>8.9 ± 0.1 (1.2)</td>
<td>10 ± 0.2 (0.062)</td>
<td>0.93 (0.89;0.97)</td>
</tr>
<tr>
<td>11g</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}[CH\textsubscript{3}]\textsubscript{2}</td>
<td>8.9 ± 0.1(1.3)</td>
<td>9.7 ± 0.1 (0.20)</td>
<td>1.02 (1.06;0.97)</td>
</tr>
<tr>
<td>11h</td>
<td>-SO\textsubscript{2}CH\textsubscript{2}CH\textsubscript{2}[CH\textsubscript{3}]\textsubscript{2}</td>
<td>8.7 ± 0.1 (2.4)</td>
<td>9.3 ± 0.1 (0.60)</td>
<td>0.73 (0.68;0.78)</td>
</tr>
</tbody>
</table>

\textsuperscript{a}pIC\textsubscript{50} ± SD (n=2) or SEM (n ≥ 3), obtained from \([35S]GTP\gamma S\) binding on recombinant human CB1 receptors stably expressed on HEK-293 cell membranes.

\textsuperscript{b}pK\textsubscript{i} ± SEM (n=3), obtained from radioligand binding assays with \([3H]CP55940\) on recombinant human CB1 receptors stably expressed on CHO cell membranes.

\textsuperscript{c}KRI ± SEM (n = 3) or KRI (n1, n2) (n = 2), obtained from dual-point competition association assays with \([3H]CP55940\) on recombinant human CB1 receptors stably expressed on CHO cell membranes.

\textsuperscript{d}n = 2.

![Diagram of molecular structure]
Table 2. In vitro pharmacology data, including conventional antagonism, binding affinity and KRI values, for human CB1 receptor antagonists with various “right arm” R\textsuperscript{2} substituents.

<table>
<thead>
<tr>
<th>Code</th>
<th>R\textsuperscript{2}</th>
<th>[^{[35]S}\text{GTP}\gamma\text{S} binding pIC\textsubscript{50} ± SD or SEM (mean IC\textsubscript{50} in nM)\textsuperscript{a}</th>
<th>pK\textsubscript{i} \textsuperscript{b} ± SEM (mean K\textsubscript{i} in nM)</th>
<th>KRI \textsuperscript{c}</th>
</tr>
</thead>
</table>
| 11d  | \begin{tikzpicture}
       \draw[thick] (0,0) -- (0.5,0);
       \draw[thick] (0,0) -- (0,0.5);
       \draw[thick] (0.5,0) -- (0,0.5);
   \end{tikzpicture} | 9.0 ± 0.03 (1.1) | 9.9 ± 0.1 (0.11) | 1.02 (1.08;0.96) |
| 14a (±) | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 8.6 ± 0.1 (2.7) | 9.6 ± 0.1 (0.27) | 0.71 ± 0.17 |
| 14b (±) \text{trans} | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 8.9 ± 0.04 (1.1) | 10 ± 0.04 (0.10) | 0.89 ± 0.12 |
| 14c (±) \text{trans} | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 8.8 ± 0.2 (1.7) | 9.7 ± 0.2 (0.30) | 0.74 ± 0.15 |
| 14d (±) \text{cis} | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 8.8 ± 0.03 (1.8) | 11 ± 0.1 (0.027) | 1.06 (1.09;1.02) |
| 19 cis : trans (0.3:1) | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 8.4 ± 0.01 (3.8) | 9.4 ± 0.1 (0.37) | 0.88 ± 0.17 |
| 22 (±) \text{cis} | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 8.2 ± 0.1 (7.1) | 9.5 ± 0.2 (0.52) | 0.79 (0.65;0.93) |
| 25 (±) cis | \begin{tikzpicture}
        \draw[thick] (0,0) -- (0.5,0);
        \draw[thick] (0,0) -- (0,0.5);
        \draw[thick] (0.5,0) -- (0,0.5);
        \draw[thick] (0.5,0.5) -- (1,0.5);
        \draw[thick] (0.5,0.5) -- (0.5,1);
        \draw[thick] (1,0.5) -- (1,1);
        \draw[thick] (0.5,1) -- (1,1);
    \end{tikzpicture} | 7.1 ± 0.1 (83) | 8.6 ± 0.2 (3.3) | 0.74 (0.74;0.73) |
Receptor association and dissociation rate constants of [3H]CP55940 were directly determined in classic radioligand association and dissociation experiments at 30 °C. The binding of [3H]CP55940 approached equilibrium after approximately 25 min (Figure 3), yielding a $k_{on}$ ($k_1$) value of $(1.4 \pm 0.08) \times 10^6 \text{ M}^{-1}\text{s}^{-1}$. Binding of the radioligand was reversible after the addition of rimonabant (10 μM), although the dissociation was rather slow. Even 240 min after the addition of rimonabant residual receptor binding (~15%) of [3H]CP55940 was observed. The dissociation rate constant, $k_{off}$ ($k_2$), of [3H]CP55940 from the hCB₁ receptor was $(1.5 \pm 0.2) \times 10^{-4}\text{s}^{-1}$. The kinetic $K_D$ value ($k_{off}/k_{on}$) of [3H]CP55940 was $0.12 \pm 0.03 \text{nM}$ (Table 3). The residence time (RT) of [3H]CP55940 was calculated as $114 \pm 16\text{ min}$. 

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$^a$ pIC$\text{so}$ ± SD (n=2) or SEM (n ≥ 3), obtained from [35S]GTPγS binding on recombinant human CB₁ receptors stably expressed on HEK-293 cell membranes.

$^b$ pKᵢ ± SEM (n=3), obtained from radioligand binding assays with [3H]CP55940 on recombinant human CB₁ receptors stably expressed on CHO cell membranes.

$^c$ KRI ± SEM (n = 3) or KRI (n₁, n₂) (n = 2), obtained from dual-point competition association assays with [3H] CP55940 on recombinant human CB₁ receptors stably expressed on CHO cell membranes.

$^d$ n = 2.
Table 3. Comparison of equilibrium binding and kinetic parameters of CP55940 determined using different methods.

<table>
<thead>
<tr>
<th>Assay</th>
<th>$K_i$ or $K_D$ (nM)</th>
<th>$k_{on}$ ($\text{M}^{-1} \cdot \text{s}^{-1}$)</th>
<th>$k_{off}$ ($\text{s}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement $^{b)}$</td>
<td>0.56 ± 0.04</td>
<td>N.A. $^{c)}$</td>
<td>N.A.</td>
</tr>
<tr>
<td>Association &amp; Dissociation $^{d)}$</td>
<td>0.12 ± 0.03</td>
<td>(1.4 ± 0.08) $\times 10^6$</td>
<td>(1.5 ± 0.2) $\times 10^4$</td>
</tr>
<tr>
<td>Competition association $^{e)}$</td>
<td>0.54 ± 0.10</td>
<td>(1.2 ± 0.1) $\times 10^6$</td>
<td>(6.5 ± 1.0) $\times 10^4$</td>
</tr>
</tbody>
</table>

$^{a)}$: Data are presented as means ± standard error of the mean (SEM) of at least three independent experiments performed in duplicate.

$^{b)}$: Equilibrium displacement of [3H]CP55940 from hCB$_1$ receptor at 30 °C.

$^{c)}$: Not applicable.

$^{d)}$: Classic association and dissociation parameters of [3H]CP55940 measured in standard kinetic assays at 30 °C.

$^{e)}$: Association and dissociation parameters of CP55940 measured in competition association assays at 30 °C.

Validation of the [3H]CP55940 competition association assay for human CB$_1$ receptor.

With the $k_{on}$ ($k_3$) and $k_{off}$ ($k_4$) values of [3H]CP55940 binding established from classical association and dissociation experiments, $k_{on}$ ($k_3$) and $k_{off}$ ($k_4$) of unlabeled CP55940 were determined by fitting the values based on the mathematical model as described in the experimental.$^{36}$ In this validation experiment we tested three different concentrations of unlabeled CP55940, corresponding to IC$_{25}$, IC$_{50}$ and IC$_{75}$ (Figure 4A). Values for $k_{on}$ and $k_{off}$ determined by this competition association method were (1.2 ± 0.1) $\times 10^6$ M$^{-1}$s$^{-1}$ and (6.5 ± 1.0) $\times 10^4$ s$^{-1}$, respectively. The $k_{on}$ value was in good
agreement with the \( k_{\text{on}} \) \((k_1)\) value determined in the classical association experiment (Table 3). The \( k_{\text{off}} \) value obtained by this method was also similar to that found in the classical kinetic dissociation experiments with \(^3\text{H}\)CP55940, with just a four-fold difference between the values (Table 3). In order to confirm the robustness of the assay with unlabeled human CB\(_1\) receptor antagonists, an experiment was performed using rimonabant (Figure 4B, Table 4). The \( k_{\text{on}} \) and \( k_{\text{off}} \) values determined by this competition association method were \((2.3 \pm 0.3) \times 10^5 \text{ M}^{-1}\cdot\text{s}^{-1}\) and \((1.4 \pm 0.2) \times 10^{-3} \text{ s}^{-1}\), respectively, demonstrating that rimonabant behaves as a short residence time antagonist \((14 \pm 2.0 \text{ min})\), in good agreement with findings reported earlier.\(^{37, 38}\)

**Screening of hCB\(_1\) receptor antagonists using the dual-point competition association assay.**

The competition association assay described above is quite laborious and time-consuming. Therefore, a so-called “dual-point competition association assay” for the hCB\(_1\) receptor was developed, according to the concept that we had previously established for the adenosine A\(_1\) receptor.\(^{32}\) To this end, \(^3\text{H}\)CP55940 and unlabeled antagonists were co-incubated at concentrations equal to, or 2 to 3-fold higher than, their \( K_i/I_{C50} \) values which had been determined in the \(^3\text{H}\)CP55940 displacement assay. The so-called kinetic rate index (KRI) was calculated by dividing the specific radioligand binding at 30 min \((t_1)\) by the binding at 240 min \((t_2)\). Antagonists with a KRI value larger than 1 indicate a slower dissociation rate, and thus a longer RT, than \(^3\text{H}\)CP55940, and vice versa. Furthermore, it was observed that the KRI values of the hCB\(_1\) receptor antagonists had no obvious correlation with their affinities (Figure 5A).
A. Competition association experiments with $[^3]H$CP55940 binding to recombinant hCB$_1$ receptors stably expressed on CHO cell membranes (30 °C) in the absence or presence of 3.5, 11, and 35 nM of unlabeled CP55940 (n=3, combined and normalized); B. Competition association experiments with $[^3]H$CP55940 binding to recombinant hCB$_1$ receptors stably expressed on CHO cell membranes (30 °C) in the absence or presence of 120 nM of unlabeled rimonabant (n=6, representative graph). $t_1$ is the radioligand binding at 30 min, while $t_2$ is the radioligand binding at 240 min.

**Table 4.** Kinetic parameters ($k_{on}$, $k_{off}$ and RT) of selected human CB$_1$ receptor antagonists.

<table>
<thead>
<tr>
<th>Code</th>
<th>$k_{on}$</th>
<th>$k_{off}$</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(M$^{-1}$s$^{-1}$)</td>
<td>(s$^{-1}$)</td>
<td>(min)</td>
</tr>
<tr>
<td>11b</td>
<td>(3.0 ± 0.5)x10$^5$</td>
<td>(2.2 ± 0.2) x 10$^4$</td>
<td>78 ± 5</td>
</tr>
<tr>
<td>14f</td>
<td>(7.2 ± 3.2)x10$^5$</td>
<td>(2.7 ± 0.5) x 10$^4$</td>
<td>62 ± 10</td>
</tr>
<tr>
<td>28</td>
<td>(3.5 ± 0.7)x10$^5$</td>
<td>(7.8 ± 0.3) x 10$^5$</td>
<td>260 ± 56</td>
</tr>
<tr>
<td>rimonabant</td>
<td>(2.3 ± 0.3)x10$^5$</td>
<td>(1.4 ± 0.2) x 10$^3$</td>
<td>14 ± 2.0</td>
</tr>
</tbody>
</table>

$^a$ $k_{on}$ ± SEM (n = 3), obtained from competition association assays with $[^3]H$CP55940 on recombinant human CB$_1$ receptors stably expressed on CHO cell membranes.

$^b$ $k_{off}$ ± SEM (n = 3), obtained from competition association assays with $[^3]H$CP55940 on recombinant human CB$_1$ receptors stably expressed on CHO cell membranes.

$^c$ RT = 1/(60 * $k_{off}$); RT is expressed in min, whereas $k_{off}$ is expressed in s$^{-1}$. 
A. The negative logarithm of the affinities of the hCB₁ receptor antagonists used in this study had no obvious linear correlation with their KRI values \((r^2 = 0.04, \ P = 0.33)\); B) The negative logarithm of \([^{35}\text{S}]\text{GTP}_{\gamma}\text{S IC}_{50}\) values of the hCB₁ receptor antagonists in this study had no obvious linear correlation with their KRI values \((r^2 = 0.12, \ P = 0.10)\).

**Figure 5:** A) The negative logarithm of the affinities of the hCB₁ receptor antagonists used in this study had no obvious linear correlation with their KRI values \((r^2 = 0.04, \ P = 0.33)\); B) The negative logarithm of \([^{35}\text{S}]\text{GTP}_{\gamma}\text{S IC}_{50}\) values of the hCB₁ receptor antagonists in this study had no obvious linear correlation with their KRI values \((r^2 = 0.12, \ P = 0.10)\).

**Structure–Affinity Relationships (SAR) versus Structure–Kinetic Relationships (SKR).**

The 1,2-diarylimidazol-4-carboxamide derivatives are rimonabant bioisosteres, in which the 2,4-dichlorophenyl, amide, aryl, and methyl moieties are maintained on an alternative heterocyclic diazo core (Figure 1a and 1d). The derivatives included in this study differ in their substituents at the \(R^1\) and \(R^2\) positions, which are at the “left” and “right” arms of the scaffold, respectively (Figure 1d).

We were conscious that compound polarity may influence the activity parameters being studied, so polarity was determined by both calculated and experimental methods. Calculated methods
included Polar Surface Area (PSA),\textsuperscript{39} ACDlogD7.4 with pK\textsubscript{a} correction\textsuperscript{40} and AZlogD7.4,\textsuperscript{41} which were supplemented with experimentally determined LogD values. A PSA of 90 Å\textsuperscript{2} has been described as a threshold value below which penetration of the blood–brain barrier is more likely, and thus serves as an indicator for potential to have CNS activity.\textsuperscript{42} The calculated PSA values (\textbf{Tables S2} and \textbf{S3}) of most of the compounds in this study were above 90 Å\textsuperscript{2}, suggesting that they would have low blood-brain barrier penetration, and be better suited for peripheral antagonism of the hCB\textsubscript{1} receptor. We observed that neither affinities nor KRI values of the CB\textsubscript{1} receptor antagonists in this study had any obvious linear correlation with their lipophilicity or PSA values (\textbf{Figures S1} and \textbf{S2}).

"Left arm" optimization.

Fixing the right arm as a piperidine moiety, as in rimonabant, various ethers with different carbon chain lengths were introduced on the left arm (\textbf{Table 1}). Extension of the trifluoromethylalkyl chain from three carbons (8a, 1.26 nM) to four atoms (11a, 0.32 nM) increased affinity by about four-fold. Reducing the level of fluorination on the terminal carbon of the linear ether side-chain from three atoms (8a, 1.26 nM) to one atom (8b, 0.34 nM) also increased the affinity. By contrast, the analogue possessing a benzyl substituent on the left arm (9, 6.28 nM) displayed the weakest affinity of the analogues studied. The aforementioned modifications did not seem to have a drastic effect on KRI, with all compounds giving values around unity (0.80 to 1.09). As part of a strategy to increase PSA a sulfonyl-containing side-chain was introduced. The ligand bearing an \textit{n}-propyl-sulfonyl moiety (11b) displayed a good affinity of 0.28 nM and a rather low KRI value of 0.59. Mono-fluorinating the terminal position led to no change in affinity (11c, 0.32 nM). In contrast to the ether substituents, trifluorination resulted in an almost three-fold increase (11d, 0.11 nM) relative to the mono-fluoro analogue. A slight increase in affinity was observed when the linear sulfonyl side-chain was extended from three carbon atoms (11b, 0.28 nM) to four (11e, 0.18 nM). Combination of this chain length with trifluoro-substitution, to give the side chain found in the CB\textsubscript{1} receptor agonist \textit{(-)-(R)-3-(2-hydroxymethyldinanyl-4-oxy)phenyl-4,4,4-trifluoro-1-sulfonate (BAY 38-7271)},\textsuperscript{43, 44} led to a very
potent antagonist of the human CB₁ receptor (11f, 62 pM). Branching the chain from n-butyl to i-pentyl did not change the affinity (11g vs. 11e), while introducing an additional methyl group led to a decrease in affinity (11h, t-hex chain, 0.60 nM). None of these ligands had a KRI value higher than 1, indicating their dissociation from the hCB₁ receptor was faster than CP55940. The analogue with the lowest KRI value (11b, 0.59) was selected for full-curve measurement (Figure 6, Table 4). As expected, its residence time (78 min) was shorter than that of CP55940 (114 min, see above) (Table 4). This result also serves as evidence that a KRI value seems to reliably reflect the corresponding dissociation rate constant.

