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Preparation of Bicyclo[4.3.0]nonanes by an Organocatalytic Intramolecular Diels–Alder Reaction

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The bicyclo[4.3.0]nonane substructure is an abundant structure found in several natural compounds. A novel enantioselective organocatalytic cycloaddition was used to prepare the bicyclo[4.3.0]nonane skeleton.

Introduction

A novel method for producing bicyclo[4.3.0]nonanes, trans-fused hexahydroindenes, (Figure 1) has been developed. These types of substructure can be found in several natural compounds. For example, Sata and Fusetani isolated and identified amaminols A (1) and B (2),[1] which are cytotoxic against P388 murine leukemia cells with an IC₅₀ value of 2.1 μg mL⁻¹. Amaminols A (1) and B (2) contain an interesting trans-fused hexahydroindene substructure (Figure 1), most probably formed from a triene through an intramolecular Diels–Alder reaction in nature.

Figure 1. Structures of amaminols A (1) and B (2).

Results and Discussion

Natural compounds related to amaminol A (1) and B (2), such as pulo’upones,[2] indanomycin (X-14547A),[3] 16-deethylindanomycin (A83094A),[4] homoisadanomycin,[5] cafamycin,[6] stavamycin,[7] cochleamycin A,[8] ikarugamycin,[9] and lepicidin A[10] have been synthesized by several different methods. The research groups of Roush,[11] Nicolaou,[12] Boeckman,[13] Ley,[14] Kurth,[15] Jones[16] Paquette,[17] Hase,[18] and Dias[19] have mostly used thermal IMDAs for the preparation of their target molecules. However, the triene precursor for the IMDA has to be chiral itself if a racemic mixture is to be avoided without use of a chiral catalyst. In some syntheses a Lewis acid and a covalently bound chiral auxiliary are used to improve the diastereo- and enantioselectivities of the IMDA cycloaddition. For example, Oppolzer,[20] Takano,[21] and Evans[22] used different covalently bound auxiliaries in their natural product syntheses. Furthermore, Evans has used asymmetric copper catalysts in IMDA during the preparation of isopuluo’upone.[23] Burke has used RHDA cycloreversion[24] in the synthesis of these types of compounds. Photocyclization also affords an elegant route to bicyclo[4.3.0]nonanes, which has been demonstrated by Whitesell.[25] However, the preparation of the precursor can be laborious, as in the synthesis of ikarugamycin (15 steps). The oxy-Cope rearrangement approach also provides a short route to bicyclo[4.3.0]nonanes, as demonstrated by the Paquette group.[26]

During the synthesis of amaminol A (1) we became interested in extending our recently developed organocatalytic Diels–Alder reaction to intramolecular cases.[27] The requisite triene starting material for cycloaddition experiments was prepared from readily available methyl sorbate in seven steps by conventional methods.[28] The resulting mixture of triene aldehydes 3 and 4 (Figure 2) was difficult to separate by distillation or chromatography, and was thus used as such, since only 3 would undergo the desired IMDA reaction.

Figure 2. Starting material mixture used for organocatalytic intramolecular Diels–Alder reactions.
We decided to employ the organocatalysts developed by McMillan[29] in our cycloaddition step. Imidazolidinone catalysts 5-9 (Scheme 1) were prepared by published procedures[20]. The stereochemistries of the catalysts 5-9 were confirmed by NOE NMR measurements. Cyclization of the amide 8 produced a diastereomeric mixture of imidazolidinones 7a/b (1:3.1). Unfortunately, the cyclization favored the trans cycloadduct. The NOE NMR data showed coupling between the protons 2-H and 5-H in the imidazolidinone ring of 7a. It was interesting to note that the cis product 7a did not racemize notably during the long reaction time. However, the trans product 7b was prone to racemization, and cycloadduct 7b was found to be entirely racemic by chiral HPLC analysis.

