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Library Synthesis in Flow

Continuous Flow Synthesis of Urea-Containing Compound Libraries Based on the Piperidin-4-one Scaffold

Alejandra Riesco-Domínguez,[a] Daniel Blanco-Ania,[a] and Floris P. J. T. Rutjes*[a]

Abstract: The advantages of performing reactions in continuous flow vs. the classic batch processes render flow chemistry a suitable technique for library synthesis. Inspired by our recent work to create fluorine-containing nitrogen heterocycles and by the potential of the urea group in drug design, we herewith describe the combination of both aspects in the continuous flow synthesis of two libraries of urea derivatives based on the piperidin-4-one scaffold.

Introduction

The urea group represents an important functionality in pharmaceutical and agrochemical products.[1] Urea-containing molecules possess an immense potential in drug design as a result of their capability for hydrogen binding to biomolecular targets.[2] Moreover, ureas are widely used in drug design for the modulation of several factors, such as selectivity, stability, toxicity and pharmacokinetic profile of lead molecules.[2] Examples of active compounds containing a urea unit are depicted in Figure 1. Trimefluor,[3] a selective pre- and post-emergence herbicide for use in cotton, and triflumuron,[4] a broad spectrum insecticide against chewing insects commercialized by Bayer CropScience, are examples of bioactive molecules containing a urea group. Another example of a urea-containing pharmaceutical is vestipitant,[5] a selective antagonist for the NK1 receptor.

Figure 1. Biologically active compounds containing a urea group.

Recently, we reported an enantio- and diastereoselective synthesis of piperidin-4-ones 2a–c from the enantiopure amino ketone 1 (Scheme 1).[6] Compounds 2a–c, containing three different fluorine functionalities (F, CF3 and SF5) to enhance their bioactivity and metabolic profile,[7] were synthesized and further derivatized into a novel library of spirocyclic compounds (3 and 4) under classic batch processes through a diastereoselective Pictet–Spengler cyclization.[6]

Scheme 1. Previously reported work (batch) and this work (flow) based on scaffolds 2a–c.

The inherent potential of this scaffold (2a–c) for derivatization combined with the advantages of flow chemistry for library synthesis[8] (including excellent heat exchange and fast mixing for better reaction control, automated small-scale optimization and rapid automated compound-library preparation) encouraged us to further develop a new class of urea derivatives in flow (5 and 6) based on scaffolds 2a–c (Scheme 1).

Results and Discussion

We started our investigations by testing the reactivity of our amines (2b and 2c) with alkyl isocyanates (ethyl [7A] or isopropyl isocyanate [7B], 1.5 equiv.) varying solvent, temperature and reaction time (see Table 1 for summarized results and Supporting Information [SI] for the entire optimization process). All reactions were carried out in a borosilicate glass reactor (channel width 600 μm, channel depth 500 μm and effective reactor volume 100 μL).[9] The microreactor was placed into a microreactor holder, which automatically aligns with the fluidic connections and makes contact with the temperature controlled...
metal plate in the microreactor holder. Then, the inlet modules were connected through the microreactor holder with the inlet ports of the microreactor and the outlet tubing was also placed at the outlet port. The tubing was connected to the syringes, which were connected to the pumps. The two solutions, one containing the piperidin-4-ones (2b or 2c) and the other one with the isocyanates 7 were pumped and brought together inside of the microreactor (Table 1). Initially, we used solvents such as MeCN or 1,2-dichloroethane in a temperature range of 50–80 °C and reaction times of 10–15 minutes (entries 1–4). Low conversions to ureas 5bA and 5bB were obtained in all these cases and only a slightly higher conversion to 5bA (ratio 5bA/2b 1:0.7) was achieved when we used MeCN at 50 °C (entry 1). The use of EtOH at 80 °C and a reaction time of 10 minutes provided a ratio of 1:1.2 for 5bB/2b (entry 5). An increase of the reaction time to 15 minutes (entry 6) gave higher conversion into product 5bB (1:0.15). By increasing the amount of isocyanate (2.0 and 2.5 equiv., entries 7 and 8, respectively), nearly full conversion to 5bB and full conversion to 5cA were obtained. However, carbamate 8 was also formed in the reaction mixture when EtOH was used as solvent, as a result of the nucleophilic attack of EtOH to the isocyanate. Therefore, we explored the use of bulkier alcohols as solvent (iPrOH and tBuOH) to avoid the formation of 8. Thus, the reaction of piperidin-4-one 2c with ethyl isocyanate (2.5 equiv.) in the presence of propan-2-ol gave full conversion to urea 5cA and less formation of the carbamate 8 (entry 9) whereas the formation of 8 was completely suppressed when tert-butyl alcohol was used (entry 10). With this result in hands, we tried to decrease the temperature of the reaction and the amount of isocyanate used. We confirmed that when using 2.0 equiv. of ethyl isocyanate and temperatures between 25–35 °C full conversion was not reached (entries 11 and 12). Finally, we found that the use of 2.0 equiv. of ethyl isocyanate at 50 °C in tBuOH were the suitable conditions to obtain full conversion to compound 5cA (entry 13). Once the conditions for the synthesis of aliphatic ureas were optimized, we attempted the synthesis of the aryl derivatives. Therefore, we first explored the reaction of 2b with 2,4-difluorophenyl isocyanate (7E, 1.5 equiv.) at 80 °C in EtOH and a reaction time of 20 minutes; the reaction, however, did not show any conversion to product 5bE and it resulted in a mixture of 2b and carbamate 8 (ratio 2b/8d 1:0.50; entry 14).