Figure 6: Competition association experiments with [³H]CP55940 binding to recombinant hCB₁ receptors stably expressed on CHO cell membranes (30 °C) in the absence or presence of unlabeled long residence time compound 28 (8.22 nM, red, representative curve) or short residence time compound 11b (12.72 nM, blue, representative curve). Data are shown as mean values from one representative experiment. At least three separate experiments each performed in duplicate.

All the linear side-chain antagonists had high affinities in the nanomolar to sub-nanomolar range, with 11f (60 pM) as the most potent derivative. However, from the perspective of drug-target kinetic studies, despite giving a range of KRLs (0.59-1.09), none of these antagonists showed a KRI value significantly higher than 1, suggesting that none had longer residence times than CP55940.
“Right arm” optimization.

To explore the “right arm” of the 1,2-diarylimidazol-4-carboxamides, we chose to fix the “left arm” as a trifluoropropyl sulfonyl moiety (11d), since this group delivered high affinity (0.11 nM) and demonstrated a residence time similar to CP55940 (KRI = 1.02, Table 1). Introducing a hydroxyl at the 3-position of the piperidine ring yielded a ligand with lower affinity and KRI value (14a, \( K_i = 0.27 \) nM, KRI = 0.71) than 11d (Table 2).

Efforts then focused on a series of ligands bearing cyclohexyl substituents instead of a piperidine. A carbocyclic analogue of 14a, bearing a trans-hydroxyl on the 3-position of the cyclohexyl ring 14b (racemic), delivered an approximately three-fold improvement in affinity and a slightly larger KRI value relative to the piperidine 14a (Table 2). Moving the hydroxyl to the 4-position gave 4-hydroxycyclohexyl analogue (19), as a mixture of cis and trans diastereoisomers in a ratio of 0.3:1, and resulted in an approximately four-fold reduction in affinity (0.37 nM), whilst the KRI was unchanged (0.88); having a mixture does not allow any further conclusions, though. Interestingly, the cis- and trans-2-hydroxycyclohexyl antagonists (14d and 14c, respectively) showed a substantial 10-fold difference in affinity, while their KRI values were quite similar. The more potent cis-isomer (14d, (+)) displayed an affinity of 27 pM and a KRI value close to unity. Switching the 2-substituent of the cyclohexane ring to an amine was detrimental, resulting in ligands with lower affinities. However, it is of note that the unsubstituted cis-amino group (22, (±), 0.52 nM) was less detrimental to affinity than a cis-dimethylamino substituent (25, (±), 3.3 nM), whilst the dissociation rates were very similar, as judged by their KRI values (Table 2). At this stage, on the basis of affinity alone, 14d with an affinity of 27 pM seems an even better lead than 11f with an affinity of 62 pM.

Last but not least, we found that by introducing an aromatic moiety, the compounds retain affinity in the sub-nanomolar range and, more importantly, their kinetic profiles were rather diverse. The analogue which bears a 4-trifluoromethoxyphenyl substituent (14e) showed high affinity (0.22 nM) and its KRI value was one of the highest measured (Table 2). Introduction of a pyridine moiety was
then studied. The 3-pyridyl analogues 14f and 14g, bearing a 6-fluoro or trifluoromethyl group, respectively, showed similar affinities (0.13 nM vs. 0.31 nM, respectively), although the latter had a much higher KRI value (1.12 vs. 0.70, respectively). This effect on KRI was increased further when the position of the nitrogen atom in the ring was switched to give the 5-substituted 2-pyridyl analogue (28, KRI = 1.39), which displayed the highest KRI value of all the compounds presented in this study. Finally, defluorinating this latter compound did not change the affinity, but gave rise to a marked reduction in KRI (14h, Kᵢ = 0.14 nM, KRI = 0.92).

The compounds with high (28) and low (11b and 14f) KRI values were tested in a full competition association assay to determine their association and dissociation rate constants (Figure 6 and Table 4). According to the full curves, the compound with KRI > 1 (28) displayed an “overshoot” in the competition association curve, indicating its slow dissociation and yielding the longer residence time of 260 min, as compared to 114 min of the radioligand. By contrast, the compounds with KRI < 1 produced gradually ascending curves, suggesting faster dissociation and consequently shorter residence times of 78 min (11b) and 62 min (14f) (Figure 6, Table 4). Additionally, we determined their affinities on the human CB₂ receptor. From Table 1 and S1 it shows that they all had higher affinity for the human CB₁ receptor, where approximately 12 to 125-fold selectivity over human CB₂ receptors was observed.

Functional assays.

As mentioned above, the antagonism in the[^35]S]GTPγS binding assay compares quite well with the affinities derived from the[^3]H]CP55940 displacement studies (Figure 2), while the KRI values of the compounds did not show any meaningful correlation with the pIC₅₀ values from the GTPγS binding assay (Figure 5B). Since 28 showed slow dissociation, we decided to study this compound further in a more elaborate[^35]S]GTPγS binding experiment, in which its functional activity in the inhibition of
CP55940 action was characterized and compared with rimonabant. Pretreatment of CHOK1 hCB₁ receptor membranes with rimonabant for 1h, prior to stimulation by the CB₁ receptor agonist CP55940 for 30 min, induced surmountable antagonism (a rightward shift of the agonist curve with little suppression of the maximum effect) as reported before. In the case of 28 insurmountable antagonism was observed; the agonist concentration-effect curve was shifted to the right with a concomitant decrease (~50%) in its maximal response (Figure 7). In both cases inverse agonism by the compounds alone (in the absence of CP55940) was also apparent (negative values at Y-axis in Figure 7).

![Figure 7: CP55940-stimulated [³⁵S]GTPγS binding to recombinant hCB₁ receptors stably expressed on CHO cell membranes (25 °C) in the absence (black, representative curve) or presence of long-residence-time compound 28 (red, representative curve) or rimonabant (blue, representative curve). Compound 28 or rimonabant was pre-incubated with the membranes for 1h prior to the challenge of agonist. [³⁵S]GTPγS was subsequently added and incubated for another 0.5 h. Plates were then filtered and the radioactivity counted. Curves were fitted to a four parameter logistic dose-response equation. Data were normalized according to the maximal response (100%) produced by CP55940. At least three separate experiments each performed in duplicate.](image)

**Computational studies.**

Finally, we investigated the ligand-receptor interactions using the recently disclosed X-ray crystal structure of hCB₁ in complex with 29 [4-(4-(1-(2,4-dichlorophenyl)-4-methyl-3-(piperidin-1-ylcarbamoyl)-1H-pyrazol-5-yl)phenyl)but-3-ynyl nitrate, AM6538], crystal structure code: 37
By docking 28 into the hCB₁ receptor it can be seen that, like 29, it lies quite deep in the binding pocket of hCB₁ in the docked pose, immediately above the conserved Trp356⁶.⁴⁸ (Figures 8A and B). The main scaffold of the imidazole core and the 2,4-dichlorophenyl ring form a π-π interaction with the side chains of Phe10₂¹*-term and Phe17₀².⁵⁷ respectively (Figure 8B). Unsurprisingly, and consistent with the SAR reported in Table 1, the “left arm” of our ligand docks into the same place as “Arm 2” of 29 in the crystal structure. This “left arm” extends into a long, narrow, and highly lipophilic channel formed by helices III, V, VI and ECL2 (Figure 8A). By contrast, the “right arm” of our ligands, which resemble “Arm 3” of 29 dock into an open cavity formed by various hydrophobic amino acid residues,³³ irrespective of whether a cyclohexyl, piperidine, or pyridine moiety is present. In the case of a pyridine moiety (14e-14h and 28), the crystal structure suggests that there may be a π-π stacking interaction with His17₈².⁶⁵. Further support for the docked pose of 28 comes from the higher resolution x-ray structure of taranabant bound to hCB₁ (PDB: 5U09),³⁴ since both compounds share a trifluoromethylpyridine moiety on their “right arm”.

A.
Figure 8: A) Docking of antagonist 28 into the binding site of the crystal structure of the CB₁ receptor (PDB: 5TGZ) co-crystallized with 29 (not shown). Compound 28 is represented by black sticks, and residues within 5 Å of 28 are visualized as green sticks. The protein is represented by green ribbons, and relevant binding site confinements are indicated by white-grey (hydrophobic), red (electronegative), and blue (electropositive) layers. Ligand and residues atoms color code: yellow = sulfur, red = oxygen, blue = nitrogen, cyan = fluorine, white = hydrogen. B) 2-D interaction map of 28 docking into the CB₁ receptor co-crystallized with 29 (PDB: 5TGZ), demonstrating π-π stacking between imidazole core of 28 and Phe102N-term, 2,4-dichlorophenyl ring and Phe1702, pyridine and His1782. C) Docking of 14f and 28 into the binding site of the crystal structure of
the CB1 receptor co-crystalized with 29 (PDB: 5TGZ) showing the overlay of numbered consecutively hydration sites of 14f (colored spheres; for color code, see below) calculated by WaterMap. Hydration sites shown as red and orange spheres represent “unstable” water molecules. White spheres symbolize “stable” water molecules, which should not be displaced by 14f or 28. For the key hydration sites (41, 69, 72, 81, 88) surrounding the –F atom of 14f, calculated ΔG values (in kcal/mol) with respect to bulk solvent are shown.

Using the crystal structure of the hCB1-29 complex, we performed WaterMap calculations to try and understand the differences in residence times observed for the ligands studied, with the hypothesis that unfavorable hydration might provide an explanation. We focused on the pyridine ring substituents on the “right arm”, and ligands 14f and 28 in particular, because of their similar binding affinities but differing residence times. The smaller of the two ligands (14f, -F substitution, relatively short RT) was docked into the hCB1 receptor, and a WaterMap was calculated for the complex. Around the –F substituent we found unstable water molecules (41, 69, 72, 81 and 88 in Figure 8C); these water molecules are coined unhappy waters. By contrast, ligand 28 was able to displace these water molecules with its larger -CF3 substituent, a process which might raise the energy of the transition state for dissociation. We postulate that this destabilization of the transition state may contribute to the prolonged residence time observed with this compound.

Conclusions

We have demonstrated that, in addition to affinity, knowledge of binding kinetics is useful for selecting and developing new hCB1 receptor antagonists in the early phases of drug discovery. In the specific case of the hCB1 receptor, a long residence time compound may be beneficial for a peripherally selective antagonist. We explored SAR and SKR parameters in a series of 1,2-diarylimidazol-4-carboxamide derivatives by examining the influence of substitutions at both “arms” of the molecules.
By introducing more polar linear sulfonyl side chains on the “left arm”, affinity could be modulated, however the KRI values indicative for the compounds’ kinetic properties were less than or similar to CP55940. Substitution of the “right arm” maintained or increased affinity, and with the introduction of an aromatic ring system KRI values >1 were obtained. With a residence time of 260 min, which is substantially longer than CP55940 (114 min.) or rimonabant (14 min.), 4-(2-(2,4-dichlorophenyl)-5-methyl-4-((5-(trifluoromethyl)pyridin-2-yl)carbamoyl)-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (28) stood out from the ligands studied. This slowly dissociating hCB1 receptor antagonist also showed insurmountability in a functional GTPγS binding assay. Using the recently resolved hCB1 crystal structures we analyzed the putative interactions of 28 with the receptor, from which we speculate that displacement of ‘unhappy’ water molecules may provide a plausible explanation for its slow dissociation. Therefore, compound 28, or derivatives with similar characteristics, may be a useful tool to test whether prolonged blockade of the (peripheral) hCB1 receptor has a beneficial effect on CB1 receptor related disorders, such as obesity.

Experimental section

Chemistry. All solvents and reagents were purchased from commercial sources and were of analytical grade. Demineralized water is simply referred to as water or H2O, as was used in all cases unless stated otherwise (i.e., brine). Thin-layer chromatography (TLC) was routinely consulted to monitor the progress of reactions, using aluminum-coated Merck silica gel F254 plates. Purification was performed on a semi-preparative high performance liquid chromatography (HPLC) with a mass triggered fraction collector, Shimadzu QP 8000 single quadrupole mass spectrometer equipped with 19 x 100 mm C8 column. The mobile phase used was, if nothing else is stated, acetonitrile and buffer (aqueous NH4OAc (0.1 M) : acetonitrile 95 : 5). For isolation of isomers, a Kromasil CN E9344 (250 x 20 mm i.d.) column was used. A mixture of heptane/ethyl acetate/diethylamine 95 : 5 : 0.1 was used as mobile phase (1 mL/min). Fraction collection was guided using a UV-detector (330 nm). Analytical
purity of the final products was determined by Waters Acquity 1-class ultra-performance liquid chromatography (UPLC) consisting of a binary solvent system, ultra-violet (UV) photo-diode array (PDA) detector, column temperature control manager and sample manager modules, coupled with in-line and mass spectrometry detection. The sample was injected onto, and separated by, a Waters Acquity BEH (C18) 1.7 mm (150x3 mm) UPLC column maintained at 40°C and eluted with 0.1% ammonium hydroxide in water (A) and acetonitrile (B) at a flow rate of 1 mL/min, using a linear gradient. Initial conditions started at 3% B, which was increased to 97% over 1.3 min, maintained for 0.2 min before returning to initial conditions over 0.2 min prior to the next injection. Eluent containing UPLC-separated analytes then flowed via the UV PDA detector scanning between 220-320 nm wavelengths at a resolution of 1.2 nm sampling at 40 points/s, into a Waters SQD single quadrupole mass spectrometer (MS) fitted with an electrospray source. All MS analyses were acquired for a total run time of 2 min, with mass scanning from 100-1000 u in both positive and negative ion modes alternately, using electrospray ionization (ESI). Typical MS settings included capillary voltage - 1kV, cone voltage - 25V, source temperature - 150°C, and desolvation temperature - 350°C. The data were acquired via a PC running MassLynx v4.1 in open access mode and processed and reported via OpenLynx software application. For each sample the purity is determined by integration of the UV absorption chromatogram. All final compounds show a single peak and are at least 95% pure.

\(^1\)H NMR measurements were performed on either a Varian Mercury 300 or a Varian Inova 500, operating at \(^1\)H frequencies of 300 and 500 MHz respectively at ambient temperature. Chemical shifts are reported in parts per million (ppm), are designated by δ, and are downfield to the internal standard tetramethylsilane (TMS) in CDCl\(_3\). Coupling constants are reported in Hz and are designated as J. High-resolution mass spectra were recorded on either a Micromass ZQ single quadrupole or a Micromass LCZ single quadrupole mass spectrometer both equipped with a pneumatically assisted electrospray interface (LC-MS). Melting points were determined on a Reichert melting point microscope and are uncorrected.
\textit{N-\{(Benzyloxy)phenyl\}-2,4-dichlorobenzamidine (2).} Compound 1 (5.0 g, 21.2 mmol) was added dropwise to a solution of ethyl magnesium bromide (44.5 mL, 1 M in THF, 44.5 mmol) in dry THF (25 mL) under a nitrogen atmosphere. After stirring for 20 minutes a solution of 2,4-dichlorobenzonitrile (3.65 g, 21.2 mmol) in THF (25 mL) was added. The reaction mixture was stirred for 20 hours at r.t.

Water (50 mL) was carefully added. Extraction with EtOAc (2 x 100 mL), drying (Na$_2$SO$_4$), filtration and evaporation to dryness afforded the crude title compound (7.7 g, 98%).

\textit{Ethyl 1-\{(Benzyloxy)phenyl\}-2-\{(2,4-dichlorophenyl\)-5-methyl-1H-imidazole-4-carboxylate (3).} To a solution of compound 2 (6.88 g, 18.5 mmol) in THF (50 mL) was added potassium carbonate (2.56 g, 18.5 mmol) and the suspension was stirred for 10 minutes. Ethyl-3-bromo-2-oxobutanoate (4.65 g, 22.2 mmol) was added dropwise over 1 hour, and the mixture was stirred for 66 hours at r.t.. The solution was filtered and evaporated to dryness. The residue was dissolved in AcOH and refluxed for 1 hour. The mixture was cooled to r.t., water (100 mL) added and the product extracted with EtOAc (2 x 200 mL). The combined organic phases were washed with saturated aqueous sodium hydrogen carbonate, dried (Na$_2$SO$_4$), filtered, and concentrated \textit{in vacuo}. Flash chromatography (silica, 30-40\% EtOAc in hexane) afforded the title compound (5.75 g, 65\%) as a pale yellow solid. $^1$H NMR (CDCl$_3$): $\delta$ 7.50-7.20 (m, 8H), 7.10-6.90 (m, 4H), 5.10 (s, 2H), 4.50 (q, 2H), 2.5 (s, 3H), 1.5 (t, 3H).

\textit{1-\{(Benzyloxy)phenyl\}-2-\{(2,4-dichlorophenyl\)-5-methyl-1H-imidazole-4-carboxylic acid (4).} To a suspension of compound 3 (3.62 g, 7.5 mmol) in MeOH (60 mL) was added potassium hydroxide (4.05 g, 72 mmol) in water (20 mL), and the reaction mixture heated to reflux. After 2 h the mixture was cooled to r.t., acidified to pH~2 with HCl (1 M) and extracted with ethyl acetate (2 x 200 mL). The combined organic phases were dried (Na$_2$SO$_4$), filtered and concentrated \textit{in vacuo} to give the crude title compound (3.38 g, 99\%).