The starting materials for the IMDA cycloadditions were mixtures of linear triene aldehyde 3 and the inseparable branched triene aldehyde 4 (Scheme 3). The linear triene aldehyde 3 was more inclined towards polymerization, so some of the experiments were performed with starting materials containing more of the branched triene aldehyde 4. However, both aldehydes 3 and 4 are capable of forming the iminium ion with the amine catalyst. The catalyst loadings were calculated according to the total aldehyde amount. The branched triene aldehyde 4 resisted cyclodaddition and was thus easily separated from the cycloadduct 13 by flash chromatography. The cycloadduct aldehyde 13 was reduced to the corresponding alcohol 14 for analytical purposes.[30] The endolexo selectivities were determined by 1H NMR spectroscopy from the crude product mixtures. The chemical shifts of the formyl protons of the endo and exo cycloadduct aldehydes 13 differed by about 0.08 ppm.

The results of the organocatalytic IMDA cycloadditions are shown in Table 1. Catalyst 8 gave the highest enantioselectivities (Entry 2, 74% ee), yields (Entry 3, 99%), and endo selectivities (Entries 2, 3, 4, and 7, >99:1) compared to other organocatalysts 7a, 9, and 12a. Trimethyloxazolidinone 9, which has a stereogenic center only at the C-5 position, was found to give low stereoselectivities (Entry 8), although oxazolidinone 9 is an excellent catalyst for Diels–Alder cycloaddition.[29b] The IMDA cycloaddition of triene aldehyde 3 was observed to be solvent-dependent. Use of a methanol solution afforded somewhat higher enantioselectivity (Entries 2 and 3) than use of an acetonitrile solution, but an extra step was required for cleavage of the acetol formed from the aldehyde 3 during the reaction, and the yield of the cycloadduct 13 was also lower in MeOH than in acetonitrile. The enantioselectivities did not improve significantly at lower temperature (Entries 9 and 10). Furthermore, the low temperature (−20 °C) retarded the reaction significantly, so that it was not complete even after several days. Surprisingly, the enantioselectivity was decreased at lower temperature in the reaction catalyzed by 8 (Entry 3 and 4). This is probably due to racemization of the catalyst during the longer reaction time. In comparison, the enantioselectivity was increased slightly, but the endolexo ratio became worse when the reaction was catalyzed by 12a at low temperature (−20 °C). Although no direct comparison between the acids can be made because the solvent system was also changed, it can be inferred that p-toluenesulfonic acid in dichloromethane/propan-2-ol afforded worse endolexo selectivities and enantioselectivities than other solvent/acid systems examined (Entries 5 and 11).

We also synthesized compound 12, with an N-benzyl group, to test it as a catalyst for this reaction. Thus, (S)-phenylalanine methyl ester hydrochloride salt 10 was directly amidated with benzylamine in high yield (88%) (Scheme 2). Cyclization of 11 produced an 18% yield of the correct diastereomer 12a. The stereochemistry of the catalyst 12a was confirmed by NOE NMR measurements, protons 2-H and 5-H in the imidazolidinone ring showing NOE. No notable racemization was observed for the cis cycloadduct 12a, but production of the trans cycloadduct 12b was accompanied by racemization.

