The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/83955

Please be advised that this information was generated on 2017-10-22 and may be subject to change.
Synthesis of Dihydrouracils Spiro-Fused to Pyrrolidines: Druglike Molecules Based on the 2-Arylethyl Amine Scaffold

Daniel Blanco-Ania 1, Carolina Valderas-Cortina 1, Pedro H.H. Hermkens 2, Leo A.J.M. Slidregt 3, Hans W. Scheeren 1 and Floris P.J.T. Rutjes 1,*

1 Institute for Molecules and Materials, Radboud University Nijmegen, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands
2 MSD Research Laboratories, P.O. Box 20, 5340 BH Oss, The Netherlands
3 Solvay Pharmaceuticals, Sector Discovery Weesp, P.O. Box 900, 1380 DA Weesp, The Netherlands

* Author to whom correspondence should be addressed; E-Mail: f.rutjes@science.ru.nl.

Received: 5 February 2010; in revised form: 26 March 2010 / Accepted: 30 March 2010 / Published: 30 March 2010

Abstract: The synthesis of a small library of dihydouracils spiro-fused to pyrrolidines is described. These compounds are synthesized from β-aryl pyrrolidines, providing products with the 2-arylethyl amine moiety, a structural feature often encountered in compounds active in the central nervous system. The β-aryl pyrrolidines are synthesized through a three-step methodology that includes a Knoevenagel condensation reaction, a 1,3-dipolar cycloaddition reaction, and a nitrile reduction.

Keywords: Knoevenagel condensation; 1,3-dipolar cycloaddition; azomethine ylide; parallel synthesis; spiro dihydouracils

1. Introduction

The 2-arylethyl amine moiety 1 (Figure 1) is an important privileged structure, which is encountered in numerous compounds active in the central nervous system (CNS). This privileged structure is present in neurotransmitters such as dopamine, epinephrine, norepinephrine, and serotonin [1]. Salmeterol [2,3] and venlafaxine [4–6], two of the ten best-selling prescription drugs in 2006 [7],
also contain this moiety. In addition, the 2-aryl ethyl amine unit occurs in many hallucinogenic drugs, such as LSD, MDMA (ecstasy), mescaline, and psilocybin (magic mushrooms) [8,9].

Figure 1. 2-Arylethyl amine (1), uracil (2), thymine (3), and zidovudine (AZT, 4).

On the other hand, pyrimidine-2,4-diones are a class of bioactive heterocyclic molecules, the most famous examples being uracil (2) and thymine (3, Figure 1), which form part of the nucleotides of RNA and DNA, respectively [10]. Pyrimidine-2,4-diones have attracted considerable attention in the pharmaceutical industry as anti-inflammatory agents [11], dopamine receptor agonists [12], serotonin uptake inhibitors [13], and antiepileptic agents [14]. A good example of a pyrimidine-2,4-dione derivative with a medicinal application is zidovudine (AZT, 4, Figure 1), used as an anti-AIDS agent [15]. This moiety is also the core structural element of some fungicides [16] and herbicides [17].

It is known that the difference in activity and receptor selectivity of drugs might be explained by the conformation of the contained privileged structure. Generation of semi-rigid drugs facilitates the study of their interactions with the receptors, may lead to more selective interactions with fewer side effects, and permits the rational design of more potent and selective drugs in the future [18,19]. Herein we present the parallel synthesis of a library comprised of compounds combining all the above features (Scheme 1). First, these compounds possess a β-aryl pyrrolidine with a conformationally constrained 2-arylethyl amine. Second, they are semirigid structures because of the spiro fusion to a dihydrouracil. It is known that the combination of privileged structures can lead to new chemical entities that may have pharmacological relevance [20,21] and increase the structural diversity.

Scheme 1. Combination of two privileged structures to generate a product with increased rigidity.

2. Results and Discussion

We envisioned that a suitable strategy to synthesize these compounds may proceed as shown retrosynthetically in Scheme 2. The spiro dihydrouracils 5 could be synthesized by an annulation reaction of α-aminomethyl esters 6 and an isocyanate. The aminomethyl group of compounds 6 could be derived from a masked amino function, such as a cyano group, by reduction. Compounds 7 possess two electron-withdrawing groups at the carbon in the 3-position of the pyrrolidine, rendering it a perfect pattern for preparation by a 1,3-cycloaddition reaction of an azomethine ylide and an electron-
deficient alkene. This would leave the 3-aryl-2-cyanoacrylates 8 as starting materials, which could be obtained by the Knoevenagel condensation reaction of methyl 2-cyanoacetate (9) and an aromatic aldehyde.

Scheme 2. Retrosynthetic analysis for the synthesis of spiro dihydouracils 5.

2.1. Knoevenagel condensation reaction

The synthesis of compound class 5 commenced with the condensation reaction of methyl 2-cyanoacetate (9) and aromatic aldehydes 10. Twelve aldehydes \{1–12\} (electron-rich aromatic, electron-rich heteroaromatic, and electron-poor heteroaromatic aldehydes; Figure 2) were selected for the formation of the scaffolds.

Figure 2. Aromatic aldehydes \{1–12\} used for the Knoevenagel reaction.

The reaction conditions for the Knoevenagel condensation reaction are critically dependent on the electron-withdrawing groups bound to the activated methylene [22] and need to be optimized in every case. Initially, these reactions were performed using EtOH as solvent, but transesterification (up to 3%) was observed and the resulting mixture of methyl and ethyl esters was impossible to separate. These reactions also took place in THF (see entry 8, Table 1), but required a longer reaction time. Finally, treatment of 9 with a catalytic amount of piperidine in MeOH (except for entry 8 because of the low solubility of 10\{8\} in MeOH) at room temperature produced the desired acrylates \{1–12\} in excellent yields (Table 1). All these compounds are only sparingly soluble in MeOH, allowing the pure crystalline products to be easily collected by filtration. These products can also be recrystallized from MeOH yielding crystals of >99.5% purity. The reaction was completely stereoselective in all cases [23], only the E alkenes were observed as could be inferred from the \(^{13}\)C-NMR coupling constants between the olefinic proton and the carbon atoms of the ester and the nitrile [24,25]. These values are \(^{3}J = 6.6–6.9\) Hz for the carbonyl group and \(^{3}J = 13.6–13.9\) Hz for the cyano group. The Knoevenagel adducts are stable at room temperature and unreactive towards the regular atmosphere, therefore remain unchanged for months.
Table 1. Knoevenagel condensation reaction to form the 2-cyanoacrylates 8{1–12}.

<table>
<thead>
<tr>
<th>Entry</th>
<th>ArCHO</th>
<th>Product</th>
<th>Time (min)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10{1}</td>
<td>8{1}</td>
<td>30</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>10{2}</td>
<td>8{2}</td>
<td>30</td>
<td>94</td>
</tr>
<tr>
<td>3</td>
<td>10{3}</td>
<td>8{3}</td>
<td>40</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>10{4}</td>
<td>8{4}</td>
<td>60</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>10{5}</td>
<td>8{5}</td>
<td>120</td>
<td>95</td>
</tr>
<tr>
<td>6</td>
<td>10{6}</td>
<td>8{6}</td>
<td>120</td>
<td>96</td>
</tr>
<tr>
<td>7</td>
<td>10{7}</td>
<td>8{7}</td>
<td>30</td>
<td>99</td>
</tr>
<tr>
<td>8</td>
<td>10{8}</td>
<td>8{8}</td>
<td>480(^a)</td>
<td>99</td>
</tr>
<tr>
<td>9</td>
<td>10{9}</td>
<td>8{9}</td>
<td>30</td>
<td>94</td>
</tr>
<tr>
<td>10</td>
<td>10{10}</td>
<td>8{10}</td>
<td>30</td>
<td>99</td>
</tr>
<tr>
<td>11</td>
<td>10{11}</td>
<td>8{11}</td>
<td>90</td>
<td>93</td>
</tr>
<tr>
<td>12</td>
<td>10{12}</td>
<td>8{12}</td>
<td>25</td>
<td>99</td>
</tr>
</tbody>
</table>

\(^a\)THF was used as solvent.

2.2. 1,3-Dipolar cycloaddition reaction

The next step in the synthesis was the formation of the pyrrolidine-core structures by a 1,3-dipolar cycloaddition reaction using an azomethine ylide. This reaction is an important method for the formation of pyrrolidines [26] and has been used in the synthesis of natural products [27,28]. Among the vast number of procedures for making azomethine ylides [29–41], the decarboxylative condensation of \(\alpha\)-amino acids with aldehydes, typically heated in toluene or DMF, was chosen [42]. Thus, the reaction of paraformaldehyde and sarcosine (N-methylglycine) in refluxing toluene in the presence of the 2-cyanoacrylates 8 cleanly provided the desired pyrrolidines 7, containing the 2-arylethyl amine motif (Table 2). The reaction was clean to such an extent that in some cases an extraction (H\(_2\)O/Et\(_2\)O) was all the purification needed (or just a short column chromatography). The reaction was totally stereospecific in most cases (entries 1–6 and 8), highly stereospecific for 8{9} (entry 9), and partially stereospecific for the electron-poor heteroaryls 8{10–12} (entries 10–12) [43]. The mixtures of diastereoisomers that arose could not be separated by column chromatography. The reaction did not take place with compound 8{7} (entry 7); after 4 h only some minor unidentified compounds were formed and most of the substrate was recovered, but there was no trace of compound 7{7}. The reaction of substrate 8{5} did form the product 7{5}, but with a lower yield compared to all the others. The reaction of substrate 8{8} formed the expected cycloadduct, but the indolic nitrogen was (dimethylamino)methylated during the reaction.
Table 2. 1,3-Dipolar cycloaddition reaction to form the pyrrolidine-core structures 7.

\[
\begin{array}{cccc}
\text{Entry} & \text{Acrylate} & \text{Product(s)*} & \text{Time (min)} & \text{Yield (%)} \\
1 & 8\{1\} & 7\{1\} & 20 & 94 \\
2 & 8\{2\} & 7\{2\} & 75 & 99 \\
3 & 8\{3\} & 7\{3\} & 80 & 95 \\
4 & 8\{4\} & 7\{4\} & 80 & 99 \\
5 & 8\{5\} & 7\{5\} & 120 & 52 \\
6 & 8\{6\} & 7\{6\} & 80 & 95 \\
7 & 8\{7\} & 7\{7\} & 240 & - \\
8 & 8\{8\} & 7\{13\} & 150 & 85 \\
9 & 8\{9\} & 7\{9\} + 11\{9\} & 80 & 87^b \\
10 & 8\{10\} & 7\{10\} + 11\{10\} & 45 & 90^c \\
11 & 8\{11\} & 7\{11\} + 11\{11\} & 25 & 72^d \\
12 & 8\{12\} & 7\{12\} + 11\{12\} & 45 & 85^e \\
\end{array}
\]

*a Ratio calculated by integration of the \(^1\)H-NMR signals of the crude reaction mixture; 
b \(7\{9\}/11\{9\} = 70:1; c \(7\{10\}/11\{10\} = 6.5:1; d \(7\{11\}/11\{11\} = 6.6:1; e \(7\{12\}/11\{12\} = 5:1

After analysis of the results obtained so far, it was decided to continue the research only with the diastereomerically pure compounds 7\{1–6\} for the construction of the library scaffolds.

2.3. Reduction

The chemoselective reduction of the nitrile was best achieved by a heterogeneous catalytic hydrogenation using Raney nickel under a hydrogen atmosphere at room temperature (Table 3) [44]. We found that the addition of NH\(_3\) or Et\(_3\)N was crucial for the reaction to go to completion [45]. Eventually, Et\(_3\)N was used since with NH\(_3\) amide 12 (Figure 3) was formed alongside the product.
Thus, compounds $7\{1–6\}$ were reacted under these conditions to complete the synthesis of the library scaffolds. After elimination of Raney nickel by filtration through diatomaceous earth and evaporation of MeOH and Et$_3$N, the reaction cleanly gave the $\alpha$-aminomethyl esters $6\{1–6\}$.

**Table 3.** Reduction of the cyano group from the $\alpha$-cyano esters $7$.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$7{1}$</td>
<td>$6{1}$</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>$7{2}$</td>
<td>$6{2}$</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>$7{3}$</td>
<td>$6{3}$</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>$7{4}$</td>
<td>$6{4}$</td>
<td>85</td>
</tr>
<tr>
<td>5</td>
<td>$7{5}$</td>
<td>$6{5}$</td>
<td>73</td>
</tr>
<tr>
<td>6</td>
<td>$7{6}$</td>
<td>$6{6}$</td>
<td>95</td>
</tr>
</tbody>
</table>

### 2.4. Parallel synthesis of spiro dihydrouracils

The procedure followed for the formation of the spiro dihydrouracils was formation of a urea by addition of an isocyanate and subsequent cyclization by reaction with a base. The conversion of chemset $6$ into chemset $5$ was accomplished using reagent chemset $13$. Eight isocyanates $13\{1–8\}$ (alkyl, electron-rich aryl, electron-poor aryl, and heteroaryl isocyanates; Figure 4) were selected for the generation of a 48-compound library.

**Figure 4.** Isocyanates $13\{1–8\}$ used for the reaction of scaffolds $6\{1–6\}$.

The reactions for the formation of the $\alpha$-ureidomethyl esters were run in either CH$_2$Cl$_2$ or DMF depending on reagent solubility and reactivity. Thus, the reactions of $6\{1–6\}$ and $13\{1,3–5\}$ in CH$_2$Cl$_2$ for 15 h at room temperature afforded the corresponding $\alpha$-ureidomethyl esters. In order to reach full conversion to the $\alpha$-ureidomethyl esters using isocyanates $13\{2,6–8\}$, DMF at 80 °C for 15 h had to be
used. After evaporation of the solvent, the crude mixture was dissolved in THF and 1 M KOBu′ in THF (1 equiv) was added [46,47]. The reactions were stirred at room temperature for 15 h and the solvent was evaporated. Liquid–liquid extraction afforded two different types of compounds, depending on the isocyanate used: (1) the alkyl isocyanates 13{1–3} gave the expected 4-aryl-spiro[dihydrouracil-5,3′-pyrrolidines] 5{1–6,1–3} with yields ranging from 49 to 80% (61% average) and with purities ranging from 60 to 99% (83% average; Scheme 3 and Table 4) according to LC-MS analysis (also confirmed by 1H-NMR spectroscopy) and (2) the aryl isocyanates 13{4–8} gave mostly the unexpected α-ureidomethyl acids 14{1–6,4–8} with yields ranging from 45 to 79% (64% average) and with purities ranging from 0 to >99% (82% average; Scheme 4 and Table 5) according to LC-MS analysis (also confirmed by 1H-NMR spectroscopy).

