Synthesis of Diastereomeric 1,4-Diphosphine Ligands Bearing Imidazolidin-2-one Backbone and Their Application in Rh(I)-Catalyzed Asymmetric Hydrogenation of Functionalized Olefins

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Dedicated to Professor Yong Hae Kim on the occasion of his retirement.

Abstract: The diastereomeric 1,4-diphosphine ligands, (*S*,*S*,*S*,*S*)-**1a**, (*R*,*S*,S,*R*)-**1b** and (*R*,*S*,*S*,*S*)-**1c**, with the imidazolidin-2-one backbone were synthesized, and utilized for an investigation of the effects of backbone chirality on the enantioselectivity in the Rh(I)-catalyzed hydrogenation of various functionalized olefinic substrates. It was found that the catalytic efficiencies are largely dependent on the configurations of the α-carbons to phosphine. Thus, the Rh complex of the pseudo-C_2-symmetrical diphosphine, (*R*,*S*,*S*,*S*)-**1c**, showed excellent enantioselectivities (93.0–98.6% ees) in the hydrogenations of a broad spectrum of substrates, and especially in the hydrogenations of methyl α-(*N*-acetyamino)-β-arylacrylates (95.3–97.0% ees). However, the enantioselectivities obtained with the C_2-symmetrical (*R*,*S*,S,*R*)-**1b** were largely dependent on the substrate (19.8–97.3% ees). The Rh complex of ligand **1a** having the (*S*,*S*,*S*,*S*)-configuration showed the lowest catalytic efficiency for all of the substrates examined (0–84.8% ees).

Keywords: asymmetric hydrogenation; backbone chirality; diphosphine ligands; olefins; rhodium

Introduction

The design and synthesis of new and unique chiral phosphine ligands with properties superior to their predecessors are important targets in catalytic asymmetric reactions, and have attracted a great deal of attention from both academia and industry.[1] Modulation of the steric and electronic properties of a specific ligand scaffold could provide an opportunity for the development of a more efficient chiral ligand. Kagan's pioneering work on the development of the historical DIOP had a significant impact in the design of new efficient chiral ligands for asymmetric hydrogenation.[2] However, due to the conformational flexibility of the seven-membered metal chelates (a number of energetically similar conformations of the chelates are available), the enantioselectivities obtained with the metal complexes of the DIOP or its analogous are not always sufficiently high. Recent efforts on the development of DIOP-type 1,4-diphosphines were mainly focused on the restriction of the conformational flexibility of the seven-membered metal chelates. Zhang et al. reduced effectively the conformational flexibility of the seven-membered metal chelates by employment of conformationally rigid backbones such as biscyclopentyl (BICP) or 1,4-dioxane (SK-Phos).[3] Zhang[4] and RanjaBabu[5] have also independently synthesized diastereomeric (*S*,*S*,*S*,*S*)- and (*R*,*S*,*S*,*R*)-DIOP* ligands, in which new stereogenic centers at the α position to the diphenylphosphine groups in DIOP were introduced. In Rh-catalyzed asymmetric hydrogenations of α-arylenamides, it was found that (*R*,*S*,*S*,*R*)-DIOP* provided excellent enantioselectivities, whereas its diastereomeric ligand, (*S*,*S*,*S*,*S*)-DIOP*, which was first synthesized by Kagan,[6] provided much lower enantioselectivity. Based on conformational analysis, it has been reasoned that the two methyl groups are oriented at pseudoequatorial positions in the effective conformer of the (*R*,*S*,*S*,*R*)-DIOP*-metal complex, therefore stabilizing the effective conformer to promote high enantioselectivity. On the other hand, the (*S*,*S*,*S*,*S*)-DIOP* has two methyl groups at pseudoaxial positions which destabilize the effective conformer and lead to diminished ees.

Recently, we reported a new type of 1,4-diphosphine ligands, BDPMI, with an imidazolidin-2-one back-

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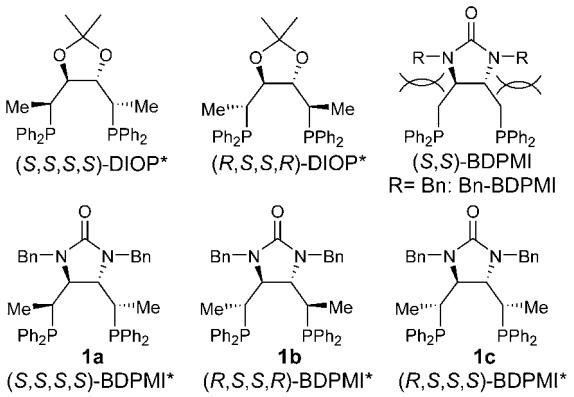


Figure 1. Chiral 1,4-diphosphine ligands.

bone[7]. The *gauche* steric interaction between the N substituents and the phosphanylmethyl group of the ligands may restrict the conformational flexibility of the seven-membered metal chelate ring. These BDPMI ligands have been successfully applied in Rh-catalyzed hydrogenations of α-arylenamides,[7a], acyclic[7b] and cyclic β-(*N*-acylamino)acrylates,[7d] and excellent enantioselectivities (up to 99% ees) have been obtained. However, the Rh complexes of BDPMI ligands furnished only low to moderate enantioselectivities in the hydrogenation of other olefinic substrates such as α-(*N*-acylamino)cinnamic acid or itaconic acid derivatives.[7c] We assumed that the introduction of α-substituents (α to the diphenylphosphine groups) in the BDPMI ligand could beneficially affect the *gauche* steric interaction between the N substituent and the phosphinomethyl groups, which may largely depend on the configuration of the α-substituent. To investigate the effects of backbone configurations on the enantioselectivity, we synthesized the new diastereomeric 1,4-diphosphine ligands, (4*S*,5*S*)-1,3-dibenzyl-4,5-di[(1*S*,1′*S*)-(1-diphenylphosphanoethyl)]imidazolidin-2-one (**1a**) [abbreviated as (*S*,*S*,*S*,*S*)-BDPMI*] and its diasteromeric analogues (*R*,*S*,*S*,*R*)-BDPMI* (**1b**) and (*R*,*S*,*S*,*S*)-BDPMI* (**1c**). In this paper, we report the synthesis of the diastereomeric ligands **1a**–**c** and their application in the Rh-catalyzed asymmetric hydrogenation of various functionalized olefins.