By changing the solvent to 1,2-dichloroethane, and using 1.3 equiv. of isocyanate 7E, full conversion to compound 5bE was obtained (entry 15).

With the final conditions in hands, five isocyanates 7A–E (alkyl and aryl isocyanates with different substituents on the phenyl ring, Figure 2) were selected for the generation of a 15-compound library (Table 2). For all experiments, three fractions (stabilization time, collected product and residual) were collected in separated vials and final products were analyzed di-

![Figure 2. Isocyanates used for the generation of the library.](image)

Table 1. Optimization process for the synthesis of alkyl and aryl ureas 5b and 5c.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>7 [equiv.]</th>
<th>Solvent</th>
<th>t [°C]</th>
<th>time [min]</th>
<th>Product 8</th>
<th>R</th>
<th>R1</th>
<th>Ratio 5/2/8</th>
<th>Flow rate [μL/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2b</td>
<td>7A (1.5)</td>
<td>MeCN</td>
<td>50</td>
<td>10</td>
<td>5bA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1.0:7:0[b]</td>
<td>10.00</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td>7A (1.5)</td>
<td>MeCN</td>
<td>80</td>
<td>10</td>
<td>5bA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1.0:1:0</td>
<td>10.00</td>
</tr>
<tr>
<td>3</td>
<td>2b</td>
<td>7A (1.5)</td>
<td>MeCN</td>
<td>80</td>
<td>15</td>
<td>5bA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1.5:0:0</td>
<td>6.67</td>
</tr>
<tr>
<td>4</td>
<td>2b</td>
<td>7B (1.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>10</td>
<td>5bB</td>
<td>8a</td>
<td>CH3CH2</td>
<td>1:1:2:0:14</td>
<td>10.00</td>
</tr>
<tr>
<td>5</td>
<td>2b</td>
<td>7B (1.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>10</td>
<td>5bB</td>
<td>8a</td>
<td>CH3CH2</td>
<td>1:0:15:0:31</td>
<td>6.67</td>
</tr>
<tr>
<td>6</td>
<td>2b</td>
<td>7B (1.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>15</td>
<td>5bB</td>
<td>8a</td>
<td>CH3CH2</td>
<td>1:0:08:0:31</td>
<td>5.88</td>
</tr>
<tr>
<td>7</td>
<td>2b</td>
<td>7B (2.0)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5bB</td>
<td>8a</td>
<td>CH3CH2</td>
<td>1:0:08:0:31</td>
<td>5.88</td>
</tr>
<tr>
<td>8</td>
<td>2c</td>
<td>7A (2.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5cA</td>
<td>8b</td>
<td>CH3CH2</td>
<td>1:0:0:92</td>
<td>5.88</td>
</tr>
<tr>
<td>9</td>
<td>2c</td>
<td>7A (2.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5cA</td>
<td>8c</td>
<td>CH3CH2</td>
<td>1:0:0:6</td>
<td>5.88</td>
</tr>
<tr>
<td>10</td>
<td>2c</td>
<td>7A (2.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5cA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1:0:0:6</td>
<td>5.88</td>
</tr>
<tr>
<td>11</td>
<td>2c</td>
<td>7A (2.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5cA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1:0:12:0:11</td>
<td>5.88</td>
</tr>
<tr>
<td>12</td>
<td>2c</td>
<td>7A (2.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5cA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1:0:10:0:11</td>
<td>5.88</td>
</tr>
<tr>
<td>13</td>
<td>2c</td>
<td>7A (2.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>17</td>
<td>5cA</td>
<td>–</td>
<td>CH3CH2</td>
<td>1:0:10:0:11</td>
<td>5.88</td>
</tr>
<tr>
<td>14</td>
<td>2b</td>
<td>7E (1.5)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>20</td>
<td>5bE</td>
<td>8d</td>
<td>2.4-F2CC6H5</td>
<td>0:1:0.50</td>
<td>5.00</td>
</tr>
<tr>
<td>15</td>
<td>2b</td>
<td>7E (1.3)</td>
<td>1,2-DCE</td>
<td>80</td>
<td>20</td>
<td>5bE</td>
<td>8d</td>
<td>2.4-F2CC6H5</td>
<td>0:1:0.50</td>
<td>5.00</td>
</tr>
</tbody>
</table>

[a] Calculated by 1H NMR of the fraction of the collected product. [b] Analyzed by 1H NMR of the fraction of stabilization time.
Table 2. Library of ureas 5aA–cE based on the piperidin-4-one scaffold.

