Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tetrahedron: Asymmetry
Tetrahedron: *Asymmetry* 16 (2005) 2243–2247

Chemoenzymatic synthesis of *N*-Boc protected (2*S*,3*R*)-3-hydroxy-3-methylproline

Mansour Haddad and Marc Larchevêque*

Laboratoire de Synthèse Organique associé au CNRS, ENSCP, 11 rue Pierre et Marie Curie, 75231 Paris Cedex 05, France

Received 15 April 2005; accepted 24 May 2005
Available online 29 June 2005

Abstract—*N*-Boc protected 3-hydroxy-2-hydroxymethyl-3-methylpyrrolidine was kinetically resolved by acylation in an organic solvent catalyzed by *Pseudomonas fluorescens* lipase to give the corresponding acetate and residual diol in 14 E. Further selective oxidation afforded the title compound in high diastereo- and enantioselectivity.

1. Introduction

Conformationally constrained amino acids have recently received much attention due to their ability to act as conformational probes when incorporated into peptides and peptidomimetics.[1] They are also frequently crucial structural features of biologically active and natural products.[2] Polyoxypeptins A **1** and B **2** are two recent examples that were isolated from *Streptomyces* culture broth.[3] Polyoxypeptin A has attracted a great deal of attention due to its significant apoptosis-inducing activity in human pancreatic carcinoma.[4] Structurally, this compound is a unique hexadepsipeptide containing novel subunits, such as the acyl side-chain moiety and the (2*S*,3*R*)-3-hydroxy-3-methylproline **3** among other non-proteinogenic α-amino acids (Fig. 1).

Various methods have been reported for the synthesis of this unusual cyclic α-amino acid including asymmetric synthesis,[5] transformation of the chiral pool[6] and chemical resolution.[7] However, all these methods require many steps and give low overall yields and there is still need of a concise method for large-scale production of this unique component.

Herein we report a chemoenzymatic synthesis of the *N*-Boc protected amino acid **4** based on the stereoselective addition of trimethylaluminium on a cyclic β-ketoester and a lipase resolution of a diol derived from the resulting β-hydroxyester.

2. Results and discussion

In order to access a compound that could be easily usable for further synthetic applications, we decided to study the resolution of 3-hydroxy-3-methylproline by enzymatic hydrolysis of a *N*-protected ester. For the

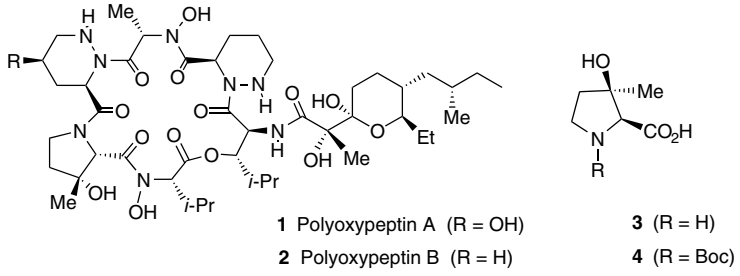


Figure 1.

* Corresponding author. Fax: +33 (0)1 43 25 79 75; e-mail: marc-larcheveque@enscp.fr

0957-4166/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2005.05.030

protecting group, Boc was selected on account of its great utility in peptide synthesis. Moreover, this choice was also dictated by the successful resolutions recently reported on structurally related compounds, such as pyrrolidines,[8] proline derivatives[9] or cyclic β-amino acids.[10]

The required protected hydroxy proline was first synthesized by Dieckmann cyclization of the ketoester **5** according the method described by Williams (Fig. 2).[11] Although this cyclization mainly afforded the required (2*R**,3*S**)-diastereomer *rac*-**6** (*rac*-**6**/*rac*-**7**: 7/3), the yield strongly decreased by the concomitant formation of the β-diketone resulting from the formation and cyclization of the enolate derived from the keto moiety. Furthermore, the two diastereomers were difficult to separate.