The reactions carried out with reagent 13{1} resulted in high purities (89% average) for the formation of the spiro dihydrouracils, due to lack of competing reactions. The purities of the products from the reactions run in DMF (reagent 13{2}) were in the range 60 to 92% (70% average). These lower purities could be due to partial decomposition of the isocyanates at the temperature used for the reactions in DMF. The reactions carried out with reagent 13{3} gave a mixture of the expected ethyl esters 5{1–6,3}, the methyl esters 5{1–6,9} (from transesterification of the ethyl ester on the R group by methoxide, formed in the cyclization), the acids 5{1–6,10} (from hydrolysis of the esters), and the deorganylated compounds 5{1–6,11} (Figure 5 and Table 4). The overall cyclization reaction worked well, since products 5{1–6,9}, 5{1–6,10}, and 5{1–6,11} were formed from 5{1–6,3}. Shorter reaction times should thus be used to avoid these side reactions.
Figure 5. Products formed from the reaction with reagent 13{3}.

![Products formed from the reaction with reagent 13{3}](image)

The above-mentioned deorganylation side reaction could have taken place through an E1cB mechanism (Scheme 5). The substrate 5{1–6,3} (or 5{1–6,9}) is deprotonated to form the enolate 5{1–6,12}, which undergoes an elimination reaction to afford 5{1–6,11} after work-up.

Scheme 5. Formation of compounds 5{1–6,11}.

![Scheme 5. Formation of compounds 5{1–6,11}](image)

The aryl-substituted dihydrouracils underwent hydrolysis (and not the alkyl-substituted dihydrouracils) because the electrophilicity of the ureide carbonyls is enhanced (with respect to the alkyl group) due to the conjugation of the imide-type nitrogen with the aryl group. Thus, residual H₂O from KOBu’ could have hydrolyzed the ureide to the ureido acid [48].

Table 4. Parallel synthesis of spiro dihydrouracil library 5{1–6,1–3}^{a,b}.

<table>
<thead>
<tr>
<th></th>
<th>5{1,1}</th>
<th>5{1,2}</th>
<th>5{1,3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>51% (89%)</td>
<td>63% (70%)</td>
<td>80% (91%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>5{2,1}</th>
<th>5{2,2}</th>
<th>5{2,3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>60% (93%)</td>
<td>64% (60%)</td>
<td>49% (88%)</td>
</tr>
</tbody>
</table>

^{a,b} Parallel synthesis of spiro dihydrouracil library 5{1–6,1–3}^{a,b}.
Table 4. Cont.

| 5{3,1} | 66% (90%) |
| 5{3,2} | 60% (68%) |
| 5{3,3} | 54% (95%)c |
| 5{4,1} | 63% (95%) |
| 5{4,2} | 64% (68%) |
| 5{4,3} | 61% (98%)c |
| 5{5,1} | 61% (99%) |
| 5{5,2} | 54% (92%) |
| 5{5,3} | 66% (79%)c |
| 5{6,1} | 69% (69%) |
| 5{6,2} | 68% (62%) |
| 5{6,3} | 62% (86%)c |

a % = Crude yield based on mass recovery; b (%) = Purity determined by LC-MS at 215 nm; c Mixture of compounds, R = CH₂CH₂CO₂Et, CH₂CH₂CO₂Me, CH₂CH₂CO₂H, and H.

Table 5. Parallel synthesis of α-ureidomethyl acid library 14{1–6,4–8}a,b.

| 14{1,4} | 49% (>99%) |
| 14{1,5} | 75% (97%) |
| 14{1,6} | 48% (>99%) |
| 14{1,7} | 54% (>99%) |
| 14{1,8} | 49% (79%) |
| 14{2,4} | 60% (99%) |
| 14{2,5} | 65% (98%) |
| 14{2,6} | 70% (>99%) |
| 14{2,7} | 60% (96%) |
| 14{2,8} | 45% (76%) |
In order to find conditions for the exclusive formation of the spiro dihydrouracils using aryl isocyanates, the α-ureidomethyl ester 15{1,4} was synthesized, isolated, and reacted with several bases under different conditions for the formation of spiro dihydrouracil 5{1,4} (Table 6).

Firstly, the reaction was attempted with an easy-to-handle base because, if successful, it would make the work-up of the reactions easy—an important factor in parallel synthesis. All the amines used were found to have insufficient basicity for this transformation to take place (entries 1–5) [49–51]. The amidine DBU gave promising results, but the separation of the product 5{1,4} from DBU (and especially from the coreagent Bu₄NBr, entry 8) was difficult and tedious, making these reaction conditions unsuitable for parallel synthesis [52,53]. Potassium tert-butoxide was the only base that caused >99% of the starting material to react [54], but it was the base that gave the largest amount of hydrolyzed product 14{1,4} (entries 9–12). Heating only (entry 15) resulted in decomposition of the starting material. To the best of our knowledge, there is no example in the literature of a dihydrouracil ring with such a tendency toward hydrolysis under basic conditions. This cyclization can also take place using acid catalysis [55-58], but this has not yet been attempted.
Table 6. Optimization of the formation of spiro dihydrouracil 5\{1,4\}.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>Products(^a) 15{1,4}/5{1,4}/14{1,4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Et(_3)N (1.1 equiv), THF, Ar, reflux, 22 h</td>
<td>1:0:0</td>
</tr>
<tr>
<td>2</td>
<td>Proton sponge (0.2 equiv), THF, 21 °C, 5 h</td>
<td>1:0:0</td>
</tr>
<tr>
<td>3</td>
<td>Proton sponge (1 equiv), THF, 21 °C, 17 h</td>
<td>1:0:0</td>
</tr>
<tr>
<td>4</td>
<td>Proton sponge (1 equiv), THF, reflux, 7 h</td>
<td>1:0:0</td>
</tr>
<tr>
<td>5</td>
<td>DIPEA (1 equiv), DMF, 90 °C, 6 h</td>
<td>1:0:0</td>
</tr>
<tr>
<td>6</td>
<td>DBU (1 equiv), THF, Ar, 26 °C, 5 h</td>
<td>1:0:0</td>
</tr>
<tr>
<td>7</td>
<td>DBU (1 equiv), THF, Ar, reflux, 17 h</td>
<td>5:1:0</td>
</tr>
<tr>
<td>8</td>
<td>DBU (1 equiv), Bu(_4)NBr, 4 Å MS, PhMe, Ar, reflux, 27 h</td>
<td>1:9:0</td>
</tr>
<tr>
<td>9</td>
<td>KOBu(^t) (1 equiv), THF, 29 °C, 30 min</td>
<td>1:3:1</td>
</tr>
<tr>
<td>10</td>
<td>KOBu(^t) (1 equiv), THF, 31 °C, 55 min</td>
<td>0:2:1</td>
</tr>
<tr>
<td>11</td>
<td>KOBu(^t) (1 equiv), THF, Ar, 21 °C, 2 h</td>
<td>0:1:2</td>
</tr>
<tr>
<td>12</td>
<td>KOBu(^t) (0.1 equiv), THF, Ar, 21 °C, 17 h</td>
<td>3:6:1</td>
</tr>
<tr>
<td>13</td>
<td>Phosphazene P(_2)-t-Bu (0.1 equiv), THF, Ar, 21 °C, 5 h</td>
<td>1:3:0</td>
</tr>
<tr>
<td>14</td>
<td>Phosphazene P(_2)-t-Bu (1 equiv), THF, Ar, 21 °C, 18 h</td>
<td>1:0:4</td>
</tr>
<tr>
<td>15</td>
<td>DMSO, 165 °C, 15 h</td>
<td>decomposition</td>
</tr>
</tbody>
</table>

\(^a\)Ratio calculated by integration of the \(^1\)H-NMR signals of the crude reaction mixture.

The compounds 5\{1–6,1–3\}, 5\{1,4\}, 6\{1–6\}, 14\{1–6,4–8\}, and 15\{1,4\} were tested on different CNS targets, but the results cannot be published because of the patent policy of the companies involved in the project.

3. Experimental

3.1. General

Reagents were obtained from commercial suppliers and were used without purification. Solvents were distilled from appropriate drying agents prior to use and were stored under nitrogen. Reactions were followed, 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\(_4\) or ninhydrin. Column or flash chromatography was carried out using ACROS silica gel (0.035–0.070 mm, pore diameter ca. 6 nm). IR spectra were recorded on an ATI Mattson Genesis Series FTIR spectrometer. High-resolution mass spectra were recorded on a JEOL AccuTOF (ESI) or a MAT900 (EI, CI, and ESI). Low-resolution ESI mass spectra were recorded on a Thermo Finnigan LCQ Advantage Max Ion Trap mass spectrometer. Elemental analyses were carried out using a Carlo Erba Instruments CHNS-O EA 1108 element analyzer. Melting points were analyzed with a Büchi melting point B-545 and are not
corrected. Gas chromatography (GC) was performed on a Hewlett Packard 5890, containing a HP1 column (25 m x 0.32 mm x 0.17 μm), FID detection, and equipped with a HP3393A integrator. NMR spectra were recorded at 298 K on a Bruker DMX 300 (300 MHz) or a Varian 400 (400 MHz) spectrometer in the solvent indicated. Chemical shifts are given in parts per million (ppm) with respect to tetramethylsilane (0.00 ppm) or CD3SOCH2D (2.50 ppm) as internal standard for 1H-NMR; and CDCl3 (77.16 ppm) or CD3SOCD3 (39.52 ppm) as internal standard for 13C-NMR [59]. Coupling constants are reported as J values in hertz (Hz). Multiplicity data are denoted by s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), b (broad), and app (apparent). Peak assignment in 13C spectra are based on 2D gHSQC and gHMBC spectra, and DEPT 135 when needed. Chain numbering corresponds to IUPAC nomenclature, so unprimed atoms belong to the principal chain, primed atoms belong to the first named substituent, doubled-primed atoms to the second named substituent, etc. LC-MS measurements were run on a Shimadzu LC-10A VP series liquid chromatography system, equipped with an SPD-10A VP UV-vis detector and a LCMS-2010A mass spectrometer. The column used for the LC analysis was an Agilent Zorbax Extend C18 (3.5 μm, 4.6 × 150 mm), and it was eluted at 1 mL/min with a gradient made up of two solvent mixtures. Solvent A consisted of 0.1% trifluoroacetic acid in water and solvent B consisted of 0.1% trifluoroacetic acid in acetonitrile. The gradient was run as follows: t (0 min, 50% A; t) 5 min, 5% A; t) 10 min, 5% A; t) 12.5 min, 50% A; t) 20 min, 50% A. A wavelength of 215 nm was selected for the analysis of purity.

3.2. General procedure for Knoevenagel condensation reaction

Piperidine (5 drops) was added to a solution of methyl 2-cyanoacetate (9) and the aldehyde 10 (1.0 equiv) in MeOH. The resulting reaction mixture was stirred at room temperature for the time indicated in each case. The reaction mixture was filtered and the precipitate was recrystallized from MeOH. The filtrate was concentrated under reduced pressure and purified by recrystallization from MeOH.

Methyl (E)-2-cyano-3-phenylacrylate (8{1}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 7.940 g, 80.13 mmol) with benzaldehyde 10{1} (8.504 g, 80.13 mmol) over 30 min afforded 8{1} (14.910 g, 99%) as a white solid. 1H-NMR [400 MHz, δ (ppm), CDCl3]: 8.21 (s, 1 H, 3-C), 7.97–7.92 (m, 2 H, 2′-CH + 6′-CH), 7.56–7.43 (m, 3 H, 3′-CH + 4′-CH + 5′-CH), 3.90 (s, 3 H, CO2C), 13C-NMR [75 MHz, δ (ppm), CDCl3]: 162.5 (CO2), 154.9 (3-C), 133.1 (4′-C), 131.1 (1′-C), 124.2 (1′-C), 129.0 (3′-C + 5′-C), 115.2 (CN), 102.4 (2-C), 53.4 (OCH3). FTIR [ν (cm−1), neat]: 3036, 2954, 2224, 1727, 1606, 1200, 767, 685. Elem. anal. calcd. for C11H9NO2: C 70.58%, H 4.85%, N 7.48%; found C 70.39%, H 4.54%, N 7.43%. Rf: 0.63 (heptane/AcOEt, 1:1). Mp: 87.9 °C (from MeOH, colorless flake-like crystals). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(4-methoxyphenyl)acrylate (8{2}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 6.804 g, 68.66 mmol) with 4-methoxybenzaldehyde 10{2} (9.349 g, 68.66 mmol) over 30 min afforded 8{2} (14.020 g, 94%) as a white solid. 1H-NMR [400 MHz, δ (ppm), CDCl3]: 8.14 (s, 1 H, 3-C), 7.01–6.95 (m, 2 H, 3′-CH + 5′-CH), 3.91 (s, 3 H, CO2C), 3.88 (s, 3 H, OCH3). 13C-NMR [75 MHz, δ (ppm), CDCl3]: 163.8 (4′-C), 163.5 (CO2), 154.5 (3-C), 133.6 (2′-C + 6′-C), 124.2 (1′-C), 116.1 (CN), 114.7 (3′-C + 5′-
Molecules 2010, 15 2281

C), 98.8 (2-C), 55.6 (OCH3), 53.1 (CO2CH3). FTIR [υ (cm⁻¹), neat]: 3084, 2954, 2846, 2215, 1714, 1580, 1264, 1174, 841. Elem. anal. calcld. for C12H11NO3: C 66.35%, H 5.10%, N 6.45%; found C 66.24%, H 4.98%, N 6.33%. Rp: 0.58 (heptane/AcOEt, 1:1). Mp: 104.1 °C (from MeOH, off-white small crystals). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(3,5-dimethoxyphenyl)acrylate (8{3}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 5.835 g, 58.89 mmol) with 3,5-dimethoxybenzaldehyde 10{3} (9.785 g, 58.89 mmol) over 40 min afforded 8{3} (12.399 g, 99%) as a yellow solid. ¹H-NMR [400 MHz, δ (ppm), CDCl3]: 8.17 (s, 1 ¹H, 3-CH), 7.15 (d, J = 2.4 Hz, 2 ¹H, 2'-CH + 6'-CH), 6.65 (t, J = 2.4 Hz, 1 ¹H, 4'-CH), 3.94 (s, 3 ¹H, CO2CH3), 3.84 (s, 6 ¹H, 2 × OCH3). ¹³C-NMR [75 MHz, δ (ppm), CDCl3]: 163.1 (CO2), 161.2 (3'-C + 5'-C), 155.6 (3-C), 133.1 (1'-C), 115.6 (CN), 108.7 (2'-C + 6'-C), 106.4 (4'-C), 103.0 (2-C), 55.8 (2 × OCH3), 53.6 (CO2CH3). FTIR [υ (cm⁻¹), neat]: 3086, 2940, 2841, 2217, 1723, 1604, 1247, 1167, 840. Elem. anal. calcld. for C13H13NO4: C 63.15%, H 5.30%, N 5.66%; found C 63.22%, H 5.14%, N 5.53%. Rp: 0.56 (heptane/AcOEt, 1:1). Mp: 121.5 °C (from MeOH, long light yellow needles). Purity: >99.5% (GC).