<table>
<thead>
<tr>
<th>Urea</th>
<th>Reaction Conditions</th>
<th>Conversion</th>
<th>Isolated Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>5aA[^a]</td>
<td>Reaction carried out in t-BuOH at 50 °C in 17 minutes using 2.0 equiv. of isocyanate.</td>
<td>99%[^d]</td>
<td>83%[^d]</td>
</tr>
<tr>
<td>5bA[^a]</td>
<td>Reaction carried out in 1,2-dichloroethane at 80 °C in 17 min using 1.3 equiv. of isocyanate.</td>
<td>99%[^d]</td>
<td>85%[^d]</td>
</tr>
<tr>
<td>5cA[^a]</td>
<td>Conversion calculated by ¹H NMR of the fraction of collected product.</td>
<td>99%[^d]</td>
<td>92%[^d]</td>
</tr>
</tbody>
</table>

[^a]: Reaction carried out in t-BuOH at 50 °C in 17 minutes using 2.0 equiv. of isocyanate.  
[^b]: Reaction carried out in 1,2-dichloroethane at 80 °C in 17 min using 1.3 equiv. of isocyanate.  
[^c]: Conversion calculated by ¹H NMR of the fraction of collected product.  
[^d]: Isolated yield of the fraction of collected product.
ureas methanolation[13] may take place in the purification process. In this case, methanolation occurred because the nitrogen in the piperidine ring might not be fully conjugated anymore with the carbonyl and therefore MeOH can form a hydrogen bond with the nitrogen. To analyze the reactivity of these ureas in MeOH, we dissolved urea $5aC$ in CD$_3$OD and monitored the mixture by $^1$H NMR (Scheme 2). We observed that compound $5aC$ was still present after 1–4 h, but after 19 h at room temperature compound $5aC$ transformed into piperidin-4-one $2a$ (protonated and deuterated substrates), phenyl isocyanate $7C$ and carbamates $9$ and $10$ (relative abundance $9/10$ 30:70). $^1$H NMR showed a mixture of compounds which was confirmed by GC–MS (Scheme 2).

Scheme 2. Methanolysis of ureas $5aC$ and $5cB$.

We also studied the decomposition of the aliphatic urea $5cB$, which also showed the presence of carbamates $9$ and $10$ (detected by GC–MS) and the starting material $2c$ (protonated and deuterated substrates).

Finally, a diastereoselective reduction of ketone $2c$ was carried out in flow using LiBH$_4$ as reducing reagent to provide full conversion to a 10:1 mixture of piperidinols $11$ and $12$ (Scheme 3). The workup of this reaction was performed offline after the reaction mixture was completely collected in the corresponding vial. The reduction of ketone $2b$ was performed in batch using $N$-Selectride$[14]$ to give alcohol $12$.$[15]$

Scheme 3. Reduction of $2a$ and $2c$ with $N$-Selectride and LiBH$_4$.

Then, we decided to perform the urea synthesis using as starting material amino alcohol $11$ (Table 3). Initially, we performed the reaction between $11$ and isocyanate $7B$ using the conditions previously developed for aliphatic isocyanates (tBuOH, 17 min and 50 °C). We decreased the amount of $7B$ to 1.0 equiv., to firstly test the reactivity of our hindered amine in the presence of the nucleophilic alcohol. We confirmed by $^1$H NMR that only the amine group reacted with the isocyanate and therefore the corresponding carbamate was not observed.

However, while using 1.0 equiv. of isocyanate, a ratio $11/6b$ 10:5 was obtained. Thus, we increased the amount of isocyanate $7B$ to 1.0 equiv. and full conversion to urea $6b$ was achieved (84 % yield). When we applied these conditions using ethyl ($7A$) and benzyl ($7F$) isocyanates, amino alcohol $11$ was converted with full conversion to ureas $6a$ and $6c$$[16]$ in 85 and 99 % yield, respectively. Finally, two additional examples with aryl isocyanates ($7C$ and $7D$) were synthesized. In this case, the use of 1.1 equiv. of isocyanate in 1,2-DCE at 80 °C was sufficient to reach full conversion to ureas $6d$ and $6e$. For compounds $6a$–$e$, a 6:1 ratio of conformers was obtained.

Table 3. Library of ureas $6a$–$e$ based on amino alcohol $11$.

<table>
<thead>
<tr>
<th>Entry</th>
<th>$^1$H [ppm] (13a)</th>
<th>[ppm] (13b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H$^2$ 4.89</td>
<td>4.36</td>
</tr>
<tr>
<td>2</td>
<td>H$^3$ 2.11/1.84</td>
<td>2.20–2.1/2.00–1.89</td>
</tr>
<tr>
<td>3</td>
<td>H$^4$ 4.43</td>
<td>4.16</td>
</tr>
<tr>
<td>4</td>
<td>H$^5$ 2.70/2.00</td>
<td>2.37/2.20–2.10</td>
</tr>
<tr>
<td>5</td>
<td>H$^6$ 5.65</td>
<td>5.12</td>
</tr>
<tr>
<td>6</td>
<td>H$^7$ 3.80–3.70</td>
<td>3.58–3.49</td>
</tr>
<tr>
<td>7</td>
<td>H$^8$ 0.88</td>
<td>0.72</td>
</tr>
<tr>
<td>8</td>
<td>H$^9$ 0.74</td>
<td>0.60</td>
</tr>
</tbody>
</table>