\textit{Ethyl 2-\{(2,4-dichlorophenyl\)-1-(4-hydroxyphenyl\)-5-methyl-1H-imidazole-4-carboxylate (5).} compound 3 (4.82 g, 10 mmol) was dissolved in HBr (33\% in AcOH, 80 mL) and stirred overnight at r.t. with exclusion of light. The solvents were evaporated and the residue co-evaporated with EtOH. The
residue was dissolved in EtOH, HCl (4 M in dioxane, 5 mL) and MgSO₄ were added, and the resulting mixture heated under reflux for 2.5 h. The reaction mixture was cooled to r.t., filtered, and concentrated in vacuo. The residue was dissolved in EtOAc and washed with water basified with triethylamine and then brine. The organic layer was dried over Na₂SO₄ and concentrated in vacuo to give the crude title compound (4.74 g) as a brown, viscous oil of sufficient purity for the next step.

**Ethyl 2-(2,4-dichlorophenyl)-5-methyl-1-(4-(3,3,3-trifluoropropoxy)phenyl)-1H-imidazole-4-carboxylate (6a).** A solution of compound 5 (978 mg, 2.5 mmol), 3,3,3-trifluoro-1-propanol (428 mg, 3.75 mmol) and triphenylphosphine (984 mg, 3.75 mmol) in anhydrous THF (12 mL) were treated with DEAD (40% in toluene, 1.72 mL, 3.75 mmol). The resulting mixture was stirred at r.t. for 30 h, then heated to 50 °C overnight. After cooling to r.t., additional 3,3,3-trifluoro-1-propanol (428 mg, 3.75 mmol) and triphenylphosphine (984 mg, 3.75 mmol) were added, followed by di-tert-butylazodicarboxylate (863 mg, 3.75 mmol), and the resulting mixture stirred at r.t. overnight. Again, additional 3,3,3-trifluoro-1-propanol (428 mg, 3.75 mmol) and triphenylphosphine (984 mg, 3.75 mmol) were added, followed by di-tert-butyl azodicarboxylate (863 mg, 3.75 mmol), and the resulting mixture stirred at r.t. overnight. The mixture was concentrated in vacuo and the residue purified by column chromatography (silica gel, 10-50% EtOAc in hexanes) to yield the title compound (880 mg, 68%) as a yellowish foam of sufficient purity for the next transformation. ¹H NMR (500 MHz, CDCl₃) δ 7.22-7.16 (m, 3H), 7.01 (d, J = 8.7 Hz, 2H), 6.83 (d, J = 8.7 Hz, 2H), 4.40 (q, J = 7.1 Hz, 2H), 4.22-4.10 (m, 2H), 2.66-2.54 (m, 2H), 2.40 (s, 3H), 1.40 (t, J = 7.1 Hz, 3H).

**Ethyl 2-(2,4-dichlorophenyl)-1-(4-(3-fluoropropoxy)phenyl)-5-methyl-1H-imidazole-4-carboxylate (6b).** A solution of compound 5 (978 mg, 2.5 mmol), 3-fluoropropan-1-ol (293 mg, 3.75 mmol) and triphenylphosphine (984 mg, 3.75 mmol) in anhydrous THF (9 mL) were treated with DEAD (40% solution in toluene, 1.72 mL, 3.75 mmol). The resulting mixture was stirred at r.t. overnight. The residue was purified by column chromatography (silica gel, 20-40% EtOAc in hexanes). The product containing fractions were combined and concentrated in vacuo. The residue was dissolved in CH₂Cl₂,
then an equal amount of hexane was added. The resulting solid was filtered off, and the filtrate concentrated in vacuo to yield the title compound (1.07 g, 85%) as a colorless foam of ca. 90% purity which was used in the next transformation without further purification. $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 7.35-7.20 (m, 3H), 7.03 (d, $J = 8.7$ Hz, 2H), 6.87 (d, $J = 8.7$ Hz, 2H), 4.73-4.60 (m, 2H), 4.44 (q, $J = 7.1$ Hz, 2H), 4.11-4.07 (m, 2H), 2.44 (s, 3H), 2.24-2.13 (m, 2H), 1.44 (t, $J = 7.1$ Hz, 3H).

2-(2,4-Dichlorophenyl)-5-methyl-1-(4-(3,3,3-trifluoropropoxy)phenyl)-1H-imidazole-4-carboxylic acid (7a). A stirred solution of compound 6a (880 mg, 1.72 mmol), in a mixture of THF (15 mL) and EtOH (15 mL), was treated with KOH (1.07 g, 19 mmol) dissolved in water (10 mL) and the resulting mixture stirred at 50 °C. After 3 h 30 min the reaction mixture was cooled to r.t. then concentrated in vacuo. The residue was partitioned between CH$_2$Cl$_2$ and HCl (1 M) and, after phase separation, the aqueous layer was extracted two more times with CH$_2$Cl$_2$. The combined organic extracts were dried over MgSO$_4$ and concentrated in vacuo to give the title compound (714 mg, 90%) as a yellowish foam. $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 7.32-7.18 (m, 3H), 7.00 (d, $J = 8.7$ Hz, 2H), 6.85 (d, $J = 8.7$ Hz, 2H), 4.18-4.14 (m, 2H), 2.66-2.55 (m, 2H), 2.42 (s, 3H).

2-(2,4-Dichlorophenyl)-1-(4-(3-fluoropropoxy)phenyl)-5-methyl-1H-imidazole-4-carboxylic acid (7b). A solution of compound 6b (1.07 g, 2.13 mmol, ca. 90% pure), in a mixture of THF (20 mL) and EtOH (20 mL), was treated with KOH (1.40 g, 25 mmol) dissolved in water (10 mL) and the resulting mixture stirred at 50 °C. After 3 h 30 min the reaction mixture was cooled to r.t. then concentrated in vacuo. The residue was partitioned between CH$_2$Cl$_2$ and HCl (1 M) and, after phase separation, the aqueous layer extracted with CH$_2$Cl$_2$ and twice with EtOAc. The combined organic extracts were dried over MgSO$_4$ and concentrated in vacuo to give the title compound (856 mg, 95%) as a yellowish foam which was sufficiently pure for the next step. $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 7.35-7.22 (m, 3H), 7.04 (d, $J = 8.7$ Hz, 2H), 6.88 (d, $J = 8.7$ Hz, 2H), 4.72-4.60 (m, 2H), 4.12-4.09 (m, 2H), 2.46 (s, 3H), 2.25-2.14 (m, 2H).
2-(2,4-Dichlorophenyl)-5-methyl-N-(piperidin-1-yl)-1-(4-(3,3,3-trifluoropropoxy)phenyl)-1H-imidazole-4-carboxamide (8a). A solution of compound 7a (643 mg, 1.4 mmol) in CH₂Cl₂ (10 mL) was treated with oxalyl chloride (200 µL, 2.36 mmol), followed by 10 µL DMF. The resulting mixture was stirred for 90 min at r.t., then concentrated in vacuo. The residue was dried under vacuum as a yellowish foam which was used without further purification. Subsequently, to a mixture of piperidin-1-amine hydrochloride (0.3 mmol) and pyridine (100 µL) in CH₂Cl₂ (1 mL) was added a portion of crude intermediate (2-(2,4-dichlorophenyl)-5-methyl-1-(4-(3,3,3-trifluoropropoxy)phenyl)-1H-imidazole-4-carbonyl chloride (96 mg, 0.2 mmol)) in CH₂Cl₂ (1 mL) and the resulting mixture stirred at r.t. for 2 h 30 min. The reaction mixture was washed with saturated aqueous NaHCO₃ (2 mL) and, after phase separation, filtered through a phase separator. The solvents were evaporated and the residue purified by preparative HPLC eluting on a reverse-phase column (5-100% acetonitrile in aqueous NH₄OAc (0.1 M)) to give the title compound (45 mg, 41%) as a colorless solid. ¹H NMR (500 MHz, CDCl₃) δ 7.90 (s, 1H), 7.35 (d, J = 1.9 Hz, 3H), 7.29 (d, J = 8.3 Hz, 1H), 7.23 (dd, J = 1.9, 8.3 Hz, 1H), 7.03 (d, J = 8.9 Hz, 2H), 6.87 (d, J = 8.9 Hz, 2H), 4.19 (t, J = 6.6 Hz, 2H), 2.94-2.81 (m, 4H), 2.69-2.60 (m, 2H), 2.47 (s, 3H), 1.82-1.73 (m, 4H), 1.49-1.41 (m, 2H); HRMS Calcd for [C₂₅H₂₅Cl₂F₃N₄O₂+H]: 541.1385. Found: 541.1366. HPLC: 100%.

2-(2,4-Dichlorophenyl)-1-(4-(3-fluoropropoxy)phenyl)-5-methyl-N-(piperidin-1-yl)-1H-imidazole-4-carboxamide (8b). A solution of compound 7b (732 mg, 1.55 mmol) in CH₂Cl₂ (20 mL) was treated with oxalyl chloride (200 µL, 2.36 mmol), followed by DMF (10 µL). The resulting mixture was stirred for 90 min at r.t., then concentrated in vacuo. The residue was dried under vacuum as a yellowish foam which was used without further purification. Subsequently, to a mixture of piperidin-1-amine hydrochloride (0.39 mmol) and pyridine (100 µL) in CH₂Cl₂ (2 mL) was added a portion of crude 2-(2,4-dichlorophenyl)-1-(4-(3-fluoropropoxy)phenyl)-5-methyl-1H-imidazole-4-carbonyl chloride (115 mg, 0.26 mmol) in CH₂Cl₂ (2 mL) and the resulting mixture was stirred at r.t. for 2 h. The reaction mixture was washed with saturated aqueous NaHCO₃ (2 mL) and, after phase separation, filtered through a phase separator. The solvents were evaporated and the residue purified by preparative
HPLC eluting on a reverse-phase column (5-100% CH$_3$CN in aqueous NH$_3$OAc (0.1 M)) to give the title compound (74 mg, 56%) as a colorless solid. $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 7.90 (s, 1H), 7.35 (d, $J = 2.0$ Hz, 1H), 7.28 (d, $J = 8.2$ Hz, 1H), 7.23 (dd, $J = 2.0$, 8.2 Hz, 1H), 7.01 (d, $J = 8.9$ Hz, 2H), 6.86 (d, $J = 8.9$ Hz, 2H), 4.66 (dt, $J = 5.7$, 4.7 Hz, 2H), 4.09 (t, $J = 6.1$ Hz, 2H), 2.95-2.82 (m, 4H), 2.47 (s, 3H), 2.25-2.13 (m, 2H), 1.81-1.73 (m, 4H), 1.49-1.40 (m, 2H); HRMS Calcd for [C$_{25}$H$_{27}$Cl$_2$F$_4$N$_4$O$_2$]+H: 505.1573. Found: 505.1572. HPLC: 100%.

1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-5-methyl-N-(piperidin-1-yl)-1H-imidazole-4-carboxamide (9). To a solution of compound 4 (3.38 g, 7.5 mmol) in CH$_2$Cl$_2$ (60 mL) were added 3 drops of DMF, followed by oxalyl chloride (1.3 mL, 14.9 mmol). The mixture was refluxed for 2 hours, then cooled to r.t. and evaporated to dryness. The residue was dissolved in CH$_2$Cl$_2$ (50 mL) and cooled to 0 °C. Triethylamine (2.1 mL, 14.9 mmol) was added, followed by piperidin-1-amine (0.9 mL, 8.2 mmol), and the mixture stirred at r.t. for 2 hours. Water (300 mL) was added and the mixture extracted with CH$_2$Cl$_2$ (3 x 100 mL). The organic extracts were dried (Na$_2$SO$_4$), filtered, and concentrated in vacuo. Flash chromatography (silica, 66-100% EtOAc in hexane) afforded the title compound (2.94 g, 74%) as a white solid. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.71 (d, $J = 8.3$ Hz, 1H), 7.42-7.32 (m, 7H), 7.29 (dd, $J = 1.9$, 8.3 Hz, 1H), 7.24 (d, $J = 9.0$ Hz, 2H), 6.98 (d, $J = 9.0$ Hz, 2H), 5.04 (s, 2H), 4.05-3.52 (m, 4H), 2.54 (s, 3H), 2.29-2.16 (m, 4H), 1.78-1.57 (m, 2H); HRMS Calcd for [C$_{25}$H$_{28}$Cl$_2$N$_4$O$_2$]+H: 535.1667. Found: 535.1667. HPLC: 96.9%.

2-(2,4-Dichlorophenyl)-1-(4-hydroxyphenyl)-5-methyl-N-(piperidin-1-yl)-1H-imidazole-4-carboxamide (10). A solution of compound 9 (2.78 g, 5.2 mmol) in CH$_2$Cl$_2$ (80 mL) was cooled to 0 °C then treated dropwise with boron tribromide (1 M in CH$_2$Cl$_2$, 10.4 mL, 10.4 mmol). The reaction mixture was stirred at r.t. for 1 hour then treated with water (200 mL). The mixture was extracted with EtOAc (3 x 200 mL). The combined organic phases were dried (Na$_2$SO$_4$), filtered, and concentrated in vacuo. Flash chromatography (silica, 75-100% EtOAc in hexane) afforded the title compound (1.34 g, 58%) as a white solid. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.66 (br s, 1H), 7.94 (br s, 1H), 7.31 (d, $J = 1.9$ Hz, 1H),
4.23 (d, J = 8.3 Hz, 1H), 7.18 (dd, J = 1.9, 8.3 Hz, 1H), 6.92-6.85 (m, 4H), 2.90-2.67 (m, 4H), 2.43 (s, 3H), 1.69-1.56 (m, 4H), 1.43-1.30 (m, 2H).

7.23 (d, J = 8.3 Hz, 1H), 7.18 (dd, J = 1.9, 8.3 Hz, 1H), 6.92-6.85 (m, 4H), 2.90-2.67 (m, 4H), 2.43 (s, 3H), 1.69-1.56 (m, 4H), 1.43-1.30 (m, 2H).