Methyl (E)-3-(1,3-benzodioxol-5-yl)-2-cyanoacrylate (8{4}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 6.002 g, 60.57 mmol) with piperonal 10{4} (9.094 g, 60.57 mmol) over 60 min afforded 8{4} (13.836 g, 99%) as a light greenish solid. ¹H-NMR [400 MHz, δ (ppm), CDCl3]: 8.12 (s, 1 ¹H, 3-CH), 7.71 (d, J = 1.9 Hz, 1 ¹H, 4'-CH), 7.41 (dd; J = 8.2, 1.9, 0.6 Hz; 1 ¹H, 6'-CH), 6.91 (d, J = 8.2 Hz, 1 ¹H, 7'-CH), 6.09 (s, 2 ¹H, 2'-CH2), 3.92 (s, 3 ¹H, OCH3). ¹³C-NMR [75 MHz, δ (ppm), CDCl3]: 163.6 (CO2), 154.7 (3-C), 152.5 (7'a-C), 148.8 (3'a-C), 130.0 (6'-C), 126.1 (5'-C), 116.1 (CN), 109.1 (4'-C), 109.0 (7'-C), 102.5 (2'-C), 99.5 (2-C), 53.4 (OCH3). FTIR [υ (cm⁻¹), neat]: 3029, 2957, 2218, 1723, 1579, 1244, 1205, 1041, 922, 819. HRMS [El (m/z)] caleld for C12H9NO4 = 231.0532, found for [M⁺] = 231.0532 (| = 0.0 ppm), peaks at (relative intensity): 231 (100), 200 (21), 170 (32), 142 (12), 114 (21). Elem. anal. calcld. for C12H9NO4: C 63.24%, H 3.92%, N 6.06%; found C 62.24%, H 3.86%, N 6.00%. Rp: 0.60 (heptane/AcOEt, 1:1). Mp: 169.6 °C (from MeOH, light green cotton-like solid). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(1-methyl-1H-pyrrol-2-yl)acrylate (8{5}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 7.107 g, 71.72 mmol) with 1-methyl-1H-pyrrole-2-carbaldehyde 10{5} (7.827 g, 71.72 mmol) over 120 min afforded 8{5} (12.932 g, 95%) as a yellow solid. ¹H-NMR [400 MHz, δ (ppm), CDCl3]: 8.08 (s, 1 ¹H, 3-CH), 7.72 (d, J = 4.4 Hz, 1 ¹H, 3'-CH), 7.01 (t, J = 1.8 Hz, 1 ¹H, 5'-CH), 6.39–6.36 (m, 1 ¹H, 4'-CH), 3.89 (s, 3 ¹H, OCH3), 3.78 (s, 3 ¹H, NCH3). ¹³C-NMR [75 MHz, δ (ppm), CDCl3]: 164.8 (CO2), 139.6 (3-C), 131.7 (5'-C), 127.5 (2'-C), 120.0 (3'-C), 117.1(CN), 112.2 (4'-C), 92.8 (2-C), 53.0 (OCH3), 34.4 (NCH3). FTIR [υ (cm⁻¹), neat]: 3120, 2957, 2899, 2210, 1717, 1591, 1243, 748. Elem. anal. calcld. for C10H10N2Oz: C 63.15%, H 5.30%, N 14.73%; found C 63.19%, H 5.09%, N 14.70%. Rp: 0.29 (heptane/AcOEt, 1:1). Mp: 154.2 °C (from MeOH, yellow solid). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(1-methyl-1H-indol-3-yl)acrylate (8{6}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 6.011 g, 60.66 mmol) with 1-methyl-1H-indole-3-carbaldehyde 10{6} (9.656 mg, 60.66 mmol) over 120 min afforded 8{6} (13.977 g, 96%) as a yellow
Molecules 2010, 15 2282

Methyl (E)-2-cyano-3-(1H-pyrrol-2-yl)acrylate (8{7}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 991 mg, 10.00 mmol) with 1H-pyrole-2-carbaldehyde 10{7} (951 mg, 10.00 mmol) over 30 min afforded 8{7} (1.744 g, 99%) as a yellow solid. H-NMR [400 MHz, δ (ppm, CDCl3): 8.56 (s, 1 H, 3-CH), 8.49 (s, 1 H, 2'-CH), 7.84–7.80 (m, 1 H, 4'-CH), 7.42–7.31 (m, 3 H, 5'-CH + 6'-CH + 7'-CH), 3.91 (s, 3 H, CO2CH3), 3.90 (s, 3 H, NCH3). C-NMR [75 MHz, δ (ppm, CDCl3): 164.6 (CO2), 146.2 (3-C), 137.0 (7'α-C), 134.9 (2'-C), 128.5 (3'a-C), 124.1 (6'-C), 122.8 (5'-C), 118.6 (4'-C), 118.5 (CN), 110.6 (7'-C), 110.1 (3'-C), 93.3 (2-C), 52.9 (OCH3), 34.2 (NCH3). FTIR [ν (cm–1), neat]: 3118, 3026, 2950, 2222, 1701, 1586, 1255, 751. HRMS [EI (m/z)] calcd for C14H12N2O2 = 240.0899, found for [M+•] = 240.0895 (| = 1.6 ppm), peaks at (relative intensity): 240 (100), 209 (53), 140 (18), 49 (12). Elem. anal. calcd for C14H12N2O2: C 69.99%, H 5.03%, N 11.66%; found C 69.69%, H 4.85%, N 11.42%. Rf: 0.37 (heptane/AcOEt, 1:1). Mp: 165.9 °C (from MeOH, yellow solid). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(1H-indol-3-yl)acrylate (8{8}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 991 mg, 10.00 mmol) with 1H-indole-3-carbaldehyde 10{8} (1.452 g, 10.00 mmol) in THF (15 mL) over 480 min afforded 8{8} (2.239 g, 99%) as a yellow solid. H-NMR [400 MHz, δ (ppm, CDCl3): 12.64 (bs, 1 H, NH), 8.64 (s, 1 H, 2'-CH), 8.63 (s, 1 H, 3-CH), 8.05–7.99 (m, 1 H, 4'-CH), 7.67–7.63 (m, 1 H, 7'-CH), 7.41–7.30 (m, 2 H, 5'-CH + 6'-CH), 3.92 (s, 3 H, OCH3). C-NMR [75 MHz, δ (ppm, CD3SOCD3): 163.3 (CO2), 146.3 (3-C), 135.9 (7'a-C), 132.4 (2'-C), 126.6 (3'a-C), 123.3 (6'-C), 121.9 (5'-C), 118.3 (4'-C), 117.8 (CN), 112.7 (7'-C), 109.7 (3'-C), 91.8 (2-C), 52.6 (OCH3). FTIR [ν (cm–1), neat]: 3266, 3132, 2989, 2943, 2212, 1695, 1589, 1241, 742. Elem. anal. calcd for C13H10N2O2: C 69.02%, H 4.46%, N 12.38%; found C 68.97%, H 4.38%, N 12.22%. Rf: 0.80 (AcOEt). Mp: 189.5 °C (from MeOH, small thin yellow needles). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(2-thienyl)acrylate (8{9}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 991 mg, 10.00 mmol) with thiophene-2-carbaldehyde 10{9} (1.121 g, 10.00 mmol) as a light brown solid. H-NMR [400 MHz, δ (ppm, CDCl3): 8.36 (s, 1 H, 3-CH), 7.84 (d, J = 3.9 Hz, 1 H, 3'-CH), 7.80 (d, J = 4.9 Hz, 1 H, 5'-CH), 7.24 (dd; J = 4.9, 3.9 Hz; 1 H, 4'-CH), 3.92 (s, 3 H, OCH3). C-NMR [75 MHz, δ (ppm, CDCl3): 162.9 (CO2), 146.7 (3-C), 137.2 (3'-C), 135.8 (2'-C), 135.2 (5'-C), 128.6 (4'-C), 115.6 (CN), 98.8 (2-C), 53.4 (OCH3). FTIR [ν (cm–1), neat]: 3087, 3028, 2964, 2216, 1718, 1590, 1271, 1214, 729. Elem. anal. calcd for C9H7NO2S: C 55.94%, H 3.65%, N 7.25%; found C 55.98%, H 3.63%, N 7.23%. Rf: 0.61 (heptane/AcOEt, 1:1). Mp: 106.9 °C (from MeOH, light brown needles). Purity: >99.5% (GC).
Methyl (E)-2-cyano-3-(2-pyridyl)acrylate (8\{10\}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 991 mg, 10.00 mmol) with pyridine-2-carbaldehyde 10\{10\} (1.071 g, 10.00 mmol) over 30 min afforded 8\{10\} (1.863 g, 99%) as a brown solid. $^1$H-NMR [400 MHz, δ (ppm), CDCl$_3$]: 8.83 (dd; $J = 4.8$, 1.6, 1.0 Hz; 1 $^1$H, 6′-CH), 8.30 (s, 1 $^1$H, 3-CH), 7.89 (app dt; $J = 7.8$, 1.2 Hz; 1 $^1$H, 3′-CH), 7.85 (app dt; $J = 1.6$, 7.8 Hz; 1 $^1$H, 4′-CH), 7.44 (ddd; $J = 7.3$, 4.9, 1.5 Hz; 1 $^1$H, 5′-CH), 3.96 (s, 3 $^1$H, OCH$_3$). $^{13}$C-NMR [75 MHz, δ (ppm), CDCl$_3$]: 162.6 (CO$_2$), 153.7 (3-C), 150.7 (6′-C), 150.0 (2′-C), 137.1 (4′-C), 126.8 (5′-C), 126.4 (3′-C), 114.8 (CN), 106.4 (2-C), 53.7 (OCH$_3$). FTIR [ν (cm$^{-1}$), neat]: 3050, 2963, 2220, 1720, 1278, 1215, 781, 740. Elem. anal. calcd for C$_{10}$H$_8$N$_2$O$_2$: C 63.83%, H 4.28%, N 14.89%; found C 64.06%, H 4.26%, N 14.79%. R$_F$: 0.34 (heptane/AcOEt, 1:1). Mp: 131.7 °C (from MeOH, small brown needles). Purity: >99.5% (GC).

Methyl (E)-2-cyano-3-(3-pyridyl)acrylate (8\{11\}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 991 mg, 10.00 mmol) with pyridine-3-carbaldehyde 10\{11\} (1.071 g, 10.00 mmol) over 90 min afforded 8\{11\} (1.750 g, 93%) as a light yellow dust. $^1$H-NMR [300 MHz, δ (ppm), CDCl$_3$]: 8.91 (d, $J = 1.8$ Hz, 1 $^1$H, 2′-CH), 8.74 (dd; $J = 4.8$, 1.8 Hz; 1 $^1$H, 6′-CH), 8.57–8.51 (m, 1 $^1$H, 4′-CH), 8.26 (s, 1 $^1$H, 3-CH), 7.46 (dd; $J = 7.8$, 4.8 Hz; 1 $^1$H, 5′-CH), 3.95 (s, 3 $^1$H, OCH$_3$). $^{13}$C-NMR [75 MHz, δ (ppm), CDCl$_3$]: 161.9 (CO$_2$), 153.3 (3-C), 152.7 (6′-C), 151.3 (2′-C), 135.8 (4′-C), 127.3 (3′-C), 123.9 (5′-C), 114.7 (CN), 105.1 (2-C), 53.8 (OCH$_3$). FTIR [ν (cm$^{-1}$), neat]: 3031, 2959, 2223, 1722, 1280, 697. R$_F$: 0.13 (heptane/AcOEt, 1:1). Mp: 129.2 °C.

Methyl (E)-2-cyano-3-(4-pyridyl)acrylate (8\{12\}): According to the general procedure, the reaction of methyl 2-cyanoacetate (9, 991 mg, 10.00 mmol) with pyridine-4-carbaldehyde 10\{12\} (1.071 g, 10.00 mmol) over 25 min afforded 8\{12\} (1.863 g, 99%) as a pink solid. $^1$H-NMR [400 MHz, δ (ppm), CDCl$_3$]: 8.86–8.80 (m, 2 $^1$H, 2′-CH + 6′-CH), 8.23 (s, 1 $^1$H, 3-CH), 7.80–7.74 (m, 2 $^1$H, 3′-CH + 5′-CH), 3.97 (s, 3 $^1$H, OCH$_3$). $^{13}$C-NMR [75 MHz, δ (ppm), CDCl$_3$]: 161.8 (CO$_2$), 152.4 (3-C), 151.2 (2′-C + 6′-C), 138.0 (4′-C), 123.3 (3′-C + 5′-C), 114.2 (CN), 107.8 (2-C), 53.8 (OCH$_3$). FTIR [ν (cm$^{-1}$), neat]: 3033, 2955, 2225, 1726, 1236, 1198, 818. Elem. anal. calcd for C$_{10}$H$_8$N$_2$O$_2$: C 63.83%, H 4.28%, N 14.89%; found C 63.94%, H 4.25%, N 14.75%. R$_F$: 0.12 (heptane/AcOEt, 1:1). Mp: 126.6 °C (from MeOH, small pink needles). Purity: >99.5% (GC).

3.3. General procedure for 1,3-dipolar cycloaddition reactions of 8

A round-bottomed flask fitted with a Dean–Stark apparatus, a reflux condenser, and a drying tube containing calcium chloride was charged with 2-cyanoacrylate 8 and toluene (0.20–0.25 M). When the mixture was under reflux, sarcosine (N-methylglycine; 1.2 equiv) and paraformaldehyde (3.6 equiv) were added. This addition was repeated every 40 min until the substrate had completely reacted. Water (20 mL) was then added and the layers were separated. The aqueous layer was extracted with Et$_2$O (3 × 30 mL) and the combined organic layers were dried (MgSO$_4$), filtered, and concentrated in vacuo.

(±)-Methyl (3R,4R)-3-cyano-1-methyl-4-phenylpyrrolidine-3-carboxylate (7\{1\}): According to the general procedure, 2-cyanoacrylate 8\{1\} (5.342 g, 28.54 mmol) afforded 7\{1\} (6.524 g, 94%) as a white solid, after column chromatography (heptane/AcOEt, 3:1→2:1). $^1$H-NMR [400 MHz, δ (ppm), CDCl$_3$]: 8.86–8.80 (m, 2 $^1$H, 2′-CH + 6′-CH), 8.23 (s, 1 $^1$H, 3-CH), 7.80–7.74 (m, 2 $^1$H, 3′-CH + 5′-CH), 3.97 (s, 3 $^1$H, OCH$_3$). $^{13}$C-NMR [75 MHz, δ (ppm), CDCl$_3$]: 161.8 (CO$_2$), 152.4 (3-C), 151.2 (2′-C + 6′-C), 138.0 (4′-C), 123.3 (3′-C + 5′-C), 114.2 (CN), 107.8 (2-C), 53.8 (OCH$_3$). FTIR [ν (cm$^{-1}$), neat]: 3033, 2959, 2223, 1726, 1236, 1198, 818. Elem. anal. calcd for C$_{10}$H$_8$N$_2$O$_2$: C 63.83%, H 4.28%, N 14.89%; found C 63.94%, H 4.25%, N 14.75%. R$_F$: 0.12 (heptane/AcOEt, 1:1). Mp: 126.6 °C (from MeOH, small pink needles). Purity: >99.5% (GC).
CDCl₃: 7.33–7.19 (m, 5 ¹H, Ph), 4.00 (app t, J = 7.8 Hz, 1 ¹H, 4-CH), 3.70 (s, 3 ¹H, OCH₃), 3.25 (d, J = 9.9 Hz, 1 ¹H, 2-CH₃), 3.18 (d, J = 9.9 Hz, 1 ¹H, 2-CH(H), 3.04 (dd; J = 9.6, 7.8 Hz; 1 ¹H, 5-CH(H)), 3.00 (dd; J = 9.6, 8.1 Hz; 1 ¹H, 5-CH(H)). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 167.6 (CO₂), 136.6 (1'-C), 128.0 (2'-C + 6'-C), 127.9 (3'-C + 5'-C), 127.5 (4'-C), 117.2 (CN), 64.9 (2'-C), 60.2 (5'-C), 54.4 (3'-C), 53.5 (CO₂CH₃), 51.8 (4'-C), 41.1 (NCH₃). FTIR [v (cm⁻¹), neat]: 2950, 2846, 2790, 2241, 1740, 1247, 772, 699. MS [ESI (m/z)] calec for (C₁₄H₁₆N₂O₂ + H)⁺ = 245, found 245. Rₚ: 0.24 (heptane/AcOEt, 1:1). Mp: 53.3 °C (from heptane, colorless crystals). Purity: >99.5% (GC).

