Concurrent Induction of Two Chiral Centers from Symmetrical 3,4-Disubstituted and 3,3,4-Trisubstituted 4-Pentenals Using Rh-Catalyzed Asymmetric Cyclizations

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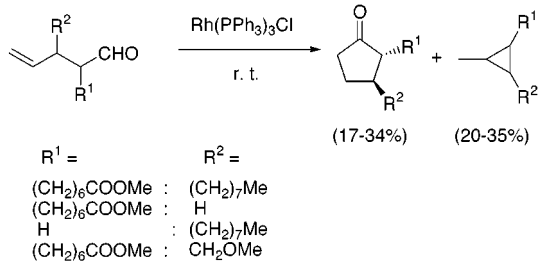
Asymmetric cyclization of symmetrical 3,4-disubstituted and 3,3,4-trisubstituted 4-pentenals was studied using Rh-complexes with chiral ligands. The cyclization of symmetrical 4-pentenals **4a**,**b** by a neutral Rh[(*R*)-BINAP]Cl afforded *cis*-3,4-disubstituted (4*R*)-cyclopentanones **9a**,**b** of >95% ee in 25−31% yields; on the other hand, the cyclization of **4a**−**c** by a cationic Rh[(*R*)-BINAP]ClO_4 afforded *trans*-3,4-disubstituted (4*S*)-cyclopentanones **10a**−**c** of >95% ee in 70−81% yields. All stereoisomers could be stereoselectively made by the selection of a neutral or cationic Rh-complex, and (*R*)- or (*S*)-BINAP ligand. The Rh-catalyzed cyclization could be applied to the construction of cyclopentanones **17** and **18** bearing a chiral quaternary carbon. The cyclization by the cationic Rh[(*R*)-BINAP]ClO_4 afforded the optically active *trans*-3,3,4-trisubstituted cyclopentanones **18a**−**c** of 92−95% ee in 75−83% yields. The catalytic cycle was also studied by using deuterium aldehyde, and the tentative mechanisms of the enantio- and diastereoselection were proposed.

Introduction

Rhodium-catalyzed intramolecular hydroacylation of 4-pentenals,[1−3] that is to say cyclization of 4-pentenals into cyclopentanones, was first discovered by one of us in 1972.[4,5] Therein, the treatment of 2,3-disubstituted 4-pentenals with a stoichiometric amount of the Wilkinson-complex [Rh$Cl(PPh_3)_3$] in $CHCl_3$ afforded the cyclopentanones in 17−34% yields, together with cyclopropanes in 20−35% yields as byproducts (Scheme 1).

Scheme 1



After this discovery, Miller[6] reported that the cyclization could proceed by using a catalytic amount of Rh$Cl(PPh_3)_3$ under ethylene pressure, and the mechanisms were also reported by several groups.[7] The generality of this cyclization was subsequently studied by Larock[8] using various substrates and neutral Rh-complexes with trialkyl- or triarylphosphines and phosphites. However, only limited turnover was attained because the catalyst was converted to the catalytically inactive Rh(CO)$(PPh_3)_2Cl$ complex, due to the competing decarbonylation. Meanwhile, we discovered the cyclization of 3,4-disubstituted 4-pentenals proceeded stereoselectively to give *cis*-3,4-disubstituted cyclopentanones, although the cyclization required more than 20% molar of the Rh-catalyst.[9] This stereoselective cyclization was applied to the enantioselective syntheses of natural products and biologically active compounds such as prostaglandins and iridoides.[10] The development of Rh-catalyzed cyclization into the asymmetric reaction was first reported by James's group.[11] They used the Rh-complex with chira-

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(1) A part of work has been reported as preliminary communication. Wu, X.-M.; Funakoshi, K.; Sakai, K. *Tetrahedron Lett.* **1993**, *34*, 5927−5930.

(2) Very recently, the Rh-catalyzed cyclization of 4-pentenals was used as name reaction by Mioskowski. See: Ducray, P.; Rousseau, B.; Mioskowski, C. *J. Org. Chem.* **1999**, *64*, 3800−3801.

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phos[12] as a chiral ligand and synthesized 2-methyl-2-phenylcyclopentanone of 52% ee in 40−50% yield by the kinetic resolution of racemic 4-pentenal. Asymmetric cyclization of prochiral 4-pentenals into chiral 3-substituted cyclopentanones was discovered by us in 1989.[13] Using the neutral Rh-complex with (+)-DIPMC[12] as a chiral ligand, the prochiral 4-substituted 4-pentenals were converted to (3*S*)-3-substituted cyclopentanones of 73−77% ee in 68−78% yields. Therein, the mechanism of stereoselectivity was tentatively proposed based on the studies using 3,4-disubstituted 4-pentenals as substrates. A cationic Rh-complex [Rh(diphosphine)]$^+$ was found to be the most effective catalyst for the intramolecular cyclization by Bosnich's group in 1988.[14] This finding prompted us to study the asymmetric cyclization using the cationic Rh-complex with chiral ligands.[15] Using 5% molar of the cationic Rh-complex with BINAP as a chiral ligand, the prochiral 4-substituted 4-pentenals were converted into the enantiomerically enriched cyclopentanones of 65−99% ee in good yields. The selection of prochiral enantiofaces of 4-pentenals by the cationic Rh[(*R*)-BINAP]ClO_4 was opposite to that by the neutral Rh[(*R*)-BINAP]Cl. These results stimulated us and Bosnich's group to study further the asymmetric cyclization.[15,16]

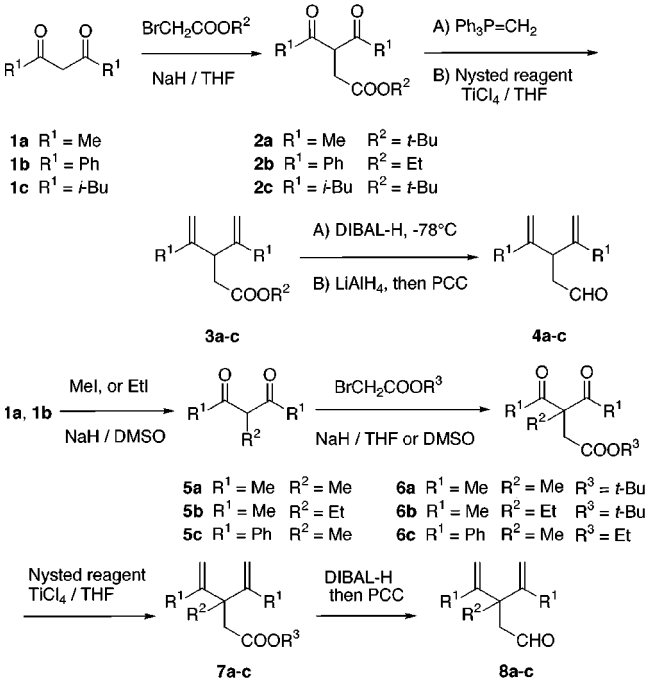
In this paper, we describe the highly diastereo- and enantioselective cyclization of symmetrical 3,4-disubstituted and 3,3,4-trisubstituted 4-pentenals catalyzed by a cationic and/or neutral Rh-complex.

Results

Design and Preparation of Substrates. At first, we designed a 4,5-disubstituted 4-pentenal as a prochiral substrate for diastereo- and enantioselective cyclization.[17] Unfortunately, the Rh-catalyzed cyclization of 4,5-disubstituted 4-pentenal could not proceed at all; therefore, the utilization of two prochiral sp^2-carbons for the diastereo- and enantioselective reaction could not be utilized.

Next, we focused our attention on the symmetry of substrates. Symmetrical 3,4-disubstituted 4-pentenals were designed as prochiral substrates. The concurrent induction of two chiral centers from symmetrical substrates was thought to be effective. Two kinds of stereochemical regulations would be made in the cyclization of symmetrical substrates. One is the diastereoselectivity of the *cis* and *trans* configurations between the substituents at the C(3)- and C(4)-positions of cyclopentanone. This selectivity would be controlled by the selection of the cationic or the neutral Rh-complexes. The other is the enantioselectivity of the products. The absolute stereochemistry of products would be controlled by changing the configuration of chiral ligands between *S* and *R*. This means that all stereoisomers of 3,4-disubstituted cyclopentanones may be prepared stereoselectively starting from one prochiral substrate by the selection of proper Rh-complexes. Furthermore, symmetrical 3,3,4-trisubstituted 4-pentenals were also designed as prochiral substrates because the chiral quaternary carbon at the C(3)-position of cyclopentanones would be easily introduced by using this methodology.

Scheme 2



In this paper, we describe the highly diastereo- and enantioselective cyclization of symmetrical 3,4-disubstituted and 3,3,4-trisubstituted 4-pentenals catalyzed by a cationic and/or neutral Rh-complex.