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Table 1. Conditions and results for the IMDA reaction of the triene aldehyde 3 catalyzed by the organocatalysts 7a, 9, and 12a.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst[a]</th>
<th>Substrate (3/4)</th>
<th>Temperature</th>
<th>Solvent</th>
<th>Acid</th>
<th>endo/exo[b]</th>
<th>Yield[c] (%)</th>
<th>ee[d] (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7a</td>
<td>21:79</td>
<td>room temp.</td>
<td>H₂O/CH₃CN</td>
<td>0.1 M HCl</td>
<td>&gt;99:1</td>
<td>59</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>73:27</td>
<td>room temp.</td>
<td>H₂O/MeOH</td>
<td>0.4 M HCl</td>
<td>&gt;99:1</td>
<td>54</td>
<td>74</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>21:79</td>
<td>room temp.</td>
<td>H₂O/CH₃CN</td>
<td>0.1 M HCl</td>
<td>&gt;99:1</td>
<td>99[1]</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>65:35</td>
<td>-20 → +6 °C</td>
<td>H₂O/CH₃CN</td>
<td>0.1 M HCl</td>
<td>&gt;99:1</td>
<td>54</td>
<td>66</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>65:35</td>
<td>-20 → +6 °C</td>
<td>CH₂Cl₂/PrOH</td>
<td>PTSA</td>
<td>25:1</td>
<td>45</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>65:35</td>
<td>-20 → +6 °C</td>
<td>H₂O/THF</td>
<td>TFA</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>8[f]</td>
<td>65:35</td>
<td>room temp.</td>
<td>H₂O/CH₃CN</td>
<td>0.1 M HCl</td>
<td>&gt;99:1</td>
<td>79</td>
<td>72</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>68:32</td>
<td>0 °C → room temp.</td>
<td>H₂O/MeOH</td>
<td>0.4 M HCl</td>
<td>3.3:1</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>12a</td>
<td>65:35</td>
<td>-20 → +6 °C</td>
<td>H₂O/CH₃CN</td>
<td>0.1 M HCl</td>
<td>17:1</td>
<td>40</td>
<td>56</td>
</tr>
<tr>
<td>10</td>
<td>12a</td>
<td>65:35</td>
<td>room temp.</td>
<td>H₂O/CH₃CN</td>
<td>0.1 M HCl</td>
<td>&gt;99:1</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>11</td>
<td>12a</td>
<td>65:35</td>
<td>-20 → +6 °C</td>
<td>CH₂Cl₂/PrOH</td>
<td>PTSA</td>
<td>14:1</td>
<td>38</td>
<td>12</td>
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<tr>
<td>12</td>
<td>12a</td>
<td>65:35</td>
<td>-20 → +6 °C</td>
<td>H₂O/THF</td>
<td>TFA</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

[a] 20 mol % of the catalyst relative to the calculated total moles of aldehydes 3 and 4 was used. [b] endo/exo ratios were determined by ¹H NMR from the aldehyde product mixture. [c] Yields of isolated pure aldehydes. The yields were correlated to the amount of linear aldehyde 3 in the beginning of the reaction. [d] For determination of the ee values, the aldehyde products were first reduced to alcohols with excess NaBH₄ in EtOH, and the resulting alcohols were analyzed by HPLC on a chiral Daicel OD column. Absolute and relative configurations were assigned by chemical correlation to compounds obtained by known methods for Diels–Alder reactions or by analogy. [e] The ratio of the linear triene aldehyde 3 to the branched triene aldehyde 4 in this reaction was 1:3.76. [f] 5.6 mol % of the catalyst was used in this reaction.

Conclusions

A new method to prepare bicyclo[4.3.0]nonane compounds by organocatalysis was found during the development of a route to synthesis amaminol A (1). The enantio-omer of the bicyclo[4.3.0]nonane substructure of amaminol A (1) was synthesized by the novel organocatalytic IMDA cycloaddition to prepare the easily modifiable intermediate aldehyde 13. It may be possible to synthesize the amaminol A (1) substructure as the major product if the IMDA cycloaddition step is catalyzed with the (R,R)-organocatalyst. Synthesis towards amaminol A (1) will be continued and reported on separate report.

