Enantioselective total synthesis of (−)-myrifabral A and B†

Tyler J. Fulton, Anthony Y. Chen, Michael D. Bartberger and Brian M. Stoltz*

A catalytic enantioselective approach to the Myrioneuron alkaloids (−)-myrifabral A and (−)-myrifabral B is described. The synthesis was enabled by a palladium-catalyzed enantioselective allylic alkylation, that generates the C(10) all-carbon quaternary center. A key N-acyl iminium ion cyclization forged the cyclohexane fused tricyclic core, while vinyl boronate cross metathesis and oxidation afforded the lactol ring of (−)-myrifabral A. Adaptation of previously reported conditions allowed for the conversion of (−)-myrifabral A to (−)-myrifabral B.

Introduction

The Myrioneuron alkaloids are a small, yet growing family of structurally diverse polycyclic (tri-, tetra-, penta-, hexa-, and decacyclic) alkaloids believed to share a common biosynthetic origin from lysine (Fig. 1).† The first Myrioneuron alkaloids from Myrioneuron nutans were reported in 2002, with altogether 10 structures reported to date.‡ Since 2013, many new alkaloids have been isolated from Myrioneuron faberi,‡ Myrioneuron tonkinensis,* and Myrioneuron effusum.‡ In addition to their interesting structural features, a number of these alkaloids possess a range of biological activities such as antimalarial properties, KB cell cytotoxicity, antimicrobial, and hepatitis C virus (HCV) replication inhibition.¶ Despite possessing promising biological properties and synthetically attractive motifs, relatively few of these alkaloids have been prepared by total synthesis efforts.δ,ε,κ,θ

We became interested in (±)-myrifabral A (4) and (±)-myrifabral B (5) in particular due to their unique cyclohexane fused octahydroquinolinizine skeletons which contain four contiguous stereogenic centers, including an all-carbon quaternary center embedded in the cyclohexane fusion. Interestingly, both 4 and 5 are isolated as racemic mixtures of α- and β-hydroxy epimers. Even as racemates, these clusters display promising HCV replication inhibition (EC₅₀ = 4.7 μM for (±)-α,β-OH-4 and 2.2 μM (±)-α,β-OH-5, respectively) with significantly reduced liver cell cytotoxicity compared to commercial pharmaceutical HCV drug telaprevir (EC₅₀ = 0.09 μM).κ She et al. recently reported a rapid total synthesis of (±)-α,β-OH-4 and (±)-α,β-OH-5, however, no asymmetric approaches have been disclosed to date.κ To enable further studies of these alkaloids in each enantiomeric series, we report herein a short, catalytic enantioselective synthesis of (−)-α,β-OH-4 and (−)-α,β-OH-5.

Scheme 1 Retrosynthetic analysis of (−)-myrifabral A.

Fig. 1 Representative Myrioneuron alkaloids.

† Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA 91125, USA. E-mail: stoltz@caltech.edu
‡ 1200 Pharma LLC, 844 East Green Street, Suite 204, Pasadena, CA, 91101, USA. E-mail: michael.bartberger@1200pharma.com
† Electronic supplementary information (ESI) available: Experimental procedures, NMR and IR spectra, SFC traces, X-ray crystallographic data. See DOI: 10.1039/d0sc01141j
Scheme 2 Initial synthesis of glutarimide 8.

In devising our strategy, we targeted (−)-myrifabral A (4), which can be directly converted to (−)-myrifabral B (5), as reported by She (Scheme 1). Retrosynthetically, we envisioned (−)-myrifabral A (4) could be simplified to tricyclic lactam (6). Importantly, the versatile ketone, allyl, and lactam functional handles in tricyclic lactam 6 provide ample opportunity for future diversification of the natural product scaffold for medicinal chemistry efforts and potential derivative synthesis. We envisioned the critical C(6)–C(7) bond could arise by means of a diastereoselective N-acyl iminium ion cyclization of enantioenriched ketone 7. Finally, the C(10) all-carbon quaternary center could be forged in an enantioselective manner by means of asymmetric allylic alkylation of glutarimide 8. In turn, glutarimide 8 could be prepared from β-ketoester 9.

Results and discussion

Our synthetic efforts commenced with the preparation of glutarimide 8 (Scheme 2). Alkylation of β-ketoester 9 (ref. 8) with sulfonylmethyl carbamate 10 in the presence of Cs₂CO₃ proceeded smoothly on a 30.0 g scale to afford β-aminoketone 11 in 95% yield. Elaboration of the Boc-protected amine to glutarimide 8 with standard protocols was low yielding and required three separate reactions. This inspired us to develop

Table 1 Development of a one-pot conversion of Mannich adduct 11 to glutarimide 8

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>% yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 : 1 DMF/TFA (0.10 M), 12 (4 equiv.), reflux, 48 h</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>3 : 1 1,4-dioxane/TFA (0.10 M), 12 (4 equiv.), reflux, 48 h</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>B(OH)₃ (3.0 equiv.), 12 (4 equiv.), xylenes, Dean–Stark, reflux, 36 h</td>
<td>90–95</td>
</tr>
<tr>
<td>4</td>
<td>B(OH)₃ (3.0 equiv.) xylenes, Dean–Stark, reflux, 72 h</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>5</td>
<td>12 (4 equiv.), xylenes, Dean–Stark, reflux, 72 h</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>6</td>
<td>13 (4 equiv.), xylenes, Dean–Stark, reflux, 72 h</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>7</td>
<td>Xylenes, Dean–Stark, reflux, 120 h</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>8</td>
<td>B(OH)₃ (10 mol%), 12 (2 equiv.), xylenes, Dean–Stark, reflux, 36 h</td>
<td>90–95</td>
</tr>
<tr>
<td>9</td>
<td>B(OH)₃ (10 mol%), 13 (2 equiv.), xylenes, Dean–Stark, reflux, 36 h</td>
<td>90–95</td>
</tr>
<tr>
<td>10</td>
<td>PhB(OH)₂ (10 mol%), 13 (2 equiv.), xylenes, Dean–Stark, reflux, 24 h</td>
<td>90–95</td>
</tr>
<tr>
<td>11</td>
<td>PhB(OH)₂ (10 mol%), 13 (2 equiv.), xylenes, Dean–Stark, reflux, 36 h</td>
<td>90–95</td>
</tr>
<tr>
<td>12</td>
<td>4-CF₃PhB(OH)₂ (10 mol%), 13 (2 equiv.), xylenes, Dean–Stark, reflux, 24 h</td>
<td>90–95</td>
</tr>
</tbody>
</table>