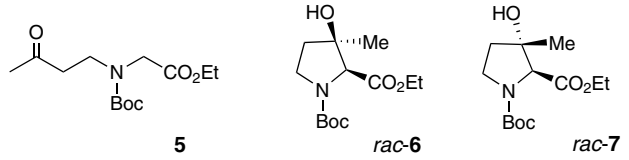
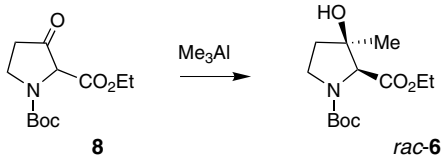


Figure 2.

We then decided to develop an alternative synthesis to access the diastereomerically pure hydroxy ester **6**. We thought that by starting from the known β-ketoester **8**,[12] it would be possible to gain access to the required tertiary alcohol by stereoselective addition of an organometallic compound. Taking advantage of a previous study related to the addition of organometallic compounds to β-ketoesters,[13] various methylating reagents were reacted with **8**. Methylmanganese chloride and trichloromethyltitanium were totally inefficient, affording complex mixtures. In contrast, the use of trimethylaluminium at room temperature allowed access to the (2*R**,3*S**)-ester **6** as a single isomer in a satisfactory yield (Scheme 1).

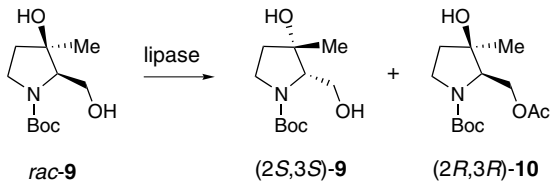


Scheme 1.

Amongst all the types of enzyme-catalyzed reactions, hydrolytic transformations involving the cleavage of the amide or ester bonds with proteases, esterases or lipases were the easiest to perform. In the case of the amino acids, the presence of two different functions offers the possibility to use different strategies such as hydrolysis of esters, acylation of amines or transesterification. Initially, we attempted to resolve compound **6** by hydrolysis of the ester moiety. Although successful results were reported on structurally related compounds,[8–10] we were unable to find an enzyme able to hydrolyze the ester function of the hydroxyproline *rac*-**6**, a result possibly due to the steric hindrance of the substrate. Attempts of enzymatic *N*-acylation of the free amino ester also proved unsuccessful.

Wanting to keep the Boc, which is a very useful protecting group for the synthesis of complex peptides, we modified our strategy. In spite of the difficulties frequently observed during the resolution of chiral primary alcohols,[14] we decided to study the resolution of diol **9** derived from ester **6**. This was easily obtained in good yield by $LiAlH_4$ reduction of the ester in THF.

In our first attempt we used *Candida antarctica* lipase B (CAL B), usually an efficient enzyme for such reactions. Although the reaction rate was relatively high, the selectivity remained very low and the acylated product was obtained in an enantiomeric excess of only 9% at 50% conversion (Table 1, entry 4). We screened other lipases, but some proved totally inactive (Table 1, entries 1–3). However, among the fifteen lipases or esterases examined, we succeeded in finding three lipases that showed moderate activity (entries 6, 11 and 12). The best result was obtained with *Pseudomonas fluorescens* lipase (Amano AK) with which a 42% conversion of the racemic diol was obtained at 35 °C after 48 h to give the corresponding acetate in 52% ee. The enantiomeric excesses were measured by GC with a chiral stationary phase directly for the acetate or after monoacylation with acetic or propionic anhydride for the residual diol. In order to determine the absolute configuration, the residual diol was oxidized into the corresponding hydroxy acid **4** or *ent*-**4** and esterified. Comparison of the rotatory power of this ester with the one previously reported for the same compound prepared by asymmetric synthesis[5c] allowed us to assign a (2*R*,3*S*)-configuration to this ester, thus a (2*S*,3*S*)-configuration was given to the residual diol isolated after resolution (Scheme 2). Alternatively, the *N*-Boc protected hydroxyacid was deprotected in the presence of trifluoroacetic acid to give the known 3-hydroxy-3-methyl proline.



Scheme 2.