Results and Discussion

Synthesis of the Diastereomeric Diphosphine Ligands 1a–1c

The *N*,*N*′-dibenzylated diastereomeric diphosphine ligands **1a**–**c** could be prepared starting from the optically pure (4*R*,5*S*)-1,3-dibenzylimidazolidin-2-one-4,5-dicarboxylic acid monocyclohexyl ester **2**, which is a key intermediate for the commercial production of biotin

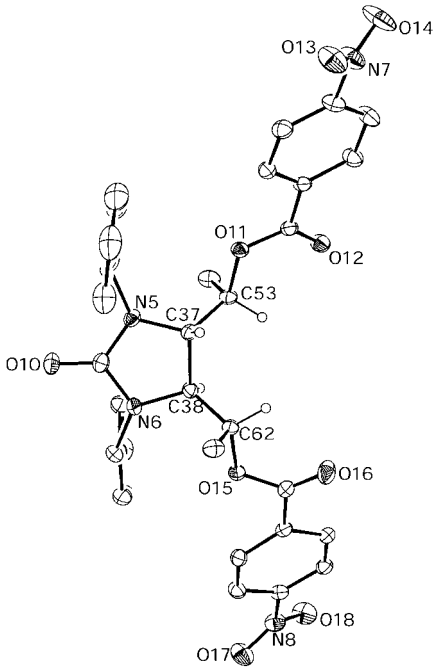
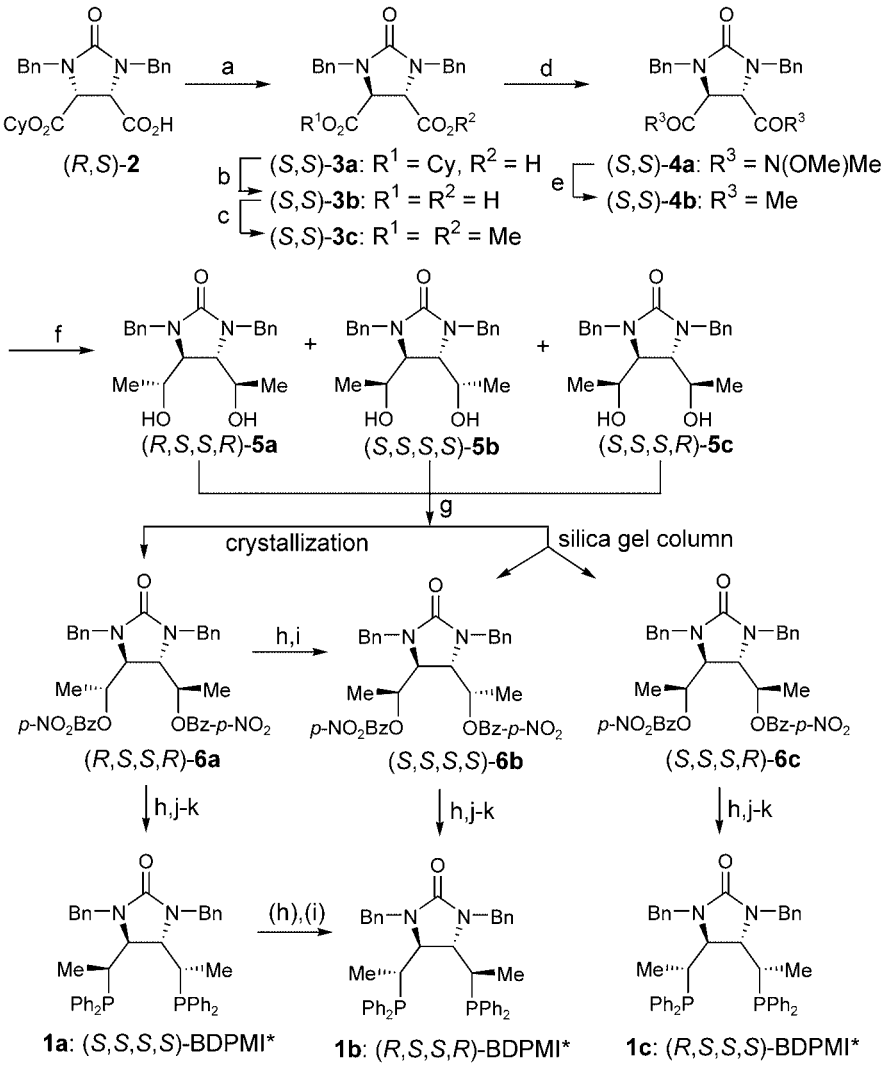


Figure 2. ORTEP diagram of (*R*,*S*,*S*,*R*)-**6a**.

(Scheme 1).[8] Selective epimerization of the α-methine proton to the ester group in the *cis*-monoester (*R*,*S*)-**2** (optical purity > 99.9% ee), followed by hydrolysis and esterification afforded the *trans*-dicarboxylic acid dimethyl ester (*S*,*S*)-**3c** in high yield (three steps with 88% overall yield). The optical purity (> 99.9% ee) of the dimethyl ester (*S*,*S*)-**3c** as determined by HPLC analysis (Dicel Chiralpak AD column) indicated that there are no loss of optical purity during these transformation processes. The *trans*-diester (*S*,*S*)-**3c** was converted to the diketone (*S*,*S*)-**4b** through the formation of the Weinreb amide (*S*,*S*)-**4a** followed by reaction with methylmagnesium bromide in 84% yield (two steps). Reduction of the diketone (*S*,*S*)-**4b** with Dibal-H afforded a mixture of diastereomeric diols **5a**–**c** in 93% yield with the ratio of **5a**:**5b**:**5c** = 68:3:29 (based on ^{1}H NMR analysis), which were not separable by silica gel column chromatography. Fortunately, the formation of the corresponding *p*-nitrobenzoates **6a**–**c** allowed the separation of each isomer. Thus, the inseparable mixture of **5a**–**c** was treated with *p*-nitrobenzoyl chloride to give the mixture of dibenzoates **6a**–**c**. Recrystallization from ethyl acetate/*n*-hexane (*ca.* 1/1, v/v) afforded the pure (*R*,*S*,*S*,*R*)-**6a** as single crystals suitable for X-ray analysis from which the absolute stereochemistries at the newly generated stereogenic centers of **6a** could be assigned unambiguously as the *R* configuration. Methanolysis of the benzoate **6a** provided an optically pure (*R*,*S*,*S*,*R*)-**5a**. From the mother liquor, the second major isomer (*S*,*S*,*S*,*R*)-**6c** could be separated by silica gel column chromatography. The minor diastereomer (*S*,*S*,*S*,*S*)-**6b** could be synthesized by Mitsunobu reaction