2-(2,4-Dichlorophenyl)-5-methyl-N-(piperidin-1-yl)-1-(4-(4,4,4-trifluorobutoxy)-phenyl)-1H-imidazole-4-carboxamide (11a). A suspension of compound 10 (351 mg, 0.79 mmol) and K$_2$CO$_3$ (218 mg, 1.58 mmol) in acetone (50 mL) was treated dropwise with 1-iodo-4,4,4-trifluorobutane (376 mg, 1.58 mmol). The reaction mixture was refluxed overnight then cooled, filtered, and concentrated in vacuo. Flash chromatography (silica, hexane : EtOAc 1:2) afforded the title compound (200 mg, 46%) as a white solid. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.91 (br s, 1H), 7.32 (d, J = 1.9 Hz, 1H), 7.27 (d, J = 8.3 Hz, 1H), 7.21 (dd, J = 2.0, 8.3 Hz, 1H), 7.00 (d, J = 8.9 Hz, 2H), 6.83 (d, J = 8.9 Hz, 2H), 3.99 (t, J = 6.0 Hz, 2H), 3.13-2.67 (m, 4H), 2.45 (s, 3H), 2.38-2.23 (m, 2H), 2.10-2.00 (m, 2H), 1.84-1.71 (m, 4H), 1.50-1.38 (m, 2H); MS m/z 578 (M+Na); HRMS Calcd for [C$_{26}$H$_{27}$Cl$_2$F$_3$N$_4$O$_2$+H]: 555.1541. Found: 555.1504. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)phenyl propane-1-sulfonate (11b). A solution of compound 10 (320 mg, 0.72 mmol) in CH$_2$Cl$_2$ (10 mL) was cooled to 0 °C. Et$_3$N (100 µL, 0.72 mmol) was added followed by 1-propanesulfonyl chloride (81 µL, 0.72 mmol) and the reaction mixture was stirred at room temperature overnight. Water was added, the mixture extracted with CH$_2$Cl$_2$ (3 x 20 mL), dried (Na$_2$SO$_4$), filtered and concentrated. Flash chromatography (silica, hexane : EtOAc 1 : 2) afforded the title compound (220 mg, 56%) as a white solid. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.82 (br s, 1H), 7.29-7.15 (m, 5H), 7.10-7.03 (m, 2H), 3.23-3.14 (m, 2H), 2.90-2.70 (m, 4H), 2.42 (s, 3H), 2.01-1.88 (m, 2H), 1.75-1.65 (m, 4H), 1.41-1.31 (m, 2H), 1.06 (t, J = 7.5 Hz, 3H); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 160.8, 149.0, 142.3, 136.8, 135.0, 135.3, 133.8, 133.4, 130.6, 129.9, 129.1, 128.2, 127.4, 123.1, 57.2, 52.9, 25.4, 23.3, 17.5, 13.0, 10.9; HRMS Calcd for [C$_{25}$H$_{28}$Cl$_2$N$_4$O$_2$S+H]: 551.1287. Found: 551.1313. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)phenyl 3-fluoropropane-1-sulfonate (11c). A suspension of compound 10 (200 mg, 0.45 mmol) in dry CH$_2$Cl$_2$ (3
mL) was treated with Et₃N (45 mg, 0.45 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3-fluoropropane-1-sulfonyl chloride (72 mg, 0.45 mmol) in dry CH₂Cl₂ (0.5 mL) was added dropwise. After 1 h 40 min at -78 °C was added 3-fluoropropane-1-sulfonyl chloride (72 mg, 0.45 mmol) and after a total of 4 h 40 min was added Et₃N (55 mg, 0.54 mmol). The reaction was allowed to reach r.t. overnight. It was then cooled to 0 °C and Et₃N (55 mg, 0.54 mmol) was added, followed by 3-fluoropropane-1-sulfonyl chloride (72 mg, 0.45 mmol) after a total of 19 h. After 1 h the reaction mixture was washed with water and concentrated in vacuo. The product was purified by HPLC (30-100% CH₃CN in aqueous NH₄OAc (0.1 M) over 40 min) to yield the title compound as a white solid (160 mg, 63%). ¹H NMR (400 MHz, CDCl₃) δ 7.88 (br s, 1H), 7.39-7.17 (m, 5H), 7.11 (d, J = 8.8 Hz, 2H), 4.58 (dt, J = 5.5, 46.8 Hz, 2H), 3.53-3.33 (m, 2H), 2.92-2.71 (m, 4H), 2.45 (s, 3H), 2.40-2.23 (m, 2H), 1.83-1.62 (m, 4H), 1.46-1.33 (m, 2H). HRMS Calcd for [C₂₅H₂₇Cl₂FN₄O₄S+H]: 569.119. Found: 569.1192. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate methanesulfonic acid salt (11d). A solution of compound 10 (0.89 g, 2.00 mmol) in CH₂Cl₂ (20 mL) was cooled to 0 °C then treated with Et₃N (0.35 mL, 2.4 mmol), followed by 3,3,3-trifluoropropanesulfonfyl chloride (prepared by an analogous method to that described in WO00/010968 for the butyl homologue) (0.35 mL, 2.40 mmol). The reaction mixture was stirred at r.t. overnight. TLC showed remaining starting material and so another portion of Et₃N and 3,3,3-trifluoropropanesulfonfyl chloride was added and the reaction mixture stirred for additional 2 h. Water was added and the product was extracted with CH₂Cl₂, dried (Na₂SO₄), filtered, and concentrated in vacuo. Flash chromatography (33-100% EtOAc in hexane) followed by recrystallisation (hexane : EtOAc) afforded the title compound (700 mg, 59%) as a colorless solid. ¹H NMR (400 MHz, CDCl₃) δ 7.92 (s, 1H), 7.34-7.24 (m, 5H), 7.20-7.13 (m, 2H), 3.54-3.48 (m, 2H), 3.00-2.82 (m, 4H), 2.84-2.73 (m, 2H), 2.50 (s, 3 H), 1.83-1.72 (m, 4 H), 1.49-1.39 (m, 2H); HRMS Calcd for [C₂₆H₂₉Cl₂F₃N₄O₄S₂+H]: 605.1004. Found: 605.1012. HPLC: 100%.
4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)phenyl butane-1-sulfonate (11e). A solution of compound 10 (320 mg, 0.72 mmol) in CH$_2$Cl$_2$ (10 mL) was cooled to 0 °C. Et$_3$N (100 µL, 0.72 mmol) was added followed by 1-butanesulfonyl chloride (93 µL, 0.72 mmol) and the reaction mixture was stirred at r.t. overnight. Water was added and the mixture extracted with CH$_2$Cl$_2$ (3 x 20 mL), dried (Na$_2$SO$_4$), filtered, and concentrated in vacuo. Flash chromatography (silica, hexane : EtOAc 1:2) afforded the title compound (230 mg, 57%) as a white solid. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.82 (br s, 1H), 7.27-7.16 (m, 5H), 7.09-7.04 (m, 2H), 3.23-3.17 (m, 2H), 2.92-2.68 (m, 4H), 2.42 (s, 3H), 1.93-1.84 (m, 2H), 1.74-1.66 (m, 4H), 1.50-1.40 (m, 2H), 1.40-1.33 (m, 2H), 0.91 (t, $J$ = 7.4 Hz, 3H); MS m/z 588 (M+Na); HRMS Calcd for [C$_{26}$H$_{30}$Cl$_2$N$_4$O$_4$S+H]: 565.1443. Found: 565.1450. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)-phenyl 4,4,4-trifluorobutane-1-sulfonate (11f). A solution of compound 10 (0.49 g, 1.20 mmol) in CH$_2$Cl$_2$ (20 mL) was cooled to 0 °C and treated with Et$_3$N (0.67 mL, 4.8 mmol), followed by 4,4,4-trifluorobutane-1-sulfonyl chloride (prepared as described in WO00/010968) (0.38 g, 1.80 mmol). The reaction mixture was stirred at r.t. for 3 h. TLC showed remaining starting material so another portion of Et$_3$N and 4,4,4-trifluorobutane-1-sulfonyl chloride was added and the reaction mixture stirred overnight. Water was added, then the mixture was extracted with CH$_2$Cl$_2$. The organic extracts were dried (Na$_2$SO$_4$), filtered, and concentrated in vacuo. Flash chromatography (33-100% EtOAc in hexane) followed by recrystallisation (hexane : EtOAc) afforded the title compound (0.45 g, 61%) as a colorless solid. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.92 (br s, 1H), 7.34-7.22 (m, 5H), 7.15 (d, $J$ = 8.7 Hz, 2H), 3.38 (t, $J$ = 7.3 Hz, 2H), 3.12-2.74 (m, 4H), 2.49 (s, 3H), 2.43-2.32 (m, 2H), 2.32-2.22 (m, 2H), 1.82-1.74 (m, 4H), 1.50-1.40 (m, 2H); HRMS Calcd for [C$_{26}$H$_{30}$Cl$_2$F$_3$N$_4$O$_4$S+H]: 619.1160. Found: 619.1148. HPLC: 96.9%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)-phenyl 3-methylbutane-1-sulfonate (11g). A solution of compound 10 (50 mg, 0.11 mmol) in CH$_2$Cl$_2$ (3 mL) was
cooled to 0 °C then treated with Et$_3$N (20 µL, 0.13 mmol). The resulting mixture was cooled to -78 °C, then 3-methylbutane-1-sulfonyl chloride (23 mg, 0.13 mmol) carefully added. The reaction was stirred at -78 °C for 1.5 h. Water was added, then the mixture was extracted with CH$_2$Cl$_2$. The organic extracts were dried, filtered, and concentrated in vacuo to give a residue which was purified by HPLC to deliver the title compound (46 mg, 71%) as a solid. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.86 (s, 1H), 7.31-7.20 (m, 5H), 7.14-7.08 (m, 2H), 3.27-3.20 (m, 2H), 2.89-2.76 (m, 4H), 2.46 (s, 3H), 1.87-1.79 (m, 2H), 1.78-1.68 (m, 5H), 1.44-1.36 (m, 2H), 0.93 (d, J = 6.5 Hz, 6H); HRMS Calcd for [C$_{26}$H$_{27}$Cl$_2$F$_3$N$_4$O$_4$S+H]: 579.1600. Found: 579.1584. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(piperidin-1-ylcarbamoyl)-1H-imidazol-1-yl)phenyl 3,3-dimethylbutane-1-sulfonyl (11h). A solution of compound 10 (50 mg, 0.11 mmol) in CH$_2$Cl$_2$ (3 mL) was cooled to 0 °C and treated with Et$_3$N (20 µL, 0.13 mmol). The resulting mixture was cooled to -78 °C and 3,3-dimethylbutane-1-sulfonyl chloride (25 mg, 0.13 mmol) was carefully added. The reaction was stirred at -78 °C for 2 h. Water was added, then the mixture extracted with CH$_2$Cl$_2$. The organic extracts were dried, filtered, and concentrated in vacuo to give a residue which was purified by preparative HPLC to deliver the title compound (46 mg, 69%) as a solid. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.85 (s, 1H), 7.32-7.17 (m, 5H), 7.11-7.09 (d, J = 8.7 Hz, 2H), 3.26-3.15 (m, 2H), 2.92-2.74 (m, 4H), 2.46 (s, 3H), 1.87-1.78 (m, 2H), 1.77-1.68 (m, 5H), 1.46-1.34 (m, 2H), 0.92 (s, 9H); HRMS Calcd for [C$_{28}$H$_{34}$Cl$_2$N$_4$O$_5$S+H]: 593.1756. Found: 593.1755. HPLC: 100%.

racemic 1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-(3-hydroxypiperidin-1-yl)-5-methyl-1H-imidazole-4-carboxamide (12a). Compound 4 (752 mg, 1.66 mmol) and SOCl$_2$ (33.2 mmol) were mixed and the resulting mixture was refluxed for 1.5 h. Excess SOCl$_2$ was removed under reduced pressure and the residue was azeotroped with toluene. 3-Hydroxy-1-aminopiperidine (6.64 mmol) was mixed with CH$_2$Cl$_2$ (15 mL) and THF (2 mL) and Et$_3$N (13.28 mmol). The mixture was cooled to -20 °C under a nitrogen atmosphere. A THF (5 mL) mixture of the acid chloride from above was added dropwise during 20 minutes. The resulting mixture was allowed to slowly warm to r.t. and stirred
overnight. Aqueous NaOH (1 M, 5 mL) and EtOH (15 mL) were added and the mixture was heated to 40 °C for 15 minutes. The reaction mixture was then diluted to 50 mL with CH₂Cl₂ and washed with water (2 x 20 mL) and brine (20 mL). The organic layer was dried (MgSO₄), filtered, and concentrated in vacuo. The residue was purified by flash chromatography (8% EtOH in CH₂Cl₂) and then by reverse phase HPLC (Kromasil C8, 60% CH₃CN in aqueous NH₄OAc (0.1 M)). The product fraction was concentrated in vacuo and then dissolved in CH₂Cl₂ and washed with water several times and then brine. The organic layer was dried (MgSO₄), filtered and concentrated in vacuo to give the title compound (160 mg, 17% yield).

racemic 1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-(3-hydroxycyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (12b). A suspension of compound 4 (2.00 g, 4.41 mmol) in CH₂Cl₂ (50 mL) was treated with oxalyl chloride (2.80 g, 22.1 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 15 min after which the solvent was removed in vacuo. The acid chloride was suspended in CH₂Cl₂ (10 mL) and added dropwise to a mixture of 3-aminocyclohexanol (610 mg, 5.29 mmol), aqueous NaOH (1 M, 30 mL) and CH₂Cl₂ (30 mL). After stirring at r.t. for 2 h, adding more 3-aminocyclohexanol after 1 h 25 min (67 mg, 0.58 mmol) and 1 h 45 min (58 mg, 0.50 mmol), water and CH₂Cl₂ were added and the phases separated. The organic phase was washed with aqueous HCl (10%) and brine, then dried (MgSO₄), filtered, and concentrated in vacuo to yield the crude title compound (2.79 g). ¹H NMR (400 MHz, CDCl₃) δ 7.40-7.16 (m, 8H), 7.03-6.88 (m, 4H), 5.01 (s, 2H), 4.44-4.32 (m, 0.5H), 4.18-4.11 (m, 0.5 H), 4.06-3.94 (m, 0.5 H), 3.76-3.66 (m, 0.5 H), 2.46 (s, 3H), 2.03-1.10 (m, 8H); MS m/z 550 (M+H).

racemic 1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-((trans)-2-hydroxycyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (12c). A suspension of compound 4 (2.00 g, 4.41 mmol) in CH₂Cl₂ (100 mL)
was treated with oxalyl chloride (2.80 g, 22.1 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 20 min after which the solvents were evaporated under reduced pressure. The acid chloride was suspended in CH$_2$Cl$_2$ (10 mL) and added dropwise to a mixture of cis-2-aminocyclohexanol hydrochloride (816 mg, 5.38 mmol), aqueous NaOH (1 M, 30 mL) and CH$_2$Cl$_2$ (30 mL). After stirring at r.t. for 2 h, water/CH$_2$Cl$_2$ were added and the phases were separated. The organic phase was washed with aqueous HCl (0.1 M) and brine, dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the crude title compound (2.40 g, 99%). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.45 (d, $J = 7.8$ Hz, 1H), 7.41-7.16 (m, 8H), 6.98 (d, $J = 8.8$ Hz, 2H), 6.90 (d, $J = 8.8$ Hz, 2H), 5.01 (s, 2H), 4.16-4.08 (m, 1H), 4.03-3.96 (m, 1H), 2.89 (br s, 1H), 2.43 (s, 3H), 1.83-1.54 (m, 6H), 1.47-1.32 (m, 2H); MS m/z 550 (M+H).

racemic 1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-((cis)-2-hydroxycyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (12d). A suspension of compound 4 (2.00 g, 4.41 mmol) in CH$_2$Cl$_2$ (100 mL) was treated with oxalyl chloride (2.85 g, 22.5 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 20 min after which the solvents were evaporated under reduced pressure. The acid chloride was suspended in CH$_2$Cl$_2$ (10 mL) and added dropwise to a mixture of trans-2-aminocyclohexanol hydrochloride (802 mg, 5.29 mmol), aqueous NaOH (1 M, 30 mL) and CH$_2$Cl$_2$ (30 mL). After stirring at r.t. for 2 h, water/CH$_2$Cl$_2$ were added and the phases were separated. The organic phase was washed with aqueous HCl (10%) and brine, dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the crude title compound (2.69 g). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.94 (s, 1H), 7.37-7.25 (m, 6H), 7.23-7.17 (m, 2H), 6.97 (d, $J = 8.6$ Hz, 2H), 6.89 (d, $J = 8.6$ Hz, 2H), 5.23 (s, 1H), 4.98 (s, 2H), 3.80-3.62 (m, 1H), 3.59-3.42 (m, 1H), 2.42 (s, 3H), 2.14-1.93 (m, 2H), 1.75-1.59 (m, 2H), 1.39-1.14 (m, 4H); MS m/z 550 (M+H).

$^1$-{(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-(4-(trifluoromethoxy)phenyl)-1H-imidazole-4-carboxamide (12e). A suspension of compound 4 (1.00 g, 2.21 mmol) in CH$_2$Cl$_2$ (15 mL) was treated with oxalyl chloride (1.40 g, 11.0 mmol) at r.t., followed by one drop of DMF. The
mixture was stirred at r.t. for 15 min after which the solvents were evaporated under reduced pressure. A mixture of 4-trifluoromethoxy-phenylamine (469 mg, 2.65 mmol), Et$_3$N (313 mg, 3.09 mmol) and CH$_2$Cl$_2$ (5 mL) was added dropwise to the acid chloride suspended in CH$_2$Cl$_2$ (15 mL). The reaction mixture was stirred at r.t. for 2 h and 10 min. CH$_2$Cl$_2$ was added and the resulting mixture was washed with aqueous HCl (10%) and brine, dried (MgSO$_4$), filtered, and evaporated to yield the crude title compound (1.42 g). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.37 (br s, 1H), 7.76-7.74 (m, 2H), 7.39-7.16 (m, 10H), 7.05-6.93 (m, 4H), 5.03 (s, 2H), 2.50 (s, 3H); MS m/z 612 (M+H).

1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-(6-fluoropyridin-3-yl)-5-methyl-1H-imidazole-4-carboxamide (12f). A suspension of compound 4 (1.00 g, 2.21 mmol) in CH$_2$Cl$_2$ (15 mL) was treated with oxalyl chloride (1.40 g, 11.0 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 5 min after which the solvents were removed in vacuo. The acid chloride was suspended in CH$_2$Cl$_2$ (8 mL) then treated dropwise with a mixture of 6-fluoro-pyridin-3-ylamine (297 mg, 2.65 mmol), Et$_3$N (313 mg, 3.09 mmol) and CH$_2$Cl$_2$ (7 mL). Stirring was continued at r.t. for 75 min, after which CH$_2$Cl$_2$ was added and the resulting mixture washed with aqueous HCl (10%) and brine. The organic extracts were dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the crude title compound (1.19 g). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.24 (s, 1H), 8.39-8.33 (m, 2H), 7.39-6.89 (m, 3H), 5.02 (s, 2H), 2.49 (s, 3H); MS m/z 547 (M+H).

1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-5-methyl-N-(6-(trifluoromethyl)pyridin-3-yl)-1H-imidazole-4-carboxamide (12g). A suspension of compound 4 (1.00 g, 2.21 mmol) in CH$_2$Cl$_2$ (15 mL) was treated with oxalyl chloride (1.40 g, 11.03 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 5 min after which the solvents were removed in vacuo. The acid chloride was suspended in CH$_2$Cl$_2$ (8 mL) then treated dropwise with a solution of 6-trifluoromethyl-pyridin-3-ylamine (407 mg, 2.51 mmol) and Et$_3$N (360 mg, 3.56 mmol) in CH$_2$Cl$_2$ (7 mL). The reaction mixture was stirred at r.t. for 1.5 h then diluted with CH$_2$Cl$_2$ and washed with aqueous HCl (10% w/w) and brine. The organic extracts were dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the
crude title product (1.32 g). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.50 (s, 1H), 8.82 (d, $J = 2.0$ Hz, 1H), 8.55 (dd, $J = 2.0$, 8.6 Hz, 1H), 7.65 (d, $J = 8.6$ Hz, 1H), 7.40-7.21 (m, 7H), 7.06-6.89 (m, 5H), 5.03 (s, 2H), 2.50 (s, 3H); MS m/z 597 (M+H).