For the target molecule, which required a (2*S*,3*R*)-configuration, it was necessary to enhance the selectivity of the resolution in order to isolate the product in an acceptable enantiomeric excess. Initially we attempted to modify the acylating reagent. The use of isopropenylacetate, which avoids the formation of acetaldehyde and frequently enhances the enantiomeric ratio was unsuccessful (entries 9 and 15). Unsatisfactory results were also obtained with acetic anhydride or mixed *i*-propyloxycarbonic propionic anhydride (entry 16).[16]

Table 1. Enzyme-catalyzed acylation of diol **9**[a]

Entry	Enzyme	Time (h)	Temp (°C)	Conv (%)	Residual diol: ee (%)	Acetate (ee%)	E[b]
1	*M. miehie*	48	30	0	—	—	—
2	*B. cepacia*	48	30	0	—	—	—
3	*M. javanicus*	48	30	0	—	—	—
4	CAL B	26	35	50	9	9	1.2
5	*R. oryzae*	48	30	4	—	70	—
6	*C. cylindracea*	26	35	28	14	52	3.6
7	*C. cylindracea*	48	20	23	16	52	3.7
8	*C. cylindracea*[c]	40	25	34	15	33	3.6
9	*C. cylindracea*[d]	48	30	0	—	—	—
10	PPL	48	30	41	3	4	—
11	*R. arrhizus*	90	35	29	20	50	3.6
12	*P. fluorescens*	48	35	42	39	52	4.6
13	*P. fluorescens*	43	25	24	15	74	7.8
14	*P. fluorescens*	96	20	35	47	80	14.3
15	*P. fluorescens*[d]	48	40	0	—	—	—
16	*P. fluorescens*[e]	48	30	25	20	45	3.2

[a] All reactions were carried out by stirring a mixture of substrate (1 mmol) vinylacetate (10 mmol) and catalyst (200 mg) in *tert*-butylmethyl ether.
[b] $E = \ln[ee_p(1 - ee_s)]/(ee_p + ee_s)/\ln[ee_p(1 + ee_s)]/(ee_p + ee_s)$.[15]
[c] Acylating agent: Ac_2O.
[d] Acylating agent: isopropenyl acetate.
[e] Acylating agent: mixed *i*-propyloxycarbonic propionic anhydride.[16]

Mixed anhydrides prepared from a longer-chain acid, such as valeric acid, were unreactive. Changing the solvent also had little effect. Finally, it was the modification of the temperature, which allowed us to increase the selectivity; by operating at 20 °C, we succeeded in obtaining the required (2*R*,3*R*)-acetate **10** in a 80% ee at 35% conversion (entry 14).

This acetate was then hydrolyzed to afford the corresponding (2*R*,3*R*)-diol **9**, which was oxidized into acid **4**. The use of Jones' reagent at low temperature was not very convenient as it gave a low yield (40%) due to a partial elimination of the Boc protecting group. Our best result was obtained when using sodium periodate in the presence of a catalytic amount of ruthenium salt.[17] The required acid **4** was then isolated in 85% yield and 78% ee. The enantiomeric excess was successfully increased to 99% by recrystallization.

3. Conclusion

In summary, diol **9** derived from *N*-protected diastereomerically pure 3-hydroxy-3-methylproline was conveniently resolved by a vinyl acetate transesterification in an organic solvent catalyzed by *Pseudomonas fluorescens* lipase. Further ruthenium catalyzed oxidation allowed access to the *N*-Boc protected (2*S*,3*R*)-3-hydroxy-3-methylproline in high enantiomeric excess.

4. Experimental

4.1. General methods

Products were purified either by distillation or by medium pressure liquid chromatography on a Jobin-Yvon Modulprep (Kieselgel 60H Merck) or by flash chromatography (Kieselgel 60 Merck: 230–400 Mesh) and analyzed by GC (Chrompack CP-Sil 8CB, 50 m capillary column) or by TLC (Merck silica gel 60F 254). NMR spectra were recorded on a Bruker AC at 300 MHz for ^1H and 75.5 MHz for ^{13}C. $CDCl_3$ was used as solvent with TMS as the internal standard. IR spectra were recorded on a spectrophotometer FT Nicolet 210. Mass spectra were recorded on a Ribermag R10-10C instrument at 70 eV ionizing voltage; ammonia was used for chemical ionization. Optical rotations were measured on a Jasco P-1010 polarimeter. The enantiomeric excesses were measured on a 25 m Chirasil-DEX CB column (Chrompack-Varian). *Rhizopus arrhizus* and *Candida cylindracea* (as immobilized in Sol–Gel AK form) were purchased from Fluka and *Pseudomonas fluorescens* lipase (Amano AK) from Sigma–Aldrich.