(±)-Methyl (3R,4R)-3-cyano-4-(4-methoxyphenyl)-1-methylpyrrolidine-3-carboxylate (7{2}): According to the general procedure, 2-cyanoacrylate 8{2} (6.16 g, 28.37 mmol) afforded 7{2} (7.688 g, 99%) as a yellow oil. ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 7.28–7.22 (m, 2 ¹H, 2'-CH + 6'-CH), 6.87–6.82 (m, 2 ¹H, 3'-CH + 5'-CH), 3.98 (app t, J = 8.0 Hz, 1 ¹H, 4-CH), 3.80 (s, 3 ¹H, CO₂CH₃), 3.76 (s, 3 ¹H, OCH₃), 3.31 (d, J = 9.9 Hz, 1 ¹H, 2-CH(2H)), 3.20 (d, J = 9.9 Hz, 1 ¹H, 2-CH(H)), 3.07 (dd; J = 9.6, 7.8 Hz; 1 ¹H, 5-CH(H)), 3.02 (dd; J = 9.6, 8.1 Hz; 1 ¹H, 5-CH(H)), 2.44 (s, 3 ¹H, NCH₃). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 168.1 (CO₂), 159.1 (4'-C), 129.4 (2'-C + 6'-C), 128.6 (1'-C), 117.8 (CN), 113.8 (3'-C + 5'-C), 65.2 (2'-C), 60.8 (5'-C), 55.2 (OCH₃), 54.9 (3'-C), 53.9 (CO₂CH₃), 51.8 (4'-C), 41.6 (NCH₃). FTIR [v (cm⁻¹), neat]: 2951, 2836, 2788, 2243, 1740, 1247, 832. MS [ESI (m/z)] calec for (C₁₅H₁₈N₃O₃ + H)⁺ = 275, found 275. Rₚ: 0.23 (heptane/AcOEt, 1:1). Purity: 98.9% (GC).

(±)-Methyl (3R,4R)-3-cyano-4-(3,5-dimethoxyphenyl)-1-methylpyrrolidine-3-carboxylate (7{3}): According to the general procedure, 2-cyanoacrylate 8{3} (9.745 g, 39.41 mmol) afforded 7{3} (11.398 g, 95%) as a white solid, after column chromatography (heptane/AcOEt, 3:1→2:1). ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 6.51 (d, J = 2.2 Hz, 2 ¹H, 2'-CH + 6'-CH), 6.41 (t, J = 2.2 Hz, 1 ¹H, 4'-CH), 3.99 (app t, J = 7.9 Hz, 1 ¹H, 4-CH), 3.84 (s, 3 ¹H, CO₂CH₃), 3.78 (s, 6 ¹H, 2 × OCH₃), 3.30 (d, J = 9.9 Hz, 1 ¹H, 2-CH(2H)), 3.24 (d, J = 9.9 Hz, 1 ¹H, 2-CH(H)), 3.09 (dd; J = 9.6, 7.8 Hz; 1 ¹H, 5-CH(H)), 3.06 (dd; J = 9.6, 8.0 Hz; 1 ¹H, 5-CH(H)), 2.47 (s, 3 ¹H, NCH₃). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 168.8 (CO₂), 161.1 (3'-C + 5'-C), 139.4 (1'-C), 118.1 (CN), 107.0 (2'-C + 6'-C), 100.2 (4'-C), 65.7 (2'-C), 60.7 (5'-C), 55.6 (2 × OCH₃), 54.8 (3'-C), 54.2 (CO₂CH₃), 52.6 (4'-C), 41.8 (NCH₃). FTIR [v (cm⁻¹), neat]: 2948, 2837, 2790, 2243, 1743, 1595, 1203, 1155. HRMS [EI (m/z)] calec for C₁₅H₁₄O₂N₂ = 264.1423, found for [M⁺] = 264.1436 (Δ| = 4.2 ppm), peaks at (relative intensity): 304 (16), 261 (18), 193 (11), 57 (100), 42 (20). Elem. anal. calec for C₁₅H₁₄O₂N₂: C 63.14%, H 6.62%, N 9.20%; found C 63.33%, H 6.65%, N 9.19%. Rₚ: 0.19 (heptane/AcOEt, 1:1). Mp: 94.7 °C (from heptane, colorless crystals). Purity: >99.5% (GC).

(±)-Methyl (3R,4R)-4-(1,3-benzodioxol-5-yl)-3-cyano-1-methylpyrrolidine-3-carboxylate (7{4}): According to the general procedure, 2-cyanoacrylate 8{4} (9.774 g, 42.27 mmol) afforded 7{4} (12.041 g, 99%) as a white solid. ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 6.88 (d, J = 1.7 Hz, 1 ¹H, 4'-CH), 6.81 (dd; J = 8.0, 1.7 Hz; 1 ¹H, 6'-CH), 6.77 (d, J = 8.0 Hz, 1 ¹H, 7'-CH), 5.95 (d, J = 1.6 Hz, 1 ¹H, 2'-CH(2H)), 5.94 (d, J = 1.6 Hz, 1 ¹H, 2'-CH(H)), 3.97 (t, J = 7.8 Hz, 1 ¹H, 4-CH), 3.84 (s, 3 ¹H, OCH₃), 3.28 (d, J = 9.9 Hz, 1 ¹H, 2-CH(2H)), 3.23 (d, J = 9.9 Hz, 1 ¹H, 2-CH(H)), 3.06 (dd; J = 9.5, 7.8 Hz; 1 ¹H, 5-CH(H)), 3.01 (dd; J = 9.5, 7.8 Hz; 1 ¹H, 5-CH(H)), 2.45 (s, 3 ¹H, NCH₃). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 168.5 (CO₂), 147.9 (3'a-C), 147.5 (7'a-C), 130.8 (5'-C), 122.0 (6'-C), 117.9 (CN),
108.8 (7′-C), 108.3 (4′-C), 101.2 (2′-C), 65.3 (2-C), 60.8 (5-C), 54.8 (3-C), 54.0 (OCH3), 52.1 (4-C), 41.5 (NCH3). FTIR [v (cm⁻¹), neat]: 2965, 2900, 2788, 2242, 1740, 1249, 1036, 929. HRMS [EI (m/z)] calcd for C15H16N2O4 = 288.1110, found for [M⁺] = 288.1097 (|Δ| = 4.5 ppm), peaks at (relative intensity): 288 (13), 57 (100), 42 (11). Elem. anal. calcd for C15H16N2O4: C 62.49%, H 5.59%, N 9.72%; found C 62.56%, H 5.61%, N 9.69%. Rf: 0.22 (heptane/AcOEt, 1:1). Mp: 87.6 °C (from heptane, colorless crystals). Purity: >99.5% (GC).

(±)-Methyl (3R,4R)-3-cyano-1-methyl-4-(1-methyl-1H-pyrrol-2-yl)pyrrolidine-3-carboxylate (7{5}): According to the general procedure, 2-cyanoacrylate 8{5} (1.132 g, 5.95 mmol) afforded 7{5} (765 mg, 52%) as a yellow oil, after column chromatography (heptane/AcOEt, 3:1→2:1). ¹H-NMR [400 MHz, δ (ppm), CDCl3]: 6.62 (dd; J = 2.7, 1.7 Hz; 1H, 5′-CH), 6.28 (dd; J = 3.6, 1.7 Hz; 1H, 3′-CH), 6.14 (dd; J = 3.6, 2.7 Hz; 1H, 4′-CH), 4.25 (app t, J = 8.2 Hz, 1H, 4-CH), 3.87 (s, 3H, OCH3), 3.57 (s, 3H, 1′-NCH3), 3.45 (d, J = 9.9 Hz, 1H, 2-CHF), 3.26 (dd; J = 9.5, 7.6 Hz; 1H, 5-CHH), 3.04 (d, J = 9.9 Hz, 1H, 2-CHF), 2.84 (app t, J = 9.1 Hz, 1H, 5-CHH), 2.44 (s, 3H, 1-NCCH3). ¹³C-NMR [75 MHz, δ (ppm), CDCl3]: 168.9 (CO2), 128.2 (2′-C), 123.5 (5′-C), 117.2 (CN), 108.7 (4′-C), 107.6 (3′-C), 65.2 (2-C), 61.3 (5-C), 54.2 (OCH3), 53.8 (3-C), 43.7 (4-C), 41.5 (1-NCH3), 34.0 (1′-NCH3). FTIR [v (cm⁻¹), neat]: 2951, 2888, 2791, 2242, 1741, 1241, 717. MS [ESI (m/z)] calcd for (C15H17N3O2 + H)⁺ = 248, found 248. Rf: 0.23 (heptane/AcOEt, 1:1). Purity: 98.2% (GC).

(±)-Methyl (3R,4R)-3-cyano-1-methyl-4-(1-methyl-1H-indol-3-yl)pyrrolidine-3-carboxylate (7{6}): According to the general procedure, 2-cyanoacrylate 8{6} (9.241 g, 38.46 mmol) afforded 7{6} (10.831 g, 95%) as a yellow solid, after column chromatography (heptane/AcOEt, 3:1→2:1). ¹H-NMR [400 MHz, δ (ppm), CDCl3]: 7.50 (dt; J = 8.1, 1.0 Hz; 1H, 4′-CH), 7.29 (dt; J = 8.3, 1.0 Hz; 1H, 7′-CH), 7.22 (dddd; J = 8.3, 7.1, 1.0 Hz; 1H, 6′-CH), 7.19 (s, 1H, 2′-CH), 7.10 (dddd; J = 8.1, 7.0, 1.0 Hz; 1H, 5′-CH), 4.43 (dd; J = 9.6, 7.5 Hz; 1H, 4-CH), 3.76 (s, 3H, OCH3), 3.74 (s, 3H, 1′-NCH3), 3.51 (d, J = 10.2 Hz, 1H, 2-CHF), 3.25 (d, J = 10.2 Hz, 1H, 2-CHH), 3.23 (dd; J = 9.6, 7.5 Hz; 1H, 5-CHH), 3.08 (t, J = 9.6 Hz, 1H, 5-CHH), 2.51 (s, 3H, 1′-NCH3). ¹³C-NMR [75 MHz, δ (ppm), CDCl3]: 169.0 (CO2), 136.8 (7′a-C), 127.7 (3′a-C), 127.4 (2′-C), 122.1 (6′-C), 119.5 (5′-C), 118.7 (4′-C), 118.5 (CN), 109.63 (3′-C), 109.58 (7′-C), 65.3 (2-C), 60.9 (5-C), 55.1 (3-C), 53.9 (OCH3), 45.2 (4-C), 42.0 (1-NCH3), 33.0 (1′-NCH3). FTIR [v (cm⁻¹), neat]: 3045, 2948, 2842, 2786, 2243, 1741, 1474, 1243, 742. HRMS [EI (m/z)] calcd for C19H19N3O3 = 297.1477, found for [M⁺] = 297.1467 (|Δ| = 3.5 ppm), peaks at (relative intensity): 297 (17), 144 (16), 57 (100), 42 (21). Rf: 0.17 (heptane/AcOEt, 1:1). Mp: 92.6 °C. Purity: 98.8% (GC).

(±)-Methyl (3R,4R)-3-cyano-4-{1-[(dimethylamino)methyl]-1H-indol-3-yl}-1-methylpyrrolidine-3-carboxylate (7{13}): According to the general procedure, 2-cyanoacrylate 8{8} (1.512 g, 6.68 mmol) afforded 7{13} (1.929 g, 85%) as a yellow solid. ¹H-NMR [300 MHz, δ (ppm), CDCl3]: 7.45 (d, J = 7.8 Hz, 1H, 4′-CH), 7.36 (d, J = 8.1 Hz, 1H, 7′-CH), 7.24 (s, 1H, 2′-CH), 7.14 (ddd; J = 8.1, 6.9, 1.0 Hz; 1H, 6′-CH), 7.05 (dddd; J = 7.8, 6.9, 1.0 Hz; 1H, 5′-CH), 4.69 (d, J = 12.9 Hz, 1H, NCH2N), 4.58 (d, J = 12.9 Hz, 1H, NCHHN), 4.40 (dd; J = 9.3, 7.6 Hz; 1H, 4-CH), 3.67 (s, 3H, OCH3), 3.43 (d, J = 10.0 Hz, 1H, 2-CHF), 3.17 (d, J = 10.0 Hz, 1H, 2-CHH), 3.16 (dd; J = 9.3, 7.6 Hz; 1H, 5-CHH), 3.04 (t, J = 9.3 Hz, 1H, 5-CHH), 2.42 (s, 3H, 1′-NCH3), 2.23 (s, 6H, N(CH3)2). ¹³C-NMR [75 MHz, δ (ppm), CDCl3]: 168.5 (CO2), 136.7 (7′a-C), 127.5 (3′a-C), 126.9 (2′-C), 121.9
(6'-C), 119.4 (5'-C), 118.3 (4'-C), 118.0 (CN), 110.21 (3'-C), 110.17 (7'-C), 68.6 (N(CH$_2$)$_3$N), 65.3 (2-C), 60.7 (5-C), 55.1 (3-C), 53.8 (OCH$_3$), 44.8 (4-C), 42.7 (N(N(CH$_3$)$_2$), 41.8 (N(CH$_3$)). FTIR [\( \nu \text{ (cm}^{-1} \text{)} \), neat]: 3049, 2942, 2842, 2778, 2242, 1740, 1460, 1239, 729. Elem. anal. calcd for C$_{10}$H$_{12}$N$_{2}$O$_2$: C 67.04%, H 7.11%, N 16.46%; found C 66.98%, H 7.05%, N 16.18%. R$_F$: 0.19 (AcOEt). Mp: 105.8 °C.