1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-5-methyl-N-(5-methylpyridin-2-yl)-1H-imidazole-4-carboxamide (12h). A suspension of compound 4 (3.00 g, 6.62 mmol) in CH$_2$Cl$_2$ (70 mL) was treated with oxalyl chloride (4.20 g, 33.1 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 5 min after which the solvents were evaporated under reduced pressure. A mixture of 5-methyl-pyridin-2-ylamine (816 mg, 7.54 mmol), Et$_3$N (890 mg, 8.80 mmol) and CH$_2$Cl$_2$ (20 mL) was added dropwise to the acid chloride suspended in CH$_2$Cl$_2$ (20 mL). The reaction mixture was stirred at r.t. for 30 min. CH$_2$Cl$_2$ was added and the resulting mixture was washed with aqueous HCl (10%) and brine, dried (MgSO$_4$), filtered and evaporated. The residue was purified by flash chromatography (20-30% EtOAc in heptane) to yield the title compound as a white solid (980 mg, 27%). $^1$H NMR (400 MHz, Pyridine-$d_5$) $\delta$ 10.11 (s, 1H), 8.52 (s, 1H), 8.04 (s, 1H), 7.40-6.88 (m, 3H), 4.80 (s, 2H), 2.39 (s, 3H), 1.88 (s, 3H); MS m/z 543 (M+H).

racemic 2-(2,4-Dichlorophenyl)-1-(4-hydroxyphenyl)-N-(3-hydroxypiperidin-1-yl)-5-methyl-1H-imidazole-4-carboxamide (13a). A mixture of racemic 1-(4-(benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-(3-hydroxypiperidin-1-yl)-5-methyl-1H-imidazole-4-carboxamide (160 mg, 0.29 mmol) and dimethyl sulfide (1.45 mmol) in CH$_2$Cl$_2$ under nitrogen atmosphere were treated dropwise with BF$_3$·OEt$_2$ (1.45 mmol). The resulting mixture was stirred for 4 days at ambient temperature while continuously adding small volumes of CH$_2$Cl$_2$ and 1,4-dioxane. EtOH was added and the mixture was stirred for 30 mins and then concentrated in vacuo. The residue was dissolved in EtOAc (50 mL) and washed with water (2 x 20 mL) and brine (20 mL). The organic layer was dried (Na$_2$SO$_4$), filtered and concentrated in vacuo to give the title compound (127 mg, 95%) as a white solid. MS m/z 461 (M+H).
racemic 2-(2,4-Dichlorophenyl)-N-(3-hydroxycyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (13b). A suspension of crude 1-(4-(benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-(3-hydroxycyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (2.79 g, 5.07 mmol) in CH$_2$Cl$_2$ (50 mL) and dimethyl sulfide (3.15 g, 50.7 mmol) was treated with boron trifluoride diethyl etherate (5.77 g, 50.7 mmol). The reaction mixture was stirred at r.t. for 36 h (dark), adding more dimethyl sulfide (3.15 g, 50.7 mmol) and boron trifluoride (5.77 g, 50.7 mmol) after 16 h. The solvent was evaporated and the residue dissolved in EtOAc/water. The phases were separated and the organic phase dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the crude title compound (2.54 g). MS m/z 460 (M+H).

racemic 2-(2,4-Dichlorophenyl)-N-((trans)-2-hydroxycyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (13c). Crude racemic 1-(4-(benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-((trans)-2-hydroxycyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (2.68 g, 4.87 mmol) was suspended in HBr (33% in AcOH, 60 mL). The mixture was stirred at r.t., in the dark, for 1 h 20 min. EtOH was added and the mixture concentrated in vacuo. The residue was dissolved in MeOH and neutralized with NaHCO$_3$ (1 M, aq). One spoon of K$_2$CO$_3$ was added and the mixture was stirred at r.t. for 1 h. The solvent was evaporated and the resulting mixture extracted with toluene followed by THF. The combined organic phases were washed with aqueous HCl (10%) and brine, dried (MgSO$_4$), filtered and evaporated. The product was purified by HPLC (30-100% CH$_3$CN in aqueous NH$_4$OAc (0.1 M) over 40 min) to yield the title compound as a white solid (829 mg, yield over 2 steps 41%). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.36-7.18 (m, 4H), 6.86-6.66 (m, 4H), 5.28 (s, 1H), 4.60 (br s, 1H), 3.85-3.74 (m, 1H), 3.52-3.41 (m, 1H), 2.37 (s, 3H), 2.13-1.97 (m, 2H), 1.78-1.67 (m, 2H), 1.44-1.15 (m, 4H); MS m/z 460 (M+H).

racemic 2-(2,4-Dichlorophenyl)-N-((cis)-2-hydroxycyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (13d). A suspension of racemic 1-(4-(benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-N-((cis)-2-hydroxycyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (2.38 g, 4.33 mmol) in HBr (33% in AcOH, 50 mL). The reaction mixture was stirred at r.t., in the dark, for 1 h.
EtOH was added and the solvents were evaporated under reduced pressure. The residue was dissolved in MeOH and neutralized with aqueous NaHCO$_3$ (1 M). The solvent was evaporated and the mixture dissolved in water/CH$_2$Cl$_2$. The phases were separated and the organic phase was washed with brine, dried (MgSO$_4$), filtered and evaporated. The residue was dissolved in MeOH and one spoon of K$_2$CO$_3$ was added, and the resulting mixture was stirred at r.t. for 1 h before the solvent was evaporated. The residue was resuspended in CH$_2$Cl$_2$ and washed with aqueous HCl (10%), and the solvents were evaporated. The residue was dissolved in THF, dried (MgSO$_4$), filtered and evaporated to yield the crude title compound (2.10 g). $^1$H NMR (400 MHz, THF-$d_8$) $\delta$ 8.65 (d, $J = 7.3$ Hz, 1H), 7.66 (d, $J = 8.3$ Hz, 1H), 7.55 (d, $J = 1.7$ Hz, 1H), 7.25 (dd, $J = 1.7$, 8.3, 1H), 7.18 (d, $J = 8.6$ Hz, 2H), 6.79 (d, $J = 8.6$ Hz, 2H), 3.99-3.91 (m, 1H), 3.91-3.82 (m, 1H), 3.64-3.55 (m, 1H), 2.47 (s, 3H), 1.86-1.63 (m, 5H), 1.58-1.44 (m, 1H), 1.38-1.28 (m, 2H); MS m/z 460 (M+H).

2-(2,4-Dichlorophenyl)-N-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (13e). Crude 12e (1.35 g, 2.20 mmol) was suspended in HBr (33% in AcOH, 25 mL). The reaction mixture was stirred at r.t., in the dark, for 1 h. EtOH was added and the solvents were evaporated at reduced pressure. The residue was dissolved in MeOH and neutralized with aqueous NaHCO$_3$ (1 M). The solvent was evaporated and the mixture dissolved in water/CH$_2$Cl$_2$. The phases were separated and the organic phase was washed with brine, dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the crude title compound (1.10 g). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.73-7.71 (m, 2H), 7.39-7.16 (m, 5H), 6.94-6.76 (m, 4H), 2.45 (s, 3H); MS m/z 522 (M+H).

2-(2,4-Dichlorophenyl)-N-(6-fluoropyridin-3-yl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (13f). Compound 12f (1.15 g, 2.10 mmol) was suspended in HBr (33% in AcOH, 25 mL). The reaction mixture was stirred at r.t., in the dark, for 2 h 30 min. EtOH was added and the solvents were evaporated under reduced pressure. The residue was dissolved in MeOH and neutralized with aqueous NaHCO$_3$ (1 M). The solvent was evaporated and the mixture dissolved in water/CH$_2$Cl$_2$. The phases were separated and the organic phase was washed with brine, dried (MgSO$_4$), filtered, and
concentrated in vacuo to give a residue which was purified by HPLC (30-60% CH₃CN in NH₂OAc (0.1 M) over 40 min, then 100% CH₃CN) to yield the title compound as a white solid (519 mg, yield over 2 steps 53%). ^1H NMR (400 MHz, CDCl₃) δ 9.14 (s, 1H), 8.37-8.30 (m, 2H), 7.34 (s, 1H), 7.25-7.20 (m, 2H), 6.96-6.90 (m, 3H), 6.79-6.77 (m, 2H), 2.48 (s, 3H); MS m/z 457 (M+H).

2-(2,4-Dichlorophenyl)-1-(4-hydroxyphenyl)-5-methyl-N-(6-(trifluoromethyl)pyridin-3-yl)-1H-imidazole-4-carboxamide (13g). A suspension of crude 12g (1.17 g, 1.96 mmol) in CH₂Cl₂ (6 mL) and dimethyl sulfide (1.22 g, 19.6 mmol) was treated with boron trifluoride (2.78 g, 19.6 mmol). The reaction mixture was stirred at r.t. for 31 h (dark). Water and CH₂Cl₂ were added and the phases separated. The organic phase was washed with water (x4) and concentrated in vacuo. The residue was dissolved in MeOH and stirred at r.t. for 20 h before water was added and the MeOH removed in vacuo. The resulting mixture was extracted with Et₂O (x 2) and the combined organic phases were washed with brine, dried (MgSO₄), filtered, and concentrated in vacuo to yield the crude title compound (776 mg). ^1H NMR (400 MHz, CDCl₃) δ 9.29 (s, 1H), 8.75 (d, J = 2.1 Hz, 1H), 8.54 (dd, J = 2.1, 8.6 Hz, 1H), 7.64 (d, J = 8.6 Hz, 1H), 7.33 (d, J = 1.7 Hz, 1H), 7.27-7.19 (m, 2H), 6.96 (d, J = 8.7 Hz, 2H), 6.78 (d, J = 8.7 Hz, 1H), 5.51 (br s, 1H), 2.48 (s, 3H); MS m/z 507 (M+H).

2-(2,4-Dichlorophenyl)-1-(4-hydroxyphenyl)-5-methyl-N-(5-methylpyridin-2-yl)-1H-imidazole-4-carboxamide (13h). Compound 12h (958 mg, 1.76 mmol) was suspended in HBr (33% in AcOH, 25 mL). The reaction mixture was stirred at r.t., in the dark, for 1 h. EtOH was added and the solvents were evaporated under reduced pressure. The residue was dissolved in MeOH and neutralized with aqueous NaHCO₃ (1 M). The solvent was evaporated and the mixture dissolved in water/CH₂Cl₂. The phases were separated and the organic phase was washed with brine, dried (MgSO₄), filtered and evaporated to yield the title compound (772 mg, 97%). ^1H NMR (400 MHz, Pyridine-d₅) δ 10.12 (s, 1H), 8.52 (s, 1H), 8.03 (s, 1H), 7.40-6.89 (m, 8H), 2.42 (s, 3H), 1.88 (s, 3H); MS m/z 453 (M+H).

racemic 4-(2-(2,4-Dichlorophenyl)-4-(3-hydroxypiperidin-1-ylcarbamoyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14a). A solution of 2-(2,4-dichlorophenyl)-1-(4-
hydroxyphenyl)-N-(3-hydroxypiperidin-1-yl)-5-methyl-1H-imidazole-4-carboxamide (118 mg, 0.25 mmol) in CH₂Cl₂ (1 mL), and THF (1 mL) was treated with Et₃N (0.25 mmol) under a nitrogen atmosphere. The solution was cooled to -78 °C and a solution of 3,3,3-trifluoropropane-1-sulfonyl chloride in CH₂Cl₂ (1 mL) was added slowly while monitoring the progress with LC-MS. The reaction mixture was quenched by addition of EtOH. The reaction mixture was concentrated in vacuo and the residue was purified by reverse phase HPLC (Kromasil C8, 5-100% CH₃CN in aqueous NH₄OAc (0.1 M)) and by flash chromatography (8% EtOH in CH₂Cl₂). The product was freeze-dried to give the title compound (40 mg, 25%) as a white powder.

1H NMR (CD₃OD) δ 7.52-7.44 (m, 2H), 7.44-7.34 (m, 5H), 3.91-3.82 (m, 1H), 3.77-3.69 (m, 2H), 3.11 (dd, J = 3.0, 10.1 Hz, 1H), 2.95-2.80 (m, 3H), 2.74-2.58 (m, 2H), 2.46 (s, 3H), 1.95-1.75 (m, 2H), 1.73-1.62 (m, 1H), 1.44-1.31 (m, 1H); MS m/z 621 (M+H); HPLC: 100%.

racemic 4-(2-(2,4-Dichlorophenyl)-4-((trans)-3-hydroxycyclohexylcarbamoyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14b). A suspension of crude 2-(2,4-dichlorophenyl)-N-(3-hydroxycyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (2.53 mg, 5.49 mmol) in dry CH₂Cl₂ (20 mL) was treated with Et₃N (667 mg, 6.59 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (1.30 mg, 6.59 mmol) was added dropwise. After stirring at -78 °C for 2 h 45 min, the reaction mixture was allowed to reach r.t., upon which it was washed with water and evaporated. The stereoisomers were separated by HPLC (30-100% CH₃CN in aqueous NH₄OAc (0.1 M)) to yield the trans-hydroxycyclohexyl product (205 mg, 7.5% over 3 steps) as a white solid. 1H NMR (400 MHz, CDCl₃) δ 7.34-7.23 (m, 5H), 7.20-7.10 (m, 3H), 4.45-4.33 (m, 1H), 4.17-4.10 (m, 1H), 3.55-3.47 (m, 2H), 2.87-2.73 (m, 2H), 2.49 (s, 3H), 2.05-1.51 (m, 8H), 1.48-1.36 (m, 1H); HRMS Calcd for [C₂₆H₂₅Cl₂F₃N₃O₅S+H]: 620.1001. Found: 620.1028. HPLC: 100%.

(-) 4-(2-(2,4-Dichlorophenyl)-4-((trans)-2-hydroxycyclohexylcarbamoyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14c). A suspension of racemic 2-(2,4-dichlorophenyl)-N-((trans)-2-hydroxycyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (829 mg,
1.80 mmol) in dry CH\textsubscript{2}Cl\textsubscript{2} (10 mL) was treated with Et\textsubscript{3}N (182 mg, 1.80 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (354 mg, 1.80 mmol) dry CH\textsubscript{2}Cl\textsubscript{2} (1 mL) was added dropwise. After stirring at -78 °C for 1 h the reaction mixture was washed with water and evaporated. The racemic product was purified by HPLC (30-100% CH\textsubscript{3}CN in aqueous NH\textsubscript{4}OAc (0.1 M) over 40 min) to yield the title compound as a white solid (710 mg, 64 %). \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \( \delta \) 7.29-7.06 (m, 8H), 3.82-3.62 (m, 2H), 3.50-3.41 (m, 2H), 3.41-3.31 (m, 1H), 2.81-2.65 (m, 2H), 2.43 (s, 3H), 2.09-1.90 (m, 2H), 1.75-1.61 (m, 2H), 1.34-1.12 (m, 4H); HRMS Calcd for [C\textsubscript{26}H\textsubscript{26}Cl\textsubscript{2}F\textsubscript{3}N\textsubscript{3}O\textsubscript{5}S+H]: 620.1001. Found: 620.1011. The (-)-enantiomer was separated from the racemate (535 mg, 0.86 mmol) by chiral chromatography (Chiralpak AD, heptane : iPrOH 85 : 15) to afford the title compound (220 mg) (95.6% ee) as white solid after freeze drying. [\( \alpha \)\textsubscript{D}] = -2.9 (c 1.04, CH\textsubscript{3}CN); \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \( \delta \) 7.29-7.06 (m, 8H), 3.82-3.62 (m, 2H), 3.50-3.41 (m, 2H), 3.41-3.31 (m, 1H), 2.81-2.65 (m, 2H), 2.43 (s, 3H), 2.09-1.90 (m, 2H), 1.75-1.61 (m, 2H), 1.34-1.12 (m, 4H); HRMS Calcd for [C\textsubscript{26}H\textsubscript{26}Cl\textsubscript{2}F\textsubscript{3}N\textsubscript{3}O\textsubscript{5}S+H]: 620.1001. Found: 620.0956. HPLC: 100%. Vibrational Circular Dichroism experiments were unable to unambiguously assign the absolute stereochemistry of the (+) and (-) enantiomers.