Scheme 1. Synthesis of the diastereomeric 1,4-diphosphine ligands **1a–1c**. (a) MeONa/MeOH, reflux, 4 h, 98%. (b) 1 M aqueous NaOH, reflux, 1 h, 95%. (c) TMSCl/MeOH, rt, 12 h, 95%. (d) HN(OMe)Me, *i*-PrMgBr, THF. (e) CH_3MgBr (two steps: 84%). (f) Dibal-H, THF, −78 °C, 3 h, 93%. (g) *p*-NO_2-C_6H_4COCl, Et_3N, DMAP, CH_2Cl_2, rt, 5 h, 94%; recrystallization in EtOAc/*n*-hexane; silica-gel column chromatography. (h) K_2CO_3, MeOH-CH_2Cl_2 (v/v, 3/1), 96–97%. (i) *p*-NO_2-C_6H_4COOH, PPh_3, DEAD, THF, rt, 4 h, 91%. (j) MsCl/Et_3N, CH_2Cl_2, 0 °C, 2 h, 97–98%. (k) $KPPh_2$ (0.5 M THF), THF, rt, 18 h, 74% for **1a**, 65% for **1b**, 47% for **1c**.

of the optically pure (*R,S,S,R*)-**5a** with *p*-nitrobenzoic acid. Methanolysis of the optically pure **6b** and **6c** afforded the corresponding diols **5b** and **5c** quantitatively. Methanesulfonylation of the diols **5a**, **5b** and **5c**, followed by reaction with potassium diphenylphosphide afforded the desired diphosphines **1a**, **1b** and **1c** in good yields. The sign of optical rotation of **1a** {$[\alpha]_D^{25}$: +26.9 (*c* 0.23 in chloroform)} and **1b** {$[\alpha]_D^{25}$: +31.7 (*c* 0.24 in chloroform)} is opposite to that of **1c** {$[\alpha]_D^{25}$: −44.7 (*c* 0.37 in chloroform)}. The ^{31}P NMR spectra of the C_2-symmetrical ligands **1a** and **1b** showed a single resonance at 1.91 and 4.02 ppm, respectively, whereas two resonance at −0.04 and 8.85 ppm were shown by the pseudo-C_2-symmetrical **1c**.

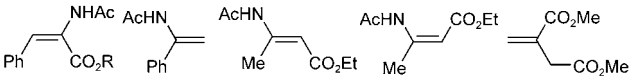
Asymmetric Hydrogenation

To investigate the catalytic efficiency of the novel diastereomeric diphosphine ligands, various kinds of prototypical olefinic substrates, α-(*N*-acylamino)cinnamic acid (**7**) and its methyl ester (**8**), α-arylenamides **9**, (*E*)-(**10a**)and (*Z*)-β-(*N*-acylamino)acrylates (**10b**), and itaconate **11**, were hydrogenated using the Rh complex of the diastereomeric BDPMI* **1a–c** and with Bn-BDPMI for comparison. All hydrogenations were carried out at 20 °C under 1 atm of H_2 pressure in the presence of 1 mol % of Rh complex *in situ* generated from $Rh(cod)_2BF_4$ and ligand, and the results are summarized in Table 1 (data of entries 1,[7c] 10[7a] and 22[7c] from our

previous reports). It was found that the backbone configurations of the ligand profoundly influenced the enantioselectivity for all substrates examined. In the hydrogenations of α-(*N*-acylamino)cinnamic acid **7**, the enantioselectivities were dramatically changed (from racemic to 94.9% ee) with changes of the configurations of the α-stereogenic centers (α to the phosphorus atom) (entries 2–4). No stereoinductions were observed with (*S,S,S,S*)-BDPMI* (**1a**) (entry 2). Moreover, the enantioselectivity obtained with the C_2-symmetrical diphosphine ligand (*R,S,S,R*)-**1b** was lower than that obtained with the parent ligand (*S,S*)-Bn-BDPMI with the opposite sense of stereoinduction (compare entries 1 with 2 and 3). Surprisingly, excellent enantioselectivities (93.0% ee, entry 4) can be achieved with the non C_2-symmetrialc ligand (*R,S,S,S*)-BDPMI* (**1c**). In the case of α-(*N*-acylamino)cinnamic acid methyl esters **8**, ligand **1a** exhibited a much higher enantioselectivity (84.8% ee) than ligand **1b** (19.8% ee). Here again, (*R,S,S,S*)-BDPMI* (**1c**) achieved the highest enantioselectivity (96.0% ee, entry 8). The enantioselectivities in the hydrogenation of α-arylenamides **9** were also affected by the backbone configurations of the ligands, but the effects were not significantly high (entries 9–12). Both C_2-symmetrical ligands **1a** (50.6% ee, entry 10) and **1b** (95.1% ee, entry 11) gave lower enantioselectivities than the parent ligand (*S,S*)-Bn-BDPMI (96.2% ee, entry 9). Again, the highest enantioselectivity could also be achieved with **1c** (98.6% ee, entry 12). Similar trends were observed in the hydrogenation of (*E*)- and (*Z*)-β-(acylamino)acrylates (**10**), which have recently received a great deal of attention due to their different stereoselectivity.[9] Both ligands **1a** (entries 14 and 19) and **1b** (entries 15 and 20) showed much lower enantioselectivity and reactivity compared with **1c** (entries 16 and 21). In the hydrogenation of (*E*)-β-(acylamino)acrylate, (*E*)-**10**, using the Rh complex of **1c**, the enantioselectivity obtained in *i*-PrOH solvent (96.3% ee, entry 17) was higher than in CH_2Cl_2 (95.7% ee, entry 16), which is a rare case, but the reaction did not go to completion (74% conversion). In contrast to the other substrates, the same enantioselectivity could be achieved in the hydrogenation of methyl itaconate with both ligands **1b** (97.3% ee, entries 24) and **1c** (97.3% ee, entry 25), but the ligand **1a** still exhibited a much lower enantioselectivity (6.0% ee, entry 23). Taken together, the enantioinduction ability of non C_2-symmetrical (*R,S,S,S*)-BDPMI* (**1c**) is clearly superior as compared to the other C_2-symmetrical diastereomeric ligands (*S,S,S,S*)-BDPMI* (**1a**) and (*S,S,S,S*)-BDPMI* (**1b**). Most gratifyingly, the Rh complex of ligand **1c** catalyzed the hydrogenation of a broad spectrum of functionalized olefins with excellent enantioselectivity.

