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Flexible, Phase-Transfer Catalyzed Approaches to 4-Substituted Prolines

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Supporting Information

ABSTRACT: A range of 4-substituted prolines can be rapidly synthesized from a protected glycine Schiff base in only four steps and in 27−55% overall yield. Phase transfer catalysis allows direct access to both enantiomeric series, and the relative stereochemistry at the 4-position is readily controlled (>10:1 dr) through the choice of hydrogenation conditions.

Proline is unique among the 20 proteinogenic amino acids in that it forms a conformationally restrained tertiary amide bond.1 Proline residues thus form an important part of protein structural features such as loops, turns, and polyproline helices;2 substituted proline derivatives3 can enhance the inherent structural constraints which proline imparts upon a peptide, or peptide mimic. Our interest in 4-substituted prolines was sparked by the incorporation of cis 4-methyl proline (cis 4-MePro) in bisebromoamide (2, Figure 1), a natural product isolated from marine cyanobacteria Lyngbya sp. that exhibits promising anticancer activity.4 Existing routes to the synthesis of this proline analogue were lengthy, reliant on expensive starting materials, poorly stereoselective or did not allow access to either enantiomeric series.5 Since 4-MePro is present in other classes of natural products which exhibit antibiotic, anticancer, and immunosuppressant activities,6 and 4-substituted proline derivatives are found in several classes of ACE inhibitor, e.g. trans 4-ChxPro in the prodrug Fosinopril (3, Figure 1),7 we set out to develop a general synthetic route which would allow ready access to both enantiomeric series of 4-substituted proline as either the cis or trans diastereomer.

Retrosynthesis of the 4-substituted prolines cis and trans 1 led us to identify the corresponding 4-substituted dehydroprolines 4 as a key target (Figure 2), since literature precedent exists for their highly selective hydrogenolytic conversion to either the cis or trans 4-substituted prolines.5a Two approaches were investigated: (i) C−N bond disconnection with backbone formation via Michael addition to an α,β-unsaturated aldehyde and (ii) C=C bond disconnection preceded by C-allylation and N-functionalization. In each case it was anticipated that the

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Figure 1. Marine natural product bisebromoamide 2 and ACE inhibitor prodrug Fosinopril 3.
required acyclic precursor (5 and 7) would be readily synthesized from commercial N-[(diphenylmethylene)glycine tert-butyl ester 8 and that access to either enantiomeric series might be achieved using asymmetric phase transfer catalysis (PTC).8

Although PTC has been widely used to mediate Michael additions of a range of nucleophiles to α,β-unsaturated ketones, esters, amides, and nitriles, the use of control the addition of nucleophiles to highly reactive α,β-unsaturated aldehydes is less common.8b We were attracted to the pseudoenantiomeric pairing of cinchonidine 9 and cinchonine 10 based catalysts (Figure 3).

Figure 3. Cinchona alkaloid based phase transfer catalysts 9 and 10.

reported by the Lygo group10 and others,11 as their use has precedent in the synthesis of unnatural amino acids.12 Indeed, as their use has through the Michael addition of a glycine Schiff base to 8,12 which has utilized RCM for the synthesis of the five-membered ring of substituted prolines.17 Thus, glycine Schiff base 8 was alkylated in the presence of TBAB with 2-methylallyl bromide to give imine 13a which was again deprotected using aqueous acid to give the corresponding primary amine 6a (Scheme 2). This

Scheme 1. Synthesis of cis 4-MePro (cis 1a) via a Michael Addition Sequence

intermediate 11a as an ~1:1 mixture of diastereomers. The diphenylmethylene protecting group was removed using aqueous acid,15 and the resultant free amine 5a spontaneously cyclized to form an unstable imine 12a. The imine was isomerized in situ to enamine 4a through base-promoted Cbz protection.14 This stable species was isolated in 42% yield over three steps; the enantiomeric excess of 4a was confirmed as 97% ee by chiral HPLC.18 Selective hydrogenation, using H2 and Pd/C,14 provided the desired cis-stereoisomer, cis 1a, in high yield and 19:1 selectivity. TFA-mediated deprotection of 1a to give the free acid confirmed the absolute configuration of the major diastereomer (Scheme 2).19 The alternate retrosynthetic disconnection (ii, Figure 2) was then investigated. Ring closing metathesis (RCM) is commonly used in the formation of six-membered cyclic amino acids, but to the best of our knowledge, there is only one successful example which has utilized RCM for the synthesis of the five-membered ring of substituted prolines.17 Thus, glycine Schiff base 8 was alkylated in the presence of TBAB with 2-methylallyl bromide to give imine 13a which was again deprotected using aqueous acid to give the corresponding primary amine 6a (Scheme 2). This

Scheme 2. RCM-Based Route to Enamine Intermediate 4a

amine was protected as either its Boc or Cbz carbamate;1b N-allylation of 14a introduced the second alkenic moiety which was readily isomerized in the presence of the Ru(II) catalyst, RuClH(CO)(PPh3)3, 15, to give the RCM precursor as a rotameric mixture of E- and Z-isomers.19 Treatment of this diene with Grubbs’ second generation catalyst20 gave the RCM product, enamine 4a, in good yield (55% P = Cbz; 44% P = Boc, over two steps).21 Hydrogenation (H2, Pd/C) of 4a (P = Cbz) gave cis 1a in only seven steps from commercial starting materials. Once again, this route lends itself to the production of either enantiomeric series through the appropriate choice of cinchonidine or cinchonine-based PTCs. To confirm that asymmetric synthesis was compatible with the RCM route, the synthesis was repeated as far as 14a (P = Cbz) with chiral PTC 9. Chiral HPLC of 14a (P = Cbz) confirmed the enantioselectivity of the unoptimized PTC-catalyzed reaction as 89% ee.