(+) 4-([2-(2,4-Dichlorophenyl)-4-([(cis-2-hydroxycyclohexyl) amino]carbonyl)-5-methyl-1H-imidazol-1-yl]phenyl)-3,3,3-trifluoropropane-1-sulfonate (14d). A suspension of crude racemic 2-(2,4-dichlorophenyl)-N-((cis)-2-hydroxycyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (2.00 g, 4.34 mmol) in dry CH\textsubscript{2}Cl\textsubscript{2} (30 mL) was treated with Et\textsubscript{3}N (440 mg, 4.34 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (854 mg, 4.34 mmol) was added dropwise. After stirring at -78 °C for 2 h 20 min, more Et\textsubscript{3}N (2 x (73 mg, 0.72 mmol)) and 3,3,3-trifluoropropane-1-sulfonyl chloride (2 x (110 mg, 0.56 mmol)) were added (2\textsuperscript{nd} addition after 1 h). After 2 h the reaction mixture was washed with water and evaporated. The racemic product was purified by HPLC (30-100% CH\textsubscript{3}CN in aqueous NH\textsubscript{4}OAc (0.1 M) over 40 min) to yield the title compounds as a white solid (1.31 g, yield over 2 steps 51%). \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \( \delta \) 7.38 (d, \( J \) = 7.7 Hz, 1H), 7.28-7.16 (m, 5H), 7.09 (d, \( J \) = 8.7 Hz, 2H), 4.13-4.02 (m, 1H), 4.00-3.89 (m, 4H).
1H), 3.49-3.38 (m, 2H), 2.80-2.65 (m, 2H), 2.42 (s, 3H), 1.78-1.47 (m, 6H), 1.44-1.28 (m, 2H); HRMS Calcd for [C26H26Cl2F3N3O5S+H]: 620.1001. Found: 620.1025. The (+) enantiomer was separated from the racemate (1.00 g, 1.61 mmol) by Chiral chromatography (Chiralpak AD, heptane/iPrOH 80/20) to yield the title compound (444 mg) (> 99.9% ee) as a white powder after freeze drying. [α]D = +9.9 (c 1.02, CH3CN); 1H NMR (400 MHz, CDCl3) δ 7.38 (d, J = 7.7 Hz, 1H), 7.28-7.16 (m, 5H), 7.09 (d, J = 8.7 Hz, 2H), 4.13-4.02 (m, 1H), 4.00-3.89 (m, 1H), 3.49-3.38 (m, 2H), 2.80-2.65 (m, 2H), 2.63-2.53 (m, 1H), 2.42 (s, 3H), 1.78-1.47 (m, 6H), 1.44-1.28 (m, 2H); HRMS Calcd for [C26H26Cl2F3N3O5S+H] 620.1001. Found: 620.0945. HPLC: 100%. Vibrational Circular Dichroism experiments were unable to unambiguously assign the absolute stereochemistry of the (+) and (-) enantiomers.

4-(2-(2,4-Dichlorophenyl)-5-methyl-1-(4-(trifluoromethoxy)phenyl)carbamoyl)-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14e). A suspension of 13e (150 mg, 0.29 mmol) in dry CH2Cl2 (2 mL) was treated with Et3N (38 mg, 0.37 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (79 mg, 0.40 mmol) in 0.5 mL dry CH2Cl2 was added dropwise. After stirring at -78 °C for 70 min, the reaction mixture was washed with water and evaporated. The product was purified by HPLC (30-100% CH3CN in aqueous NH4OAc (0.1 M) over 35 min) to yield the title compound as a white solid (84 mg, yield over 3 steps 43%). 1H NMR (400 MHz, CDCl3) δ 9.10 (s, 1H), 7.71 (d, J = 9.0 Hz, 2H), 7.36-7.24 (m, 9H), 7.22-7.15 (m, 4H), 3.54-3.47 (m, 2H), 2.86-2.72 (m, 2H), 2.53 (s, 3H); HRMS Calcd for [C27H19Cl2F6N3O5S+H]: 682.0405. Found: 682.0403. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-4-(6-fluoropyridin-3-yl)carbamoyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14f). A suspension of 2-(2,4-dichlorophenyl)-N-(6-fluoropyridin-3-yl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (150 mg, 0.33 mmol) in dry CH2Cl2 (2 mL) was treated with Et3N (43 mg, 0.43 mmol) at r.t.. The resulting mixture was cooled to -78°C and 3,3,3-trifluoropropane-1-sulfonyl chloride (90 mg, 0.46 mmol) in dry CH2Cl2 (0.5 mL) was added dropwise. After stirring at -78 °C for 2 h 30 min, more 3,3,3-trifluoropropane-1-sulfonyl chloride (14
mg, 0.07 mmol) was added and the mixture stirred for another 2 h. The reaction mixture was washed with water and evaporated. The product was purified by HPLC (30-100% CH$_3$CN in aqueous NH$_4$OAc (0.1 M) over 35 min) to yield the title compound as a white solid (133 mg, 66%). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.09 (s, 1H), 8.40-8.31 (m, 2H), 7.37-7.24 (m, 5H), 7.19 (d, $J = 8.8$ Hz, 2H), 6.95-6.88 (m, 1H), 3.55-3.46 (m, 2H), 2.86-2.72 (m, 2H), 2.53 (s, 3H). $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 161.5, 160.7, 158.9, 148.7, 142.6, 138.4 (d, $J = 15.1$), 137.2, 135.5 (d, $J = 38.6$), 134.0, 133.3, 133.0 (d, $J = 4.5$), 132.7 (d, $J = 7.5$), 130.8, 130.0, 129.4, 127.7, 127.6, 125.1 (q, $J = 276.6$), 123.2, 109.5 (d, $J = 38.8$), 44.6 (q, $J = 3.3$), 29.3 (q, $J = 31.9$), 11.0.; HRMS Calcd for [C$_{25}$H$_{18}$Cl$_2$F$_4$N$_4$O$_4$S]$^+$: 617.0440. Found: 617.0473. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(6-(trifluoromethyl)pyridin-3-ylcarbamoyl)-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14g). A suspension of crude 13g (150 mg, 0.30 mmol) in dry CH$_2$Cl$_2$ (2 mL) was treated with Et$_3$N (39 mg, 0.38 mmol) at r.t. then cooled to -78 °C. To this was added dropwise 3,3,3-trifluoropropane-1-sulfonyl chloride (91 mg, 0.46 mmol) in dry CH$_2$Cl$_2$ (0.5 mL). After stirring at -78 °C for 70 min, the mixture was washed with water and concentrated in vacuo to give a residue which was purified by HPLC (30-100% CH$_3$CN in aqueous NH$_4$OAc (0.1 M) over 40 min) to yield the title compound as a white solid (131 mg, yield over 3 steps 52%). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.29 (s, 1H), 8.77 (d, $J = 2.1$ Hz, 1H), 8.56 (dd, $J = 2.1$, 8.6 Hz, 1H), 7.66 (d, $J = 8.6$ Hz, 1H), 7.37-7.16 (m, 7H), 3.55-3.46 (m, 2H), 2.86-2.72 (m, 2H), 2.53 (s, 3H); HRMS Calcd for [C$_{26}$H$_{18}$Cl$_2$F$_6$N$_4$O$_4$S$^+$]: 667.0408. Found: 667.0389. HPLC: 100%.

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(5-methylpyridin-2-ylcarbamoyl)-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (14h). A suspension of 13h (150 mg, 0.33 mmol) in dry CH$_2$Cl$_2$ (2 mL) was treated with Et$_3$N (44 mg, 0.43 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (94 mg, 0.48 mmol) in dry CH$_2$Cl$_2$ (0.5 mL) was added dropwise. After stirring at -78 °C for 80 min, the reaction mixture was washed with water and evaporated. The product was purified by HPLC (30-100% CH$_3$CN in aqueous NH$_4$OAc (0.1 M) over 40 min) to yield the title compound as a white solid (133 mg, 66%). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.09 (s, 1H), 8.40-8.31 (m, 2H), 7.37-7.24 (m, 5H), 7.19 (d, $J = 8.8$ Hz, 2H), 6.95-6.88 (m, 1H), 3.55-3.46 (m, 2H), 2.86-2.72 (m, 2H), 2.53 (s, 3H). $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 161.5, 160.7, 158.9, 148.7, 142.6, 138.4 (d, $J = 15.1$), 137.2, 135.5 (d, $J = 38.6$), 134.0, 133.3, 133.0 (d, $J = 4.5$), 132.7 (d, $J = 7.5$), 130.8, 130.0, 129.4, 127.7, 127.6, 125.1 (q, $J = 276.6$), 123.2, 109.5 (d, $J = 38.8$), 44.6 (q, $J = 3.3$), 29.3 (q, $J = 31.9$), 11.0.; HRMS Calcd for [C$_{26}$H$_{18}$Cl$_2$F$_6$N$_4$O$_4$S$^+$]: 667.0408. Found: 667.0389. HPLC: 100%.
min) to yield the title compound as a white solid (132 mg, 65%). 1H NMR (400 MHz, CDCl3) δ 9.63 (s, 1H), 8.23 (d, J = 8.4 Hz, 1H), 8.11 (d, J = 1.4 Hz, 1H), 7.51 (dd, J = 2.1, 8.4 Hz, 1H), 7.34-7.24 (m, 5H), 7.18 (d, J = 8.9 Hz, 2H), 3.55-3.44 (m, 2H), 2.86-2.71 (m, 2H), 2.53 (s, 3H), 2.28 (s, 3H). HRMS Calcd for [C26H21Cl2F3N4O4S+H]: 613.0691. Found: 613.0702. HPLC: 100%.

2,2,2-Trichloroethyl-1-(4-(benzyl)phenyl)-2-(2,4-dichlorophenyl)-5-methyl-1H-imidazole-4-carboxylate (15). A solution of compound 4 (10.0 g, 22.1 mmol) in CH2Cl2 (210 mL) was treated with oxalyl chloride (18.5 g, 145 mmol), followed by a few drops of DMF. The mixture was stirred at r.t. for 2 h after which the solvents were evaporated. The residue was dissolved in CH2Cl2 (80 mL) and the mixture was cooled to 0 °C, upon which 2,2,2-trichloroethanol (3.63 g, 24.3 mmol) was added followed by DIPEA (3.42 g, 26.5 mmol). The ice bath was then removed and the reaction mixture was stirred at r.t. for 3 h, adding DMAP (279 mg, 2.28 mmol) after 1 h 40 min. The reaction mixture was diluted with CH2Cl2, washed with water, dried (MgSO4), filtered and concentrated in vacuo to yield the crude title compound (14.9 g). 1H NMR (400 MHz, CDCl3) δ 7.40-7.14 (m, 8H), 7.04-6.98 (m, 2H), 6.94-6.88 (m, 2H), 5.01 (4H, s), 2.45 (s, 3H); MS m/z 583 (M+H).

2,2,2-Trichloroethyl-2-(2,4-dichlorophenyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxylate (16). Crude 15 (14.77 g) was dissolved in HBr (33% in AcOH, 200 mL). After having stirred at r.t. for an additional hour the reaction mixture was cooled to 0 °C and EtOH was added. The mixture was stirred for 10 min before the solvents were evaporated. The residue was dissolved in MeOH and neutralized with aqueous NaHCO3 (1 M). The solvent was evaporated and the mixture dissolved in CH2Cl2. The organic phase was washed with brine and water, dried (MgSO4), filtered and concentrated in vacuo to yield the title compound (10.4 g, 95% over 2 steps). 1H NMR (400 MHz, CDCl3) δ 8.63 (br s, 1H), 7.25-7.08 (m, 3H), 6.86-6.68 (m, 4H), 4.95 (s, 2H), 2.43 (s, 3H); MS m/z 493 (M+H).

2,2,2-Trichloroethyl-2-(2,4-dichlorophenyl)-5-methyl-1-(4-(3,3,3-trifluoropropylsulfonyloxy)phenyl)-1H-imidazole-4-carboxylate (17). A suspension of 16 (5.01 g, 10.13 mmol) in dry CH2Cl2 (100 mL)
under nitrogen was treated with Et$_3$N (1.23 g, 12.2 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (2.19 g, 11.1 mmol) was added dropwise. The reaction mixture was stirred at -78 °C for 3 h, adding more 3,3,3-trifluoropropane-1-sulfonyl chloride (0.28 g 1.43 mmol) after 2 h. Water was added and the phases were separated on a phase separator. The organic phase was concentrated in vacuo to yield the title compound (6.43 g, 97%). $^1$H NMR (400 MHz, CDCl$_3$) δ 7.37-7.15 (m, 7H), 5.01 (s, 2H), 3.53-3.45 (m, 2H), 2.84-2.70 (m, 2H), 2.48 (s, 3H); MS m/z 653 (M+H).

2-(2,4-Dichlorophenyl)-5-methyl-1-(4-(3,3,3-trifluoropropylsulfonyloxy)phenyl)-1H-imidazole-4-carboxylic acid (18). A solution of 17 (6.43 g, 9.82 mmol) in AcOH (100 mL) was treated with zinc dust (9.74 g, 148.91 mmol). The reaction mixture was stirred at r.t. for 3 h after which it was filtered through celite and evaporated. The residue was dissolved in CH$_2$Cl$_2$ and washed with aqueous HCl (0.1 M), dried, filtered, and concentrated in vacuo to yield the crude title compound (5.28 g). MS m/z 523 (M+H).

4-(2-(2,4-Dichlorophenyl)-4-(4-hydroxycyclohexylcarbamoyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (19). A solution of 18 (crude 528 mg) in CH$_2$Cl$_2$ (25 mL) was treated with oxalyl chloride (641 mg, 5.00 mmol). A precipitate formed immediately after the addition so more CH$_2$Cl$_2$ (15 mL) was added, followed by a few drops of DMF. The reaction mixture was stirred at r.t. for 2 h after which more oxalyl chloride (641 mg, 5.00 mmol) was added. After another 10 min the solvents were evaporated. Half of the crude material was suspended in CH$_2$Cl$_2$ (5 mL) and added dropwise to a mixture of 4-aminocyclohexanol (74 mg, 0.64 mmol), NaOH (1 M, 10 mL) and CH$_2$Cl$_2$ (5 mL). The reaction mixture was stirred at r.t. for 2 h after which water/CH$_2$Cl$_2$ were added and the phases separated. The organic phase was washed with aqueous HCl (0.1 M) and concentrated in vacuo. The product was purified by HPLC to yield the title compound as a white solid after freeze drying (164 mg, 54% over 2 steps). Note that the title compound is a mixture of cis- and trans-isomers in a ratio of 0.3 : 1. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.33-7.19 (m, 6H), 7.17-7.11 (m, 2H), 7.02 (d,
$J = 8.4 \text{ Hz, 0.6H}, 4.07 - 3.99 \text{ (m, 0.3H), 3.99 - 3.86 \ (1H, m), 3.66 - 3.56 \ (m, 0.6H), 3.52 - 3.45 \ (m, 2H), 2.85 - 2.71 \ (m, 2H), 2.48 \text{ and 2.47 (2 x s, 3H), 2.12 - 1.95 \ (m, 2.6H), 1.81 - 1.65 \ (m, 3.8H), 1.49 - 1.26 \ (m, 2.7H);}$

HRMS Calcd for $[C_{26}H_{30}Cl_2F_3N_3O_5S+H]$: 620.1001. Found: 620.1002. HPLC: 100%.

**racemic** $N$-((cis)-2-Aminocyclohexyl)-1-[4-(benzyloxy)phenyl]-2-(2,4-dichlorophenyl)-5-methyl-1H-imidazole-4-carboxamide (20). A suspension of compound 4 (2.00 g, 4.41 mmol) in CH$_2$Cl$_2$ (50 mL) was treated with oxalyl chloride (2.80 mg, 22.1 mmol) at r.t., followed by one drop of DMF. The mixture was stirred at r.t. for 30 min after which the solvents were evaporated under reduced pressure. Half of the amount of the acid chloride (1.04 mg, 2.20 mmol) suspended in CH$_2$Cl$_2$ (250 mL) was added dropwise during 31 h to a mixture of (cis)-cyclohexane-1,2-diamine (5.00 mg, 43.79 mmol), aqueous NaOH (1 M, 50 mL) and CH$_2$Cl$_2$ (50 mL). After the addition was complete water was added and the phases were separated. The organic phase was washed with aqueous HCl (10%) and brine, dried (MgSO$_4$), filtered and evaporated to yield the crude title compound (1.31 mg). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.57 (br s, 2H), 7.69 (br s, 1H), 7.37 - 6.90 (m, 2H), 5.00 (s, 2H), 4.41 (br s, 1H), 3.72 (br s, 1H), 2.42 (s, 3H), 2.18 - 1.40 (m, 8H); MS m/z 549 (M+H).

**racemic** $N$-((cis)-2-Aminocyclohexylcarbamoyl)-2-(2,4-dichlorophenyl)-5-methyl-1H-imidazole-4-carboxamide (21). A suspension of crude racemic 20 (791 mg, 1.44 mmol) in CH$_2$Cl$_2$ (5 mL) and dimethyl sulfide (894 mg, 14.39 mmol) was treated with boron trifluoride (2.04 g, 14.4 mmol). The reaction mixture was stirred at r.t. for 2.5 days (dark). Water and EtOAc were added and the phases separated. The organic phase was washed with aqueous HCl (10%) and brine, dried (MgSO$_4$), filtered and evaporated to yield the crude title compound (715 mg). MS m/z 459 (M+H).