Finally, various β-aryl-α-dehydroamino acid methyl esters, which are known to be notorious substrates for DIOP-type 1,4-diphosphine ligands, were hydrogenated with excellent enantioselectivities using the Rh complex of (*R,S,S,S*)-BDPMI* (**1c**), and the results are summarized in Table 2. As exemplified by the substrates with methyl groups in *ortho*-, *meta*- and *para*-positions (entries 2–4), the steric properties of the substrates slightly

Table 1. Rh(I)-catalyzed asymmetric hydrogenation of functionalized olefins **7**–**11** using **1a**–**c** and Bn-BDPMI.[a]

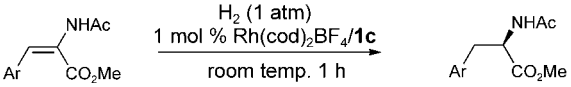


7: R = H, **8**: R = Me | **9** | (*E*)-**10** | (*Z*)-**10** | **11**

Entry	Substrate	Ligand	% ee[k] (confuration)[l]
1[b]	**7**	**Bn-BDPMI**	75.0 (*S*)
2	**7**	**1a**	rac (-)
3	**7**	**1b**	71.4 (*S*)
4	**7**	**1c**	93.0 (*R*)
5[c]	**8**	**Bn-BDPMI**	16.0 (*R*)
6	**8**	**1a**	84.8 (*R*)
7	**8**	**1b**	19.8 (*R*)
8	**8**	**1c**	96.0 (*R*)
9[d]	**9**	**Bn-BDPMI**	96.2 (*R*)
10	**9**	**1a**	50.6 (*R*)
11	**9**	**1b**	95.1 (*R*)
12	**9**	**1c**	98.6 (*R*)
13[d]	(*E*)-**10**	**Bn-BDPMI**	91.7 (*R*)
14	(*E*)-**10**	**1a**	13.0 (*R*)[e]
15	(*E*)-**10**	**1b**	78.2 (*R*)
16	(*E*)-**10**	**1c**	95.7 (*R*)
17	(*E*)-**10**	**1c**	96.3 (*R*)[f]
18[g]	(*Z*)-**10**	**Bn-BDPMI**	96.2 (*R*)
19	(*Z*)-**10**	**1a**	50.3 (*R*)[h]
20	(*Z*)-**10**	**1b**	80.2 (*R*)[i]
21	(*Z*)-**10**	**1c**	97.2 (*R*)
22[j]	**11**	**Bn-BDPMI**	42.5 (*R*)
23	**11**	**1a**	6.0 (*R*)
24	**11**	**1b**	97.3 (*R*)
25	**11**	**1c**	97.3 (*R*)

[a] All hydrogenations were carried out at room temperature using 1 mol % of Rh complex *in situ* generated from $Rh(cod)_2BF_4$ and ligand, and achieved 100% conversion unless otherwise noted.
[b] Reactions for the substrate **7** were carried out in acetone for 1 h.
[c] Reactions for the substrate **8** were carried in THF for 1 h.
[d] Reactions for the substrates **9** and (*E*)-**10** were carried out in CH_2Cl_2 for 12 h.
[e] 53% conversion.
[f] Reaction was carried out in *i*-PrOH for 12 h, 74% conversion.
[g] Reactions for the substrate (*Z*)-**10** were carried out in *i*-PrOH for 12 h.
[h] 20% conversion.
[i] 75% conversion.
[j] Reactions for the substrate **11** were carried out in *i*-PrOH for 1 h.
[k] Determined by GC analysis.
[l] Determined by the sign of the optical rotation.

Table 2. Rh(I)-catalyzed asymmetric hydrogenation of methyl α-(*N*-acetylamino)-β-arylacrylates using **1c** as a ligand.[a]



Entry	Ar	% ee[b]
1	Ph	96.0
2	*ortho*-Me-C_6H_4	95.4
3	*meta*-Me-C_6H_4	96.8
4	*para*-Me-C_6H_4	97.0
5	*para*-F-C_6H_4	95.8
6	*para*-Cl-C_6H_4	96.4
7	*para*-Br-C_6H_4	96.4
8	*para*-OMe-C_6H_4	95.3
9	3,4-methylenedioxy-C_6H_3	95.5
10	2-naphthyl	95.4

[a] All hydrogenations were carried out in THF at room temperature using 1 mol % of Rh complex *in situ* generated from $Rh(cod)_2BF_4$ and ligand, and achieved 100% conversion as determined by NMR and GC analysis.
[b] Determined by GC analysis.

affected the enantioselectivity. On the other hand, the enantioselectivities are not much dependent on the electronic property of the substrates. Both substrates bearing electron-donating and electron-withdrawing groups at the *para*-position were hydrogenated with almost the same enantioselectivities. Although the enantioselectivities (95.3–97.0% ees) are not extremely high (>99% ee), it is noteworthy that these are among the highest enantioselectivities obtained from the Rh-catalyzed hydrogenation of α-dehydroamino acid derivatives using DIOP-type 1,4-diphosphine ligands.[10]

Conclusion

In conclusion, novel diastereomeric 1,4-diphosphine ligands have been synthesized starting from an intermediate for the commercial production of biotin, and their catalytic efficiencies were investigated in Rh(I)-catalyzed asymmetric hydrogenations of various functionalized olefins. Pronounced effects of the backbone configuration on the enantioselectivity, reactivity as well as substrate scope have been observed. These results should be very helpful in the design of new efficient chiral ligands. Further studies on the structural variation of the ligands are in progress.

Experimental Section

General Remarks

All reactions and manipulations were performed in a nitrogen atmosphere using standard Schlenk techniques. The reaction solvents were distilled prior to use. All purchased reagents were used without further purification. Anhydrous solvents were transferred by oven-dried syringes. Flasks were dried with a flame under a stream of nitrogen. The NMR spectra were recorded on a Bruker 300 spectrometer at 300 MHz (^{1}H), 75.5 MHz (^{13}C) and 121 MHz (^{31}P). The chemical shifts are given in ppm relative to the corresponding reference; TMS for ^{1}H NMR and $P(O)(OPh)_3$ (as an external reference) for ^{31}P NMR. GC analyses were performed using a Hewlett-Packard 5890 Model. HPLC analyses were performed using Agilent 1100 interfaced to an HP 71 series computer workstation. The enantiomeric excesses of the hydrogenation products were determined by chiral capillary GC column using CP-Chirasil-Dex-CB (dimensions 30 m × 0.32 mm i.d.), CP-Chirasil-L-Val (dimensions 30 m × 0.25 mm i.d.) and γ-DEX 225 (dimensions 30 m × 0.32 mm i.d.) columns with N_2 as carrier gas (2 mL/min). The racemic products were obtained by hydrogenation of substrates with Pd/C or an achiral rhodium catalyst.

Chemical analyses were carried out by the Advanced Analysis Center at Korea Institute of Science and Technology. The optically pure *cis*-monocyclohexyl ester 2 was generously donated by Samcho Biochemical Ltd., Korea.