As previously mentioned, the presence of the conformers (rotamers or atropisomers) was caused by the hindered rotation around one of the single N–CO bonds of the urea.$[17]$ NOESY experiments of compound $13a$ (the major product of reaction between alcohol $12$ and isocyanate $7B$) showed correlations between the NH of the urea with both benzylic protons (Table 4), indicating therefore the existence of atropisomerism (in case of rotamers, each rotamer would show only one corre-
of the equipment may take long; therefore, a stabilization time is calculated and run before the collecting product fraction. The stabilization time is calculated following Equation (1).\(^\text{[12]}\)

\[
\text{Stabilization Time} = 3 \times \frac{\text{Reactor Volume}}{\text{Total Flow Rate}} \quad (1)
\]

For all reactions, products were analyzed from the collected fraction and therefore calculations and yields based on this fraction.

**General Procedure for the Synthesis of Alkyl Ureas 5aA, 5aB, 5aA, 5bB, 5cA and 5cB:** According to the general procedure, the reaction of piperidin-4-one 2 (3.63 mg, 0.011 mmol) in tBuOH (99.8 mmol) with 7A afforded urea 5aA (3.67 mg, 9.16 μmol). \(^\text{1}^\text{H NMR} (400 MHz, CDCl}_3): \delta = 7.39–7.31 (m, 2 H), 7.08–7.01 (m, 2 H), 6.85 (d, J = 8.2 Hz, 1 H, 6.75 (dd, J = 8.2, 2.1 Hz, 1 H), 6.64 (d, J = 2.1 Hz, 1 H), 6.00 (t, J = 5.4 Hz, 1 H), 5.22 (d, J = 9.7, 4.9 Hz, 1 H), 4.40 (t, J = 5.2 Hz, 1 H), 3.86 (s, 3 H), 3.73 (s, 3 H), 3.18–3.07 (m, 3 H), 2.88–2.73 (m, 2 H), 2.60 (dd, J = 17.6, 4.9 Hz, 1 H), 0.88 (t, J = 7.2 Hz, 3 H) ppm. \(^{13}\text{C NMR} (101 MHz, CDCl}_3): \delta = 207.8, 162.1 (d, J = 247.5 Hz), 159.1, 150.1, 149.0, 139.0 (d, J = 33.9 Hz), 134.9, 128.4 (d, J = 8.0 Hz), 117.9, 116.0 (d, J = 21.5 Hz), 111.4, 108.9, 56.1, 56.0, 52.4, 46.1, 43.6, 36.2, 15.2 ppm. FTIR: 3420, 2947, 2762, 1639, 1511, 1264, 1228, 1025 cm\(^{-1}\). HRMS (ESI (m/z)) calc. for \(\text{C}_{23}\text{H}_{25}\text{F}_{3}\text{N}_{2}\text{O}_{4}\) + Na\(^+\) = 473.16547, found 473.16547 (\(|\Delta| = 1.0 \text{ppm})\). \(R_F\) 0.27 (Heptane/AcOEt, 1:2). **Yield:** 83 %.

**Conclusion**

In summary, we have synthesized a small library of ureas in continuous flow. The reactions utilized for their syntheses were achieved in a reaction time of 17 min without further need of purification rendering drug-like molecules. Moreover, we have also diastereoselectively reduced the ketone group in flow in 3 min reaction time. Additional urea formation of amino alcohol 11 was also performed to create five different urea derivatives. NMR studies confirmed the formation of conformers caused by the hindered rotation around one of the single N–CO bonds of the urea. The elucidation of these species to be identified as either rotamers or atropisomers could not be clarified. This methodology could be applied to a wide range of substrates as a tool to prepare libraries of potentially bioactive molecules.

**Experimental Section**

**General Information:** Reagents were obtained from commercial suppliers and were used without purification. Standard syringe techniques were applied for the transfer of dry solvents and air- or moisture-sensitive reagents. Reactions were followed by \(^{1}H\) NMR, and \(R_F\) values were obtained, using thin layer chromatography (TLC) on silica gel-coated plates (Merck 60 F254) with the indicated solvent mixture. Detection was performed with UV light, and/or by charring at ca. 150 °C after dipping into a solution of KMnO\(_4\). Infrared spectra were recorded on an IR-ATR Bruker TENSOR 27 spectrometer. High-resolution or accurate mass measurement (\(\Delta M < 3 \text{millu or 5 ppm}\)) were recorded on a JEOL AccuTOF-CS JMS-T100CS for Electrospray (spectra recorded in infusion in MeOH containing 50 \(\text{mM PPG-475 as internal mass-drift compensation standard}\). High-resolution or accurate mass measurement (\(\Delta M < 3 \text{millu or 5 ppm}\)) were recorded on a JEOL AccuTOF-GCV JMS-T100GC (GC/Electron Ionization MS, column bleeding at high temperature used as internal mass drift compensation standard) for methanalysis experiments. NMR spectra were recorded at 298 K on a Varian Inova 400 (400 MHz), Bruker Avance III 600 MHz or Bruker Avance III 500 MHz spectrometer in the solvent indicated. Chemical shifts are given in parts per million (ppm) with respect to tetramethylsilane (\(\delta = 0.00 \text{ppm}\)) as internal standard for \(^{1}H\) NMR and CDCl\(_3\) (\(\delta = 77.16 \text{ppm}\)) as internal standard for \(^{13}\text{C}\) NMR spectroscopy. Coupling constants are reported as \(J\) values in Hertz (Hz). \(^{1}H\) NMR spectroscopic data are reported as follows: chemical shift (ppm), multiplicity (s = singlet, d = doublet, dd = doublet of doublets, dt = doublet of triplets, dq = doublet of quartets, ddd = doublet of doublet of doublets, quint = quintet, t = triplet, td = triplet of doublets, m = multiplet), coupling constants (Hz), and integration. Compounds were fully characterized by \(^{1}H\), \(^{13}\text{C}\), COSY, HSQC, HMBC and NOESY. Reactions were carried out using the FlowStart Evo equipment and microreactors purchased by FutureChemistry (futurechemistry.com accessed Sep 11, 2017). At very low flow rates, stabilization and pressure