The 3,4-disubstituted 4-pentenals **4a**−**c** were prepared as shown in Scheme 2. The 1,3-diketones **1a**−**c** were coupled with ethyl or *tert*-butyl bromoacetate by treatment with NaH in THF.[18] Subsequent methylenation of 1,3-dicarbonyl compounds **2a**−**c** by the Wittig or Nysted reagent[19] afforded the diene **3a**−**c** in 46−80% yields. Reduction of the ester function of **3a**−**c** to the aldehyde by DIBAL-H reduction or reduction with $LiAlH_4$, and subsequent PCC oxidation afforded the prochiral 3,4-disubstituted 4-pentenals **4a**−**c** in 42−78% yields.

The 3,3,4-trisubstituted 4-pentenals **8a**−**c** were also prepared from **1a**,**b** as shown in Scheme 2. The 1,3-dicarbonyl compounds **1a**,**b** were alkylated by methyl iodide or ethyl iodide to give 1,3-diketones **5a**−**c**, and these compounds **5a**−**c** were converted into the trisubstituted 4-pentenals **8a**−**c** in a manner similar to that described for the preparation of **4a**−**c**.

Asymmetric Cyclization of the Symmetrical 3,4-Disubstituted 4-Pentenals. The results of cyclization of the symmetrical 3,4-disubstituted 4-pentenals are

(12) Abbreviations: chiraphos: (2*S*,3*S*)-Bis(diphenylphosphino)-butane; BINAP: 2,2′-Bis(diphenylphosphino)-1,1′-binaphthyl; (+)-DIPMC: (1*S*,2*S*)-(+)-1,2-Bis(diphenylphosphinomethyl)cyclohexane; (+)-DIOP: (4*S*,5*S*)-(+)-4,5-Bis(diphenylphosphinomethyl)-2,3-dimethyl-1,3-dioxolane.

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(17) Unpublished results. Cyclization of 4,5-disubstituted 4-pentenals did not proceed at all by Wilkinson-complex.

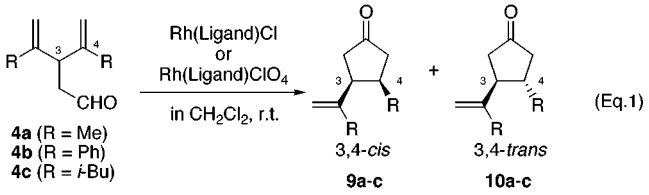
(18) 2,8-Dimethylnonane-4,6-dione **1c** was prepared starting from isobutyraldehyde and 4-methyl-2-pentanone. See Supporting Information.

(19) Nysted reagent is commercially available from Aldrich Co.: Matsubara, S.; Sugihara, M.; Utimoto, K. *Synlett* **1998**, 313−315.

Table 1. Asymmetric Cyclization of the Symmetrical 3,4-Disubstituted 4-Pentenals

entry	substrate	Rh-complex	(equiv)[a]	reaction time (h)	isolated yield (%)	*cis*/*trans*	opt. purity of major product (% ee)	abs config
1	**4a**	$Rh(PPh_3)_3Cl$	0.3	2	67	98/2	–	–
2	**4a**	Rh[(*R*)-BINAP]Cl	0.5	72	25	97/3	>95	3*S*,4*R*
3	**4a**	Rh[(*S*)-BINAP]Cl	0.5	72	31	97/3	>95	3*R*,4*S*
4	**4a**	Rh[(+)-DIPMC]Cl	0.5	1	74	73/27	36	3*S*,4*R*
5	**4a**	Rh[(+)-DIOP]Cl	0.5	1	71	71/29	74	3*S*,4*R*
6	**4a**	Rh[(*R*)-BINAP]ClO_4	0.05	1	81	3/97	>95	3*S*,4*S*
7	**4a**	Rh[(*S*)-BINAP]ClO_4	0.05	1	84	4/96	>95	3*R*,4*R*
8	**4b**	$Rh(PPh_3)_3Cl$	0.5	2	95	>99/0	–	–
9	**4b**	Rh[(*R*)-BINAP]Cl	0.5	72	25	>99/0	>95	3*S*,4*R*
10	**4b**	Rh[(*S*)-BINAP]Cl	0.5	72	30	>99/0	>95	3*R*,4*S*
11	**4b**	Rh[(*R*)-BINAP]ClO_4	0.05	2	70	18/82	>95	3*S*,4*S*
12	**4b**	Rh[(*S*)-BINAP]ClO_4	0.05	2	76	17/83	>95	3*R*,4*R*
13	**4c**	$Rh(PPh_3)_3Cl$	0.5	2	67	98/2	–	–
14	**4c**	Rh[(*S*)-BINAP]Cl	0.5	72	0	–	–	–
15	**4c**	Rh[(*R*)-BINAP]ClO_4	0.05	3	74	2/98	>95	3*S*,4*S*
16	**4c**	Rh[(*S*)-BINAP]ClO_4	0.05	4	77	2/98	>95	3*R*,4*R*

[a] In the cyclizations by the neutral Rh-complexes, more than 0.3 equiv of Rh-complexes and long reaction time were required because of their low catalytic activities and decarbonylation side reaction. In the cyclizations by the cationic Rh[BINAP]ClO_4, only 0.05 equiv of Rh-complexes and short reaction time were required.[2,16,21]



(Eq.1)

summarized in Table 1 and eq 1. The cyclization of **4a** by an achiral $Rh(PPh_3)_3Cl$ afforded *cis*-3,4-disubstituted cyclopentanone **9a**, predominantly. The ratio of *cis*-**9a** and *trans*-**10a** was calculated based on the integral of methyl proton signals in the ^1H NMR spectrum. The ratio of products by $Rh(PPh_3)_3Cl$ was 98 (*cis*) to 2 (*trans*). The relative stereochemistry of products was determined by the ^1H NMR spectra. The methyl proton signal of the major product **9a** was observed at δ 0.82 (d, $J = 7.3$ Hz, 3H); on the other hand, the signal of the minor product **10a** appeared at δ 1.08 (d, $J = 6.3$ Hz, 3H) in the ^1H NMR spectrum. As we previously reported,[20] the chemical shift of the methyl proton of 3,4-*cis*-3-alkyl-4-methylcyclopentanone was observed at higher field than that of 3,4-*trans*-3-alkyl-4-methylcyclopentanone because of the deshielding effect of the C(3)-alkyl group. This stereoselectivity was consistent with our previous results using 4-pentenals derived from limonene.[10] The asymmetric cyclization by the neutral Rh-complex with BINAP afforded the optically active cyclopentanones in the ratio of 97 (*cis*) to 3 (*trans*). The chemical yield was not satisfactory (25−31%) because of the decarbonylation side reaction. Fortunately, the enantiomeric excess of the major product *cis*-**9a** by Rh[BINAP]Cl was very high (>95% ee). The cyclization by the neutral Rh[(*R*)-BINAP]-Cl afforded the (4*R*)-cyclopentanone, and the cyclization by Rh[(*S*)-BINAP]Cl afforded the (4*S*)-cyclopentanone. The enantiomeric excesses of the cyclopentanones were determined by ^1H NMR and/or ^{13}C NMR spectra, after acetalization of the ketone with (2*R*,3*R*)-butanediol using TsOH in refluxing benzene. The cyclization by the neutral Rh-complex with (+)-DIPMC or (+)-DIOP afforded **9a** and **10a** in moderate yields. Neither the diastereoselectivities of *cis*-**9a** and *trans*-**10a**, nor the enantioselectivities of the major *cis*-**9a** cyclized by the Rh-complex with (+)-DIPMC or (+)-DIOP were good. The cyclization by the cationic Rh(BINAP)ClO_4 proceeded to afford the *trans*-**10a** in good yields (81−84%). The reaction required only 5% molar of the Rh-catalyst.[2,16,21] The ratio of *cis*- and *trans*-stereoselectivity was 4 (*cis*) to 96 (*trans*), and the enantiomeric excess of the major *trans*-**10a** was >95% ee. The absolute stereochemistry at the C(4)-position of the cyclopentanone by the cationic Rh-complex was opposite to that by the neutral Rh-complex, that is to say the cyclization by Rh[(*R*)-BINAP]ClO_4 afforded the (4*S*)-cyclopentanone (+)-**10a**, and the cyclization by Rh[(*S*)-BINAP]ClO_4 afforded the (4*R*)-cyclopentanone (−)-**10a**. Cyclization by the cationic Rh-complex with (+)-DIPMC or (+)-DIOP did not proceed at all.