4.2. Ethyl 1-(*tert*-butoxycarbonyl)-3-oxopyrrolidine-2-carboxylate 8

Under argon, a solution of *N*-Boc protected 3-(ethoxycarbonylmethyl-amino)-propionic acid ethyl ester[12c] (12.12 g, 0.04 mol) in toluene (20 mL) was slowly added to a vigorously stirred suspension of potassium *tert*-butoxide (3.36 g, 0.08 mol, 2 equiv) in toluene (160 mL) cooled to −5 °C by means of an external ice–NaCl bath. The reaction mixture was stirred at −5 °C for 4 h and then quenched with acetic acid (4.5 mL, in one portion), followed by a cold solution of $NaH_2PO_4{\cdot}H_2O$ (22 g) in H_2O (220 mL). The layers were separated and the aqueous layer extracted with $CHCl_3$ (2 × 100 mL). The combined organic extracts were washed with pH 7 phosphate buffer (2 × 40 mL), dried over anhydrous $MgSO_4$ and concentrated in vacuo to give an oil. The crude product was purified by flash chromatography on silica gel (cyclohexane/ethyl acetate: 7/3) to afford the compound **8** (6.17 g, 60%) as a colourless oil with spectral data identical to those previously reported.[12b]

4.3. Ethyl (2*R**,3*S**)-1-(*tert*-butoxycarbonyl)-3-hydroxy-3-methylpyrrolidine-2-carboxylate 6

Under argon, 2 M trimethylaluminium in toluene (20 mL, 0.04 mol, 2 equiv) was slowly added to a solution of the *N*-Boc protected ketoester **8** (5.14 g, 0.02 mol) in toluene (100 mL) cooled to 0 °C. The solution was stirred for 3 h at 0 °C and quenched with ice cold aqueous $KHSO_4$. After extraction with diethyl ether, the organic layer was dried over $MgSO_4$ and evaporated to give a mixture of the starting compound and the stereochemically pure hydroxyester **6** (4/6). These compounds were separated on silica gel (cyclohexane/ethyl acetate: 6/4) to afford the *rac*-**6** ester as a colourless oil (2.4 g, conv: 60%, yield: 73%). IR (KBr) cm^{-1}: 3450, 2973, 1745, 1706, 1685, 1410, 1190, 1167; ^1H NMR (300 MHz, $CDCl_3$): two conformers at 25 °C; δ 1.26 (t, 3H, $J = 7$ Hz), 1.39 and 1.47 (s, 9H); 1.44 (s, 3H); 1.85 (dt, 1H, $J = 6.2$ and 12.5 Hz); 2.0–2.1 (m, 1H), 3.4–3.5 (m, 1H), 3.55–3.65 (m, 1H), 4.00 and 4.07 (s, 1H); 4.20 (q, 2H, $J = 7$ Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 14.3, 26.7, 28.2 and 28.3, 38.2 and 38.8, 44.3 and 44.8, 61.0 and 61.1, 68.2 and 68.8, 77.8 and 78.9, 80.0 and 80.2, 153.9 and 154.3, 170.4 and 170.6; MS (CI NH_3) *m*/*z* 291 ($M+NH_4^+$, 32%), 274 ($M+H^+$, 53%), 235 (100%), 218 (18%), 174 (19%).

4.4. (2*S**,3*S**)-1-(*tert*-Butoxycarbonyl)-3-hydroxy-2-hydroxymethyl-3-methylpyrrolidine 9