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According to the general procedure, the reaction of piperidin-4-one 2a (3.49 mg, 0.01 mmol) in tBuOH (99.9 mmol) with 7B afforded 5aB (3.72 mg, 8.98 μmol).1H NMR (400 MHz, CDCl3): δ = 7.67–7.71 (m, 2 H), 6.80 (d, J = 8.2 Hz, 1 H), 6.75 (dd, J = 8.2, 2.2 Hz, 1 H), 6.55 (d, J = 2.1 Hz, 1 H), 6.46 (t, J = 5.2 Hz, 1 H), 5.11 (dd, J = 10.2, 4.9 Hz, 1 H), 4.33 (d, J = 7.2 Hz, 1 H), 3.88–3.82 (m, 1 H), 3.86 (s, 3 H), 3.18 (dd, J = 18.4, 4.7 Hz, 1 H), 2.87 (dd, J = 18.4, 5.7 Hz, 1 H), 2.74 (dd, J = 17.5, 10.2 Hz, 1 H), 2.61 (dd, J = 17.5, 4.9 Hz, 1 H), 0.97 (d, J = 6.5 Hz, 3 H), 0.82 (d, J = 6.5 Hz, 3 H) ppm.13C NMR (101 MHz, CDCl3): δ = 207.2, 158.3, 150.3, 149.2, 147.5, 134.8, 129.9 (indirect observation), 127.3, 126.1 (q, J = 3.6 Hz, 1 H), 122.5 (indirect observation), 117.9, 111.5, 108.7, 56.5, 56.1, 56.0, 52.3, 46.3, 43.9, 23.3, 23.0 ppm. FTIR: ν = 3420, 2947, 2968, 1722, 1642, 1516, 1262, 1238, 1123, 767 cm–1. HRMS ([ESI (m/z)] calcd. for (C26H25FN2O4 + Na)+ = 471.16568, found 471.16560 ([Δ] = 1.6 ppm). Rp = 0.70 (heptane/AcOEt, 1:2). Yield: 88%.