The absolute configuration of products was first assumed based on our previous report, in which the cyclization of 4-pentenals by the neutral Rh[(*R*)-BINAP]Cl affords (4*R*)-cyclopentanones and by the neutral Rh[(*S*)-BINAP]Cl affords (4*S*)-cyclopentanones, while the cyclization by the cationic Rh[(*R*)-BINAP]ClO_4 generates (4*S*)-cyclopentanones and that by the cationic Rh[(*S*)-BINAP]ClO_4 generates (4*R*)-cyclopentanones, regardless of the C(3)-configuration.[2,15a] Finally, the relative and absolute stereochemistry of (+)-**10a** was unambiguously confirmed by the chemical correlation with *d*-limonene, as shown in Scheme 3. Cyclopentanone **11** prepared from *d*-limonene by the known route[10a] was converted to the ketoacetal **12**, by protection of the carbonyl function as ethylene acetal and subsequent oxidation of the secondary alcohol with PDC in 68% overall yields. The ketone **12** was converted into alcohol **13** by a three-step sequence: [(i) $(TMS)_2NH$, TMSI; (ii) O_3; (iii) $NaBH_4$] in 63% yield.[22] Iodination of **13** by I_2, Ph_3P, and pyridine followed by dehydroiodination with $Ni(PPh_3)_2Cl_2$ gave an olefin **14** in 45% yield.[23] Oxidation of the olefin function in **14** by treatment with $Pd(OAc)_2$ and 30% H_2O_2 proceeded to give the diketone **15** in 22% yield, accompanied with deprotection of the acetal function. Epimerization of the acetyl function at the C(3)-position of cyclopentanone by treatment with NaOMe in MeOH afforded the *trans*-3,4-disubstituted cyclopentanone **16** in 67% yield. The rela-

(20) Inoue, K.; Ide, J.; Sakai, K. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 2361−2365.

(21) The amount of Rh-catalyst could be reduced to less than 1.0%, but here we used 5% molar of Rh-complex for the reproducibility.

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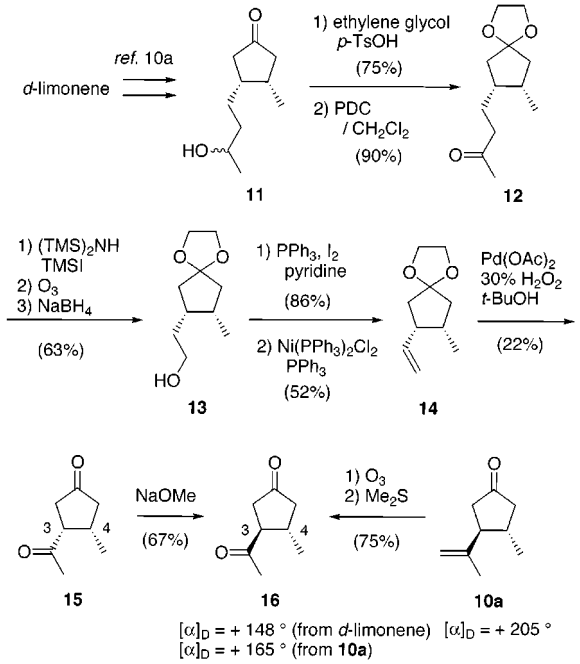
(23) Henningsen, M. C.; Jeropoulos, S.; Smith, E. H. *J. Org. Chem.* **1989**, *54*, 3015−3018.

Scheme 3. Determination of the Stereochemistry of Cyclopentanone 10a

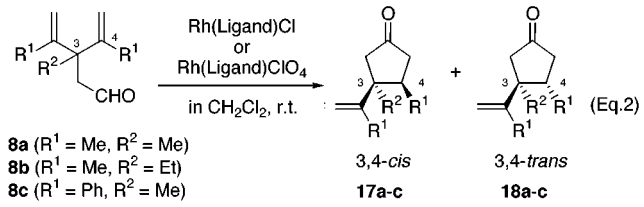


tive stereochemistry of compounds **15** and **16** was confirmed by the NOESY $^1H-^1H$ NMR spectra. In the *cis*-**15**, NOEs were observed between the methyl proton signals δ 2.24 (s, 3H) at the acetyl function and the methyl proton signals δ 0.96 (d, J = 7.1 Hz, 3H) at the C(4)-position. On the other hand, in the ^1H NMR spectrum of *trans*-**16**, NOEs were observed between the methine proton signal δ 2.88 (q, J = 8.0 Hz, 1H) at the C(3)-position and the methyl proton signals δ 1.19 (d, J = 6.4 Hz, 3H) at the C(4)-position. The specific rotation of **16** showed + 148°. The cyclopentanone (+)-**10a** cyclized by Rh[(*R*)-BINAP]ClO_4, was also converted to the diketone **16** by ozonolysis of the olefin in 75% yield. The specific rotation of this material showed +165°. By comparison of the specific rotation, the absolute configuration of (+)-**10a** produced by Rh[(*R*)-BINAP]ClO_4, could be determined to be 3*S*,4*S*, which is consistent with the empirical rule. In the ^{13}C NMR spectra of (*R*,*R*)-butanediol acetals, the signals of the (*R*,*R*)-acetal derived from (3*S*,4*R*)-(+)-**9a** appeared at upper field than those of (3*R*,4*S*)-(−)-**9a** in the region of δ 15.0−25.0 (methyl carbon signals), and the signals of (3*S*,4*S*)-(+)-**10a** derivative also appeared at upper field than those of (3*R*,4*R*)-(−)-**10a** derivative in the region of δ 15.0−20.0 (methyl carbon signals).

The cyclization of **4b** by the achiral $Rh(PPh_3)_3Cl$ afforded the *cis*-3,4-disubstituted product **9b** in 95% yield, exclusively. The asymmetric cyclization by the neutral Rh[(*R*)-BINAP]Cl afforded the (3*S*,4*R*)-3,4-disubstituted cyclopentanone (+)-**9b** of >95% ee in 25% yield, and the cyclization by Rh[(*S*)-BINAP]Cl afforded (3*R*,4*S*)-(−)-**9b** of >95% ee in 30% yield. The chemical yield was not satisfactory, but the stereoselectivity was very high and no stereoisomer, neither an enantiomer nor a diastereomer, was detected. The relative stereochemistry of **9b** was determined to be 3,4-*cis* by the NOESY $^1H-^1H$ NMR spectra. NOEs were observed between the methine proton signal δ 3.93 (m, 1H) at the C(3)-position and the methine proton signal δ 3.76 (br q, J = 6.2 Hz, 1H) at the C(4)-position. Furthermore, the ^1H NMR spectra of 3-isopropenyl-4-substituted cyclopentanones indicated that the geminal olefinic proton signals of 3,4-*cis*-products appeared at a very different region of the chemical shift (Δ δ 0.20−0.40); on the other hand, those of 3,4-*trans*-products appeared at a narrow region of the chemical shift (Δ δ 0.05). This empirical rule of ^1H NMR spectra also supported the relative stereochemistry of product **9b**. The cyclization of **4b** by the cationic Rh[(*R*)-BINAP]ClO_4 gave **9b** and **10b** in the ratio of 18 (*cis*) to 82 (*trans*), and the enantiomeric excess of the major product *trans*-(+)-**10b** was determined to be >95% ee. The absolute stereochemistry of major product *trans*-(+)-**10b** was assumed to be 3*S*,4*S*, based on the chemical shift pattern of ^{13}C NMR of the acetals derived from (*R*,*R*)-butanediol.

The cyclization of **4c** by $Rh(PPh_3)_3Cl$ afforded the product **9c** and **10c** in the ratio of 98 (*cis*) to 2 (*trans*) in 67% yield; however, cyclization by the neutral Rh[(*S*)-BINAP]Cl did not proceed at all. The cyclization by the cationic Rh[(*R*)-BINAP]ClO_4 afforded the cyclopentanone **9c** and **10c** in the ratio of 2 (*cis*) to 98 (*trans*). The enantiomeric excess of the major *trans*-**10c** was determined to be >95% ee. The cyclization of **4c** by the cationic Rh[(*R*)-BINAP]ClO_4 afforded (3*S*,4*S*)-(−)-cyclopentanone of >95% ee and the cyclization by Rh[(*S*)-BINAP]ClO_4 afforded (3*R*,4*R*)-(+)-cyclopentanone of >95% ee. The absolute configuration was assumed based on the signal pattern of the ^{13}C NMR spectra of the corresponding (*R*,*R*)-butanediol acetals.

Asymmetric Cyclization of the Symmetrical 3,3,4-Trisubstituted 4-Pentenals.[24] The results of cyclization of the symmetrical 3,3,4-trisubstituted 4-pentenals with a prochiral quaternary carbon are summarized in Table 2 and eq 2. The cyclization of **8a** by the achiral $Rh(PPh_3)_3$-



Cl gave the 3,3,4-trisubstituted cyclopentanones bearing a chiral quaternary carbon in 70% yield. The ratio of **17a** and **18a** was 97 (*cis*) and 3 (*trans*). The relative stereochemistry of products **17a** and **18a** was determined by the NOESY $^1H-^1H$ NMR spectra. NOEs were observed between the methyl proton signal δ 1.78 (s, 3H) of the isopropenyl function at the C(3)-position and the methyl proton signal δ 0.88 (d, J = 6.9 Hz, 3H) at the C(4)-position in *cis*-**17a**, and NOEs were shown between the methyl proton signal δ 1.05 (s, 3H) at the C(3)-position and the methyl proton signal δ 0.99 (d, J = 6.6 Hz, 3H) at the C(4)-position in *trans*-**18a**. In addition, the aforementioned empirical rule, based on the difference in chemical shifts between the geminal olefinic protons of the isopropenyl function, was also applicable in these cases. That is to say, the region of the chemical shift (Δ δ value) of **17a** was 0.18 ppm and that of **18a** was 0.05 ppm. This rule also supported the relative stereochemistry of the product **17a** as *cis* and **18a** as *trans*. The asymmetric cyclization of **8a** by the neutral Rh[(*R*)-BINAP]Cl afforded *cis*-**17a** and *trans*-**18a** in the ratio of

(24) Corey, E. J.; Guzman-Perez, A. *Angew. Chem., Int. Ed.* **1998**, *37*, 388−401.