(4*S*,5*S*)-1,3-Dibenzylimidazolidin-2-one-4,5-dicarboxylic Acid Monocyclohexyl Ester [(*S*,*S*)-3a]

To a solution of sodium methoxide generated from sodium metal (0.34 g, 14.9 mmol) in methanol (100 mL) was added *cis*-monocyclohexyl ester (*R*,*S*)-**2** (5 g, 11.5 mmol) in one portion. The reaction mixture was refluxed for 4 h, and allowed to cool to room temperature. The solution was acidified with 3% aqueous HCl solution until the solution had pH = 4. After evaporation of the methanol on a rotary evaporator, the organic materials was extracted with ethyl acetate (50 mL × 3). The combined organic layer was dried over anhydrous $MgSO_4$, and the ethyl acetate was evaporated to give product (*S*,*S*)-**3a** as a viscous oil; yield: 4.9 g (98%); $[\alpha]_D^{25}$: −13.6 (*c* 2.22, MeOH); ^{1}H NMR (acetone-d_6): δ = 1.17–1.31 (m, 6H), 1.54–1.89 (m, 4H), 3.60 (m, 1H), 4.02–4.25 (m 4H), 4.93 (d, *J* = 15.3 Hz, 2H), 5.08 (d, 2H, *J* = 15.3 Hz, 2H), 7.23–7.35 (m, 10H); ^{13}C NMR (acetone-d_6): δ = 24.0, 25.2, 34.8, 46.4, 46.7, 56.8, 57.5, 70.7, 127.6, 127.9, 128.0, 128.1, 128.6, 135.7, 159.1, 169.6, 171.0; anal. calcd. for $C_{25}H_{28}N_2O_5$: C 68.79, H 6.47, N 6.42; found: C 68.3, H 6.7, N, 6.1.

(4*S*,5*S*)-1,3-Dibenzylimidazolidin-2-one-4,5-dicarboxylic Acid [(*S*,*S*)-3b]

A solution of *trans*-monocyclohexyl ester (*S*,*S*)-**3a** (5 g, 11.5 mmol) in 1 M aqueous NaOH solution (50 mL) was heated to reflux for 1 h. The reaction mixture was cooled to room temperature and treated with 3% aqueous HCl until the solution had pH = 4. The solution was extracted with ethyl acetate (50 mL × 3), and the combined organic layer was dried over anhydrous $MgSO_4$, and the solvent removed to give *trans*-diacid (*S*,*S*)-**3b** as a white solid; yield: 3.9 g (95%); mp 164–166 °C; $[\alpha]_D^{25}$: −16.7 (*c* 1.11, chloroform); ^{1}H NMR (acetone-d_6): δ = 4.15 (s, 2H), 4.18 (d, *J* = 15.4 Hz, 2H), 5.02 (d, 2H, *J* = 15.4 Hz, 2H), 7.28–7.36 (m, 10H); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = 46.4, 57.7, 127.8, 128.2, 128.9, 137.5, 159.1, 170.6;

anal. calcd. for $C_{19}H_{18}N_2O_5$: C 64.40, H 5.12, N 7.91; found: C 64.0, H 5.1, N 7.8.

(4*S*,5*S*)-1,3-Dibenzylimidazolidin-2-one-4,5-dicarboxylic Acid Dimethyl Ester [(*S*,*S*)-3c]

To a solution of diacid (*S*,*S*)-**3b** (27 g, 80 mmol) in methanol (200 mL) was added dropwise chlorotrimethylsilane (29 mL, 0.23 mol) at room temperature. The reaction mixture was stirred at room temperature for 12 h. The solvent was evaporated, and the residue was purified by short silica gel column (ethyl acetate:*n*-hexane = 1:2) to give diester (*S*,*S*)-**3c** as a white solid; yield: 27.7 g (95%); mp 66–67 °C; R_f = 0.31 (ethyl acetate:*n*-hexane = 1:2); $[\alpha]_D^{25}$: −5.8 (*c* 0.49, chloroform); ^{1}H NMR ($CDCl_3$): δ = 3.64 (s, 6H), 4.04 (s, 2H), 4.19 (d, *J* = 15.3 Hz, 2H), 4.98 (d, 2H, *J* = 15.3 Hz, 2H), 7.23–7.33 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 46.7, 52.7, 57.3, 127.7, 128.1, 128.6, 136.1, 158.6, 169.7; anal. calcd. for $C_{21}H_{22}N_2O_5$: C 65.96, H 5.80, N 7.33; found: C 65.7, H 5.8, N 7.3.

(4*S*,5*S*)-1,3-Dibenzylimidazolidin-2-one-4,5-dicarboxylic Acid Bis(methoxymethyl)amide [(*S*,*S*)-4a]

To a suspension of diester (*S*,*S*)-**3c** (1.00 g, 2.61 mmol) and *N*,*O*-dimethylhydroxyamine hydrochloride (0.77 g, 7.84 mmol) in THF (30 mL) was added dropwise isopropylmagnesium bromide (6.6 mL of 2 M solution in THF, 13.1 mmol) at −28 °C. The reaction mixture was stirred at the same temperature for 20 min, and then, quenched with saturated aqueous NH_4Cl solution. The organic materials were extracted with ethyl acetate (20 mL × 3), and the combined organic layer was dried over anhydrous $MgSO_4$ and filtered. Evaporation of the solvent afforded viscous oil (1.25 g), which was crystallized from *n*-hexane/ethyl acetate to give white solid; mp 86–87 °C; R_f = 0.24 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: −23.1 (*c* 0.8, chloroform); ^{1}H NMR ($CDCl_3$): δ = 2.99 (s, 6H), 3.18 (s, 6H), 4.15 (d, *J* = 15.4 Hz, 2H), 4.34 (s, 2H), 5.00 (d, *J* = 15.4 Hz, 2H), 7.21–7.35 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 32.5, 46.4, 55.1, 61.0, 127.4, 128.2, 128.5, 136.3, 159.5, 169.8; anal. calcd. for $C_{23}H_{28}N_4O_5$: C 62.71, H 6.41, N 12.72; found: C 62.5, H 6.5, N 12.7.

(4*S*,5*S*)-4,5-Diacetyl-1,3-dibenzylimidazolidin-2-one [(*S*,*S*)-4b]

To a solution of Weinreb amide (*S*,*S*)-**4a** (1.0 g, 2.27 mmol) in THF (30 mL) was added dropwise methylmagnesium bromide (2.3 mL of 3 M solution in THF, 6.81 mmol) at 0 °C. The reaction mixture was stirred at room temperature for 12 h, and the reaction was quenched with saturated aqueous NH_4Cl solution. The organic materials were extracted with ethyl acetate (20 mL × 3), and the combined organic layer was dried over anhydrous $MgSO_4$, filtered. After evaporation of the solvent, the residue was purified by column chromatography (eluent: ethyl acetate:*n*-hexane = 1:2) on silica gel to give diketone (*S*,*S*)-**4b** as a white solid; yield 0.58 g [84% from diester (*S*,*S*)-**3c**]; mp 70–71 °C; R_f = 0.28 (ethyl acetate:*n*-hexane = 1:2); $[\alpha]_D^{25}$: +9.1 (*c* 0.42, chloroform); ^{1}H NMR ($CDCl_3$): δ = 1.94 (s, 6H), 3.59 (s, 2H), 4.01 (d, *J* = 14.9 Hz, 2H), 4.99 (d, *J* = 14.9 Hz, 2H), 7.18–7.35 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 25.3, 47.2, 62.6, 128.1, 128.4, 135.6, 159.1, 204.3; anal. calcd. for $C_{21}H_{22}N_2O_3$: C 71.98, H 6.33, N 7.99; found: C 71.9, H 6.3, N 8.0.