(2S,6R)-2-(3,4-Dimethoxyphenyl)-4-oxo-6-(4-[pentfluoro-1,1'-sulfanil]phenyl)piperidine-1-carboxamide (5cB): According to the general procedure, the reaction of piperidin-4-one 4c (2.49 mg, 0.01 mmol) in tBuOH (100.2 mmol) with 7B afforded 5cB (4.48 mg, 9.65 μmol).1H NMR (400 MHz, CDCl3): δ = 7.37–7.28 (m, 2 H), 7.25–7.21 (m, 2 H), 7.17–7.13 (m, 2 H), 6.88–6.84 (m, 2 H), 6.36–6.32 (m, 1 H), 5.97 (d, J = 10.8 Hz, 1 H), 4.92 (q, J = 18.7 Hz, 1 H), 2.71 (dd, J = 17.5, 7.2 Hz, 1 H), 2.61 (dd, J = 17.5, 4.9 Hz, 1 H), 0.97 (d, J = 6.5 Hz, 3 H), 0.82 (d, J = 6.5 Hz, 3 H) ppm.13C NMR (101 MHz, CDCl3): δ = 207.2, 158.3, 150.3, 149.2, 147.5, 134.8, 129.9 (indirect observation), 127.3, 126.1 (q, J = 3.6 Hz, 1 H), 122.5 (indirect observation), 117.9, 111.5, 108.7, 56.5, 56.1, 56.0, 52.3, 46.5, 43.9, 23.3, 23.0 ppm. FTIR: ν = 3420, 2947, 2968, 1722, 1642, 1516, 1262, 1238, 1123, 767 cm–1. HRMS ([ESI (m/z)] calcd. for (C26H25FN2O4 + Na)+ = 471.16568, found 471.16560 ([Δ] = 1.6 ppm). Rp = 0.70 (heptane/AcOEt, 1:2). Yield: 89%. Simulation and Synthesis of 2-Chlorophenyl-2-(3,4-dimethoxyphenyl)-4-oxopiperidine-1-carboxamide (5dB): According to the general procedure, the reaction of piperidin-4-one 2a (2.4 mg, 7.28 μmol) in 1,2-DCE (90.2 μmol) with 7D afforded 5dD (2.58 mg, 5.34 μmol).1H NMR (400 MHz, CDCl3): δ = 8.09 (dd, J = 8.2, 1.5 Hz, 1 H), 7.44–7.37 (m, 2 H), 7.25–7.17 (m, 2 H), 7.11–7.04 (m, 2 H), 7.02 (s, 1 H), 6.98–6.90 (m, 1 H), 6.85 (dd, J = 8.2, 1.9 Hz, 1 H), 6.82 (d, J = 8.2 Hz, 1 H), 6.73 (d, J = 1.9 Hz, 1 H), 6.15 (t, J = 5.6 Hz, 1 H), 5.50 (dd, J = 9.3, 5.1 Hz, 1 H), 3.86 (s, 3 H), 3.75 (s, 3 H), 3.17 (dd, J = 18.3, 5.6 Hz, 1 H).
According to the general procedure, the reaction of piperidin-4-one 2b (1.37 mg, 3.61 μmol) in 1,2-DCE (82.8 μmol) with 7E afforded 5bE (2.15 mg, 4.03 μmol). 1H NMR (500 MHz, CDCl3): δ = 8.09 (dd, J = 8.3, 1.5 Hz, 1 H), 7.67–7.63 (m, 2 H), 7.60–7.56 (m, 2 H), 7.25–7.19 (m, 2 H), 7.04 (s, 1 H), 6.95 (dd, J = 8.1, 1.4, 1.5 Hz, 1 H), 6.86 (dd, J = 8.3, 2.1, 2 Hz), 6.82 (d, J = 8.3, 1 Hz, 1 H), 6.65 (d, J = 2.1 Hz, 1 H), 6.31 (t, J = 5.4 Hz, 1 H), 5.43 (dd, J = 9.7, 5.1 Hz, 1 H), 3.85 (s, 3 H), 3.70 (s, 3 H), 3.22 (dd, J = 18.5, 5.1 Hz, 1 H), 2.94 (ddd, J = 18.5, 1.8, 0.9 Hz, 1 H), 2.80 (d, J = 17.6, 9.7 Hz, 1 H), 2.74–2.68 (m, 3 H), 2.05 (s, 1 H), 1.69 (dd, J = 8.2, 1.5 Hz, 1 H), 1.68 (dd, J = 8.2, 1.5 Hz, 1 H), 1.68 (d, J = 2.1 Hz, 1 H), 1.63 (t, J = 5.4 Hz, 1 H), 1.50 (dd, J = 9.7, 5.1 Hz, 1 H), 3.85 (s, 3 H), 3.63 (s, 3 H), 3.21 (d, J = 18.6, 5.0 Hz, 1 H), 2.94 (ddd, J = 18.6, 1.8, 5.0 Hz, 1 H), 2.86 (d, J = 17.6, 9.7 Hz, 1 H), 2.74 (d, J = 17.6, 5.1 Hz, 1 H) ppm. 13C NMR (100 MHz, CDCl3): δ = 206.3, 154.2, 149.3, 146.3, 133.6, 132.3, 130.2 (q, J = 32.7 Hz, 128.9), 127.4, 127.2, 126.1 (q, J = 3.6 Hz, 124.1), 127.4 (q, J = 272.5 Hz, indirect observation), 123.1, 122.2, 118.5, 111.7, 108.8, 56.6, 56.0, 55.9, 52.8, 46.5, 43.0 ppm. FTIR: ν = 3356, 2951, 2724, 1766, 1593, 1517, 1439, 1327, 1263, 1234, 1124, 754 cm⁻¹. HRMS [ESI (m/z)] calcd. for (C₂H₂F₂Cl₂F₄N₄O₄ + Na⁺) = 555.12689, found 555.12901 ([Δ] = 2.8 ppm). Rf: 0.33 (heptane/AcOEt, 2:1). Yield: 77%.
(2S,4S,6R)-2-(3,4-Dimethoxyphenyl)-4-hydroxy-6-[4-(trifluoromethyl)phenyl]piperidin-4-ol (12): N-Selectride (3.95 mL, 3.95 mmol, 1.0 M solution in THF) was added to a solution of piperidin-4-one 2b (500 mg, 1.32 mmol) in dry THF (96 mL) at ~78 °C. The reaction was stirred for 1 h and it was quenched with H2O (100 mL). The solution was allowed to reach 21 °C and then AcOEt was added. The organic layer was separated and the aqueous layer was extracted with AcOEt (3 × 50 mL). The combined organic layers were washed with brine, dried with anhydrous Na2SO4, filtered off and concentrated in vacuo. The residue was purified by SCX-2 column to afford amino alcohol 12 (456 mg, 1.20 mmol). 1H NMR (400 MHz, CDCl3): δ = 7.66–7.53 (m, 4 H), 7.04–6.97 (m, 2 H), 6.84 (d, J = 8.1 Hz, 1 H), 4.40–4.32 (m, 2 H), 4.25 (dd, J = 11.7, 2.7 Hz, 1 H), 3.91 (s, 3 H), 3.87 (s, 3 H), 1.95–1.87 (m, 2 H), 1.86–1.70 (m, 2 H) ppm. 13C NMR (101 MHz, CDCl3): δ = 149.4, 149.1, 148.4, 137.5 (indirect observation), 129.4 (indirect observation), 127.3, 125.5 (q, J = 3.7 Hz), 123.0 (indirect observation), 118.9, 111.3, 110.2, 66.2, 50.9, 57.0, 55.7, 41.6 ppm. FTIR: ν = 2936, 1517, 1465, 1326, 1263, 1163, 1123, 1067, 1027, 806 cm–1. HRMS [ESI (m/z)] calcd. for (C22H27F5N2O4S+N+) = 382.16300, found 382.16336 (|Δ| = 0.94 ppm). Yield: 91 %.