Table 2. Asymmetric Cyclization of the Symmetrical 3,3,4-Trisubstituted 4-Pentenals

entry	substrate	Rh-complex	(equiv)	reaction time (h)	isolated yield (%)	*cis*/*trans*	opt. purity of major product (% ee)	abs config[a]
1	**8a**	$Rh(PPh_3)_3Cl$	0.5	48	70	97/3	–	–
2	**8a**	Rh[(*R*)-BINAP]Cl	0.5	72	5	95/5	88	3*S*,4*R*
3	**8a**	Rh[(*S*)-BINAP]Cl	0.5	72	5	95/5	88	3*R*,4*S*
4	**8a**	Rh[(*R*)-BINAP]ClO_4	0.05	0.5	83	2/98	>95	3*S*,4*S*
5	**8a**	Rh[(*S*)-BINAP]ClO_4	0.05	0.5	75	2/98	>95	3*R*,4*R*
6	**8b**	$Rh(PPh_3)_3Cl$	0.5	48	74	94/6	–	–
7	**8b**	Rh[(*S*)-BINAP]Cl	0.5	72	0	–	–	–
8	**8b**	Rh[(*R*)-BINAP]ClO_4	0.05	3	75	3/97	92	3*S*,4*S*
9	**8b**	Rh[(*S*)-BINAP]ClO_4	0.05	3	82	3/97	92	3*R*,4*R*
10	**8c**	$Rh(PPh_3)_3Cl$	0.5	24	95	99/0	–	–
11	**8c**	Rh[(*S*)-BINAP]Cl	0.5	72	0	–	–	–
12	**8c**	Rh[(*R*)-BINAP]ClO_4	0.1	48	80	21/79	>95[b]	3*S*,4*S*
13	**8c**	Rh[(*S*)-BINAP]ClO_4	0.1	48	80	21/79	>95	3*R*,4*R*

[a] Absolute configurations of products were assumed based on the signal pattern of ^{13}C NMR of the corresponding (*R*,*R*)-2,3-butandiol acetals. [b] Enantiomeric excess and absolute configuration of major *trans*-**18c**.

95 (*cis*) to 5 (*trans*). However, the yield was not satisfactory even in the case of using 50% molar of the Rh-catalyst. The low yield would be attributable to the steric hindrance between the methyl substituent at the C(3)-position and the bulky BINAP ligand in the Rh-complex, and to the competitive decarbonylation reaction. The enantiomeric excess of major *cis*-(+)-**17a** was determined to be 88% ee by the ^1H NMR and ^{13}C NMR spectra of the corresponding (*R*,*R*)-butanediol acetals. The cyclization by Rh[(*S*)-BINAP]Cl afforded the enantiomer (−)-**17a**. Fortunately, the cyclization of **8a** by using 5% molar of cationic Rh[(*R*)-BINAP]ClO_4 afforded cyclopentanone **17a** and **18a** in the ratio of 2 (*cis*) to 98 (*trans*) in 75−83% yield, and the enantiomeric excess of the major *trans*-(+)-**18a** was determined to be >95% ee. The cyclization by Rh[(*S*)-BINAP]ClO_4 also afforded the enantiomer (−)-**18a** of >95% ee. The cyclization of **8b** bearing an ethyl substituent gave similar results to those of **8a** bearing a methyl substituent with the exception that the cyclization by the neutral Rh[(*S*)-BINAP]Cl did not proceed at all. The enantiomeric excess of **18b** obtained by Rh[(*R*)- or (*S*)-BINAP]ClO_4 was 92% ee. The cyclization of **8c** bearing two phenyl substituents at the C(4)-positions by $Rh(PPh_3)_3Cl$ gave *cis*-3,3,4-trisubstituted cyclopentanone **17c** bearing a quaternary carbon in good yield as the sole product, and *trans*-**18c** was not detected at all. The cyclization of **8c** by the neutral Rh[(*S*)-BINAP]Cl did not proceed, but the cyclization by the cationic Rh[(*R*)-BINAP]ClO_4 proceeded to afford *cis*-**17c** and *trans*-**18c** in the ratio of 21 (*cis*) to 79 (*trans*) in 80% yield. The diastereoselectivities of products were not good, and this low diastereoselectivity would be attributed to the phenyl substituents. This result was similar to that of the cyclization of **4b** by the cationic Rh[(*R*)-BINAP]ClO_4 which also showed low selectivity. The enantiomeric excess of the major *trans*-**18c** was determined to be >95% ee based on the ^1H NMR and ^{13}C NMR spectra of (*R*,*R*)-butanediol acetals.

The absolute configuration of products was assumed based on the ^{13}C NMR chemical shift pattern of the corresponding (*R*,*R*)-butanediol acetals. In the ^{13}C NMR spectra of (*R*,*R*)-butanediol acetals derived from cyclopentanones **9a**,**b** and **10a**,**b**, the ^{13}C NMR signals in δ 15.0−30.0 region (methyl carbon signals) of (3*S*,4*R*)-cyclopentanones generally appeared at upper field than those of 3*R*,4*S* enantiomers, and also the ^{13}C NMR signals in δ 15.0−30.0 region of (3*S*,4*S*)-cyclopentanones appeared at upper field than those of 3*R*,4*R* enantiomers. On the basis of these patterns, the absolute configuration of (+)-**17a** by the neutral Rh[(*R*)-BINAP]Cl was assumed to be 3*S*,4*R*, and those of **18a**−**c** by the cationic Rh[(*R*)-BINAP]ClO_4 to be 3*S*,4*S* configuration.

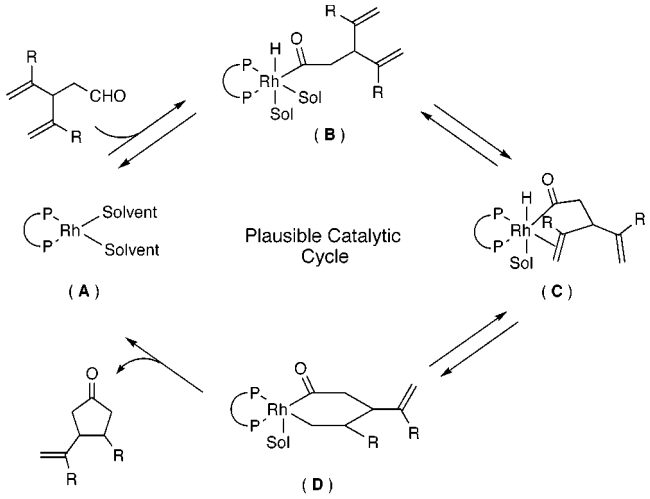


Figure 1.

Discussion

The mechanisms of cyclization were reported by several groups,[7,8,15,16] and the major catalytic cycle was proposed to be an intramolecular hydroacylation as follows: (i) the oxidative addition of the aldehyde to the rhodium atom to afford the acylrhodium hydride intermediate **B**, (ii) the coordination of a double bond to the rhodium **C**, (iii) the formation of the six-membered ring metallocycle **D** by the migration of hydride to the double bond, and (iv) the reductive elimination to give the cyclopentanone and Rh-complex **A**. These processes could be reversible, except for the last step of the reductive elimination of cyclopentanone. These mechanisms were first supported by deuterium experiment, in which the deuterium of deuterium aldehyde was transferred to the β-position of cyclopentanone (Figure 1).

However, besides the above major catalytic cycle, an unusual complex and the numerous intermediates in this cyclization reaction were revealed by Bosnich's deuterium scrambling experiments.[16c,d] His group also reported that the enantioselectivity would depend on the relative rates of formation of the diastereomeric six-membered metallocyclic intermediates and on their rates of reductive elimination to the cyclopentanone, in the case of 3-phen-

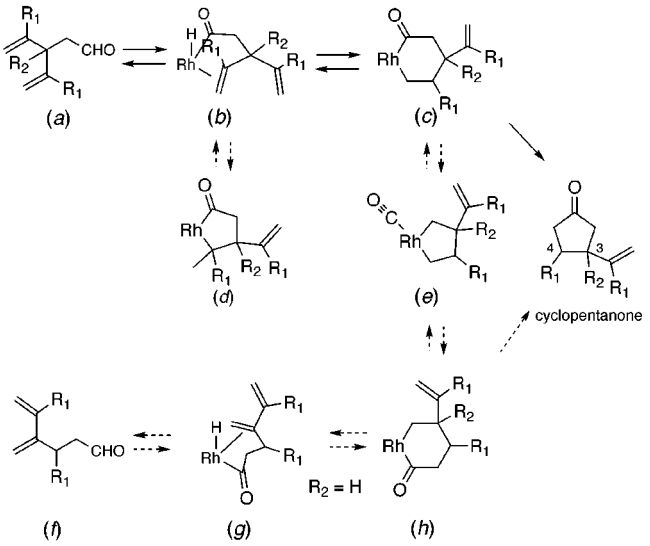


Figure 2.