(\( \pm \))-Methyl (3R,4R)-3-cyano-1-methyl-4-(2-thienyl)pyrrolidine-3-carboxylate (7\{9\}): According to the general procedure, 2-cyanoacrylate 8\{9\} (720 mg, 3.73 mmol) afforded 7\{9\} (814 mg; 87%, combined yield including 11\{9\}) as a yellow oil, after column chromatography (heptane/AcOEt, 1:1). 1H-NMR [300 MHz, \( \delta \) (ppm), CDCl$_3$]: 7.23 (dd; \( J = 5.1, 1.0 \text{ Hz} \), 1\{1\} H, 4'-CH), 7.04 (dt; \( J = 3.6, 1.0 \text{ Hz} \), 1\{1\} H, 3'-CH), 6.98 (dd; \( J = 5.1, 3.6 \text{ Hz} \), 1\{1\} H, 4'-CH), 4.32 (app t; \( J = 7.8 \text{ Hz} \), 1\{1\} H, 4-CH), 3.85 (s, 3\{1\} H, OCH$_3$), 3.40 (d; \( J = 9.9 \text{ Hz} \), 1\{1\} H, 2-CHH), 3.24 (dd; \( J = 9.6, 7.2 \text{ Hz} \), 1\{1\} H, 5-CHH), 3.17 (d; \( J = 9.9 \text{ Hz} \), 1\{1\} H, 2-CHH), 3.00 (dd; \( J = 9.6, 8.4 \text{ Hz} \), 1\{1\} H, 5-CHH), 2.46 (s, 3\{1\} H, NCH$_3$). MS [ESI (m/z)] calcd for (C$_{12}$H$_{14}$N$_2$O$_2$ + H)$^+$ = 251, found 251. FTIR [\( \nu_\text{ (cm}^{-1} \text{)} \), neat]: 1680 (CO$_2$), 1501 (2'-C), 1496 (6'-C), 135.9 (4'-C), 133.2 (3'-C), 123.5 (5'-C), 117.6 (CN), 65.1 (2-C), 60.6 (5-C), 54.4 (3-C), 54.1 (CO$_2$CH$_3$), 49.4 (4-C), 41.3 (NCH$_3$). MS [ESI (m/z)] calcd for (C$_{13}$H$_{15}$N$_3$O$_2$ + H)$^+$ = 246, found 246. R$_F$: 0.07 (heptane/AcOEt, 1:1).

(\( \pm \))-Methyl (3R,4R)-3-cyano-1-methyl-4-(3-pyridyl)pyrrolidine-3-carboxylate (7\{10\}): According to the general procedure, 2-cyanoacrylate 8\{10\} (1.006 g, 5.35 mmol) afforded a 6.6:1 mixture of 7\{10\}/11\{10\} (1.182 g; 90%, combined yield) as a white solid, after column chromatography (CH$_2$Cl$_2$/MeOH, 24:1). (Measured from a 6.5:1 mixture of 7\{10\}/11\{10\}) 1H-NMR [400 MHz, \( \delta \) (ppm), CDCl$_3$]: 8.61 (d; \( J = 4.8 \text{ Hz} \), 1\{1\} H, 6'-CH), 7.68 (app t; \( J = 1.8, 7.6 \text{ Hz} \), 1\{1\} H, 4'-CH), 7.30 (d; \( J = 7.8 \text{ Hz} \), 1\{1\} H, 3'-CH), 6.91 (ddd; \( J = 7.6, 4.8, 0.7 \text{ Hz} \), 1\{1\} H, 5'-CH), 4.30 (t; \( J = 8.0 \text{ Hz} \), 1\{1\} H, 4-CH), 3.88 (s, 3\{1\} H, OCH$_3$), 3.38 (d; \( J = 9.6 \text{ Hz} \), 1\{1\} H, 2-CHH), 3.28 (dd; \( J = 9.3, 8.0 \text{ Hz} \), 1\{1\} H, 5-CHH), 3.26 (d; \( J = 9.6 \text{ Hz} \), 1\{1\} H, 2-CHH), 3.22 (dd; \( J = 9.3, 8.0 \text{ Hz} \), 1\{1\} H, 5-CHH), 2.49 (s, 3\{1\} H, NCH$_3$). MS [ESI (m/z)] calcd for (C$_{12}$H$_{14}$N$_2$O$_2$ + H)$^+$ = 246, found 246. R$_F$: 0.07 (heptane/AcOEt, 1:1).
5-CH, 2-CN), 3.40 (d, J = 10.2 Hz, 1 H, 2-CHH), 3.35 (d, J = 10.2 Hz, 1 H, 2-CHH), 3.27 (s, 3 H, OCH3), 3.09 (dd; J = 9.3, 6.6 Hz; 1 H, 5-CHH), 2.97 (dd; J = 9.3, 8.6 Hz; 1 H, 5-CHH), 2.51 (s, 3 H, NCH3). 13C-NMR [75 MHz, δ (ppm), CDCl3]: 166.6 (CO2), 150.0 (2'-C), 149.60 (6'-C), 135.9 (4'-C), 131.9 (3'-C), 123.2 (5'-C), 120.2 (CN), 63.4 (2'-C), 59.6 (5'-C), 53.4 (4'-C), 53.1 (CO2CH3), 52.4 (3'-C), 41.2 (NCH3). Rf: 0.10 (heptane/AcOEt, 1:1).

(±)-Methyl (3R,4R)-3-cyano-1-methyl-4-(4-pyridyl)pyrrolidine-3-carboxylate (7112): According to the general procedure, 2-cyanoacrylate 8112 (1.037 g, 5.51 mmol) afforded a 5:1 mixture of 7112/1112 (1.145 g; 85%, combined yield) as a light yellow oil, after column chromatography (CH2Cl2/MeOH, 24:1). (Measured from a 5:1 mixture of CH2Cl2/MeOH, 24:1). 1H-NMR [200 MHz, δ (ppm), CDCl3]: 8.62–8.58 (m, 2 H, 2'-CH + 6'-CH), 7.32–7.28 (m, 2 H, 3'-CH + 5'-CH), 4.03 (app t, J = 7.6 Hz, 1 H, 4-CH), 3.86 (s, 3 H, OCH3), 3.32 (d, J = 10.0 Hz, 1 H, 2-CHH), 3.26 (d, J = 10.0 Hz, 1 H, 2-CHH), 3.09 (dd; J = 9.8, 7.2 Hz; 1 H, 5-CHH), 3.06 (dd; J = 9.8, 7.8 Hz; 1 H, 5-CHH), 2.47 (s, 3 H, NCH3). MS [ESI (m/z)] calcd for (C13H15N3O2 + H)+ = 246, found 246. Rf: 0.06 (heptane/AcOEt, 1:1).

3.4. General procedure for reduction

An excess (7–8 heaped teaspoons) of freshly washed (with MeOH) Raney nickel was added to a solution of α-cyano ester 7 with Et3N (ca. 1 equiv) in MeOH (0.25–0.30 M). The mixture was stirred for 15 h at room temperature under a hydrogen atmosphere (1 atm). The catalyst was separated by filtration with suction through a glass filter with a 0.5 cm layer of diatomaceous earth. The catalyst was washed thoroughly with MeOH. The combined methanolic solutions were concentrated on a rotary evaporator.

(±)-Methyl (3R,4S)-3-(aminomethyl)-1-methyl-4-phenylpyrrolidine-3-carboxylate (617): According to the general procedure, α-cyano ester 711 (5.040 g, 20.63 mmol) afforded 611 (4.858 g, 95%) as a colorless oil. 1H-NMR [200 MHz, δ (ppm), CDCl3]: 7.36–7.21 (m, 5 H, Ph), 3.93 (dd; J = 8.6, 7.3 Hz; 1 H, 4-CH), 3.79 (s, 3 H, OCH3), 3.35 (d, J = 9.6 Hz, 1 H, 2-CHH), 3.08 (dd; J = 9.2, 7.3 Hz; 1 H, 5-CHH), 2.77 (app t, J = 9.0 Hz, 1 H, 5-CHH), 2.62 (d, J = 13.0 Hz, 1 H, CH2NHz2), 2.52 (d, J = 13.0 Hz, 1 H, CH2NHz2), 2.48 (d, J = 9.6 Hz, 1 H, 2-CHH), 2.41 (s, 3 H, NCH3), 1.78 (bs, 2 H, NH2). 13C-NMR [75 MHz, δ (ppm), CDCl3]: 175.9 (CO2), 138.4 (1'-C), 128.7 (2'-C + 6'-C), 127.9 (3'-C + 5'-C), 126.6 (4'-C), 64.0 (2-C), 61.6 (5-C), 58.6 (3-C), 52.2 (CO2CH3), 49.9 (4-C), 46.7 (CH2NH2), 42.2 (NCH3). FTIR [v (cm−1), neat]: 3386, 3028, 2946, 2781, 1727, 1701, 1455, 1174, 772, 703. HRMS [ESI (m/z)] calcd for (C13H15N3O2 + H)+ = 249.16030, found 249.15963 (|Δ| = 2.71 ppm). Rf: 0.30 (CH2Cl2/MeOH, 8:1). Purity: 99.1% (GC).

(±)-Methyl (3R,4S)-3-(aminomethyl)-4-(4-methoxyphenyl)-1-methylpyrrolidine-3-carboxylate (622): According to the general procedure, α-cyano ester 721 (6.997 g, 25.51 mmol) afforded 622 (6.731 g, 95%) as a colorless oil. 1H-NMR [400 MHz, δ (ppm), CDCl3]: 7.27–7.23 (m, 2 H, 2'-CH + 6'-CH), 6.86–6.82 (m, 2 H, 3'-CH + 5'-CH), 3.88 (app t, J = 8.0 Hz, 1 H, 4-CH), 3.79 (s, 3 H, CO2CH3), 3.78 (s, 3 H, OCH3), 3.33 (d, J = 9.9 Hz, 1 H, 2-CHH), 3.06 (dd; J = 8.8, 7.8 Hz; 1 H, 5-CHH), 2.71 (app t, J = 8.9 Hz, 1 H, 5-CHH), 2.63 (d, J = 13.2 Hz, 1 H, CH2NHz2), 2.52 (d, J = 13.2 Hz, 1 H,
CHHNH₂), 2.46 (d, J = 9.9 Hz, 1 ¹H, 2-CHH), 2.40 (s, 3 ¹H, NCH₃), 0.92 (bs, 2 ¹H, NH₂). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 176.1 (CO₂), 158.2 (4'-C), 130.3 (1'-C), 129.7 (2'-C + 6'-C), 113.5 (3'-C + 5'-C), 64.1 (2'-C), 61.8 (5'-C), 58.6 (3'-C), 55.2 (OCH₃), 52.3 (CO₂CH₃), 49.2 (4'-C), 46.8 (CH₃NH₂), 42.3 (NCH₃). FTIR [ν (cm⁻¹), neat]: 3383, 3222, 2947, 2834, 2779, 1724, 1247, 834. HRMS [ESI (m/z)] caleed for (C₁₅H₂₂N₂O₃ + H)⁺ = 279.17087, found 279.17006 (|Δ| = 2.87 ppm). Rₓ: 0.27 (CH₂Cl₂/MeOH, 8:1). Purity: 98.1% (GC).

(±)-Methyl (3R,4S)-3-(aminomethyl)-4-(3,5-dimethoxyphenyl)-1-methylpyrrolidine-3-carboxylate (6{3}): According to the general procedure, α-cyano ester 7{3} (7.452 g, 25.06 mmol) afforded 6{3} (6.730 g, 89%) as a yellow oil, after column chromatography (CH₂Cl₂/MeOH, 9:1). ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 6.51 (d, J = 2.2 Hz, 2 ¹H, 2'-CH + 6'-CH), 6.35 (t, J = 2.2 Hz, 1 ¹H, 4'-CH), 3.87 (app t, J = 7.9 Hz, 1 ¹H, 4-CH), 3.80 (s, 3 ¹H, CO₂CH₃), 3.78 (s, 6 ¹H, 2 × OCH₃), 3.31 (d, J = 9.8 Hz, 1 ¹H, 2-CHH), 3.06 (dd; J = 9.0, 7.8 Hz; 1 ¹H, 5-CHH), 2.72 (app t, J = 8.8 Hz, 1 ¹H, 5-CHH), 2.71 (d, J = 13.0 Hz, 1 ¹H, CH₃NH₂), 2.58 (d, J = 13.0 Hz, 1 ¹H, CH₃NH₂), 2.48 (d, J = 9.8 Hz, 1 ¹H, 2-CHH), 2.40 (s, 3 ¹H, NCH₃), 1.45 (bs, 2 ¹H, NH₂). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 176.5 (CO₂), 160.6 (3'-C + 5'-C), 141.2 (1'-C), 107.5 (2'-C + 6'-C), 98.6 (4'-C), 64.2 (2'-C), 61.6 (5'-C), 58.7 (3'-C), 55.3 (2 × OCH₃), 52.4 (CO₂CH₃), 50.0 (4'-C), 46.6 (CH₃NH₂), 42.3 (NCH₃). FTIR [ν (cm⁻¹), neat]: 3380, 3188, 2942, 2835, 2781, 1723, 1593, 1203, 1152. HRMS [ESI (m/z)] caleed for (C₁₆H₂₄N₂O₄ + H)⁺ = 309.18143, found 309.18062 (|Δ| = 2.62 ppm). Rₓ: 0.30 (CH₂Cl₂/MeOH, 8:1). Purity: 98.2% (GC).

(±)-Methyl (3R,4S)-3-(aminomethyl)-4-(1,3-benzodioxol-5-yl)-1-methylpyrrolidine-3-carboxylate (6{4}): According to the general procedure, α-cyano ester 7{4} (7.009 g, 24.31 mmol) afforded 6{4} (6.055 g, 85%) as a light yellow oil, after column chromatography (CH₂Cl₂/MeOH, 9:1). ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 6.88 (d, J = 1.7 Hz, 1 ¹H, 4'-CH), 6.78 (dd; J = 8.1, 1.5 Hz; 1 ¹H, 6'-CH), 6.72 (d, J = 8.1 Hz, 1 ¹H, 7'-CH), 5.92 (s, 2 ¹H, 2'-CH₂), 3.83 (app t, J = 7.7 Hz, 1 ¹H, 4-CH), 3.78 (s, 3 ¹H, OCH₃), 3.27 (d, J = 9.9 Hz, 1 ¹H, 2-CHH), 3.01 (dd; J = 9.3, 7.6 Hz; 1 ¹H, 5-CHH), 2.67 (app t, J = 8.7 Hz, 1 ¹H, 5-CHH), 2.66 (d, J = 12.9 Hz, 1 ¹H, CH₃NH₂), 2.53 (d, J = 12.9 Hz, 1 ¹H, CH₃NH₂), 2.48 (d, J = 9.9 Hz, 1 ¹H, 2-CHH), 2.38 (s, 3 ¹H, NCH₃), 1.01 (bs, 2 ¹H, NH₂). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 176.3 (CO₂), 147.4 (3'a-C), 146.3 (7'a-C), 132.5 (5'-C), 122.0 (6'-C), 109.3 (4'-C), 107.8 (7'-C), 100.8 (2'-C), 63.8 (2'-C), 61.8 (5'-C), 58.6 (3'-C), 52.1 (OCH₃), 49.5 (4'-C), 46.6 (CH₂NH₂), 42.0 (NCH₃). FTIR [ν (cm⁻¹), neat]: 3320, 3317, 2946, 2841, 2776, 1721, 1248, 1232, 1034, 929. HRMS [ESI (m/z)] caleed for (C₁₃H₂₁N₂O₄ + H)⁺ = 293.15013, found 293.14936 (|Δ| = 2.63 ppm). Rₓ: 0.25 (CH₂Cl₂/MeOH, 8:1). Purity: 97.4% (GC).