Experimental Section

General Remarks: Solvents and starting materials were used as purchased from the suppliers unless otherwise noted. Distilled water was filtered through Millipore filtration system. The glassware was oven-dried (>120 °C) or flame-dried under oil-pump vacuum when dry conditions were required. The reactions were performed under argon when necessary. NMR spectra were recorded with a Varian 400 spectrometer (¹H NMR, 399.99 MHz, ¹³C NMR 100.58 MHz) and a Bruker Avance DPX 400 spectrometer (¹H NMR, 400.13 MHz, ¹³C NMR 100.62 MHz). Thin layer chromatography was performed on silica mesh 60 coated aluminumium plates. For visualization, UV light (254 nm) and ninhydrin, phosphomolybdic acid, anisaldehyde, and permanganate solutions were used. Mass spectra were determined with a JEOL JMS-DX303 apparatus (Helsinki University of Technology) and an LCT Micromass (ES+) (University of Oulu, Department of Chemistry). Flash chromatography was performed with 60 mesh silica. TIFR spectra were measured with a Perkin-Elmer Spectrum One instrument. The melting points were determined with a Gallenkamp MFB-595 apparatus and are not corrected. GC was performed with a Hewlett-Packard 6810 instrument with a Supelco gas chromatograph 120 column, 30 m, 0.25 mm, 0.25 μm film with He as the carrier gas. Gas velocity was 28 cm s⁻¹. An FID detector was used. For chiral HPLC, a Daicel OD column was used (5 × 0.46 cm, 25 × 0.46 cm) with UV detection at λ = 254 nm, and a flow rate of 0.8 mL min⁻¹, unless otherwise noted. The eluent was a mixture of propan-2-ol and hexane.

(2E,7E,9E)-11-Benzoyloxynodeca-2,7,9-trienal (3): Crude 11-benzoyloxynodeca-2,7,9-trien-1-ol (0.313 g, 1.15 mmol, 100 mol %) was dissolved in CH₂Cl₂ (20 mL), and MnO₂ (0.600 g, 6.9 mmol, 600 mol %) was added. Stirring was continued for 15 h and a second portion of MnO₂ (0.102 g, 1.17 mmol, 102 mol %) was added, and stirring was then continued for another 3.5 h and a third portion of MnO₂ (0.298 g, 3.43 mmol, 298 mol %) was added. Stirring was continued for a further 5 h and the reaction mixture was filtered through a thin pad of Celite and concentrated to give 0.461 g of a yellowish oil. The crude product was purified by flash chromatography (14% MTBE/hexane) to yield 3 (0.264 g, 89% over 2 steps) as a clear oil. Rₚ (40% MTBE in hexanes) = 0.22. ¹H NMR (CDCl₃, 400.132 MHz): δ = 9.51 (d, J = 7.8 Hz, 1 H), 7.35–7.26 (m, 5 H), 6.83 (dt, J = 15.6, 6.8 Hz, 1 H Hz), 6.24 (dd, J = 14.8, 10.8 Hz, 1 H Hz), 6.15–6.04 (m, 2 H), 5.75–5.61 (m, 2 H), 4.51 (s, 2 H), 4.05 (d, J = 6.0 Hz, 2 H), 2.34 (qd, J = 7.3, 1.4 Hz, 2 H Hz), 2.15 (q, J = 7.3 Hz, 2 H), 1.62 (q, J = 7.3 Hz, 2 H) ppm. ¹³C NMR (CDCl₃, 100.62 MHz): δ = 194.7, 158.9, 140.8, 139.0, 136.0, 134.4, 133.8, 133.5, 131.2, 129.0, 128.3, 72.7, 71.1, 32.7, 32.6, 28.0 ppm. LRMS (EI+): m/z (%) = 270, 180, 105, 91 (100), 79, 65. HRMS (EI+): calcd. for [M + 43] = 227.1435; found 227.1491.