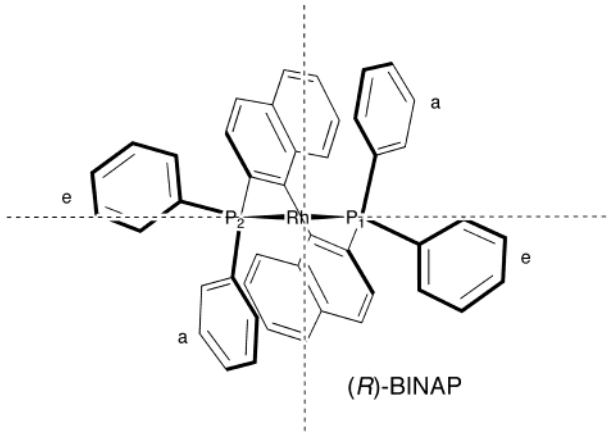


Figure 3.

yl-4-pentenal,[16c] and that there might be no single enantioselective step. Therefore, the enantiomeric excess would be controlled by a complex mix of rates.[16f] Contrary to Bosnich's results, the reaction of the symmetrical 4-pentenals **4** and **8** with the Rh-complex did not afford the dienes (*f*) at all. It is natural that the dienes (*f*) would not be isolated by reaction of 3,3,4-trisubstituted 4-pentenals **8a**−**c** with the Rh-complex, due to the fact that the *β*-elimination of rhodium hydride from intermediate (*h*) could not take place. In the case of reaction using 3,4-disubstituted 4-pentenals **4a**−**c** with the Rh-complex, the steric hindrance of substituents in intermediate (*c*) probably prevents the formation of intermediate (*e*). Therefore, we considered that the migration processes of the carbonyl function (*e*,*f*) would be negligible in the symmetrical substrates **4** and **8**, and the enantioselectivity would be determined by the relative rates of formation of the diastereomeric metallocycles (*c*) and by their rates of reductive elimination to give the cyclopentanones. The cyclization of deuterium aldehyde of **4b** by the cationic Rh[(*S*)-BINAP]ClO_4 exclusively afforded the 4-deuterium cyclopentanone **10b**, and no deuterium scrambling was observed.[25] This deuterium experiment also suggested that the formation of five-membered matallocycle (*d*) did not proceed because of the steric hindrance of substituents. Consequently, the absolute and relative stereochemistry of products could be expected by considering the putative intermediate (**C** or *b*), even though the actual enantioselective step is unclear.

To explain the stereochemical outcome of products, we assumed that the hydride would locate *cis* to the BINAP ligand in the intermediate **C**. On this assumption, the carbon−carbon double bond would coordinate rhodium with *cis* to the hydride ligand for the occurrence of hydride−olefin insertion, and the carbon atom at the C(4)-position of pentenal would locate *syn* to the hydride for the formation of six-membered metallocycle. In the (*R*)-BINAP ligand, two axial phenyl groups (edge) relative to the rhodium−phosphorus plane construct the hindered regions at the *β*-side of P_1 and α-side of P_2, and these hindered regions would strongly affect the stereoselection. Two equatorial phenyl groups (face) may form the hindered regions at the horizontal side of P_1 and P_2, and these regions would exert only minimal effect on the stereoselection (Figure 3).[16a,f,26,27] As a consequence, the four plausible diastereomeric intermediates [i−iv] could be considered as precursors to produce the cyclopentanones. All intermediates in Figure 4 could be mutually interchangeable, but are not at equilibrium. Among the putative intermediates [i−iv], the intermediate [iv] seems to be the most unfavorable because two steric repulsions exist between the R_1-substituent and Rh−H, moreover, between the R_1-substituent and a phenyl group of the *β*-side of P_1. Even though in the case that the R_2-substituent at the C(3)-position is an ethyl group of **8b**, the ethyl group would be smaller than the other substituent (isopropenyl) at the C(3)-position. These factors may destabilize the intermediate [iv], and this [iv] could be regarded as the most unstable diastereomer of the intermediates [i−iv]. In contrast to intermediate [iv], the intermediate [i] seems to be the most favorable because no steric repulsion between the Rh-complex and 4-pentenal is observed. There is one steric repulsion between the R_1-substituent and the phenyl group of the *β*-side of P_1 in the intermediate [iii], and between the R_1-substituent and Rh−H in the intermediate [ii], respectively. The cyclization by the neutral Rh[(*R*)-BINAP]Cl would proceed via the most stable intermediate [i], in which no unfavorable steric factors were observed, to produce (3*S*,4*R*)-*cis*-cyclopentanones. That is to say, the thermodynamically preferred major intermediate [i] would afford the prevailing enantiomer in the case of the neutral Rh-complex. On the other hand, the cyclization by the cationic Rh[(*R*)-BINAP]ClO_4 would proceed via the least stable intermediate [iv], in which two sterically unfavorable factors were observed, to give (3*S*,4*S*)-*trans*-cyclopentanones. The rate of reductive elimination might govern the enantioselectivity in the case of a cationic Rh-complex, that is to say, the rate of reductive elimination from intermediate [iv] is faster than that of other diastereomers. This kind of phenomenon has already been reported in the case of the enantioselective hydrogenation of amino acid precursors with a cationic Rh-catalyst, in which the minor diastereomer of intermediate is more reactive.[28]

(25) The deuterium aldehyde of **4b** was prepared from **3b** by $LiAlD_4$ reduction and PCC oxidation. The cyclization of deuterium aldehyde **4b** by Rh[(*S*)-BINAP]ClO_4 exclusively afforded the 4-deuterium cyclopentanone, in which the signals of *δ* 3.76 (br q, J = 6.2 Hz, 0.17H) and 3.45 (m, 0.83H) observed in the ^{1}H NMR spectrum of the mixture of **9b** (17) and **10b** (83), disappeared completely.

(26) Miyashita, A.; Takaya, H.; Souchi, T.; Noyori, R. *Tetrahedron*, **1984**, *40*, 1245−1253.

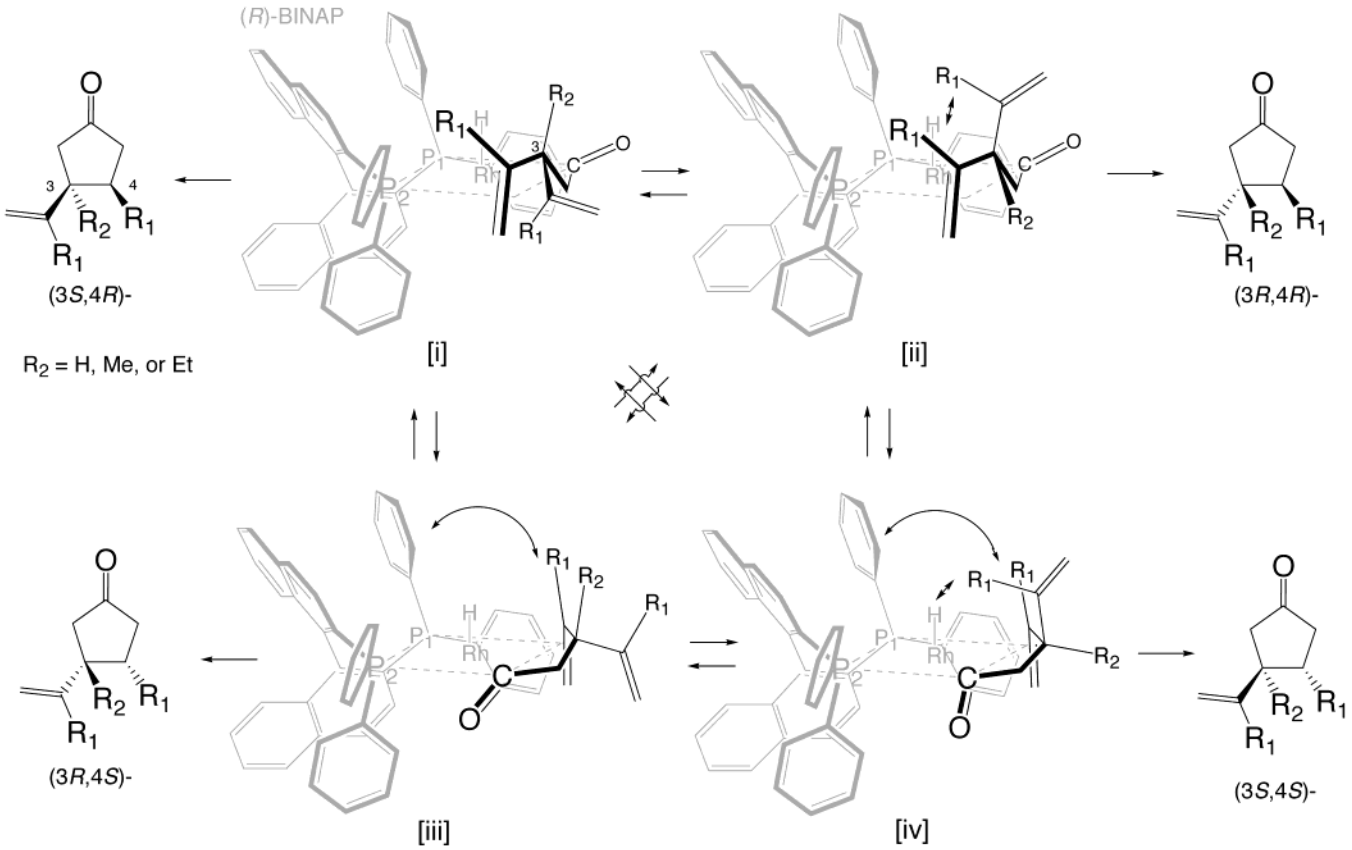


Figure 4. Plausible mechanism for stereoselectivity.