(±)-Methyl (3R,4S)-3-(aminomethyl)-1-methyl-4-(1-methyl-1H-pyrrol-2-yl)pyrrolidine-3-carboxylate (6{5}): According to the general procedure, α-cyano ester 7{5} (752 mg, 3.04 mmol) afforded 6{5} (559 mg, 73%) as a light yellow oil, after column chromatography (CH₂Cl₂/MeOH, 9:1). ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 6.54 (dd; J = 2.4, 1.8 Hz; 1 ¹H, 5'-CH), 6.07 (dd; J = 3.6, 2.7 Hz; 1 ¹H, 4'-CH), 6.04 (dd; J = 3.8, 1.7 Hz; 1 ¹H, 3'-CH), 4.10 (dd; J = 10.5, 7.2 Hz; 1 ¹H, 4-CH), 3.78 (s, 3 ¹H, OCH₃), 3.60 (s, 3 ¹H, 1'-NCH₃), 3.39 (d, J = 9.9 Hz, 1 ¹H, 2-CHH), 3.19 (app t, J = 8.2 Hz, 1 ¹H, 5-CHH), 2.72 (d, J = 13.2 Hz, 1 ¹H, CH₃NH₂), 2.62 (d, J = 13.2 Hz, 1 ¹H, CH₃NH₂), 2.47 (app t, J = 9.8 Hz, 1 ¹H, 2-CHH), 2.35 (s, 3 ¹H, 1-NCH₃), 2.21 (d, J = 9.9 Hz, 1 ¹H, 2-CHH), 1.35 (bs, 2 ¹H,
NH₂). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 177.1 (CO₂), 129.8 (2'-C), 122.3 (5'-C), 107.8 (3'-C), 107.3 (4'-C), 65.3 (2-C), 62.5 (5-C), 58.4 (3-C), 52.5 (OCH₃), 46.7 (CH₂NH₂), 42.2 (1-NCH₃), 40.9 (4-C), 34.2 (1'-NCH₃). FTIR [ð (cm⁻¹), neat]: 3390, 3099, 2946, 2839, 2780, 1729, 1242, 712. HRMS [ESI (m/z)] calcd for (C₁₃H₂₁N₃O₂ + H)⁺ = 252.17120, found 252.17083 (|Δ| = 1.49 ppm). Rₚ: 0.24 (CH₂Cl₂/MeOH, 8:1). Purity: 97.9% (GC).

(±)-Methyl (3R,4S)-3-(aminomethyl)-1-methyl-4-(1-methyl-1H-indol-3-yl)pyrrolidine-3-carboxylate (6{6}): According to the general procedure, α-cyano ester 7{6} (7.628 g, 25.65 mmol) afforded 6{6} (7.337 g, 95%) as a yellow oil, after column chromatography (CH₂Cl₂/MeOH, 9:1). ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 7.72 (dt; J = 8.0, 1.0 Hz; 1 H, 4'-CH₂), 7.28 (dt; J = 8.0, 1.0 Hz; 1 H, 7'-CH), 7.21 (ddd; J = 8.0, 6.8, 1.0 Hz; 1 H, 6'-CH), 7.11 (ddd; J = 8.0, 6.8, 1.0 Hz; 1 H, 5'-CH), 6.98 (s, 1 H, 2'-CH), 4.32 (dd; J = 9.3, 7.3 Hz; 1 H, 4-CH₂), 3.83 (s, 3 H, OCH₃), 3.76 (s, 3 H, 1'-NCH₃), 3.43 (d, J = 10.0 Hz, 1 H, 2-CH₂), 3.17 (dd; J = 9.3, 7.3 Hz; 1 H, 5-CH₂), 2.75 (d, J = 13.2 Hz, 1 H, CH₂N=C), 2.68 (t, J = 9.3 Hz, 1 H, 5-CH₂), 2.60 (d, J = 13.2 Hz, 1 H, CH₂NH₂), 2.45 (d, J = 10.0 Hz, 1 H, 2-CH₂), 2.42 (s, 3 H, 1-NCH₃), 1.04 (bs, 2 H, NH₂). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 177.1 (CO₂), 136.9 (7’a-C), 128.3 (7’a-C), 127.3 (2’-C), 122.0 (6’-C), 119.9 (5’-C), 119.3 (4’-C), 112.0 (3’-C), 109.3 (7’-C), 64.8 (2’-C), 62.5 (5’-C), 58.4 (3’-C), 52.4 (OCH₃), 47.1 (CH₂NH₂), 42.5 (4’-C), 41.6 (1-NCH₃), 32.9 (1’-NCH₃). FTIR [ð (cm⁻¹), neat]: 3386, 3047, 2946, 2834, 2779, 1720, 1472, 1172, 741. HRMS [EI (m/z)] calcd for C₁₇H₂₃N₃O₂ = 301.1790, found for [M⁺] = 301.1776 (|Δ| = 4.7 ppm), peaks at (relative intensity): 301 (7), 284 (93), 228 (18), 157 (100), 144 (22), 57 (27). Rₚ: 0.22 (CH₂Cl₂/MeOH, 8:1). Purity: 98.0% (GC).

(±)-(3R,4R)-3-Cyano-1-methyl-4-phenylpyrrolidine-3-carboxamide (12{11}): ¹H-NMR [300 MHz, δ (ppm), CDCl₃]: 7.41–7.26 (m, 5 H, Ph), 6.58 (s, 1 H, NHH), 6.40 (s, 1 H, NHH), 3.99 (app t, J = 8.1 Hz, 1 H, 4-CH₂), 3.34 (d, J = 9.8 Hz, 1 H, 2-CH₂), 3.16 (app t, J = 8.7 Hz, 1 H, 5-CH₂), 3.12 (d, J = 9.8 Hz, 1 H, 2-CH₂), 3.03 (app t, J = 8.9 Hz, 1 H, 5-CH₂), 2.47 (s, 3 H, NCH₃). ¹³C-NMR [75 MHz, δ (ppm), CDCl₃]: 169.4 (CON), 137.1 (1’-C), 128.6 (2’-C + 6’-C), 128.4 (3’-C + 5’-C), 128.2 (4’-C), 119.0 (CN), 65.2 (2-C), 60.9 (5-C), 55.9 (3-C), 53.1 (4-C), 41.6 (NCH₃). FTIR [ð (cm⁻¹), neat]: 3334, 3192, 2950, 2846, 2794, 2241, 1684, 772, 698. Elem. anal. calcd for C₁₅H₁₅N₃O: C 68.11%, H 6.59%, N 18.33%; found C 68.10%, H 6.48%, N 18.13%. Rₚ: 0.40 (AcOEt). Mp: 121.7 °C (from propan-2-ol, small white needles). Purity: >99.5% (GC).

3.5. Parallel synthesis

3.5.1. General procedure 1 for spiro dihydropyracil/α-ureidomethyl acid formation using parallel synthesis

A solution of isocyanate 13 (0.12 mmol for 1, 0.10 mmol for 3–5) from a 0.3 M stock solution in CH₂Cl₂ was added to a solution of α-aminomethyl ester (0.10 mmol) in CH₂Cl₂ (1.5 mL). The resulting reaction mixture was stirred at room temperature for 15 h. After that time, the solvent was evaporated and THF (1.5 mL) and 1 M KOBu' in THF (0.10 mmol) were added. The reaction mixture was then stirred at room temperature for 15 h. A saturated solution of NH₄Cl (1.0 mL) was added and the layers were separated (centrifugation was needed for the separation when aryl isocyanate was
The aqueous layer was extracted with CH₂Cl₂ (2 × 1.5 mL) and the combined organic layers were evaporated to dryness under vacuum.

3.5.2. General procedure 2 for spiro dihydrouracil/α-ureidomethyl acid formation using parallel synthesis

A solution of isocyanate 13{2,6–8} (0.10 mmol) from a 0.3 M stock solution in DMF was added to a solution of α-aminomethyl ester (0.10 mmol) in DMF (1.5 mL). The resulting reaction mixture was stirred at 80 °C for 15 h. After that time, the solvent was evaporated and THF (1.5 mL) and 1 M KOBu' in THF (0.10 mmol) were added. The reaction mixture was then stirred at room temperature for 15 h. A saturated solution of NH₄Cl (1.0 mL) was added and the layers were separated (centrifugation was needed for the separation when aryl isocyanate was used). The aqueous layer was extracted with CH₂Cl₂ (2 × 1.5 mL) and the combined organic layers were evaporated to dryness under vacuum.

(±)-(4R,5S)-7-Ethyl-2-methyl-4-phenyl-2,7,9-triazaspiro[4.5]decan-6,8-dione (5{1,1}): (From 6{1})

1H-NMR [400 MHz, δ (ppm), CDCl₃]: 7.30–7.19 (m, 5 1H, Ph), 5.60 (bd, J = 2.1 Hz, 1 1H, NH), 4.20 (dd; J = 8.1, 5.4 Hz; 1 1H, 4-CH), 3.85 (dq; J = 12.9, 7.2 Hz; 1 1H, CH₂CH₃), 3.80 (dq; J = 12.9, 7.2 Hz; 1 1H, CH₂CH₂CH₃), 3.06 (dd; J = 9.6, 5.4 Hz; 1 1H, 3-CHH), 2.99 (dd; J = 9.6, 8.1 Hz; 1 1H, 3-CHH), 2.95 (d, J = 9.3 Hz, 1 1H, 1-CHH), 2.94 (dd; J = 12.6, 4.2 Hz; 1 1H, 10-CHH), 2.68 (d, J = 9.3 Hz, 1 1H, 1-CHH), 2.66 (d, J = 12.6 Hz, 1 1H, 10-CHH), 2.41 (s, 3 1H, NCH₃), 1.16 (t, J = 7.2 Hz, 3 1H, CH₂CH₃). 13C-NMR [75 MHz, δ (ppm), CDCl₃]: 173.1 (6-C), 154.1 (8-C), 139.4 (1′-C), 128.7 (2′-C + 6′-C), 128.6 (3′-C + 5′-C), 127.3 (4′-C), 64.0 (1-C), 62.0 (3-C), 52.0 (5-C), 48.3 (4-C), 43.4 (10-C), 42.0 (NCH₃), 36.4 (CH₂CH₃), 13.8 (CH₂CH₂). FTIR [ν (cm⁻¹), neat]: 3240, 2937, 2841, 2784, 1716, 1673, 763, 703. MS [APCI (m/z)] cTed for (C₁₆H₂₁N₃O₂ + H)⁺ = 288, found 288. Crude yield: 51%. Purity: 89% (LC).

(±)-(4R,5S)-7-Ethyl-2-methyl-4-phenyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5{1,2}): (From 6{1})

1H-NMR [400 MHz, δ (ppm), CDCl₃]: 7.33–7.15 (m, 10 1H, 2 × Ph), 5.66 (bd, J = 3.4 Hz, 1 1H, NH), 4.16 (dd; J = 8.0, 5.4 Hz; 1 1H, 4-CH), 4.04 (dt; J = 13.0, 7.6 Hz; 1 1H, NCH₂CH₂C₂H₃), 3.98 (dt; J = 13.0, 7.6 Hz; 1 1H, NCH₂CH₂C₂H₃), 3.05 (dd; J = 9.3, 5.4 Hz; 1 1H, 3-CHH), 2.98–2.83 (m, 5 1H, 1-CHH + 3-CHH + 10-CHH + NCH₂CH₂C₂H₃), 2.56 (d, J = 9.5 Hz, 1 1H, 1-CHH), 2.55 (d, J = 13.2 Hz, 1 1H, 10-CHH), 2.39 (s, 3 1H, NCH₃). 13C-NMR [75 MHz, δ (ppm), CDCl₃]: 173.2 (6-C), 154.0 (8-C), 139.3 (1′-C), 138.6 (1′-C), 129.2 (2′-C + 6′-C), 128.8 (2′′-C + 6′′-C), 128.6 (3′′-C + 5′′-C), 128.5 (3′-C + 5′-C), 127.3 (4′-C), 126.5 (4′-C), 64.0 (1-C), 61.9 (3-C), 52.1 (5-C), 48.2 (4-C), 43.4 (10-C), 42.2 (NCH₂CH₂C₂H₃), 41.9 (NCH₃), 34.5 (NCH₂CH₂C₂H₃). FTIR [ν (cm⁻¹), neat]: 3254, 2937, 2841, 2784, 1716, 1673, 758, 701. MS [APCI (m/z)] cTed for (C₂₂H₂₅N₃O₂ + H)⁺ = 364, found 364. Crude yield: 63%. Purity: 70% (LC).

(±)-Ethyl 3-{(4R,5S)-2-methyl-6,8-dioxo-4-phenyl-2,7,9-triazaspiro[4.5]decan-7-yl}propanoate (5{1,3}): (From 6{1}) MS [APCI (m/z)] cTed for (C₁₉H₂₅N₃O₄ + H)⁺ = 360, found 360. Crude yield: 80% (combined yield of 5{1,3}, 5{1,9}, 5{1,10}, and 5{1,11}). Purity: 91% (LC; combined purity of 5{1,3}, 5{1,9}, 5{1,10}, and 5{1,11}).
(±)-(4R,5S)-7-Ethyl-4-(4-methoxyphenyl)-2-methyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5{2,1}): From 6{2}) MS [APCI (m/z)] calcd for (C_{17}H_{23}N_{3}O_{5} + H)^{+} = 318, found 318. Crude yield: 60%. Purity: 93% (LC).

(±)-(4R,5S)-4-(4-Methoxyphenyl)-2-methyl-7-phenethyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5{2,2}): From 6{2}) MS [APCI (m/z)] calcd for (C_{23}H_{27}N_{3}O_{5} + H)^{+} = 394, found 394. Crude yield: 64%. Purity: 60% (LC).

(±)-Ethyl 3-{(4R,5S)-4-(4-methoxyphenyl)-2-methyl-6,8-dioxo-2,7,9-triazaspiro[4.5]decan-7-yl}propanoate (5{2,3}): From 6{2}) FTIR [v (cm^{-1}), neat]: 3245, 2935, 2837, 2784, 1719, 1674, 1247, 835. MS [APCI (m/z)] calcd for (C_{20}H_{27}N_{3}O_{5} + H)^{+} = 390, found 390. Crude yield: 49% (combined yield of 5{2,3}, 5{2,9}, 5{2,10}, and 5{2,11}). Purity: 88% (LC; combined purity of 5{2,3}, 5{2,9}, 5{2,10}, and 5{2,11}).