Synthesis and Full Characterization of Alkyl Ureas 6a–c: Solution A: compound 11 (1.0 equiv.) dissolved in rBuOH (94.3–96.5 mm). Solution B: alkyl isocyanate (7A, 7B or 7F, 1.5 equiv.) dissolved in rBuOH (0.1 ml). Solution A (2.35 μL/min) was combined with B (3.53 μL/min) inside the glass microreactor (internal volume: 100 μl). The reaction was performed at 50 °C for 17 min.

(2S,4S,6R)-2-(3,4-Dimethoxyphenyl)-N-ethyl-4-hydroxy-6-[4-(pentafluoro-λ6-t-butyl)phenyl]piperidine-1-carboxamide 13a and –ethyl-4-hydroxy-6-[4-(trifluoromethyl)phenyl]piperidine-1-carboxamide 13b: According to the general procedure, the reaction of amino alcohol 11 (2.37 mg, 5.39 μmol) in rBuOH (94.6 mm) afforded urea 13a (2.56 mg, 4.54 μmol). 1H NMR (400 MHz, CDCl3): δ = 7.78–7.76 (m, 2 H), 7.75–7.70 (m, 2 H), 7.20–7.14 (m, 2 H), 6.99–6.90 (m, 4 H), 6.87 (d, J = 8.2 Hz, 1 H), 6.56 (s, 1 H), 6.51 (d, J = 2.1 Hz, 1 H), 5.80 (t, J = 5.8 Hz, 1 H), 4.61 (dd, J = 12.0, 4.3 Hz, 1 H), 4.36–4.24 (m, 2 H), 3.88 (s, 3 H), 3.62 (s, 3 H), 2.58 (dt, J = 14.3, 6.9 Hz, 1 H), 2.37 (dt, J = 14.9, 5.4 Hz, 1 H), 2.18 (dt, J = 13.6, 5.1 Hz, 1 H), 2.03 (dt, J = 13.7, 11.6 Hz, 1 H), 1.89–1.85 (m, 1 H) ppm. 13C NMR (101 MHz, CDCl3): δ = 157.6, 152.6 (indirect observation), 150.4, 149.3, 148.9, 138.5, 135.3, 129.0, 128.2, 124.6–126.2 (m), 123.6, 119.8, 118.5, 111.6, 109.1, 65.1, 59.1, 56.2, 55.9, 53.8, 41.0, 36.6 ppm. FTIR: ν = 3388, 2933, 2841, 1686, 1647, 1501, 1443, 1420, 1264, 1247, 1130, 1027, 843, 754 cm–1. HRMS [ESI (m/z)] calcd. for (C22H27F5N2O4S+N+) = 533.15094, found 531.15049, found 531.15049 (|Δ| = 1.26 ppm). Yield: 85 %.

(2S,4S,6R)-2-(3,4-Dimethoxyphenyl)-4-hydroxy-6-[4-(pentafluoro-λ6-sulfanyl)phenyl]piperidine-1-carboxamide (6d): According to the general procedure, the reaction of amino alcohol 11 (2.57 mg, 5.85 μmol) in 1,2-DCE (95.6 mm) afforded urea 6d (3.26 mg, 5.84 μmol). 1H NMR (400 MHz, CDCl3): δ = 7.80–7.76 (m, 2 H), 7.75–7.70 (m, 2 H), 7.20–7.14 (m, 2 H), 6.99–6.90 (m, 4 H), 6.87 (d, J = 8.2 Hz, 1 H), 6.56 (s, 1 H), 6.51 (d, J = 2.1 Hz, 1 H), 5.80 (t, J = 5.8 Hz, 1 H), 4.61 (dd, J = 12.0, 4.3 Hz, 1 H), 4.36–4.24 (m, 2 H), 3.88 (s, 3 H), 3.62 (s, 3 H), 2.58 (dt, J = 14.3, 6.9 Hz, 1 H), 2.37 (dt, J = 14.9, 5.4 Hz, 1 H), 2.18 (dt, J = 13.6, 5.1 Hz, 1 H), 2.03 (dt, J = 13.7, 11.6 Hz, 1 H), 1.89–1.85 (m, 1 H) ppm. 13C NMR (101 MHz, CDCl3): δ = 157.6, 152.6 (indirect observation), 150.4, 149.3, 148.9, 138.5, 135.3, 129.0, 128.2, 124.6–126.2 (m), 123.6, 119.8, 118.5, 111.6, 109.1, 65.1, 59.1, 56.2, 55.9, 53.8, 41.0, 36.6 ppm. FTIR: ν = 3388, 2933, 2841, 1686, 1647, 1501, 1443, 1420, 1264, 1247, 1130, 1027, 843, 754 cm–1. HRMS [ESI (m/z)] calcd. for (C22H27F5N2O4S+N+) = 533.15094, found 581.15094, found 581.15049 (|Δ| = 1.70 ppm). Yield: 99 %.
(1.2 mL) at 21 °C and the reaction was stirred for 20 h. The solvent was removed under vacuo and the crude was purified by column chromatography (CH2Cl2 → CH2Cl2/MeOH, 10:1) to afford compounds 13a and 13b (21.5 mg, 0.046 mmol). Combined yield: 38%.