By use of the neutral Rh[(*R*)-BINAP]Cl, cyclization of **8** bearing a quaternary carbon did not proceed at all, or proceeded in very low yields. In these cases, the formation of the intermediate (*b*) may be difficult due to the steric repulsion between the quaternary carbon and the Rh-complex, and the catalyst is less reactive than the cationic Rh-complex. In the case of 4-pentenals **4b** and **8c** bearing phenyl groups, the ratios of *cis*- and *trans*-products cyclized by the cationic Rh[(*R*)-BINAP]ClO_4 were not good, although the enantiomeric excesses were excellent. These low diastereoselectivities may be attributable to stacking of the phenyl group of 4-pentenal with the phenyl group in BINAP, or the interacting Rh atom with the phenyl group of 4-pentenal through π-arene coordination,[26,29] and therefore the rate of reductive elimination and the steric repulsions in the intermediates may be affected.

Conclusion

Cyclization of the symmetrical 3,4-disubstituted 4-pentenals by a Rh-complex afforded the chiral 3,4-disubstituted cyclopentanones (**9a**−**c** and **10a**−**c**) in excellent stereoselectivities. The concurrent induction of two chiral centers could be made, and all four stereoisomers of the cyclopentanones could be stereoselectively prepared as we wished by the selection of a cationic or neutral Rh-complex, and (*R*)- or (*S*)-BINAP. The cyclization could proceed at room temperature, and in the case of the cationic Rh-complex, only 5% molar amount of catalyst was required. The cyclization of the symmetrical 3,3,4-trisubstituted 4-pentenals by the Rh-complex afforded the chiral cyclopentanones (**17a** and **18a**−**c**) bearing a quaternary carbon. Although the cyclization by the neutral Rh[(*R*)-BINAP]Cl was not satisfactory, the cyclization by the cationic Rh[(*R*)-BINAP]ClO_4 proceeded to give *trans*-cyclopentanones bearing a chiral quaternary carbon in excellent enantiomeric excess. The strategy using the symmetrical dienes for the Rh-catalyzed cyclization would be a useful and effective method to construct various optically active cyclopentanones and chiral quaternary carbons.[24]

Experimental Section

Preparation of Substrates.

***tert*-Butyl 3-Acetyl-4-oxopentanoate (2a).** A solution of acetylacetone (10.67 g, 107 mmol) in THF (20 mL) was added to the stirred suspension of NaH (5.13 g, 60%, 128 mmol), which was washed with small amount of hexane, in THF (150 mL) at 0 °C. The mixture was stirred at 0 °C for 1 h, and then *tert*-butyl bromoacetate (23.0 g, 118 mmol) in THF (50 mL) was added dropwisely. After being stirred at room-temperature overnight, the solution was diluted with saturated aqueous NH_4Cl and extracted with ether. The ethereal extract was washed with brine and dried over $MgSO_4$. Removal of the solvent afforded an oily residue, which was purified by column chromatography on silica gel (30% EtOAc in hexane) to give **2a** (14.84 g, 65%) as a colorless oil: IR (neat) 1735, 1720, 1705, 1600 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.07 (t, J = 7.3 Hz, 0.6H), 3.22−3.12 (m, 1.2H), 2.81 (d, J = 7.3 Hz, 1.2H), 2.25 (s, 3H), 2.16 (s, 3H), 1.45, 1.43 (each s, total-9H); EIMS *m*/*z* 214 (M^+); HRMS calcd for $C_{11}H_{18}O_4$ (M^+) 214.1205, found 214.1201.

(27) We thought that the axial phenyl groups formed the hindered regions, but Bosnich et al. thought that the equatorial phenyl groups formed the hindered regions.

(28) Morrison, J. D. *Asymmetric Synthesis*; Academic Press: New York, **1985**; Vol. 5, pp 46−66.

(29) Singewald, E. T.; Slone, C. S.; Stern, C. L.; Mirkin, C. A.; Yap, G. P. A.; Liable-Sands, L. M.; Rheingold, A. L. *J. Am. Chem. Soc.* **1997**, *119*, 3048−3056.

Ethyl 4-Oxo-4-phenyl-3-(phenylcarbonyl)butanoate (2b). Compound **2b** was prepared from dibenzoylmethane in a manner similar to that described for the preparation of **2a**; 46% yield; colorless crystals: mp 83.5−85.0 °C (recryst from hexane); IR (KBr) 1725, 1690, 1670, 1600 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 7.96−8.00 (m, 4H), 7.42−7.61 (m, 6H), 5.80 (t, J = 6.9 Hz, 1H), 4.15 (q, J = 7.2 Hz, 2H), 3.10 (d, J = 6.9 Hz, 2H), 1.24 (t, J = 7.2 Hz, 3H). Anal. Calcd for $C_{19}H_{18}O_4$: C, 73.53; H, 5.85 Found: C, 73.60; H, 5.87.

***tert*-Butyl 6-Methyl-3-(3-methylbutanoyl)-4-oxoheptanoate (2c).** A solution of **1c** (6.00 g, 32.6 mmol) in DMSO (20 mL) was added to the stirred mixture of *t*-BuOK (3.66 g, 32.6 mmol) in DMSO (120 mL) at 0 °C. The whole was stirred for 5 min, and then a solution of *tert*-butyl bromoacetate (6.36 g, 32.6 mmol) in DMSO (14 mL) was added dropwise to the stirred mixture. After being stirred for 2 days, the solution was diluted with brine, extracted with ether, and then dried over $MgSO_4$. Removal of the solvent in vacuo gave an oily residue, which was purified by column chromatography on silica gel. The fraction eluted with 2% EtOAc in hexane afforded **2c** (2.92 g, 30%) as a pale yellowish oil: IR (neat) 3440, 1725, 1705, 1370, 1260, 1160 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.03 (t, J = 7.0 Hz, 0.5H), 3.16−3.18 (m, 1.5H), 2.76 (d, J = 7.0 Hz, 1H), 2.28−2.41 (m, 4H), 2.13 (m, 2H), 1.41−1.48 (m, 9H), 0.84−0.97 (m, 12H); EIMS m/z 298 (M^+); HRMS calcd for $C_{17}H_{30}O_4$ (M^+) 298.2144, found 298.2140.

***tert*-Butyl 3-Isopropenyl-4-methylpent-4-enoate (3a).** A mixture of methyltriphenylphosphonium bromide (21.5 g, 60 mmol) and *t*-BuOK (6.72 g, 60 mmol) in benzene (300 mL) was refluxed for 1 h. Then, a solution of diketone **2a** (4.28 g, 20 mmol) in benzene (30 mL) was added to the mixture at room temperature, and then the whole was refluxed for 3 h. After being cooled to room temperature, the mixture was diluted with saturated aqueous NH_4Cl and extracted with ether. The extract was washed with brine and dried over $MgSO_4$. Removal of the solvent in vacuo gave an oily residue, which was purified by column chromatography on silica gel. The fraction eluted with 5% ether in hexane afforded **3a** (3.37 g, 80%) as a colorless oil: IR (neat) 1730, 1640 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.86 (m, 2H), 4.77 (m, 2H), 3.13 (t, J = 7.8 Hz, 1H), 2.46 (d, J = 7.8 Hz, 2H), 1.65 (br s, 6H), 1.42 (s, 9H); EIMS m/z 210 (M^+); HRMS calcd for $C_{13}H_{22}O_2$ (M^+) 210.1620 found 210.1610.

Ethyl 4-Phenyl-3-(1-phenylvinyl)pent-4-enoate (3b). A solution of **2b** (4.1 g, 14 mmol) in THF (70 mL) was added dropwise to the vigorous stirred suspension of Nysted reagent (20% suspension in THF, 83.3 g) in THF (50 mL) at − 78 °C and stirred for 15 min. Then, $TiCl_4$ (3.13 mL, 28 mmol) was added dropwise to the stirred mixture at − 78 °C, and then the whole was warmed to room temperature and stirred for 30 min. The mixture was diluted with water and extracted with EtOAc. The extract was washed with 5% aqueous $NaHCO_3$ and brine and dried over $MgSO_4$. After removal of the solvent, the oily residue was purified by column chromatography on silica gel (5% EtOAc in hexane) to give **3b** (1.86 g, 46%) as a colorless oil: IR (neat) 1730, 1625, 1600, 1150 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 7.27−7.44 (m, 10H), 5.37 (s, 2H), 5.20 (s, 2H), 4.40 (t, J = 7.6 Hz, 1H), 4.06 (q, J = 7.0 Hz, 2H), 2.68 (d, J = 7.6 Hz, 2H), 1.18 (t, J = 7.0 Hz, 3H); FAB(+)HRMS calcd for $C_{21}H_{23}O_2$ (M^+ + 1) 307.1698, found 307.1701.