A solution of ester **6** (1.91 g, 7 mmol) in THF (15 mL) was added to a suspension of $LiAlH_4$ (319 mg, 8.4 mmol, 1.2 equiv) in THF (25 mL) cooled to 0 °C. After stirring for 2 h, water (319 μL) was added followed by 15% NaOH (319 μL) and water again (957 μL). The mixture was stirred for 2 h and the suspension was filtered. The residual solid was stirred for 15 min with THF (25 mL), filtered again and washed twice with THF (20 mL). The combined organic phases were evaporated in vacuo to afford a solid (1.21 g, 80% yield), which was purified by crystallization in hexane/*i*-$Prop_2O$: 9/1. Mp: 90–91 °C; IR (KBr) cm^{-1}: 3408, 2973, 1693, 1666, 1455, 1167; ^1H NMR (300 MHz, $CDCl_3$): δ 1.43 (s, 9H); 1.79 (m, 3H), 2.0 (m, 1H), 2.78 (dd, 1H, $J = 9.8$ and 16.2 Hz), 2.85 (m, 1H), 3.30 (m, 2H), 3.64 (s, 3H), 4.10 (br s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 26.3, 28.4, 38.7, 45.0, 62.3, 67.3, 77.8, 80.1, 156.0; MS (CI NH_3) *m*/*z* 232 (M+1, 100%), 193 (22%), 176 (19%). Anal. Calcd for $C_{11}H_{21}NO_4$: C 57.12, H 9.15, N 6.06; Found: C 57.25, H 9.21, N 6.01.

4.5. Lipase-catalyzed resolution

A solution of diol **9** (1.15 g, 5 mmol) in *tert*-butylmethyl ether (55 mL) was stirred at 150 rpm with *Pseudomonas fluorescens* (Amano AK) lipase (1 g) and vinyl acetate (10.0 g, 0.1 mol, 20 equiv) at 20 °C. After four days, the suspension was filtered through a small pad of Celite to remove the enzyme and the residual mixture chromatographed on silica gel (cyclohexane/ethyl acetate: 4/6) to give acetate **10** (0.48 g, 35%) and the residual diol (0.73 g, 63%).

4.5.1. (2*S*,3*S*)-1-(*tert*-Butoxycarbonyl)-3-hydroxy-2-hydroxymethyl-3-methylpyrrolidine.

$[\alpha]_D^{20} = +15.1$ (*c* 3.73, MeOH), ee: 47%.

4.5.2. (2*R*,3*R*)-2-Acetoxymethyl-1-(*tert*-butoxycarbonyl)-3-hydroxy-3-methylpyrrolidine 10.

$[\alpha]_D^{20} = -18.5$ (*c* 2.0, CH_2Cl_2), ee: 80%; IR (KBr) cm^{-1}: 3441, 2975, 1743, 1697, 1673, 1394, 1243, 1166; ^1H NMR (400 MHz, $CDCl_3$): δ 1.38 (s, 3H), 1.47 (s, 9H); 1.75–1.85 (m, 1H), 1.9–2.0 (m, 1H), 2.05 (s, 3H), 3.41 (dd, 2H, $J = 6.2$ and 7.8 Hz), 3.65 (br s, 1H), 4.32 (dd, 1H, $J = 3.5$ and 11.3 Hz), 4.46 (dd, 1H, $J = 6.0$ and 11.3 Hz); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.0, 27.8, 28.4, 37.9, 43.9, 62.4, 63.5, 77.3, 80.1, 154.6, 171.0; MS (CI NH_3) *m*/*z* 274 (M+1, 73%), 235 (14%), 218 (100%), 174 (33%). Anal. Calcd for $C_{13}H_{23}NO_5$: C 57.13, H 8.48, N 5.12; Found: C 57.21 H 8.55 N 5.07.

4.5.3. (2*S*,3*R*)-1-(*tert*-Butoxycarbonyl)-2-carboxy-3-hydroxy-3-methylpyrrolidine 4.