13a: 1H NMR (400 MHz, CDCl3): δ = 7.59–7.49 (m, 4 H), 6.84–6.74 (m, 2 H), 6.64 (br s, 1 H), 5.65 (t, J = 5.4 Hz, 1 H), 4.90 (dd, J = 10.0, 4.1 Hz, 1 H), 4.43 (quint, J = 5.2 Hz, 1 H), 4.33 (d, J = 7.4 Hz, 1 H), 3.83 (s, 3 H), 3.82–3.71 (m, 1 H), 3.71 (s, 3 H), 2.76–2.64 (m, 1 H), 4.1 Hz, 1 H), 4.43 (quint, J = 3.8 Hz, 1 H), 0.89 (d, J = 1.70 ppm).

13b: 1H NMR (400 MHz, CDCl3): δ = 7.69–7.62 (m, 2 H), 7.61–7.54 (m, 2 H), 6.90–6.84 (m, 1 H), 6.81 (dd, J = 8.2, 0.8 Hz, 1 H), 6.67 (d, J = 1.9 Hz, 1 H), 5.12 (dd, J = 7.3, 5.2 Hz, 1 H), 4.36 (dd, J = 11.7, 3.9 Hz, 1 H), 4.32 (d, J = 7.5 Hz, 1 H), 4.23–4.11 (m, 1 H), 3.86 (s, 3 H), 3.73 (s, 3 H), 3.60–3.47 (m, 1 H), 2.41–2.33 (m, 1 H), 2.20–2.10 (m, 2 H), 2.01–1.91 (m, 1 H), 0.72 (d, J = 5.9Hz, 3 H), 0.61 (d, J = 6.6 Hz, 3 H) ppm. 13C NMR (101 MHz, CDCl3): δ = 159.3, 149.7, 148.65–148.59 (m), 148.5, 136.1, 129.2 (q, J = 32.6 Hz), 127.4, 125.5 (q, J = 3.7 Hz), 122.8 (indirect observation), 118.3, 111.3, 109.6, 62.4, 56.0, 55.9, 54.1, 52.1, 42.8, 39.6, 36.1, 23.2, 22.9 ppm. FTIR: ν = 3415, 2965, 2937, 1619, 1517, 1465, 1327, 1262, 1164, 1123, 1070, 1019, 808 cm–1.

HRMS [ESI (m/z)] calcd. for (C_{24}H_{29}F_{3}N_{2}O_{4} + Na)^+ = 489.19771, found 489.19688 (|Δ| = 1.43 ppm).

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Keywords: Continuous flow · Nitrogen heterocycles · Atropisomers · Nitrogen heterocycles · Compound Libraries

[9] Reactions were carried out using the FlowStart Evo equipment and microreactors purchased from FutureChemistry (futurechemistry.com accessed Sep 11, 2017).
[10] 1,3-Diethyurea was obtained as a side product in the reaction mixture (ratio 5cA/1,3-diethyurea 1:0.28).
[11] The presence of 1,3-diethyurea was reduced (ratio 5cA/1,3-diethyurea 1:0.1).
[12] At very low flow rates, stabilization and pressure of the equipment may take long; therefore, a stabilization time is calculated and run before the collecting product fraction. The stabilization time is calculated in Equation (1), experimental section.
[15] The reduction of ketone 2 to alcohol 12 was unsuccessfully performed in flow.
[16] 1,3-Dibenzylurea was present in the reaction mixture (ratio 6c/1,3-di-benzylurea 1:0.15).
[18] We do not rule out the possibility of a mixture of rotamers because the 13C NMR chemical shift of the carbamoyl carbon is δ = 159.3 ppm and the IR stretching frequency of the C=O is at 1619 cm–1 in the IR (higher values would be expected if atropisomers were observed, although the absence of examples of this phenomenon in the literature makes the prediction of those values difficult).
[19] Compounds 13a and 13b were isolated after column chromatography of the reaction in batch of amino alcohol 12 and isopropyl isocyanate 7B.

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