***tert*-Butyl 4-(2-Methylpropyl)-3-[1-(2-methylpropyl)vinyl]pent-4-enoate (3c).** Compound **3c** was prepared from **2c** in a manner similar to that described for the preparation of **3a**; 57% yield; colorless oil: IR (neat) 1735, 1640, 1370, 1150 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.88 (s, 2H), 4.83 (s, 2H), 3.14 (t, J = 8.0 Hz, t), 2.43 (d, J = 8.0 Hz, 2H), 1.70−1.95 (m, 6H), 1.42 (s, 9H), 0.85−0.91 (m, 12H); EIMS m/z 294 (M^+); HRMS calcd for $C_{19}H_{34}O_2$ (M^+) 294.2559, found 294.2565.

3-Isopropenyl-4-methylpent-4-enal (4a). DIBAL-H (10.8 mL, 10 mmol, 0.93 M in hexane) was added dropwise to the stirred solution of **3a** (2.10 g, 10 mmol) in CH_2Cl_2 at − 78 °C, and the solution was stirred for 1 h. The reaction was quenched with MeOH (3 mL), and the mixture was diluted with 1N HCl (50 mL). The solution was extracted with CH_2Cl_2, washed with brine, and dried over $MgSO_4$. After removal of the solvent, the residue was purified by column chromatography on silica gel (3% ether in pentane) to give **4a** (842 mg, 61%) as a colorless oil: IR (neat) 1730, 1640 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 9.67 (t, J = 2.3 Hz, 1H), 4.91 (br s, 2H), 4.79 (br s, 2H), 3.25 (t, J = 7.6 Hz, 1H), 2.62 (dd, J = 2.3, 7.6 Hz, 2H), 1.66 (s, 6H); EIMS m/z 138 (M^+); HRMS calcd for $C_9H_{14}O_1$ (M^+) 138.1045, found 138.1043.

4-Phenyl-3-(1-phenylvinyl)pent-4-enal (4b). Compound **4b** was prepared from **3b** in a manner similar to that described for the preparation of **4a**; 78% yield; colorless oil: IR (neat) 1730, 1630, 1600 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 9.70 (t, J = 1.8 Hz, 1H), 7.24−7.43 (m, 10H), 5.43 (s, 2H), 5.17 (s, 2H), 4.43 (t, J = 7.5 Hz, 1H), 2.78 (dd, J = 1.8, 7.5 Hz, 2H); EIMS m/z 262 (M^+); HRMS calcd for $C_{19}H_{18}O_1$ (M^+) 262.1358, found 262.1355.

4-(2-Methylpropyl)-3-[1-(2-methylpropyl)vinyl]pent-4-enal (4c). A solution of **3c** (2.35 g, 7.99 mmol) in THF (12 mL) was added to the stirred suspension of $LiAlH_4$ (1.36 g, 40.0 mmol) in THF (32 mL) at 0 °C, and the whole was warmed to room temperature, and then stirred for 1 day. The reaction was quenched with EtOAc and saturated aqueous NH_4Cl (2 mL). The precipitate was filtered off, and the filtrate was concentrated in vacuo to give an oily residue, which was purified by column chromatography on silica gel. The fraction eluted with 50% EtOAc in hexane afforded an alcohol (806 mg, 45%) as a colorless oil: IR (neat) 3320, 1635 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.89 (s, 2H), 4.85 (s, 2H), 3.58−3.67 (m, 2H), 2.78 (t, J = 7.6 Hz, 1H), 1.63−1.93 (m, 8H), 0.80−0.95 (m, 12H); EIMS m/z 224 (M^+). A mixture of the alcohol (701 mg, 3.13 mmol) and PCC (3.41 g, 15.8 mmol) in CH_2Cl_2 (30 mL) was stirred at room temperature for 2 h. The mixture was diluted with ether followed by filtered through florisil. The evaporation of filtrate afforded an oily residue, which was purified by column chromatography on silica gel. The fraction eluted with 10% EtOAc in hexane gave **4c** (648 mg, 93%) as a colorless oil: IR (neat) 1730, 1640 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 9.66 (t, J = 2.2 Hz, 1H), 4.89 (s, 2H), 4.87 (s, 2H), 3.24 (t, J = 7.6 Hz, 1H), 2.60 (dd, J = 7.6, 2.2 Hz, 2H), 1.59−1.93 (m, 6H), 0.82−0.95 (m, 12H); EIMS m/z 222 (M^+); HRMS calcd for $C_{15}H_{26}O_1$ (M^+) 222.1984, found 222.1984.

***tert*-Butyl 3-Acetyl-3-methyl-4-oxopentanoate (6a).** Compound **6a** was prepared from 3-methylpentane-2,4-dione in a manner similar to that described for the preparation of **2a**; 98% yield; colorless oil: IR (neat) 1730, 1700 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 2.86 (s, 2H), 2.16 (s, 6H), 1.46 (s, 3H), 1.42 (s, 9H); FAB(+)HRMS calcd for $C_{12}H_{21}O_4$ (M^+ + 1) 229.1440, found 229.1443.

***tert*-Butyl 3-Acetyl-3-ethyl-4-oxopentanoate (6b).** Compound **6b** was prepared from 3-ethylpentane-2,4-dione in a manner similar to that described for the preparation of **2a**; 77% yield; colorless oil: IR (neat) 1720 (br) cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 2.89 (s, 2H), 2.14 (s, 6H), 2.05 (q, J = 7.6 Hz, 2H), 1.41 (s, 9H), 0.80 (t, J = 7.6 Hz, 3H); FAB(+)HRMS calcd for $C_{13}H_{23}O_4$ (M^+ + 1) 243.1596, found 243.1591.

Ethyl 3-Methyl-4-oxo-4-phenyl-3-(phenylcarbonyl)butanoate (6c). Compound **6c** was prepared in a manner similar to that described for the preparation of **2a**; 43% yield; colorless crystals: mp 85.5−87.0 °C; IR (KBr) 1720, 1650 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 7.82−7.86 (m, 4H), 7.30−7.49 (m, 6H), 4.04 (q, J = 7.2 Hz), 3.22 (s, 2H), 1.80 (s, 3H), 1.16 (t, J = 7.2 Hz, 3H); EIMS m/z 324 (M^+). Anal. Calcd for $C_{20}H_{20}O_4$: C, 74.06; H, 6.21 Found: C, 73.92; H, 6.20.

***tert*-Butyl 3-Methyl-3-isopropenyl-4-methylpent-4-enoate (7a).** Compound **7a** was prepared from compound **6a** in a manner similar to that described for the preparation of **3b**; 69% yield; yellowish oil: IR (neat) 1730, 1640 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.88 (m, 2H), 4.78 (br s, 2H), 2.51 (s, 2H), 1.64 (br s, 6H), 1.41 (s, 9H), 1.33 (s, 3H); EIMS m/z 224 (M^+); HRMS calcd for $C_{14}H_{24}O_2$ (M^+) 224.1776, found 224.1778.

***tert*-Butyl 3-Ethyl-3-isopropenyl-4-methylpent-4-enoate (7b).** Compound **7b** was prepared from compound **6b** in a manner similar to that described for the preparation of **3b**; 80% yield; yellowish oil: IR (neat) 1730, 1635 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.95 (m, 2H), 4.75 (br s, 2H), 2.47 (s, 2H), 1.78 (q, J = 7.5 Hz), 1.60 (br s, 6H), 1.39 (s, 9H), 0.81 (t, J =

7.5 Hz, 3H); EIMS *m*/*z* 240 (M^+ + 2), 239 (M^+ + 1); HRMS calcd for $C_{15}H_{27}O_2$ (M^+ + 1) 239.2011, found 239.2011.

Ethyl 3-Methyl-4-phenyl-3-(1-phenylvinyl)pent-4-enoate (7c). Compound **7c** was prepared from compound **6c** in a manner similar to that described for the preparation of **3b**; 22% yield; yellowish oil: IR (neat) 1730 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 7.20−7.40 (m, 10H), 5.26 (s, 2H), 5.22 (s, 2H), 4.00 (q, J = 7.3 Hz, 2H), 2.62 (s, 2H), 1.44 (s, 3H), 1.16 (t, J = 7.3 Hz, 3H); FAB(+)HRMS calcd for $C_{22}H_{25}O_2$ (M^+ + 1) 321.1854, found 321.1850.