Mixture of (4*S*,5*S*)-1,3-Dibenzyl-4,5-bis(1-hydroxyethyl)imidazolidin-2-one (5a–c)

To a stirred solution of diketone (*S*,*S*)-**4b** (0.17 g, 0.49 mmol) in THF was added Dibal-H (1.46 mL of 1 M solution in toluene, 1.46 mmol) at −78 °C. The reaction mixture was stirred at the same temperature for 3 h. To the reaction mixture, methanol (2 mL) was added and stirring at the same temperature was continued for 30 min, and then water (5 mL) was added. The mixture was extracted with dichloromethane and dried over anhydrous $MgSO_4$, filtered, and the solvent was removed. The residue was purified by column chromatography on silica gel to give a mixture of **5a–c** (yield: 0.16 g, 93%) with the ratio of **5a**:**5b**:**5c** = 68:3:29 by ^{1}H NMR analysis.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*R*,1′*R*)-*p*-nitrobenzoyloxyethyl]imidazolidin-2-one (6a) and (4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*S*,1′*R*)-*p*-nitrobenzoyloxyethyl]imidazolidin-2-one (6c)

To a stirred solution of diol 5 (mixture of **5a–c**, 1.5 g, 4.23 mmol), triethylamine (1.9 mL, 12.7 mmol) and DMAP (0.1 g, 0.85 mmol, 20 mol%) in dichloromethane was added *p*-nitrobenzoyl chloride (2.4 g, 12.7 mmol) in one portion at ice bath temperature. The reaction mixture was stirred at room temperature for 5 h. The reaction was quenched with water and extracted with dichloromethane. The combined organic layer was washed with 3% aqueous HCl, dried over anhydrous $MgSO_4$, and filtered. After evaporation of the solvent, the residue was purified by short column chromatography on silica gel to give the diastereomeric mixture **6a–c** (yield: 2.6 g, 94%). Recrystallization with ethyl acetate/*n*-hexane (*ca.* 1/1, v/v) afforded the optically pure diastereomer **6a** (yield: 1.05 g, 40%).

The filtrate was evaporated and optically pure **6c** separated by column chromatography on silica gel (eluent: ethyl acetate:hexane = 1:4–1:2) (yield: 0.4 g, 16%).

6a: mp 162–163 °C; R_f = 0.19 (ethyl acetate:*n*-hexane = 1:2); $[\alpha]_D^{25}$: −30.9 (*c* = 1.10, chloroform); ^{1}H NMR ($CDCl_3$): δ = 1.26 (d, *J* = 6.6 Hz, 6H), 3.59 (s, 2H), 4.13 (d, *J* = 15.2 Hz, 2H), 5.09 (d, *J* = 15.2 Hz, 2H), 5.28 (q, *J* = 6.6 Hz, 2H), 7.09–7.29 (m, 10H), 8.01 (m, 4H), 8.27 (m, 4H); ^{13}C NMR ($CDCl_3$): δ = 14.1, 46.2, 56.4, 71.7, 123.6, 127.8, 128.3, 128.7, 130.7, 134.9, 136.3, 150.6, 159.7, 163.9; anal. calcd. for $C_{35}H_{32}N_4O_9$: C 64.41, H 4.94, N 8.58; found: C 64.2, H 4.9, N 8.5.

Crystal data of 6a: $C_{35}H_{32}N_4O_9$, monoclinic, *a* = 10.5246(11), *b* = 22.836(2), *c* = 13.6412(14) Å, *V* = 3265.3(6) Å^3, *Z* = 4, $D_{calcd.}$ = 1.328 g/cm^3, F(000) = 1368, Goodness of fit on F^2 = 1.060, 20037 independent reflections with I/σ (I) = 2.0 were used in the analysis. Data for crystallographic analysis were measured on an Enraf-Nonius CAD-4 diffractormeter using graphite-monochromated MoKα (λ = 0.71073 Å) and ω̄-2 scans in the range of θ; 1.50 < θ < 23.30. Structure was solved by direct methods and refined by least squares using SHEL-

X. Crystallographic data (excluding structure factors) for the structure(s) reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-249564. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [Fax: int. code + 44(1223)336–033; E-mail: deposit@ccdc.cam.ac.uk].

6c: mp 73 °C; R_f = 0.23 (ethyl acetate:*n*-hexane = 1:2); $[\alpha]_D^{25}$: −106.5 (*c* = 0.61, chloroform); ^{1}H NMR ($CDCl_3$): δ = 1.03 (d, *J* = 6.6 Hz, 3H), 1.06 (d, *J* = 6.7 Hz, 3H), 3.54 (dd, *J* = 4.1, 4.1 Hz, 1H), 3.78 (dd, *J* = 1.6, 4.1 Hz, 1H), 4.08 (d, *J* = 15.1 Hz, 1H), 4.15 (d, *J* = 14.9 Hz, 1H), 4.93 (d, *J* = 14.9 Hz, 1H), 5.16 (d, *J* = 15.2 Hz, 1H), 5.15 (m, 1H), 5.39 (m, 1H), 7.14–7.40 (m, 10H), 8.07 (m, 2H), 8.21–8.32 (m, 6H); ^{13}C NMR ($CDCl_3$): δ = 12.9, 13.7, 46.5, 46.6, 54.9, 55.6, 69.7, 73.0, 123.6, 123.7, 127.8, 128.1, 128.3, 128.6, 128.8, 128.9, 130.7, 131.0, 134.8, 135.0, 136.2, 136.4, 150.7, 159.4, 163.8, 163.8.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*S*,1′*S*)-*p*-nitrobenzoyloxyethyl]imidazolidin-2-one (6b)

To a stirred solution of diol **5a** (0.30 g, 0.85 mmol) obtained by methanolysis of **6a**, triphenylphosphine (0.89 g, 3.39 mmol) and *p*-nitrobenzoic acid (0.57 g, 3.39 mmol) in THF (20 mL) were added DEAD (0.53 mL, 3.39 mmol) at ice bath temperature. The reaction mixture was stirred at room temperature for 4 h. After quenching the reaction by addition of methanol (5 mL), the volatiles were evaporated. The residue was purified by column chromatography on silica gel to give **6b**; yield: 0.50 g (91%); mp 186–187 °C; R_f = 0.19 (ethyl acetate:*n*-hexane = 1:2); $[\alpha]_D^{25}$: −18.7 (*c* 0.45, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.95 (d, *J* = 7.2 Hz, 6H), 3.79 (d, *J* = 3.3 Hz, 2H), 4.18 (d, *J* = 14.7 Hz, 2H), 4.90 (d, *J* = 14.7 Hz, 2H), 5.23 (dq, *J* = 3.9, 6.6 Hz, 2H), 7.27–7.46 (m, 10H), 7.79 (m, 4H), 7.92 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 13.1, 46.6, 53.9, 69.9, 99.9, 123.1, 128.0, 128.8, 128.9, 130.4, 134.4, 136.5, 150.3, 158.8, 163.4.