A solution of the acetate (1.36 g, 5 mmol) in methanol (2 mL) was added to 3 M aqueous LiOH (10 mL) and stirred for 2 h at room temperature. The solution was extracted with diethyl ether and dried over $MgSO_4$. After removing the solvent, the crude diol was isolated as a solid. This was then oxidized at 0 °C under argon with $NaIO_4$ (4.8 g, 20 mmol) and $RuCl_3 \cdot nH_2O$ (26 mg, 0.125 mmol, 2.5%) in a well-stirred mixture 1/1/1.5 CCl_4, CH_3CN, H_2O (105 mL). After 4 h, the mixture was extracted with Et_2O (6×30 mL) and the organic phase dried over $MgSO_4$. After removing the solvent, the crude solid was dissolved in THF and refluxed for half an hour in the presence of carbon black. The hot solution was filtered on celite to give after removing the solvent a solid (85% yield), which was recrystallized. White solid: mp 163–164 °C (*i*-$Prop_2O$/THF: 3/1); $[\alpha]_D^{20} = -19.5$ (*c* 1.34, MeOH) ee: 99% (as methyl ester); IR (KBr) cm^{-1}: 3397, 3014, 1696, 1677, 1414, 1230, 1194; ^1H NMR (300 MHz, CD_3COCD_3): two conformers at 25 °C; δ 1.16 and 1.20 (s, 9H), 1.26 (s, 3H), 1.60–1.65 (m, 1H), 1.80–1.85 (m, 1H), 2.80 (m, 1H), 3.20–3.25 (m, 1H), 3.35–3.40 (m, 1H), 3.76 and 3.77 (s, 1H); ^{13}C NMR (75.5 MHz, CD_3COCD_3): δ 27.3, 28.5, 38.8 and 39.3, 45.1 and 45.6, 69.2 and 69.7, 78.0 and 79.0, 79.8, 154.5 and 154.9, 171.9; MS (CI NH_3) *m*/*z* 263 (73%), 246 (21%), 207 (10%), 139 (14%), 122 (60%), 88 (100%). Anal. Calcd for $C_{11}H_{19}NO_5$: C 53.87, H 7.81, N 5.71; Found: C 53.95, H 7.83, N 5.76.

4.5.4. (2*S*,3*R*)-3-Hydroxy-3-methylproline.

Acid **4** (245 mg, 1 mmol) was stirred with trifluoroacetic acid (4 mL) for 2 h at 0 °C. The solvent was then removed in vacuo and the residue taken up into water (2 mL). This aqueous solution was passed through a column of acidic ion-exchange resin (Dowex 50 W). The acid was eluted with water and then with a 2 M solution of NH_4OH. After lyophilization, pure acid was obtained as a white solid: mp 198–200 °C (dec); $[\alpha]_D^{20} = -38.6$ (*c* 1.49, H_2O) lit.[4a] $[\alpha]_D^{20} = -41.0$ (*c* 0.40, H_2O); ^1H NMR (300 MHz, D_2O): δ 1.51 (s, 3H), 2.0–2.1 (m, 2H), 3.3–3.4 (m, 1H), 3.45 (m, 1H,) 3.77 (s, 1H); ^{13}C NMR (75.5 MHz, D_2O): δ 23.4, 39.0, 42.9, 69.3, 78.0, 170.3.