**racemic** 4-(4-((cis)-2-Aminocyclohexylcarbamoyl)-2-(2,4-dichlorophenyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (22). A suspension of crude racemic 21 (715 mg, 1.56 mmol) in CH$_2$Cl$_2$ (15 mL) and Et$_3$N (0.987 g, 9.76 mmol) was treated with TBDMSocl (0.985 g, 6.53 mmol). The reaction mixture was stirred at r.t. for 22 h. CH$_2$Cl$_2$ and water were added and the phases separated. The organic phase was dried (MgSO$_4$), filtered and evaporated to yield the crude silylated...
intermediate an oil (1.14 g, 1.99 mmol). MS m/z 573 (M+H). A solution of the crude intermediate (1.14 g, 1.99 mmol) in THF (10 mL) was treated with (Boc)₂O (444 mg, 2.03 mmol). The reaction mixture was stirred at r.t. for 4 h after which the solvent was evaporated at reduced pressure and the residue dissolved in CH₂Cl₂. The organic phase was washed with water, dried (MgSO₄), filtered, and concentrated in vacuo. The residue was purified by flash chromatography (10-100% EtOAc in heptane) to yield the Boc-protected intermediate (620 mg, yield over 4 steps 70%). ¹H NMR (400 MHz, CDCl₃) δ 7.37 (d, J = 8.2 Hz, 1H), 7.24-7.08 (m, 3H), 6.85 (d, J = 8.7 Hz, 2H), 6.70 (d, J = 8.7 Hz, 2H), 5.12 (d, J = 4.5 Hz, 1H), 4.32-4.19 (m, 1H), 3.83-3.74 (m, 1H), 2.38 (s, 3H), 1.79-1.39 (m, 8H), 1.33 (s, 9H), 0.87 (s, 9H), 0.11 (s, 6H); MS m/z 673 (M+H). A suspension of the fully protected intermediate (610 mg, 0.91 mmol) in dry THF (3 mL) was treated with TBAF (1.0 M THF, 237 mg, 0.91 mmol). The reaction mixture was stirred at r.t. for 1 h 45 min. The solvent was evaporated and the residue dissolved in CH₂Cl₂, washed with water, dried (MgSO₄), filtered and evaporated. The residue was dissolved in EtOAc and some silica gel was added. The suspension was filtered through a plug of silica gel and eluted with EtOAc. The solvent was evaporated to yield the crude desilylated intermediate (529 mg). ¹H NMR (400 MHz, CDCl₃) δ 7.36 (d, J = 8.1 Hz, 1H), 7.21 (d, J = 1.6 Hz, 1H), 7.13 (d, J = 8.3 Hz, 1H), 7.09 (dd, J = 1.6, 8.3 Hz, 1H), 6.80 (d, J = 8.6 Hz, 2H), 6.68 (d, J = 8.6 Hz, 2H), 5.07 (d, J = 6.6 Hz, 1H), 4.28-4.16 (m, 1H), 3.84-3.72 (m, 1H), 2.32 (s, 3H), 1.55-1.37 (m, 8H), 1.31 (9H, s); MS m/z 559 (M+H). A suspension of the crude intermediate (506 mg, 0.91 mmol) in dry CH₂Cl₂ (6 mL) was treated with Et₃N (110 mg, 1.09 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (181 mg, 0.92 mmol) in dry CH₂Cl₂ (0.2 mL) was added dropwise. After stirring at -78 °C for 3 h (including extra additions of 3,3,3-trifluoro-propane-1-sulfonyl chloride (2 x 43 mg, 0.22 mmol) after 1.5 h and 2.5 h), the reaction mixture was washed with water and evaporated to yield the crude intermediate (655 mg). MS m/z 719 (M+H). To a suspension of the Boc-protected intermediate (655 mg, 0.91 mmol) in MeOH (10 mL) at 0 °C was added dropwise a solution of thionyl chloride in MeOH (prepared by dropwise addition of thionyl chloride (5.41 g, 45.5 mmol) to MeOH (10 mL) at -40 °C). After the addition the ice bath was removed. The
reaction mixture was stirred at r.t. for 1 h after which the solvents were evaporated. The product was purified by HPLC (30-100% CH₃CN (with 0.1 % formic acid) in 0.1% formic acid (aq) during 40 min). The CH₃CN was evaporated and the resulting mixture extracted with CH₂Cl₂. The organic phase was washed with aqueous NaHCO₃ (1 M), dried (MgSO₄), filtered, and concentrated in vacuo to yield the title compound as a slightly yellow solid (315 mg yield over 3 steps 56%). ¹H NMR (400 MHz, CDCl₃) δ 7.51 (d, J = 8.7 Hz, 1H), 7.32-7.20 (m, 5H), 7.14 (d, J = 8.8 Hz, 2H), 4.20-4.09 (m, 1H), 3.52-3.44 (m, 2H), 3.15-3.06 (m, 1H), 2.84-2.71 (m, 2H), 2.47 (s, 3H), 1.70-1.39 (m, 10H); HRMS Calcd for [C₂₆H₂₇Cl₂F₃N₄O₄S+H]: 619.1160. Found: 619.1216. HPLC: 95.4%.

racemic 1-((4-Benzylxy)phenyl)-2-(2,4-dichlorophenyl)-N-((cis)-2-(dimethylamino)cyclohexyl)-5-methyl-1H-imidazole-4-carboxamide (23). To a suspension of racemic 20 (493 mg, 0.90 mmol) in CH₃CN (10 mL) was added formaldehyde, 36% (135 mg, 4.49 mmol) and sodium borohydride (75 mg, 1.97 mmol) in portions. The suspension was stirred at r.t. for 2 days adding after 2.5 h sodium borohydride (77 mg, 2.04 mmol), 3.5 h formaldehyde (36% in H₂O, 67 mg, 2.24 mmol), 18.5 h formaldehyde (36% in H₂O, 67 mg, 2.24 mmol) and sodium borohydride (77 mg, 2.04 mmol) (the temperature was increased to 40 °C for 4.5 h), 23 h AcOH (1.85 mL) at r.t., 28 h formaldehyde (36% in H₂O, 135 mg, 4.49 mmol) followed by sodium cyanoborohydride (112 mg, 1.78 mmol), 42 h formaldehyde (36% in H₂O, 135 mg, 4.49 mmol) followed by sodium cyano borohydride (126 mg, 2.01 mmol). The reaction mixture was diluted with CH₂Cl₂, washed with NaOH (1 M) and brine, dried (MgSO₄), filtered and evaporated. The residue was purified by HPLC (30-100% CH₃CN in aqueous NH₄OAc (0.1 M) over 30 min). The CH₃CN was evaporated and the resulting mixture extracted with CH₂Cl₂, dried (MgSO₄), filtered and evaporated to yield the title compound (163 mg, 32%). MS m/z 577 (M+H).

racemic 2-(2,4-Dichlorophenyl)-N-((cis)-2-(dimethylamino)cyclohexyl)-1-(4-hydroxyphenyl)-5-methyl-1H-imidazole-4-carboxamide (24). A suspension of racemic 23 (163 mg, 0.28 mmol) in CH₂Cl₂ (2 mL) and dimethyl sulfide (351 mg, 5.64 mmol) was treated with boron trifluoride (801 mg, 5.64 mmol).
The reaction mixture was stirred at r.t. for 2 days (dark) adding more of dimethyl sulfide (176 mg, 2.82 mmol) and boron trifluoride (401 mg, 2.82 mmol) after 17 h. Water and CH$_2$Cl$_2$ were added and the phases separated. The organic phase was washed with water, dried (MgSO$_4$), filtered, and concentrated in vacuo to yield the crude title compound (104 mg). MS m/z 487 (M+H).

racemic 4-(2-(2,4-Dichlorophenyl)-4-((cis)-2-(dimethylamino)cyclohexylcarbamoyl)-5-methyl-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (25). A suspension of racemic 24 (104 mg, 0.21 mmol) in dry CH$_2$Cl$_2$ (1.5 mL) was treated with Et$_3$N (26 mg, 0.26 mmol) at r.t.. The resulting mixture was cooled to -78 °C and 3,3,3-trifluoropropane-1-sulfonyl chloride (50 mg, 0.26 mmol) in dry CH$_2$Cl$_2$ (0.5 mL) was added dropwise. After stirring at -78 °C for 6.5 h (and adding more 3,3,3-trifluoropropane-1-sulfonyl chloride (2 x 50 mg, 0.26 mmol) after 2 h and 4 h, and Et$_3$N (26 mg, 0.26 mmol) after 4 h), the reaction mixture was washed with water and evaporated. The residue was purified by HPLC (30-100% CH$_3$CN (with 0.1% formic acid) in 0.1% formic acid over 40 min) and freeze dried. The product was dissolved in CH$_2$Cl$_2$ and washed with NaHCO$_3$ (1 M) and water, dried (MgSO$_4$), filtered and concentrated in vacuo to yield the title compound as a slightly yellow oil (37 mg yield over 2 steps 20%). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.54 (d, $J = 7.6$ Hz, 1H), 7.37 (d, $J = 8.3$ Hz, 1H), 7.31 (d, $J = 2.0$ Hz, 1H), 7.29 (d, $J = 8.9$ Hz, 1H), 7.26 (dd, $J = 2.0, 8.3$ Hz, 1H), 7.17 (d, $J = 8.9$ Hz, 1H), 4.59-4.51 (m, 1H), 3.56-3.48 (m, 2H), 2.86-2.76 (m, 2H), 2.51 (s, 3H), 2.31 (s, 6H), 2.26-2.19 (m, 1H), 2.07 (dt, $J = 3.8, 11.8$ Hz, 1H), 2.04-1.96 (m, 2H), 1.85-1.77 (m, 1H), 1.54-1.25 (m, 5H); HRMS Calcd for [C$_{28}$H$_{31}$Cl$_3$F$_3$N$_4$O$_5$S+H]: 647.1473. Found: 647.1472. HPLC: 100%.

1-(4-(Benzyloxy)phenyl)-2-(2,4-dichlorophenyl)-5-methyl-N-(5-(trifluoromethyl)pyridin-2-yl)-1H-imidazole-4-carboxamide (26). A solution of 2-amino-5-(trifluoromethyl)pyridine (404 mg, 2.49 mmol) in CH$_2$Cl$_2$ (2.5 mL) under argon was carefully treated with trimethylaluminium (2.0 M in toluene, 1.25 mL, 2.5 mmol) over 5 min. The solution was stirred at r.t. for 1.5 h to give a 0.66 M solution of the amidation reagent. A portion of this solution (3.75 mL, 2.5 mmol) was added to compound 3 (400 mg, 0.83 mmol). After stirring at 45 °C overnight the mixture was cooled to 0 °C and quenched with HCl
(aq, 2 M, 7.5 mL). The mixture was diluted with dichloromethane and neutralized by addition of KOH (aq, 2 M). The organic phase was separated and the aqueous phase was extracted further with dichloromethane. The collected organic phases were washed with H$_2$O, dried (Na$_2$SO$_4$), filtered, and concentrated in vacuo to give a residue which was purified by preparative HPLC to give the title compound (319 mg, 64%) as a solid. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.91 (s, 1H), 8.57 (s, 1H), 8.52 (d, $J = 8.8$ Hz, 1H), 7.92 (dd, $J = 2.1$, 8.8 Hz, 1H), 7.44-7.32 (m, 6H), 7.30-7.21 (m, 2H), 7.04 (d, $J = 8.9$ Hz, 2H), 6.95 (d, $J = 8.9$ Hz, 2H), 5.05 (s, 2H), 2.52 (s, 3H); MS m/z 597 (M+H).

2-(2,4-Dichlorophenyl)-1-(4-hydroxyphenyl)-5-methyl-N-(5-(trifluoromethyl)pyridin-2-yl)-1H-imidazole-4-carboxamide (27). Compound 26 (319 mg, 0.53 mmol) was dissolved in HBr (4.1 M in acetic acid, 7.5 mL, 30.8 mmol) and the mixture stirred at r.t. for 4 h. The acetic acid was co-evaporated with EtOH, the residue neutralized with ammonia and dissolved in methanol. Purification by flash chromatography gave the title compound (266 mg, 98%). $^1$H NMR (400 MHz, DMF-d7) $\delta$ 10.36 (s, 1H), 10.09 (s, 1H), 8.89 (d, $J = 1.0$ Hz, 1H), 8.69 (d, $J = 8.9$ Hz, 1H), 8.45 (dd, $J = 1.0$, 8.9 Hz, 1H), 7.85 (d, $J = 8.3$ Hz, 1H), 7.80 (s, 1H), 7.67 (d, $J = 8.3$ Hz, 1H), 7.40 (d, $J = 8.4$ Hz, 2H), 7.06 (d, $J = 8.4$ Hz, 2H), 2.65 (s, 3H); MS m/z 507 (M+H).

4-(2-(2,4-Dichlorophenyl)-5-methyl-4-(5-(trifluoromethyl)pyridin-2-ylcarbamoyl)-1H-imidazol-1-yl)phenyl 3,3,3-trifluoropropane-1-sulfonate (28). A mixture of 27 (136 mg, 0.27 mmol) and Et$_3$N (40 µL, 0.32 mmol) in CH$_2$Cl$_2$ (4.0 mL) was cooled to -78 °C then carefully treated with 3,3,3-trifluoropropane-1-sulfonyl chloride (63 mg, 0.32 mmol). The resulting mixture was stirred at -78 °C for 1 h, then allowed to reach room temperature. Water was added to the reaction, and the phases were separated. The organic phase was washed with NaHCO$_3$, and brine, then dried (Na$_2$SO$_4$), filtered, and concentrated in vacuo to give a residue which was purified by preparative HPLC to give the title compound (88 mg, 49%) as a solid. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.87 (s, 1H), 8.55 (s, 1H), 8.49 (d, $J = 8.8$ Hz, 1H), 7.91 (dd, $J = 2.1$, 8.8 Hz, 1H), 7.36-7.21 (m, 5H), 7.19 (d, $J = 8.8$ Hz, 2H), 3.55-3.46 (m, 2H), 2.87-2.71 (m, 2H), 2.54 (s, 3H); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 162.0, 154.3, 148.6, 145.6
(q, J = 4.1), 142.7, 137.0, 136.2, 135.6 (q, J = 3.2), 135.2, 134.1, 133.4, 131.0, 130.0, 129.3, 127.9, 127.5, 125.1 (q, J = 277.1), 123.8 (q, J = 271.3), 123.2, 122.1 (q, J = 32.7), 113.1, 44.5 (q, J = 3.3), 29.3 (q, J = 31.5), 11.1. HRMS Calcd for \([\text{C}_{20}\text{H}_{18}\text{Cl}_2\text{F}_6\text{N}_4\text{O}_4\text{S} + \text{H}]\): 667.0408. Found: 667.0540. HPLC: 100%.

**Biology. Chemicals and Reagents.** \[^3\text{H}]\text{CP55940} \text{ (specific activity 141.2 Ci/mmol) was purchased from Perkin Elmer (Waltham, MA). Bicinchoninic acid (BCA) and BCA protein assay reagent were obtained from Pierce Chemical Company (Rochford, IL). Rimonabant was from Cayman Chemical Company (Ann Arbor, MI). CHOK1hCB\(_1\)_bgal cells (catalog number 93-0959C2) were obtained from DiscoveRx (Fremont, CA). The membranes (catalog number RBHCB1M400UA) used for \[^{35}\text{S}]\text{GTP\gammaS} \text{ antagonism experiment were purchased from Perkin Elmer (Waltham, MA). All other chemicals were of analytical grade and obtained from standard commercial sources.}

**Cell Culture and Membrane Preparation.** CHOK1hCB\(_1\)_bgal cells were cultured in Ham’s F12 Nutrient Mixture supplemented with 10% fetal calf serum, 1 mM glutamine, 50 μg/mL penicillin, 50 μg/ml streptomycin, 300 mg/mL hygromycin and 800 μg/mL geneticin in a humidified atmosphere at 37 °C and 5% CO\(_2\). Cells were subcultured twice a week at a ratio of 1:10 on 10-cm Ø plates by trypsinization. For membrane preparation the cells were subcultured 1:10 and transferred to large 15-cm Ø plates. Membrane fractions were prepared exactly as described before.\(^{50}\)

**Equilibrium Radioligand Displacement Assays.** \[^3\text{H}]\text{CP55940} \text{ displacement assays on 96-well plate were used for the determination of affinity (IC\(_{50}\) and \(K_i\) values of antagonists for the cannabinoid CB\(_1\) receptors. The displacement experiments were performed using 6 concentrations of competing antagonists in 25 μL of assay buffer (50 mM Tris–HCl, 5 mM MgCl\(_2\), 0.1% BSA, pH 7.4) in the presence of another 25 μL of assay buffer with a final concentration of 3.5 nM \[^3\text{H}]\text{CP55940}. \text{ At this concentration, total radioligand binding did not exceed 10% of that added to prevent ligand depletion. Membrane aliquots containing 5 μg of CHOK1hCB\(_1\)_bgal membrane in 100 μL assay buffer were incubated at 30 °C for 60 min. Nonspecific binding (NSB) was determined in the presence of 10 μM rimonabant. Incubation was terminated by rapid filtration performed on 96-well GF/C filter
plates (Perkin Elmer, Groningen, the Netherlands), presoaked for 30 min with 0.25% PEI (PolyEthyleneImine), using a PerkinElmer Filtermate-harvester (Perkin Elmer, Groningen, the Netherlands). After 30 min of dehydration of the filter plate at 50 °C, the filter-bound radioactivity was determined by scintillation spectrometry using the 2450 MicroBeta2 Plate Counter. The binding values were recorded in both counts per minute (CPM) and disintegrations per minute (DPM). Each antagonist was measured in duplicate and at least 3 individual experiments were performed.