Of the two approaches, the PTC-catalyzed Michael addition gives more direct access to 4-substituted proline derivatives. We thus expanded this route to encompass the synthesis of a number of cis-substituted targets 1b–e (Table 1),22 noting that high yields and % ee were maintained in the PTC reaction, and high diastereoselectivity (cis:trans) was observed in the Pd/C catalyzed hydrogenation.23 In cases where the % ee dropped slightly (e.g., for the 4-cyclohexyl substituted proline, 4-ChxPro), lowering the reaction temperature from −78 to −95 °C gave rise to a significant improvement in % ee, albeit accompanied by a reduction in yield. Although the synthesis of protected 4-EtPro has been reported using two different Wittig/reduction
trans-1e enamine as the 4-ChxPro species found in Fosinopril, Chx substituted Ir(I) catalyst, 5a generating diastereomer (Scheme 3). Cbz deprotection (H2, Pd/C) gave Scheme 3. Synthesis of Fosinopril Intermediate strategies,24 4-

Table 1. Synthesis of 4-Substituted Proline Derivatives, cis 1

<table>
<thead>
<tr>
<th>R</th>
<th>yield 4 (%)</th>
<th>ee 4 (%)</th>
<th>dr 1 (cis:trans)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Me</td>
<td>42</td>
<td>97</td>
</tr>
<tr>
<td>b</td>
<td>Et</td>
<td>35</td>
<td>95</td>
</tr>
<tr>
<td>c</td>
<td>Pr</td>
<td>57</td>
<td>93</td>
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<tr>
<td>d</td>
<td>Bn</td>
<td>31</td>
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<tr>
<td>e</td>
<td>Chx</td>
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<td>80</td>
</tr>
<tr>
<td>e</td>
<td>Chx</td>
<td>54^a</td>
<td>93</td>
</tr>
</tbody>
</table>

“Yield over three steps from 8. ^a PTC reaction conducted at −95 °C.

To demonstrate the applicability of this method to the synthesis of trans 4-substituted prolines (trans 1, Figure 2), such as the 4-ChxPro species found in Fosinopril, Chx substituted enamine 4e was treated with H2 in the presence of Crabtree’s Ir(1) catalyst,3a generating 18 in 75% yield as a single diastereomer (Scheme 3). Cbz deprotection (H2, Pd/C) gave trans 1e also in high yield (72%),26,27 allowing direct comparison with the previously synthesized diastereomer cis 1e.28

The proline scaffold is a privileged motif that is found in Nature and has been exploited in many catalytic processes. By judicious choice of either the Michael- or RCM-based routes presented herein, a range of 4-substitutions (4-XPro) may be accessed from readily available, or easily prepared, achiral starting materials. This should allow the application of this interesting modification of the proline scaffold to be explored in more depth in future studies. The two routes intercept a common enamine intermediate 4 which can be obtained in high % ee using cinchona alkaloid-based PTCs, and from this either the cis or trans diastereomer of 1 is readily accessed through the appropriate choice of hydrogenation conditions. Other transformations which exploit the reactivity of the enamine intermediate (beyond hydrogenation) are yet to be explored.

## ASSOCIATED CONTENT

### Supporting Information

Experimental procedures for the preparation of α,β-unsaturated aldehydes, 4a-e, 1a-e, and 18. Chiral HPLC traces for 4a-e and ent-4a. 1H and 13C NMR spectra for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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**Notes**

The authors declare no competing financial interest.

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### REFERENCES


(14) The use of other carbamate protecting groups (Boc, Fmoc, etc.) has not been reported in the literature for this type of reaction and was not investigated at this time.
Slow addition of a precooled solution of methacrolein to the reaction mixture was found to be critical to the reproducibility of high enantioselectivity in this reaction.


For practical reasons, the carbamate protecting groups investigated in this study were limited to one that would be removed by hydrogenolysis and one that would not.


Attempts to introduce a vinyl group to 14a through Pd-catalyzed vinyl transfer for a more direct RCM reaction or to conduct relay metathesis on appropriate derivatives of 14a were both unsuccessful. When the one-pot conversion (via in situ isomerization and RCM) of the allyl intermediate 7a (P = Cbz) was attempted, formation of the unsaturated piperidine 17a was favored.

Noncommercial unsaturated aldehyde precursors were synthesized in one or two steps as described in the Supporting Information.

The absolute stereochemistry of 4b–e was also defined as (2S) on the following grounds: the major enantiomer of each of 4a–e was observed to elute first using the same chiral stationary phase; the mixture of enantiomers for each of 4a–e was found to have an $\alpha_D$ value in the range $-70$ to $-130$.


It is imperative that the enamine starting material is removed before being submitted for hydrogenolysis to avoid any subsequent contamination with the cis diastereomer.

Use of protic solvents for hydrogenolysis can result in N-alkylation; this was avoided by carrying out the reaction in DCM.

For the cis substituted 4-XPro derivatives 1a–c, the NHCH$_3$H$_5$ carbon was observed to lie in the range 60.3–60.2 ppm, whereas for the trans substituted 4-ClH$_3$Pro 1e the NHCH$_3$H$_5$ proton was observed at 2.8 ppm and the C($\alpha$) carbon was at 60.7 ppm.