References

1. (a) Dado, G. P.; Gellman, S. H. *J. Am. Chem. Soc.* **1994**, *116*, 1054–1062; (b) Crisma, M.; Formaggio, F.; Pantano, M.; Valle, G.; Bonora, G. M.; Toniolo, C.; Schoemaker, H. E.; Kamphuis, J. *J. Chem. Soc., Perkin Trans. 2* **1994**, 1735–1742; (c) Seebach, D.; Overhand, M.; Kühnle, F. N. M.; Martinoni, B.; Oberer, L.; Hommel, U.; Widmer, H. *Helv. Chim. Acta* **1996**, *79*, 913–941; (d) Seebach, D.; Matthews, J. L. *Chem. Commun.* **1997**, 2015–2016; (e) Gellman, S. H. *Acc. Chem. Res.* **1998**, *31*, 173–180.
2. (a) Sewald, N. In *Bioorganic Chemistry, Highlights and New Aspects*; Diederichsen, U., Lindhorst, T. K., Westermann, B., Wessjohann, L. A., Eds.; Wiley-VCH: Weinheim, Germany, 1999, Chapter 4.2, p 193; (b) Sasaki, N. A.; Dockner, M.; Chiaroni, A.; Riche, C.; Potier, P. *J. Org. Chem.* **1997**, *62*, 765–770; (c) Hammer, K.; Undheim, K. *Tetrahedron: Asymmetry* **1998**, *9*, 2359–2368; (d) Rutjes, F. P. J. T.; Schoemaker, H. E. *Tetrahedron Lett.* **1997**, *38*, 677–680.
3. (a) Umezawa, K.; Nakazawa, K.; Uemura, T.; Ikeda, Y.; Kondo, S.; Naganawa, H.; Kinoshita, N.; Hashizume, H.; Hamada, M.; Takeuchi, T.; Ohba, S. *Tetrahedron Lett.* **1998**, *39*, 1389–1392; (b) Umezawa, K.; Nakazawa, K.; Ikeda, Y.; Naganawa, H.; Kondo, S. *J. Org. Chem.* **1999**, *64*, 3034–3038.
4. Umezawa, K.; Nakazawa, K.; Uchihata, Y.; Otsuka, M. *Adv. Enzyme Regul.* **1999**, *39*, 145–156.
5. (a) Noguchi, Y.; Uchiro, H.; Yamada, T.; Kobayashi, S. *Tetrahedron Lett.* **2001**, *42*, 5253–5256; (b) Qin, D.-G.; Zha, H.-Y.; Yao, Z.-J. *J. Org. Chem.* **2002**, *67*, 1038–1040; (c) Shen, J.-W.; Qin, D.-G.; Zhang, H.-W.; Yao, Z.-J. *J. Org. Chem.* **2003**, *68*, 7479–7484; (d) Suzuki, T.; Makino, K.; Hamada, Y. *Pept. Sci. Symp.* **2004**, *40*, 57–60; (e) Davis, F. A.; Ramachandar, T.; Liu, H. *Org. Lett.* **2004**, *6*, 3393–3395.
6. (a) Makino, K.; Kondoh, A.; Hamada, Y. *Tetrahedron Lett.* **2002**, *43*, 4695–4698; (b) Merino, P.; Revuelta, J.; Tejero, T.; Cicchi, S.; Goti, A. *Eur. J. Org. Chem.* **2004**, 776–782.
7. Makino, K.; Suzuki, T.; Hamada, Y. *Bull. Chem. Soc. Jpn.* **2004**, *77*, 1649–1653.
8. Schieweck, F.; Altenbach, H.-J. *Tetrahedron: Asymmetry* **1998**, *9*, 403–406.
9. (a) Stürmer, R.; Schäfer, B.; Wolfart, V.; Stahr, H.; Kazmaier, U.; Helmchen, G. *Synthesis* **2001**, 46–48; (b) Sigmund, A. E.; Hong, W.; Shapiro, R.; DiCosimo, R. *Adv. Synth. Catal.* **2001**, *343*, 587–590; (c) Kurokawa, M.; Shindo, T.; Suzuki, M.; Nakajima, N.; Ishihara, K.; Sugai, T. *Tetrahedron: Asymmetry* **2003**, *14*, 1323–1333.
10. Pousset, C.; Callens, R.; Haddad, M.; Larchevêque, M. *Tetrahedron: Asymmetry* **2004**, *15*, 3407–3412.
11. Stocking, E. M.; Sanz-Cervera, J. F.; Williams, R. M. *J. Am. Chem. Soc.* **2000**, *122*, 1675–1683.
12. (a) Blake, J.; Willson, C. D.; Rapoport, H. *J. Am. Chem. Soc.* **1964**, *86*, 5293–5299; (b) Knight, D. W.; Sibley, A. W. *J. Chem. Soc., Perkin Trans. 1* **1997**, 2179–2187; (c) Williams, R. M.; Cao, J.; Tsujishima, H.; Cox, R. J. *J. Am. Chem. Soc.* **2003**, *125*, 12172–12178.
13. Taniguchi, M.; Fuji, H.; Oshima, K.; Utimoto, K. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 2514–2521.
14. Weissfloch, A. N. E.; Kazlauskas, R. J. *J. Org. Chem.* **1995**, *60*, 6959–6969.
15. Chen, C. S.; Fujimoto, Y.; Girdaukas, G.; Sih, C. J. *J. Am. Chem. Soc.* **1982**, *104*, 7294–7299.
16. Guibé-Jampel, E.; Chalecki, Z.; Bassir, M.; Gelo-Pujic, M. *Tetrahedron* **1996**, *52*, 4397–4402.
17. Carlsen, P. H. J.; Katsuki, T.; Martin, V. S.; Sharpless, K. B. *J. Org. Chem.* **1981**, *46*, 3936–3938.