* Reaction performed on a 0.16 mmol scale unless otherwise stated. Isolated yield; ranges reflect yields obtained from 3–4 reactions. Reaction performed on a 0.80 mmol scale.
a more practical, one-pot procedure to enable the installation of the glutarimide moiety (Table 1). Initially, trifluoroacetic acid mediated conditions were explored, with the most promising results observed in 3:1 DMF/TFA at reﬂuxing temperature (entry 1) and 3:1 1,4-dioxane/TFA (entry 2). Further investigation revealed that stoichiometric boric acid could mediate the transformation in excellent yield in xylenes at 140 °C (entry 3). While aryl boronic acids have been demonstrated as effective catalysts for amidation of carboxylic acids with amines, we were surprised to observe concomitant Boc protection smoothly afforded full reduction of the lactam to the corresponding tertiary amine. A modiﬁed Fieser work up then provided desired amino alcohol 16 in 97% yield. Initially, we found the terminal oleﬁn recalcitrant to both direct and two-step oxidations to the aldehyde due to challenges with oleﬁn isomerization and undesired or poor reactivity. To our delight, oleﬁn cross metathesis using Hoveyda-Grubbs II catalyst of amino alcohol 16 with vinyl boronic acid pinacol ester (17) as an aldehyde surrogate smoothly afforded metathesis product 18. Elaboration of the vinyl boronate was then affected by deprotection and oxidation of the boronic acid, with in situ lactolization providing (−)-myrifabral A in 50% yield. X-ray crystallography allowed for the determination of the absolute stereochemistry of the (−)-myrifabral A enantiomeric series. Adaptation of She’s conditions for the synthesis of (±)-myrifabral B then provided

Completion of the synthesis required reduction of the lactam and ketone and elaboration of the terminal oleﬁn to an aldehyde (Scheme 4). Toward that end, a one-pot procedure was developed wherein the ketone was ﬁrst reduced by s-selectride with exceptional diastereoselection (>19:1). Following the reduction of the ketone, addition of LiAlH4 and heating to reﬂux afforded ful reduction of the lactam to the corresponding tertiary amine. A modiﬁed Fieser work up then provided desired amino alcohol 16 in 97% yield. Initially, we found the terminal oleﬁn recalcitrant to both direct and two-step oxidations to the aldehyde due to challenges with oleﬁn isomerization and undesired or poor reactivity. To our delight, oleﬁn cross metathesis using Hoveyda-Grubbs II catalyst of amino alcohol 16 with vinyl boronic acid pinacol ester (17) as an aldehyde surrogate smoothly afforded metathesis product 18. Elaboration of the vinyl boronate was then affected by deprotection and oxidation of the boronic acid, with in situ lactolization providing (−)-myrifabral A in 50% yield. X-ray crystallography allowed for the determination of the absolute stereochemistry of the (−)-myrifabral A enantiomeric series. Adaptation of She’s conditions for the synthesis of (±)-myrifabral B then provided

Scheme 3 Enantioselective synthesis of tricyclic lactam 6.
access to \((-\text{-myrifabral B})\) in 70% yield (Scheme 5).\(^4\)\(^6\) Interestingly, both \((-\text{-myrifabral B})\) and \((-\text{-myrifabral A})\) are isolated as oils, whereas racemates of these compounds are isolated as solids.\(^3\)\(^\text{-}^6\) Spectroscopic data obtained were in excellent agreement with the natural compound (see ESI†).

### Conclusions

We have described the first enantioselective total synthesis of \((-\text{-myrifabral A})\) and \((-\text{-myrifabral B})\). Critical to the success of this strategy was the development of a direct and high yielding one-pot conversion of a Boc-protected amine (11) to the glutarimide (8). Palladium catalyzed decarboxylative asymmetric allylic alkylation provided the C(10) all-carbon quaternary center in 88% ee, setting the stage for ketone protection, glutarimide reduction, and an exquisitely diastereoselective N-acyl iminium ion cyclization. Following ketone and lactam reduction, cross metathesis with vinyl boronic acid pinacol boronate and subsequent boronic acid deprotection and oxidation afforded \((-\text{-myrifabral A})\). Utilizing previously reported conditions, \((-\text{-myrifabral A})\) was converted to \((-\text{-myrifabral B})\). This marks the first catalyst-controlled asymmetric synthesis of myrifabral A and B, enabling future biological study of individual enantiomeric series.

### Conflicts of interest

There are no conflicts to declare.

### Acknowledgements

We thank NIH-NIGMS (R01GM080269) and Caltech for financial support. Dr Scott Virgil (Caltech) is thanked for instrumentation and SFC assistance. We thank Dr David Vander Velde (Caltech) for NMR expertise, and Dr Mona Shahgholi (Caltech) and Naseem Torian (Caltech) for mass spectrometry assistance.

### Notes and references


13 See ESI† for details.