Typical Procedure for Methanolysis of Dibenzoate 6a–c

To a stirred solution of dibenzoate **6a** (1.05 g, 1.61 mmol) in methanol (30 mL) and dichloromethane (10 mL) was added anhydrous potassium carbonate (1.10 g, 8.04 mmol) at room temperature. The reaction mixture was stirred at room temperature for 1 h. The solid was filtered off, and the filtrate was concentrated. The residue was purified by column chromatography (ethyl acetate:*n*-hexane = 1:1) on silica gel to give **5a**; yield: 0.55 g (97%).

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*R*,1′*R*)-hydroxyethyl)]imidazolidin-2-one (5a): mp 125–126 °C; R_f = 0.27 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: +4.0 (*c* 0.50, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.91 (d, *J* = 6.6 Hz, 6H), 1.96 (bs, 2H), 3.22 (s, 2H), 3.76 (dq, *J* = 2.7, 6.6 Hz, 2H), 4.30 (d, *J* = 15.3 Hz, 2H), 4.79 (d, *J* = 15.3 Hz, 2H), 7.24–7.33 (m, 10H); ^{13}C NMR ($CDCl_3$) δ 17.2, 46.7, 58.3, 66.4, 127.6, 128.1, 128.7, 137.4, 160.7; anal. calcd. for $C_{21}H_{26}N_2O_3$: C 71.16, H 7.39, N 7.90; found: C 70.4, H 7.2, N 7.6.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis-[(1*S*,1′*S*)-(hydroxyethyl)]imidazolidin-2-one (5b): Yield: 97%; R_f = 0.27 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: −20.0 (*c* 0.57, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.81 (d, *J* = 6.0 Hz, 6H), 3.08 (bs, 2H), 3.35 (dd, *J* = 4.5, 8.4 Hz, 2H), 3.87 (m, 2H), 3.93 (d, *J* = 15.3 Hz, 2H), 4.84 (d, *J* = 15.6 Hz, 2H), 7.22–7.32 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 16.5, 46.7, 55.8, 65.4, 127.7, 128.4, 128.6, 136.5, 160.1.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis-[(1*R*,1′*S*)-(hydroxyethyl)]imidazolidin-2-one (5c): Yield: 96%; mp 158–159 °C; R_f = 0.27 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: −14.2 (*c* 0.45, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.77 (d, *J* = 6.4 Hz, 3H), 0.94 (d, *J* = 6.4 Hz, 3H), 2.61 (bs, 1H), 2.68 (bs, 1H), 3.20 (dd, *J* = 2.4, 4.2 Hz, 1H), 3.24 (dd, *J* = 4.2, 4.2 Hz, 1H), 3.74 (m, 2H), 4.06 (d, *J* = 13.2 Hz, 1H), 4.12 (d, *J* = 13.1 Hz, 1H), 4.72 (d, *J* = 15.2 Hz, 1H), 4.72 (d, *J* = 15.0 Hz, 1H), 7.21–7.31 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 16.9, 17.2, 46.4, 47.1, 57.6, 57.9, 66.5, 67.5, 127.5, 127.6, 128.2, 128.5, 128.5, 136.9, 160.5.

Typical Procedure for the Methanesulfonylation of Diol 5a–c

To a stirred solution of diol **5a** (56.4 mg, 0.16 mmol) and triethylamine (0.072 mL, 0.48 mmol) in dichloromethane was added dropwise methanesulfonyl chloride (0.037 mL, 0.48 mmol) at ice bath. The reaction mixture was stirred at room temperature for 2 h. The mixture was quenched with water and extracted with dichloromethane, dried over anhydrous $MgSO_4$, and filtered. After evaporation of the solvent, the residue was purified by column chromatography (ethyl acetate:*n*-hexane = 1:1) on silica gel to give the corresponding mesylate; yield: 79 mg (98%).

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*R*,1′*R*)-methanesulfonyloxyethyl]imidazolidin-2-one (5a): R_f = 0.54 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: +19.6 (*c* 0.65, chloroform); ^{1}H NMR ($CDCl_3$): δ = 1.16 (d, *J* = 6.6 Hz, 6H), 2.81 (s, 6H), 3.33 (s, 2H), 4.03 (d, *J* = 15.3 Hz, 2H), 4.75 (q, *J* = 6.6 Hz, 2H), 5.08 (d, *J* = 14.7 Hz, 2H), 7.30–7.37 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 15.8, 38.8, 46.1, 56.7, 76.8, 128.1, 128.9, 129.0, 136.2, 159.3; anal. calcd. for $C_{23}H_{30}N_2O_7S_2$: C 54.10, H 5.92, N 5.49; found: C 53.7, H 5.9, N 5.4.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*S*,1′*S*)-methanesulfonyloxyethyl]]imidazolidin-2-one (5b): Yield: 97%; R_f = 0.54 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: −31.2 (*c* 0.71, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.93 (d, *J* = 6.6 Hz, 6H), 2.88 (s, 6H), 3.61 (d, *J* = 3.3 Hz, 2H), 4.03 (d, *J* = 14.7 Hz, 2H), 4.71 (dq, *J* = 3.3, 6.6 Hz, 2H), 4.84 (d, *J* = 14.7 Hz, 2H), 7.31–7.37 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 13.8, 38.2, 46.6, 54.3, 74.1, 128.3, 128.9, 129.0, 135.9, 158.4.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*R*,1′*S*)-methanesulfonyloxyethyl]]imidazolidin-2-one (5c): Yield: 98%; R_f = 0.54 (ethyl acetate:*n*-hexane = 2:1); $[\alpha]_D^{25}$: −16.8 (*c* 0.60, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.90 (d, *J* = 6.6 Hz, 3H), 1.13 (d, *J* = 6.5 Hz, 3H), 2.84 (s, 3H), 2.89 (s, 3H), 3.45 (dd, *J* = 1.6, 3.6 Hz, 1H), 3.49 (dd, *J* = 4.0, 4.0 Hz, 1H), 3.98 (d, *J* = 14.9 Hz, 1H), 4.07 (d, *J* = 14.8 Hz, 1H), 4.75 (d, *J* = 14.6 Hz, 1H), 4.71 (m, 1H), 4.80 (m, 1H), 5.11 (d, *J* = 14.9 Hz, 1H), 7.30–7.38 (m, 10H); ^{13}C NMR ($CDCl_3$): δ = 13.6, 15.4, 38.3, 38.5, 46.8, 46.8, 55.2, 55.7, 74.5, 128.0, 128.2, 128.8, 128.9, 139.0, 135.9, 136.0, 158.9.