(±)-(4R,5S)-4-(3,5-Dimethoxyphenyl)-7-ethyl-2-methyl-2,7,9-triazaspiro[4.5]decane-6,8-dione 5{3,1}): From 6{3}) MS [APCI (m/z)] calcd for (C_{19}H_{25}N_{3}O_{5} + H)^{+} = 348, found 348. Crude yield: 66%. Purity: 90% (LC).

(±)-(4R,5S)-4-(3,5-Dimethoxyphenyl)-2-methyl-7-phenethyl-2,7,9-triazaspiro[4.5]decane-6,8-dione 5{3,2}): From 6{3}) MS [APCI (m/z)] calcd for (C_{24}H_{29}N_{3}O_{5} + H)^{+} = 424, found 424. Crude yield: 60%. Purity: 68% (LC).

(±)-Ethyl 3-{(4R,5S)-4-(3,5-dimethoxyphenyl)-2-methyl-6,8-dioxo-2,7,9-triazaspiro[4.5]decan-7-yl}propanoate (5{3,3}): From 6{3}) MS [APCI (m/z)] calcd for (C_{23}H_{25}N_{3}O_{4} + H)^{+} = 408, found 408. Crude yield: 54% (combined yield of 5{3,3}, 5{3,9}, 5{3,10}, and 5{3,11}). Purity: 95% (LC; combined purity of 5{3,3}, 5{3,9}, 5{3,10}, and 5{3,11}).

(±)-(4R,5S)-4-(1,3-Benzodioxol-5-yl)-7-ethyl-2-methyl-2,7,9-triazaspiro[4.5]decane-6,8-dione 5{4,1}): From 6{4}) MS [APCI (m/z)] calcd for (C_{17}H_{23}N_{3}O_{4} + H)^{+} = 332, found 332. Crude yield: 63%. Purity: 95% (LC).

(±)-(4R,5S)-4-(1,3-Benzodioxol-5-yl)-2-methyl-7-phenethyl-2,7,9-triazaspiro[4.5]decane-6,8-dione 5{4,2}): From 6{4}) MS [APCI (m/z)] calcd for (C_{23}H_{27}N_{3}O_{4} + H)^{+} = 408, found 408. Crude yield: 64%. Purity: 68% (LC).

(±)-Ethyl 3-{(4R,5S)-4-(1,3-benzodioxol-5-yl)-2-methyl-6,8-dioxo-2,7,9-triazaspiro[4.5]decan-7-yl}propanoate (5{4,3}): From 6{4}) MS [APCI (m/z)] calcd for (C_{23}H_{25}N_{3}O_{6} + H)^{+} = 404, found 404. Crude yield: 61% (combined yield of 5{4,3}, 5{4,9}, 5{4,10}, and 5{4,11}). Purity: 98% (LC; combined purity of 5{4,3}, 5{4,9}, 5{4,10}, and 5{4,11}).

(±)-(4R,5S)-7-Ethyl-2-methyl-4-(1-methyl-1H-pyrrol-2-yl)-2,7,9-triazaspiro[4.5]decane-6,8-dione 5{5,1}): From 6{5}) ¹H-NMR [400 MHz, δ (ppm), CDCl₃]: 6.52 (dd; J = 2.8, 1.6 Hz; 1 H, 5'-CH₃), 6.05 (dd; J = 3.5, 2.8 Hz; 1 H, 4'-CH), 6.03 (dd; J = 3.5, 1.6 Hz; 1 H, 3'-CH₃), 5.84 (bd; J = 3.5 Hz, 1 H, NH), 4.35 (app t; J = 8.0 Hz, 1 H, 4'-CH), 3.85 (dq; J = 13.1, 7.0 Hz; 1 H, CH₂CH₃), 3.79 (dq; J
((±)-(4R,5S)-2-Methyl-4-(1-methyl-1H-indol-3-yl)-7-phenethyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5\{5,2\}): (From 6\{5\}) \(^1\)H-NMR [400 MHz, δ (ppm), CDCl\(_3\)]: 7.32–7.15 (m, 5 \(^1\)H, Ph), 6.51 (dd; J = 2.8, 1.6 Hz; 1 \(^1\)H, 5′-CH\(_3\)), 6.05 (dd; J = 3.5, 2.8 Hz; 1 \(^1\)H, 4′-CH\(_3\)), 6.02 (dd; J = 3.5, 1.6 Hz; 1 \(^1\)H, 3′-CH\(_3\)), 5.96 (bd, J = 4.0 Hz, 1 \(^1\)H, NH), 4.31 (app t, J = 8.1 Hz, 1 \(^1\)H, 4-CH\(_3\)), 4.08–3.95 (m, 2 \(^1\)H, NCH\(_2\)CH\(_2\)), 3.34 (s, 3 \(^1\)H, 1′-NCH\(_3\)), 3.13 (app t, J = 8.6 Hz, 1 \(^1\)H, 3-CH\(_3\)), 2.92 (dd; J = 12.9, 4.7 Hz; 1 \(^1\)H, 10-CH\(_{2}\)H\(_3\)), 2.91–2.83 (m, 2 \(^1\)H, NCH\(_2\)CH\(_2\)), 2.80 (d, J = 9.8 Hz, 1 \(^1\)H, 1-CH\(_{2}\)H\(_{2}\)), 2.76 (app t, J = 8.8 Hz, 1 \(^1\)H, 3-CH\(_{2}\)H\(_3\)), 2.62 (d, J = 9.8 Hz, 1 \(^1\)H, 2-CH\(_{2}\)H\(_{2}\)), 2.55 (d, J = 12.9 Hz, 1 \(^1\)H, 10-CH\(_{2}\)H\(_3\)), 2.35 (s, 3 \(^1\)H, 2-CH\(_{2}\)H\(_{2}\)). \(^{13}\)C-NMR [75 MHz, δ (ppm), CDCl\(_3\)]: 173.6 (6-C), 154.2 (8-C), 138.6 (1′′-C), 129.8 (2′′-C), 129.2 (2′′′-C + 6′′-C), 128.5 (3′′-C + 5′′-C), 126.5 (4′′′-C), 122.4 (5′′′-C), 107.5 (3′′′-C), 107.2 (4′′′-C), 65.9 (1-C), 62.0 (3-C), 51.0 (5-C), 43.8 (10-C), 42.2 (NCH\(_2\)CH\(_2\)), 41.9 (2-NCH\(_2\)CH\(_2\)), 39.3 (4-C), 34.4 (NCH\(_2\)CH\(_2\)), 34.1 (1′-NCH\(_3\)). FTIR [\(\nu\) (cm\(^{-1}\)), neat]: 3251, 2941, 2843, 2785, 1716, 1671, 761, 728, 699. MS [APCI (m/z)] calcd for (C\(_{21}\)H\(_{26}\)N\(_4\)O\(_2\) + H\(^+\)) = 367, found 367. Crude yield: 54%. Purity: 92% (LC).

((±)-(4R,5S)-7-Ethyl-2-methyl-4-(1-methyl-1H-indol-3-yl)-7-phenethyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5\{5,1\}): (From 6\{6\}) MS [APCI (m/z)] calcd for (C\(_{21}\)H\(_{26}\)N\(_4\)O\(_2\) + H\(^+\)) = 341, found 341. Crude yield: 69%. Purity: 69% (LC).

((±)-(4R,5S)-7-Ethyl-2-methyl-4-(1-methyl-1H-indol-3-yl)-7-phenethyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5\{5,2\}): (From 6\{6\}) MS [APCI (m/z)] calcd for (C\(_{25}\)H\(_{28}\)N\(_4\)O\(_2\) + H\(^+\)) = 417, found 417. Crude yield: 68%. Purity: 62% (LC).

((±)-Ethyl \(3-\{(4R,5S)-2-methyl-4\)-(1-methyl-1H-indol-3-yl)-6,8-dioxo-2,7,9-triazaspiro[4.5]decane-7-y1\}propanoate (5\{6,3\}): (From 6\{6\}) MS [APCI (m/z)] calcd for (C\(_{22}\)H\(_{28}\)N\(_4\)O\(_3\) + H\(^+\)) = 413, found 413. Crude yield: 62% (combined yield of 5\{6,3\}, 5\{6,9\}, 5\{6,10\}, and 5\{6,11\}). Purity: 86% (LC; combined purity of 5\{6,3\}, 5\{6,9\}, 5\{6,10\}, and 5\{6,11\}).
(±)-(3R,4S)-1-Methyl-4-phenyl-3-[(3-phenylureido)methyl]pyrrolidine-3-carboxylic acid (14{1,4}): (From 6{1}) MS [APCI (m/z)] calcd for (C_{20}H_{23}N_{3}O_{3} + H)^+ = 354, found 354. Crude yield: 49%. Purity: >99% (LC).

(±)-(3R,4S)-1-Methyl-4-phenyl-3-[(3-[4-(trifluoromethyl)phenyl]ureido)methyl]pyrrolidine-3-carboxylic acid (14{1,5}): (From 6{1}) MS [APCI (m/z)] calcd for (C_{21}H_{22}F_{3}N_{3}O_{3} + H)^+ = 422, found 422. Crude yield: 75%. Purity: 97% (LC).

(±)-(3R,4S)-3-[(3-(4-Ethoxyphenyl)ureido)methyl]-1-methyl-4-phenylpyrrolidine-3-carboxylic acid (14{1,6}): (From 6{1}) MS [APCI (m/z)] calcd for (C_{21}H_{22}F_{3}N_{3}O_{3} + H)^+ = 398, found 398. Crude yield: 48%. Purity: >99% (LC).

(±)-(3R,4S)-3-[(3-(3-Cyanophenyl)ureido)methyl]-1-methyl-4-phenylpyrrolidine-3-carboxylic acid (14{1,7}): (From 6{1}) MS [APCI (m/z)] calcd for (C_{21}H_{22}N_{4}O_{3} + H)^+ = 379, found 379. Crude yield: 54%. Purity: >99% (LC).

(±)-(3R,4S)-1-Methyl-4-phenyl-3-[(3-(3-pyridyl)ureido)methyl]pyrrolidine-3-carboxylic acid (14{1,8}): (From 6{1}) MS [APCI (m/z)] calcd for (C_{19}H_{22}N_{4}O_{3} + H)^+ = 355, found 355. Crude yield: 49%. Purity: 79% (LC).

(±)-(3R,4S)-4-(4-Methoxyphenyl)-1-methyl-3-[(3-phenylureido)methyl]pyrrolidine-3-carboxylic acid (14{2,4}): (From 6{2}) MS [APCI (m/z)] calcd for (C_{21}H_{22}N_{3}O_{4} + H)^+ = 384, found 384. Crude yield: 60%. Purity: 99% (LC).

(±)-(3R,4S)-4-(4-Methoxyphenyl)-1-methyl-3-[(3-(3-hydroxyphenyl)ureido)methyl]pyrrolidine-3-carboxylic acid (14{2,5}): (From 6{2}) MS [APCI (m/z)] calcd for (C_{22}H_{24}N_{4}O_{4} + H)^+ = 452, found 452. Crude yield: 65%. Purity: 98% (LC).

(±)-(3R,4S)-3-[(3-(4-Ethoxyphenyl)ureido)methyl]-4-(4-methoxyphenyl)-1-methylpyrrolidine-3-carboxylic acid (14{2,6}): (From 6{2}) MS [APCI (m/z)] calcd for (C_{23}H_{29}N_{3}O_{5} + H)^+ = 428, found 428. Crude yield: 70%. Purity: >99% (LC).

(±)-(3R,4S)-3-[(3-(3-Cyanophenyl)ureido)methyl]-4-(4-methoxyphenyl)-1-methylpyrrolidine-3-carboxylic acid (14{2,7}): (From 6{2}) MS [APCI (m/z)] calcd for (C_{22}H_{24}N_{4}O_{4} + H)^+ = 409, found 409. Crude yield: 60%. Purity: 96% (LC).

(±)-(3R,4S)-4-(3,5-Dimethoxyphenyl)-1-methyl-3-[(3-phenylureido)methyl]pyrrolidine-3-carboxylic acid (14{3,4}): (From 6{3}) MS [APCI (m/z)] calcd for (C_{22}H_{27}N_{3}O_{5} + H)^+ = 414, found 414. Crude yield: 76%. Purity: 97% (LC).
(±)-(3R,4S)-4-(3,5-Dimethoxyphenyl)-1-methyl-3-[(3-[4-(trifluoromethyl)phenyl]ureido)methyl]pyrrolidine-3-carboxylic acid (14{3,5}):

(±)-(3R,4S)-4-(3,5-Dimethoxyphenyl)-1-methyl-3-[(3-[4-(trifluoromethyl)phenyl]ureido)methyl]pyrrolidine-3-carboxylic acid (14{3,6}):

(±)-(3R,4S)-3-[(3-Cyanophenyl)ureido]methyl]-4-(3,5-dimethoxyphenyl)-1-methylpyrrolidine-3-carboxylic acid (14{3,7}):

(±)-(3R,4S)-4-(3,5-Dimethoxyphenyl)-1-methyl-3-[(3-[3-pyridyl]ureido)methyl]pyrrolidine-3-carboxylic acid (14{3,8}):
1H, NCH3), 2.58 (dd; J = 12.9, 2.4 Hz; 1H, CHNH). 13C-NMR [75 MHz, δ (ppm), CD3SOCD3]: 176.7 (CO2), 155.4 (NCON), 147.1 (3’-a-C), 146.1 (7’-a-C), 140.8 (1”-C), 131.3 (5’-C), 128.5 (3’’-C + 5’’-C), 121.9 (6’-C), 120.7 (4’’-C + 6’’-C), 117.4 (2’’-C), 107.9 (7’’-C), 100.9 (2’-C), 62.2 (C), 59.4 (5-C), 55.9 (3-C), 49.5 (4-C), 42.8 (NCH3), 40.5 (CH2NH). FTIR [ν (cm−1), neat]: 3359, 3254, 2954, 2898, 2780, 1671, 1597, 1549, 1495, 1228, 1035, 931, 756, 694. MS [APCI (m/z)] calcd for (C21H23N3O5 + H)+ = 398, found 398. Crude yield: 74%. Purity: >99% (LC).

(±)-(3R,4S)-4-(1,3-Benzodioxol-5-yl)-1-methyl-3-{(3-[4-(trifluoromethyl)phenyl]ureido)methyl}pyrrolidine-3-carboxylic acid (14{4,5}): (From 6{4}) FTIR [ν (cm−1), neat]: 3358, 3254, 2958, 2904, 1675, 1601, 1546, 1504, 1489, 1321, 1231, 1035, 931. MS [APCI (m/z)] calcd for (C22H22F3N3O5 + H)+ = 466, found 466. Crude yield: 68%. Purity: >99% (LC).

(±)-(3R,4S)-4-(1,3-Benzodioxol-5-yl)-1-methyl-3-{(3-(4-ethoxyphenyl)ureido)methyl}pyrrolidine-3-carboxylic acid (14{4,6}): (From 6{4}) MS [APCI (m/z)] calcd for (C23H27N3O6 + H)+ = 442, found 442. Crude yield: 61%. Purity: 77% (LC).