Classic Radioligand Kinetic Assays. Association experiments were performed by incubating membrane aliquots containing 5 μg of CHOK1hCB1 bgal membrane in a total volume of 100 μL of assay buffer at 30 °C with 3.5 nM [3H]CP55940. The amount of radioligand bound to the receptor was measured at different time intervals during a total incubation of 120 min. Dissociation experiments were performed by preincubating membrane aliquots containing 5 μg of protein in a total volume of 100 μL of assay buffer for 60 min. After the preincubation, radioligand dissociation was initiated by the addition of 10 μM unlabeled rimonabant. The amount of radioligand still bound to the receptor was measured at various time intervals for a total of 240 min. to ensure that full dissociation from cannabinoid CB1 receptor was reached. Incubation was terminated by rapid filtration performed on GF/C filters (Whatman International, Maidstone, UK), presoaked for 30 min with 0.25% PEI, using a Brandel harvester (Brandel, Gaithersburg, MD). Filter-bound radioactivity was determined by scintillation spectrometry using a Tri-Carb 2900 TR liquid scintillation counter (Perkin Elmer, Boston, MA).

Competition Association Assays. Kinetic Rate Index (KRI) values are an average of at least two independent experiments, each consisting of two replicates. Kinetic rate constant values are an average of at least three independent experiments, each consisting of two replicates. The binding kinetics of unlabeled ligands was quantified using the competition association assay based on the theoretical framework by Motulsky and Mahan. A concentration of 1 to 3-fold of the IC50 value was used to determine the binding kinetics of unlabeled CB1 receptor antagonists. The competition
association assay was initiated by adding membrane aliquots (5 μg/well) at different time points for a total of 240 min to a total volume of 100 μL of assay buffer at 30 °C with 3.5 nM [³H]CP55940 in the absence or presence of competing CB₁ receptor antagonists (1 to 3-fold IC₅₀). Incubations were terminated, and samples were obtained as described under Equilibrium Radioligand Displacement Assay. The “dual-point” competition association assays³² were run similarly, with only two time points, at 30 and 240 min, respectively.

[^35S]GTPγS Binding Assays. Antagonism assay: The antagonism of all tested compounds was evaluated at 30 °C in a[^35S]GTPγS binding assay as reported earlier.⁵¹ Insurmountability assay: Membrane homogenates containing the CB₁ receptor (5 μg) were equilibrated in the assay buffer (50 mM Tris–HCl, 5 mM MgCl₂, 1 mM EDTA, 100 mM NaCl, 0.05% BSA, pH7.4) supplemented with 1 μM GDP, 1 mM DTT and 5 μg saponin. Membrane preparations were pre-incubated with or without antagonists (10-fold Kᵢ values on the CB₁ receptor) for 1 h prior to the challenge of a CB₁ receptor agonist, CP55940 at 25 °C with concentrations ranging from 1 μM to 0.1 nM. Subsequently, [³⁵S]GTPγS (final concentration 0.3 nM) was added and incubation continued for another 30 min at 25 °C. Incubations were terminated and samples were obtained as described under Equilibrium Radioligand Displacement Assays.

Data analysis. All experimental data were analyzed using the nonlinear regression curve fitting program GraphPad Prism 6.0 (GraphPad Software, Inc., San Diego, CA). From displacement assays, IC₅₀ values were obtained by non-linear regression analysis of the displacement curves. The obtained IC₅₀ values were converted into Kᵢ values using the Cheng-Prusoff equation to determine the affinity of the ligands.⁵² The kₘₑₐₜ and kₐₜₜ values for radiolabeled and unlabeled ligands were fitted and calculated, and the kₘₑₐₜ and kₐₜₜ values were used to calculate residence times (in min) and kinetic dissociation binding constants (kinetic Kᵦ). Association and dissociation rates for unlabeled compounds were calculated by fitting the data into the competition association model using “kinetics of competitive binding”.³⁶
\[ K_A = k_1[L] \cdot 10^{-9} + k_2 \\
K_B = k_3[I] \cdot 10^{-9} + k_4 \\
S = \sqrt{(K_A - K_B)^2 + 4 \cdot k_1 \cdot k_3 \cdot L \cdot I \cdot 10^{-18}} \\
K_F = 0.5(K_A + K_B + S) \\
K_S = 0.5(K_A + K_B - S) \\
Q = \frac{B_{\text{max}} \cdot k_1 \cdot L \cdot 10^{-9}}{K_F - K_S} \\
Y = Q \cdot \left( \frac{k_2 \cdot (K_F - K_S)}{K_F \cdot K_S} + \frac{k_4 - K_F}{K_F} e^{(-K_F \cdot X)} - \frac{k_4 - K_S}{K_S} e^{(-K_S \cdot X)} \right) \]

Where \( k_1 \) is the \( k_{\text{on}} \) of the radioligand (M\(^{-1}\)s\(^{-1}\)), \( k_2 \) is the \( k_{\text{off}} \) of the radioligand (s\(^{-1}\)), \( L \) is the radioligand concentration (nM), \( I \) is the concentration of the unlabeled competitor (nM), \( X \) is the time (min) and \( Y \) is the specific binding of the radioligand (DPM). During a competition association these parameters are set, obtaining \( k_1 \) from the control curve without competitor and \( k_2 \) from previously performed dissociation assays described under Traditional Radioligand Kinetic Assays. With that the \( k_3 \), \( k_4 \) and \( B_{\text{max}} \) can be calculated, where \( k_3 \) represents the \( k_{\text{on}} \) (M\(^{-1}\)s\(^{-1}\)) of the unlabeled ligand, \( k_4 \) stands for the \( k_{\text{off}} \) (s\(^{-1}\)) of the unlabeled ligand and \( B_{\text{max}} \) equals the total binding (DPM). All competition association data were globally fitted. Residence times (RT, expressed in min) were calculated as RT = 1/(60*\( k_{\text{off}} \)).

Computational studies. All computational studies were performed in the Schrödinger suite,\(^53\) and based on the crystal structure of the CB\(_1\) receptor co-crystalized with 29 (PDB: STGZ).\(^33\) The crystal structure was prepared with the protein preparation wizard.\(^53\) Ligands were docked using induced fit docking,\(^54\) with core constraints on the 2,4-dichlorophenyl ring of 29 (all ligands share this moiety). To study whether the difference in RTs among 11d, 14f and 28 could be explained by unfavorable hydration, we generated a WaterMap around 14f.\(^47, 48\) Figures were rendered using PyMol.\(^55\)

References


52. Cheng, Y.-C.; Prusoff, W. H. Relationship between the inhibition constant (K) and the concentration of inhibitor which causes 50 percent inhibition (IC50) of an enzymatic reaction. *Biochem. Pharmacol.* 1973, 22, 3099-3108.


Supporting information

Determination of target selectivity between human CB\(_1\) and CB\(_2\) receptors and physicochemical properties for human CB1 receptor antagonists

1. Selectivity data for representative human CB\(_1\) receptor antagonists at human CB\(_2\) receptor

Method: The antagonism of all tested compounds was evaluated at 30 °C in a \(^{35}\text{S}\)GTP\(\gamma\)S binding assay as reported earlier.\(^{51}\)

Table S1. Selectivity data for representative human CB\(_1\) receptor antagonists at human CB\(_2\) receptor.

<table>
<thead>
<tr>
<th>Antagonist</th>
<th>(^{35}\text{S})GTP(\gamma)S binding pIC(<em>{50}) ± SD or SEM (mean IC(</em>{50}) in nM)</th>
<th>pK(_i) ± SEM (mean K(_i) in nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11b</td>
<td>N. D. (^c)</td>
<td>7.5 ± 0.01 (35)</td>
</tr>
<tr>
<td>11d</td>
<td>6.6 ± 0.05 (288)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>11f</td>
<td>6.5 (320)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>11g</td>
<td>6.6 ± 0.01 (271) (^d)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>11h</td>
<td>5.9 ± 0.03 (1358)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>14b ((\pm)) trans</td>
<td>6.4 ± 0.1 (425) (^d)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>14d ((\pm)) cis</td>
<td>6.4 ± 0.2 (440) (^d)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>22 ((\pm)) cis</td>
<td>6.1 ± 0.03 (805) (^d)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>14f</td>
<td>N. D. (^c)</td>
<td>8.9 ± 0.1 (1.4)</td>
</tr>
<tr>
<td>14h</td>
<td>6.4 ± 0.05 (400) (^d)</td>
<td>N. D. (^c)</td>
</tr>
<tr>
<td>28</td>
<td>6.9 ± 0.04 (133) (^d)</td>
<td>8.3 ± 0.1 (4.9)</td>
</tr>
</tbody>
</table>

\(^a\) pIC\(_{50}\) ± SD (n=2) or SEM (n ≥ 3), except 11f was n=1, obtained from \(^{35}\text{S}\)GTP\(\gamma\)S binding on recombinant human CB\(_2\) receptors stably expressed on HEK-293 cell membranes.

\(^b\) pK\(_i\) ± SEM (n=3), obtained from radioligand binding assays with \(^{3}\text{H}\)CP55940 on recombinant human CB\(_2\) receptors stably expressed on CHO cell membranes.

\(^c\) N.D. = Not determined.

\(^d\) n=2.
2. Calculating Polar Surface Area (PSA)

Method: PSA is an in-house implementation (AstraZeneca, Vladimir Sherbukin) of a literature model. In brief, Van der Waals surface area around polar atoms (N, O and H attached either to N or O), all other atoms are treated as non-polar. The algorithm sums up atomic contributions and subtracts buried surfaces where two atomic spheres intersect making a bond. Parameters for the following elements are available: H, C, N, O, S, F and Cl. If any other element occurs in the molecule, the value will be missing.

3. Calculating ACDlogD7.4 with pKa correction

Method: the values of ACDlogD7.4 with pKa correction were calculated using the ACD software, version 12 (www.acdlabs.com) with utilization of in house pKa data (AstraZeneca) as a pKa correction library.

4. Calculating AZlogD7.4

Method: the values of AZlogD7.4 were obtained from AstraZeneca’s Auto-QSAR method.

5. LogD determination

Method: measurement of LogD_{O/W} is based on the traditional shake flask technique, but with the modification of measuring compounds in mixtures of ten at a time using UPLC with quantitative mass spectrometry (MS) as a method to measure the relative octanol and aqueous concentrations. Two quality control (QC) samples (Cyclobenzaprine with moderate LogD, and Nicardipine with high LogD) are used in all pools to ensure good quality. Caffeine, with low LogD, is used as an additional QC sample and is randomly placed in all runs. The method has been thoroughly validated against the previous shake flask methodologies. The range of LogD values that can be determined by this method is dependent on the solubility of the compound in octanol and buffer, as well as the MS response of the individual compounds, and varies typically between approximately 0 to 4.
Equipment:
Robot, samples: Hamilton Star
Robot, optimization: BRAVO Velocity11, Biomek FX
Mass spectrometer: Waters Micromass TQS with MassLynx 4.1
LC-system: Waters Acquity Ultra Performance LC
Column: Acquity UPLC HSS T3 1.8 µm, 2.1-50 mm or Acquity UPLC BEH C18 1.7 µm, 2.1-50 mm
Vortexer: IKA-VIBRAX-VXR
Shaker: Edmund Bühler SM25
Centrifuge: Eppendorf Centrifuge 5810 R
Plates: 2 ml U96 deep well plate PP (Nunc Cat No 278752)
1.3 ml U96 deep well plate PP (Nunc Cat No 260252)
Nunc microtiter plate 96-well V-bottom PP (Nunc Cat No 249944).

Phosphate buffer:
Na$_2$HPO$_4$$\times$2H$_2$O (p.a grade) and NaH$_2$PO$_4$$\times$H$_2$O (p.a grade) purchased from Merck or other vendor. A stock solution of 100 mM (pH approximately 7.2) is prepared by dissolving 12.731 g Na$_2$HPO$_4$$\times$2H$_2$O and 3.929 g NaH$_2$PO$_4$$\times$H$_2$O in 1 L of water. This stock solution can be stored in room temperature for at least one year.

The stock solution is diluted ten times and pH adjusted to 7.4. Thereafter, equal parts of buffer and 1-octanol are vigorously mixed in a separation funnel three times (at least 15 minutes between each mixing) to saturate the solutions. The mixture is left overnight to separate the upper octanol phase from the lower buffer phase before being used in experiments.

All the physicochemical properties are summarized in Table S2 and S3. Their correlations with affinities and KRI values are summarized in Figure S1 and S2.

Table S2. Physicochemical parameters of “left arm” (R$_1$) compounds.

<table>
<thead>
<tr>
<th>Code</th>
<th>R$_1$</th>
<th>Calculated PSA ($\text{Å}^2$)</th>
<th>ACDlogD7.4 with pKa correction</th>
<th>AZ logD7.4</th>
<th>LogD</th>
</tr>
</thead>
<tbody>
<tr>
<td>8a</td>
<td>-CH$_2$CF$_3$</td>
<td>56.91</td>
<td>5.482</td>
<td>4.4</td>
<td>5.40</td>
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<tr>
<td>8b</td>
<td>-CH$_2$CH$_2$F</td>
<td>56.91</td>
<td>5.347</td>
<td>3.96</td>
<td>5.30</td>
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<tr>
<td>9</td>
<td>-CH$_2$Ph</td>
<td>56.91</td>
<td>6.073</td>
<td>4.6</td>
<td>&gt;5.30</td>
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<tr>
<td>11a</td>
<td>-CH$_2$CH$_2$CF$_3$</td>
<td>56.91</td>
<td>5.876</td>
<td>4.83</td>
<td>&gt;5.50</td>
</tr>
<tr>
<td>11b</td>
<td>-SO$_2$CH$_2$CH$_3$</td>
<td>94.14</td>
<td>5.053</td>
<td>3.64</td>
<td>4.60</td>
</tr>
<tr>
<td>11c</td>
<td>-SO$_2$CH$_2$CH$_2$F</td>
<td>94.14</td>
<td>4.704</td>
<td>3.46</td>
<td>4.15</td>
</tr>
<tr>
<td>Code</td>
<td>R²</td>
<td>Calculated PSA (Å²)</td>
<td>ACDlogD7.4 with pKa correction</td>
<td>AZ logD7.4</td>
<td>LogD</td>
</tr>
<tr>
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<td>----------</td>
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<tr>
<td>11d</td>
<td>-SO₂CH₂CH₂CF₃</td>
<td>94.14</td>
<td>5.039</td>
<td>4.07</td>
<td>4.90</td>
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<tr>
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<td>5.563</td>
<td>3.97</td>
<td>5.10</td>
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<td>-SO₂CH₂CH₂CF₃</td>
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<td>4.15</td>
<td>5.30</td>
</tr>
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<td>11g</td>
<td>-SO₂CH₂CH₂(CH₂)₂</td>
<td>94.14</td>
<td>5.916</td>
<td>4.29</td>
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<tr>
<td>11h</td>
<td>-SO₂CH₂CH₃(CH₃)₃</td>
<td>94.14</td>
<td>6.327</td>
<td>4.56</td>
<td>&gt; 5.80</td>
</tr>
</tbody>
</table>

Table S3. Physicochemical parameters of “right arm” (R²) compounds.
Figure S1: Absence of correlation between physicochemical parameters and affinities a) The calculated PSA values (X-axis) had no obvious linear correlation with the negative logarithm of affinity values (pKᵢ, Y-axis) of the hCB₁ receptor antagonists (r² = 0.14, P = 0.068); b) The calculated LogD values (X-axis, ACDlogD7.4 with pKa correction) had no obvious linear correlation with the negative logarithm of affinity values (pKᵢ, Y-axis) of the hCB₁ receptor antagonists (r² = 0.012, P = 0.62); c) The calculated LogD values (X-axis, AZ logD74) had no obvious linear correlation with the negative logarithm of affinity values (pKᵢ, Y-axis) of the CB₁ receptor antagonists (r² = 8.2e-006; P = 0.99); d) The experimentally determined LogD values (X-axis, LogD) had no obvious linear correlation with the negative logarithm of affinity values (pKᵢ, Y-axis) of the hCB₁ receptor antagonists (r² = 0.24, P = 0.065).
Figure S2: Absence of correlation between physicochemical parameters and KRI values

a) The calculated PSA (X-axis) had no obvious linear correlation with the KRI values (Y-axis) of the hCB₁ receptor antagonists ($r^2 = 0.0044$, $P = 0.76$);
b) The calculated LogD values (X-axis, ACDlogD7.4 with pKa correction) had no obvious linear correlation with the KRI values (Y-axis) of the hCB₁ receptor antagonists ($r^2 = 0.045$, $P = 0.32$);
c) The calculated LogD values (X-axis, AZ logD74) had no obvious linear correlation with the KRI values (Y-axis) of the hCB₁ receptor antagonists ($r^2 = 0.38$; $P = 0.0029$);
d) The experimentally determined LogD values (X-axis, LogD) had no obvious linear correlation with the KRI values (Y-axis) of the hCB₁ receptor antagonists ($r^2 = 0.22$, $P = 0.070$).

References