General Procedure for Preparation of Phosphine Ligands 1a–c

To a stirred solution of (4*S*,5*S*)-1,3-dibenzyl-4,5-bis[(1*R*,1′*R*)-methanesulfonyloxyethyl]-imidazolidin-2-one (60 mg, 0.12 mmol) in THF (10 mL) was added potassium diphenylphosphide (0.7 mL of 0.5 M solution in THF, 0.36 mmol) at 0 °C. The reaction mixture was stirred at room temperature for 18 h. The precipitate was filtered off through celite and washed with toluene, the filtrate was concentrated and the residue was purified by column chromatography (ethyl acetate:*n*-hexane = 1:5) on silica gel to give diphosphine **1a**; yield: 60 mg (74%).

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*S*,1′*S*)-diphenylphosphinoethyl]imidazolidin-2-one (1a): R_f = 0.14 (ethyl acetate:*n*-hexane = 1:5); $[\alpha]_D^{25}$: +26.9 (*c* 0.23, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.69 (dd, *J* = 7.2, 11.1 Hz, 6H), 2.42 (m, 2H), 3.59 (m, 2H), 3.77 (d, *J* = 15.0 Hz, 2H), 4.69 (d, *J* = 14.9 Hz, 2H), 7.04–7.34 (m, 30H); ^{13}C NMR ($CDCl_3$): δ = 12.3, 34.3, 46.6, 57.1, 57.3, 57.5, 127.5, 128.1, 128.2, 128.2, 128.3, 128.5, 128.8, 129.1, 132.7, 132.8, 132.9, 134.4, 134.5, 134.7, 135.9, 136.0, 136.1, 136.3, 136.4, 136.4, 137.0, 160.4; ^{31}P NMR ($CDCl_3$): δ = 1.91; HRMS: *m/z* calcd. for $C_{45}H_{44}N_2OP_2$: 691.3007; found: 691.2991.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*R*,1′*R*)-diphenylphosphinoethyl]imidazolidin-2-one (1b): Yield: 63%; R_f = 0.14 (ethyl acetate:*n*-hexane = 1:5); $[\alpha]_D^{25}$: +31.7 (*c* 0.24, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.64 (dd, *J* = 7.1, 13.3 Hz, 6H), 1.51 (m, 2H), 3.00 (m, 2H), 4.31 (d, *J* = 15.8 Hz, 2H), 4.69 (d, *J* = 15.8 Hz, 2H), 6.84–7.35 (m, 30H); ^{13}C NMR ($CDCl_3$): δ = 10.0, 10.2, 34.8, 35.0, 46.2, 46.3, 55.6, 55.7, 55.8, 55.9, 127.0, 128.0, 128.1, 128.2, 128.3, 128.3, 128.4, 128.5, 128.8, 129.0, 133.1, 133.4, 133.6, 133.9, 137.0, 137.2, 137.4, 161.8; ^{31}P NMR ($CDCl_3$): δ = 4.02; HRMS: *m/z* calcd. for $C_{45}H_{44}N_2OP_2$: 691.3007; found: 691.3013.

(4*S*,5*S*)-1,3-Dibenzyl-4,5-bis[(1*R*,1′*S*)-diphenylphosphinoethyl]imidazolidin-2-one (1c): Yield: 47%; R_f = 0.19 (ethyl acetate:*n*-hexane = 1:5); $[\alpha]_D^{25}$: −44.7 (*c* 0.37, chloroform); ^{1}H NMR ($CDCl_3$): δ = 0.36 (dd, *J* = 6.9, 13.5 Hz, 3H), 0.61 (dd, *J* = 6.9, 14.4 Hz, 3H), 2.35 (m, 1H), 2.71 (m, 1H), 3.31 (m, 1H), 3.90 (m, 1H), 3.95 (d, *J* = 15.1 Hz, 1H), 4.51 (dd, *J* = 5.0, 15.5 Hz, 1H), 5.05 (d, *J* = 15.0 Hz, 1H), 5.19 (d, J = 15.5 Hz, 1H), 7.15–7.39 (m, 30H); ^{13}C NMR ($CDCl_3$): δ = 9.0, 9.2, 10.2, 10.4, 30.8, 31.0, 36.9, 37.1, 45.4, 46.9, 47.1, 52.8, 52.9, 57.7. 57.8, 57.9, 127.1, 127.6, 128.2, 128.2, 128.3, 128.3, 128.4, 128.5, 128.6, 128.6, 128.6, 128.7, 128.9, 128.9, 129.0, 129.1, 129.2, 133.2, 133.4, 133.5, 133.5, 133.7, 133.8, 134.5, 134.6, 134.8, 134.9, 135.3, 135.5, 135.8, 136.0, 136.0, 136.3, 136.8, 137.0, 137.3, 160.4; ^{31}P NMR ($CDCl_3$): δ = −0.04, 8.85; HRMS: *m/z* calcd. for $C_{45}H_{44}N_2OP_2$: 691.3007; found: 691.3019.

General Procedure for Asymmetric Hydrogenation

In an inert atmosphere glove-box, a reaction flask was charged with $[Rh(cod)_2]BF_4$ (2.3×10^{-3} mmol) and chiral ligand (2.7×10^{-3} mmol) in 2 mL of solvent, and the mixture was stirred for 20 min at 20 °C. A substrate (0.23 mmol) was added to the reaction mixture, and then hydrogenation was performed under 1 atm of H_2 for 1 h. The reaction mixture was passed through a short silica gel column to remove the catalyst. After evaporation of the solvent, the crude reaction mixture was subjected to ^{1}H NMR and capillary GC analyses to determine the conversion and enantiomeric excess, respectively.

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[10] To date, BICP is the leading DIOP-type 1,4-bisphosphine ligand for the Rh(I)-catalyzed hydrogenation of α-dehydroamino acids (96.8–99% ees), see: ref.[3a]