(±)-(3R,4S)-4-(1,3-Benzodioxol-5-yl)-1-methyl-3-{(3-(3-cyanophenyl)ureido)methyl}pyrrolidine-3-carboxylic acid (14{4,7}): (From 6{4}) MS [APCI (m/z)] calcd for (C22H22N4O5 + H)+ = 423, found 423. Crude yield: 62%. Purity: 99% (LC).

(±)-(3R,4S)-4-(1,3-Benzodioxol-5-yl)-1-methyl-3-{(3-(3-pyridyl)ureido)methyl}pyrrolidine-3-carboxylic acid (14{4,8}): (From 6{4}) MS [APCI (m/z)] calcd for (C20H22N4O5 + H)+ = 399, found 399. Crude yield: 54%. Purity: 71% (LC).

(±)-(3R,4S)-1-Methyl-4-(1-methyl-1H-pyrrol-2-yl)-3-{(3-phenylureido)methyl}pyrrolidine-3-carboxylic acid (14{6,4}): (From 6{5}) MS [APCI (m/z)] calcd for (C19H24N4O3 + H)+ = 357, found 357. Crude yield: 58%. Purity: 14% (LC).

(±)-(3R,4S)-1-Methyl-4-(1-methyl-1H-pyrrol-2-yl)-3-{(3-[4-(trifluoromethyl)phenyl]ureido)methyl}pyrrolidine-3-carboxylic acid (14{5,5}): (From 6{5}) MS [APCI (m/z)] calcd for (C20H23F3N4O3 + H)+ = 425, found 425. Crude yield: 65%. Purity: 79% (LC).

(±)-(3R,4S)-3-{(3-(4-Ethoxyphenyl)ureido)methyl}-1-methyl-4-(1-methyl-1H-pyrrol-2-yl)pyrrolidine-3-carboxylic acid (14{5,6}): (From 6{5}) MS [APCI (m/z)] calcd for (C21H28N4O4 + H)+ = 401, found 401. Crude yield: 62%. Purity: 16% (LC).

(±)-(3R,4S)-3-{(3-3-Cyanophenyl)ureido)methyl}-1-methyl-4-(1-methyl-1H-pyrrol-2-yl)pyrrolidine-3-carboxylic acid (14{5,7}): (From 6{5}) MS [APCI (m/z)] calcd for (C20H23N5O3 + H)+ = 382, found 382. Crude yield: 61%. Purity: 99% (LC).

(±)-(3R,4S)-1-Methyl-4-(1-methyl-1H-indol-3-yl)-3-{(3-phenylureido)methyl}pyrrolidine-3-carboxylic acid (14{6,4}): (From 6{6}) MS [APCI (m/z)] calcd for (C23H26N3O3 + H)+ = 407, found 407. Crude yield: 79%. Purity: 97% (LC).
(±)-(3R,4S)-1-Methyl-4-((1-methyl-1H-indol-3-yl)-3-\{(3-\{(3-\{4-(trifluoromethyl)phenyl\}ureido)\}methyl\}pyrrolidine-3-carboxylic acid (14\{6,5\}): From 6\{6\} MS [APCI (m/z)] calcd for (C_{24}H_{25}F_3N_4O_3 + H)^+ = 475, found 475. Crude yield: 76%. Purity: >99% (LC).

(±)-(3R,4S)-3-\{(3-{4-Ethoxyphenyl}ureido)methyl\}-1-methyl-4-((1-methyl-1H-indol-3-yl)pyrrolidine-3-carboxylic acid (14\{6,6\}): From 6\{6\} \^\text{1}H-NMR [400 MHz, δ (ppm), CD_3SOCD_3]: 8.92 (bs, 1 \^1H, NHAr), 7.62 (d, J = 7.8 Hz, 1 \^1H, 4"-CH), 7.38 (d, J = 8.4 Hz, 1 \^1H, 7"-CH), 7.34 (s, 1 \^1H, 2"-CH), 7.29–7.21 (m, 2 \^1H, 2'-CH + 6'-CH), 7.12 (app t, J = 7.5 Hz, 1 \^1H, 6'-CH), 6.96 (app t, J = 7.5 Hz, 1 \^1H, 5"-CH), 6.77–6.69 (m, 2 \^1H, 3'-CH + 5'-CH), 6.18 (bd, J = 6.9 Hz, 1 \^1H, CH_2NH), 4.11 (dd; J = 9.6, 7.5 Hz; 1 \^1H, 4-CH), 3.91 (q, J = 6.9 Hz, 2 \^1H, CH_2CH_3), 3.77 (s, 3 \^1H, 1"'-NCH_3), 3.54 (d, J = 10.2 Hz, 1 \^1H, 2-CHH), 3.53–3.49 (m, 1 \^1H, 5-CHH), 3.21 (dd; J = 13.2, 8.4 Hz; 1 \^1H, CH/NNH), 3.22–3.16 (m, 1 \^1H, 5-CHH), 2.86 (d, J = 10.2 Hz, 1 \^1H, 2-CHH), 2.68 (s, 3 \^1H, 1'-NCH_3), 2.66 (dd; J = 13.2, 2.1 Hz; 1 \^1H, CH/NNH), 1.27 (t, J = 6.9 Hz, 3 \^1H, CH_2CH_3). FTIR [\upsilon (cm\(^{-1}\)), neat]: 3330, 2938, 2880, 1664, 1595, 1540, 827, 733. MS [APCI (m/z)] calcd for (C_{25}H_{30}N_4O_4 + H)^+ = 451, found 451. Crude yield: 70%. Purity: 94% (LC).

(±)-(3R,4S)-3-\{(3-{3-Cyanophenyl}ureido)methyl\}-1-methyl-4-((1-methyl-1H-indol-3-yl)pyrrolidine-3-carboxylic acid (14\{6,7\}): From 6\{6\} \^\text{1}H-NMR [400 MHz, δ (ppm), CD_3SOCD_3]: 10.07 (bs, 1 \^1H, NHAr), 8.02 (s, 1 \^1H, 2'-CH), 7.67 (d, J = 8.1 Hz, 1 \^1H, 6'-CH), 7.61 (d, J = 7.8 Hz, 1 \^1H, 4"-CH), 7.39–7.36 (m, 1 \^1H, 7"-CH), 7.37 (app t, J = 7.8 Hz, 1 \^1H, 5'-CH), 7.36 (s, 1 \^1H, 2'-CH), 7.27 (d, J = 7.5 Hz, 1 \^1H, 4'-CH), 7.10 (app t, J = 7.5 Hz, 1 \^1H, 6'-CH), 6.88 (app t, J = 7.5 Hz, 1 \^1H, 5'-CH), 6.74 (bs, 1 \^1H, CH_2NH), 4.17 (dd; J = 9.9, 7.8 Hz; 1 \^1H, 4-CH), 3.77 (s, 3 \^1H, 1"'-NCH_3), 3.73–3.63 (m, 2 \^1H, 2-CHH + 5-CHH), 3.36 (app t, J = 9.9 Hz, 1 \^1H, 5-CHH), 3.29 (dd; J = 13.4, 9.0 Hz; 1 \^1H, CH/NNH), 2.99 (d, J = 9.9 Hz, 1 \^1H, 2-CHH), 2.80 (s, 3 \^1H, 1-NCH_3), 2.68 (dd; J = 13.4, 2.1 Hz; 1 \^1H, CH/NNH). \^\text{13}C-NMR [75 MHz, δ (ppm), CD_3SOCD_3]: 177.3 (CO_2), 155.5 (NCON), 142.0 (1'-C), 136.6 (7"'-a-C), 129.8 (5'-C), 127.7 (3"'-a-C), 127.6 (2"'-C), 123.9 (4'-C), 122.0 (6'-C), 121.3 (6'-C), 119.8 (2'-C), 119.4 (5'-C), 119.1 (CN), 118.6 (4'-C), 111.3 (3'-C), 109.6 (3'-C), 109.3 (7"'-C), 62.6 (2'-C), 59.1 (5-C), 55.4 (3-C), 42.4 (1-NCH_3), 41.9 (4-C), 41.0 (CH_2NH), 32.5 (1'-NCH_3). FTIR [\upsilon (cm\(^{-1}\)), neat]: 3361, 2940, 2226, 1685, 1583, 1564, 742. MS [APCI (m/z)] calcd for (C_{24}H_{25}N_4O_3 + H)^+ = 432, found 432. Crude yield: 67%. Purity: 99% (LC).

(±)-(3R,4S)-1-Methyl-4-((1-methyl-1H-indol-3-yl)-3-\{(3-{3-pyridyl}ureido)methyl\}pyrrolidine-3-carboxylic acid (14\{6,8\}): From 6\{6\} MS [APCI (m/z)] calcd for (C_{22}H_{25}N_5O_3 + H)^+ = 408, found 408. Crude yield: 71%. Purity: 36% (LC).

(±)-Methyl (3R,4S)-1-methyl-4-phenyl-3-\{(3-phenylureido)methyl\}pyrrolidine-3-carboxylate (15\{1,4\}): Phenyl isocyanate (2.563 g, 21.52 mmol) was added to a solution of α-aminomethyl ester 6\{1\} (4.858 g, 19.56 mmol) in dry CH_2Cl_2 (40 mL). The resulting reaction mixture was stirred at room temperature for 2.5 h and the solvent was then evaporated to afford 15\{1,4\} (6.895 g, 96%) as a white foam, after column chromatography (CH_2Cl_2/MeOH, 14:1). \^\text{1}H-NMR [300 MHz, δ (ppm), CDCl_3]: 7.47 (bs, 1 \^1H, NHPh), 7.28–7.15 (m, 9 \^1H, Ph^+ + 2"'-CH + 3"'-CH + 5"'-CH + 6'-CH), 7.03–6.96 (m, 1 \^1H, 4'-CH), 5.35 (bdd; J = 7.8, 3.6 Hz; 1 \^1H, CH_2NH), 3.91 (app t, J = 8.2 Hz, 1 \^1H, 4-CH), 3.70 (s, 3 \^1H, OCH_3), 3.44 (dd; J = 14.1, 8.4 Hz; 1 \^1H, CH/NNH), 3.20 (d, J = 9.6 Hz, 1 \^1H, 2-CHH), 3.05 (app t, J = 8.6 Hz,
1 H, 5-CHH), 2.96 (app t, J = 9.0 Hz, 1 H, 5-CHH), 2.80 (dd; J = 14.1, 3.9 Hz; 1 H, CHHNNH), 2.72 (d, J = 9.6 Hz, 1 H, 2-CHH), 2.39 (s, 3 H, NCH3). 13C-NMR [75 MHz, δ (ppm), CDCl3]: 176.0 (CO2), 156.1 (NCON), 138.8 (1′′-C), 137.3 (1′-C), 129.0 (2′-C + 6′-C)*, 128.5 (3′-C + 5′-C)*, 128.4 (3″-C + 5″-C)*, 127.2 (4′-C), 123.2 (4″-C), 120.5 (2″-C + 6″-C), 63.3 (2-C), 60.4 (5-C), 57.0 (3-C), 52.8 (OCH3), 50.8 (4-C), 44.0 (CH3NH), 42.3 (NCH3). FTIR [ν (cm−1), neat]: 3323, 2952, 2836, 2790, 1725, 1656, 1597, 751, 710. HRMS [ESI (m/z)] calcd for (C21H25N3O3 + H) + = 368.19687, found 368.19803 (Δ = 1.7 ppm). Rf: 0.40 (CH2Cl2/MeOH, 8:1). Mp: 160.6 °C.

(±)-(4R,5S)-2-Methyl-4,7-diphenyl-2,7,9-triazaspiro[4.5]decane-6,8-dione (5{1,4}): A 1 M solution of KOBu in THF (120 μL, 120 μmol) was added to a solution of α-ureido ester 15{1,4} (44 mg, 120 μmol) in THF (4 mL). The resulting reaction mixture was stirred for 55 min at 31 °C. Brine (1 mL) was then added. The layers were separated and the aqueous phase was extracted with CH2Cl2 (2 × 1.5 mL). The combined organic layers were dried over Na2SO4 and concentrated in vacuo. The residue afforded 5{1,4} (23 mg, 57%) as a white solid, after column chromatography (CH2Cl2/MeOH, 19:1). 1H-NMR [300 MHz, δ (ppm), CD3SOCD3]: 7.79 (bd, J = 3.0 Hz, 1 H, NH), 7.43–7.20 (m, 8 H, Ph′ + 3″-CH + 4″-CH + 5″-CH), 7.16–7.11 (m, 2 H, 2″-CH + 6″-CH), 4.05 (app t, J = 6.9 Hz, 1 H, 4-CH), 2.98 (dd; J = 9.0, 6.6 Hz; 1 H, 3-CHH), 2.95–2.84 (m, 4 H, 1-CH2 + 3-CHH + 10-CHH), 2.67 (dd; J = 12.6, 1.5 Hz; 1 H, 10-CHH), 2.36 (s, 3 H, NCH3). 13C-NMR [75 MHz, δ (ppm), CDCl3]: 173.3 (6-C), 153.9 (8-C), 139.0 (1′′-C), 135.4 (1′-C), 129.1 (3″-C + 5″-C), 128.63 (3′-C + 5′-C)*, 128.58 (2″-C + 6″-C)*, 128.5 (2′-C + 6′-C)*, 128.4 (4″-C), 127.2 (4′-C), 64.0 (1-C), 62.0 (3-C), 52.5 (5-C), 48.3 (4-C), 43.7 (10-C), 42.1 (NCH3). FTIR [ν (cm−1), neat]: 3254, 2945, 2835, 2792, 1725, 1684, 767, 753, 707, 693. Elem. anal. calcd for C28H29N3O3: C 71.62%, H 6.31%, N 12.53%; found C 71.70%, H 6.17%, N 12.48%. Rf: 0.44 (CH2Cl2/MeOH, 8:1). Mp: 231.5 °C (from MeOH, colorless crystals). Purity: >99.5% (GC).

5. Conclusions

In summary, we have developed a general high-yielding method for the synthesis of trans-4-aryl-substituted 3-(aminomethyl)pyrrolidine-3-carboxylates. We have shown that these aryl groups can be phenyl or electron-rich aryls (4-methoxyphenyl, 3,5-dimethoxyphenyl, and 1,3-benzodioxol-5-yl) and electron-rich heteroaryls (1-methylpyrrol-2-yl and 1-methylindol-3-yl). As a result, we anticipate that this methodology can be successfully applied for a wide range of aromatic groups, although with electron-poor heteroaryls (2-, 3-, and 4-pyridyl) mixtures of cis–trans isomers are formed after the cycloaddition step.

We have also developed a method for the synthesis of a small library of 7-alkylidihydrouracils spiro-fused to pyrrolidines to the 3-position. The corresponding 7-aryl derivatives hydrolyzed under the conditions utilized for the cyclization and yielded α-ureidomethyl acids. The optimization of this cyclization should be further developed.

Acknowledgements

We would like to thank Richard H. Blaauw and Chiralix B.V. (Nijmegen, The Netherlands) for the use of their parallel-synthesis facilities. This work was financially supported by the Council of
References and Notes


Sample Availability: Contact the authors.

© 2010 by the authors; licensee Molecular Diversity Preservation International, Basel, Switzerland. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/3.0/).