(2S,5S)-5-Benzyl-3-methyl-2-phenylimidazolidin-4-one (7a): The HCl salt of amine 6 (2.37 g, 11.1 mmol, 100 mol %) was treated with a saturated solution of NaHCO₃ (45 mL). The free amine was extracted with CHCl₃ (3 × 50 mL). The organic layers were washed with Na₂SO₄, filtered, and concentrated to give 2.05 g of a yellowish oil. Methanol (20 mL), benzaldehyde (1.29 g, 12.2 mmol, 110 mol %), and para-toluenesulfonic acid monohydrate (0.21 g, 1.1 mmol, 10 mol %) were added, and the reaction mixture was warmed with an oil bath to +75 °C. Stirring was continued for 3 d and the reaction mixture was allowed to cool to room temp. The solvents were evaporated to give 3.26 g of an orange oil. The crude product was purified by flash chromatography (50–100% EtOAc/hexane) to yield 7a (0.31 g, 11% as a yellow oil. The ratio of (S,S)/(R,R) products was 1:3.1 by ¹H NMR spectroscopy. Rₚ (S,S) (75% EtOAc in hexanes) = 0.16. [α]₂₀ = -46.5 (c = 1.12, CHCl₃). Rₚ (R,R,S) (75% EtOAc in hexanes) = 0.33. The product was analyzed by chiral HPLC (10% iPrOH in hexane, flow rate 1.0 mL min⁻¹). The retention times were 13.59 min for (S,S) and...
amine product was purified by flash chromatography (32% EtOAc/hexane) = 0.65. 1H NMR (CDCl₃, 400.132 MHz): δ = 174.4, 138.4, 136.7, 129.8, 129.5, 129.0, 128.8, 127.1, 126.9, 77.6, 60.4, 36.8, 27.3 ppm. 13C NMR (CDCl₃, 100.62 MHz): δ = 128.1, 128.0, 127.4, 73.6, 71.2, 63.2, 46.1, 44.5, 41.7, 38.7, 28.7, 27.1, 22.5 ppm. HRMS (EI): calcd. for C₁₈H₂₄O₂: 270.1776; found 272.1786.

(2S,5S)-3,5-Dibenzyl-2-tert-butylimidazolidin-4-one (12a): Free amine 11 (2.22 g, 8.73 mmol, 100 mol%) was dissolved in MeOH (15 mL). Trimethylacetaldehyde (0.83 g, 9.60 mmol, 110 mol %) and para-toluene sulfonic acid monohydrate (0.17 g, 0.87 mmol, 10 mol %) were added. The resulting mixture was warmed with an oil bath to +75°C. Stirring was continued under reflux for 2 d and the reaction mixture was allowed to cool to room temp. The solvent was evaporated to give 2.72 g of a yellow oil. The crude product was purified by flash chromatography (32% EtOAc/hexane) to yield 12a (0.52 g, 18%) as a clear oil. The ratio of (S,S)/(S,R,R,S) was determined by 1H NMR spectroscopy. ρ₅(S,S) (70% EtOAc/hexane) = 0.49. [α]D²⁰ = +128.0 (c = 1.11, CHCl₃). ρ₅(S,R,R,S) (70% EtOAc/hexane) = 0.65. [α]D²⁰ (CDCl₃, 400.132 MHz): δ = 7.32–7.13 (m, 10 H), 5.06 (d, J = 15.7 1 H), 4.25 (d, J = 15.7 Hz, 1 H), 4.13 (s, 1 H), 3.85 (ddd, J = 7.5, 4.1, 1.4 Hz, 1 H), 3.22 (dd, J = 13.7, 4.1 Hz, 1 H), 3.04 (d, J = 13.7, 7.5 Hz, 1 H), 0.76 (s, 9 H) ppm. 13C NMR (CDCl₃, 100.62 MHz): δ = 174.4, 138.4, 136.7, 129.8, 129.5, 129.0, 128.8, 127.1, 126.9, 77.6, 60.4, 36.8, 27.3 ppm. The (S,S) configuration was confirmed by COSY/PFGF (coupling between δ = 4.13 and 3.85 ppm was observed). HRMS (EI): calcd. for C₁₈H₂₄O₂: 272.2045; found 272.2045.


Acknowledgments

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[30] The opposite enantiomer has been synthesized by use of the pure (R) enantiomer of phenyloxazolidinone as a covalently attached chiral auxiliary. Its structure and absolute and relative stereochemistry were determined by X-ray crystallography: S. A. Selkälä, Ph.D. Thesis (Total synthesis of amaminol A), 2003, Helsinki University of Technology.