3,4-Dimethyl-3-propenylpent-4-enal (8a). A solution of DIBAL-H (0.93 M) in hexane (33.6 mL) was added dropwise to the stirred solution of **7a** (3.5 g, 15.6 mmol) in CH_2Cl_2 at − 78 °C, and the whole was stirred for 30 min. The solution was diluted with cold MeOH (3 mL), and cold 1N HCl (30 mL). Then, the mixture was extracted with EtOAc, washed with 5% aqueous $NaHCO_3$, brine, and dried over $MgSO_4$. After removal of the solvent, the residue was purified by column chromatography on silica gel (15% EtOAc in hexane) to afford an alcohol (2.1 g, 88%) as a colorless oil: IR (neat) 3300, 1635 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.88 (m, 2H), 4.84 (br s, 2H), 3.58−3.65 (m, 2H), 1.91 (t, J = 7.6 Hz, 3H), 1.61 (br s, 6H), 1.38 (m, 1H), 1.18 (s, 3H). A mixture of PCC (4.33 g, 19.8 mmol) and the alcohol (2.0 g, 13.2 mmol) in CH_2Cl_2 was stirred at room temperature for 3 h. Then, the mixture was diluted with ether, and followed by filtered through florisil to remove the chromate. The filtrate was concentrated in vacuo to afford an oily residue, which was purified by column chromatography on silica gel. The fraction eluted with 10% ether in pentane gave **8a** (1.8 g, 89%) as a colorless oil: IR (neat) 1720, 1640 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 9.65 (t, J = 3.0 Hz, 1H), 4.96 (br s, 2H), 4.84 (s, 2H), 2.56 (d, J = 3.0 Hz, 2H), 1.65 (br s, 6H), 1.22 (s, 3H); EIMS *m*/*z* 152 (M^+); HRMS calcd for $C_{10}H_{16}O_1$ (M^+) 152.1201, found 152.1203.

3-Ethyl-4-methyl-3-propenylpent-4-enal (8b). Compound **8b** was prepared from compound **7b** in a manner similar to that described for the preparation of **8a**; 61% yield; colorless oil: IR (neat) 1720, 1630 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 9.57 (t, J = 3.1 Hz, 1H), 5.03 (br s, 2H), 4.84 (s, 2H), 2.53 (d, J = 3.1 Hz, 2H), 1.71 (q, J = 7.5 Hz, 2H), 1.61 (br s, 6H), 0.78 (t, J = 7.5 Hz, 3H); EIMS *m*/*z* 167 (M^+ + 1); HRMS calcd for $C_{11}H_{19}O_1$ (M^+ + 1) 167.1436, found 167.1433.

3-Methyl-4-phenyl-3-(1-phenylvinyl)pent-4-enal (8c). Compound **8c** was prepared from compound **7c** in a manner similar to that described for the preparation of **8a**; 51% yield; colorless crystals; mp 96.0−98.0 °C (recryst. from Et_2O−hexane); IR (KBr) 1710 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 9.66 (t, J = 2.8 Hz, 1H), 7.25−7.40 (m, 10H), 5.31 (s, 2H), 5.28 (s, 2H), 2.60 (d, J = 2.8 Hz, 2H), 1.38 (s, 3H); FABMS *m*/*z* 276 (M^+). Anal. Calcd for $C_{20}H_{20}O_1$: C, 86.92; H, 7.29 Found: C, 86.66; H, 7.35.

General Procedure for Cyclization by the Cationic Rh-Complex. A solution of [Rh(NBD)(*R*)-BINAP]ClO_4 (23 mg, 0.025 mmol) in CH_2Cl_2 (3 mL) was stirred under H_2 atmosphere at room temperature for 2 h. Then, Ar gas was bubbled into the solution for 15 min. This bright red solution of [Rh(*R*)-BINAP]ClO_4 was used for the cyclization without isolation. A solution of 4-pentenal (0.50 mmol) in CH_2Cl_2 (3 mL) was added dropwise to the stirred solution of [Rh(*R*)-BINAP]ClO_4 under an Ar atmosphere. After being stirred at room temperature for 3 h, the solution was concentrated in vacuo to leave a residue. The residue was dissolved in ether (20 mL), and the precipitated Rh-complex was filtered off. After removal of the solvent, the residue was purified by column chromatography on silica gel to afford the cyclopentanone.

General Procedure for Cyclization by the Neutral Rh-Complex. A mixture of [RhCl(cyclooctene)]$_2$ (125 mg, 0.25 mmol) and bisphosphine (BINAP or DIPMC, 0.50 equiv) in CH_2Cl_2 (5 mL) was stirred at room temperature for 1 h, then a solution 4-pentenal (0.5 mmol) in CH_2Cl_2 (2 mL) was added dropwise to the stirred solution. After being stirred at room temperature for 1−72 h, the solution was concentrated in vacuo to leave the residue, which was dissolved in ether (20 mL), and the precipitated Rh-complex was filtered off. Removal of the solvent gave the residue, and the residue was purified by column chromatography on silica gel to afford the cyclopentanone.

General Procedure for Cyclization by Wilkinson-Complex. A solution of 4-pentenal (0.5 mmol) in CH_2Cl_2 (2 mL) was added dropwise to the stirred solution of $RhCl(PPh_3)_3$ (115 mg, 0.25 mmol) in CH_2Cl_2 (3 mL), and the solution was stirred at room temperature for 2 h. Removal of the solvent afforded the residue, which was dissolved in ether (30 mL), and the precipitated Rh-complex was filtered off. After removal of ether, the residue was purified by column chromatography on silica gel to give the cyclopentanone.

General Procedure for the Determination of Enantiomeric Excesses of Cyclopentanones. A mixture of cyclopentanone (0.30 mmol), (*R*,*R*)-butanediol (81 mg, 0.90 mmol), and *p*-TsOH−H_2O (10 mg) in benzene (20 mL) was refluxed for 3 h with a Dean−Stark apparatus. After being cooled to room temperature, the solution was washed with 5% aqueous $NaHCO_3$ and brine and dried over $MgSO_4$. After removal of the solvent, the residue was briefly purified by column chromatography on silica gel to give the crude acetal.

***cis*-3-Isopropenyl-4-methylcyclopentanone (9a).** Cyclization of **4a** by the neutral Rh[(*R*)-BINAP]Cl (0.50 equiv) afforded (3*S*,4*R*)-(+)-**9a** (25% yield, *cis*/*trans* = 97/3, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ +75.9° (*c* 0.39, $CHCl_3$); IR (neat) 1740, 1645 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.92 (m, 1H), 4.67 (br s, 1H), 2.85 (m, 1H), 2.63 (m, 1H), 2.08−2.49 (m, 4H), 1.79 (br s, 3H), 0.82 (d, J = 7.3 Hz, 3H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 218.8, 144.0, 111.0, 47.4, 46.6, 39.3, 32.0, 22.2, 14.7; EIMS *m*/*z* 138 (M^+), 96, 81, 68, 53, 42; HRMS calcd for $C_9H_{14}O_1$ (M^+) 138.1045, found 138.1040. Cyclization of **4a** by the neutral Rh[(*S*)-BINAP]Cl (0.50 equiv) afforded (3*R*,4*S*)-(−)-**9a** (31% yield, *cis*/*trans* = 97/3, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ −79.2° (*c* 0.42, $CHCl_3$).

The enantiomeric excesses of **9a** were determined by ^1H NMR and ^{13}C NMR spectra of the acetals derived from (*R*,*R*)-2,3-butandiol. (*R*,*R*)-2,3-Butanediol acetal of (+)-**9a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 145.17, 116.10, 109.86, 78.36, 77.99, 47.91, 46.73, 39.40, 32.62, 22.66, 17.11, 16.79, 15.33. (*R*,*R*)-2,3-Butanediol acetal of (−)-**9a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 145.33, 116.05, 109.92, 78.71, 78.01, 47.64, 46.54, 39.84, 32.55, 22.73, 17.32, 17.24, 15.86. The ^1H NMR spectrum of the butanediol acetal of (+)-**9a** showed the methyl proton signal at δ 0.765 (d, J = 6.9 Hz, 3H), while the corresponding signal from (−)-**9a** was observed at δ 0.779 (d, J = 7.3 Hz, 3H).

***trans*-3-Isopropenyl-4-methylcyclopentanone (10a).** Cyclization of **4a** by the cationic Rh[(*R*)-BINAP]ClO_4 (0.05 equiv) afforded (3*S*,4*S*)-(+)-**10a** (81% yield, *cis*/*trans* = 3/97, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ + 204.8° (*c* 1.71, $CHCl_3$); IR (neat) 1745, 1645 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 4.85 (m, 2H), 2.35−2.55 (m, 3H), 2.08−2.25 (m, 2H), 1.86 (m, 1H), 1.72 (br s, 3H), 1.08 (d, J = 6.3 Hz, 3H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 217.7, 144.0, 112.3, 52.3, 47.0, 44.5, 34.9, 19.1, 18.3; EIMS *m*/*z* 138 (M^+), 96, 81, 68, 53, 42. Cyclization of **4a** by the cationic Rh[(*S*)-BINAP]ClO_4 (0.05 equiv) afforded (3*R*,4*R*)-(−)-**10a** (84% yield, *cis*/*trans* = 4/96, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ −206.8° (*c* 2.06, $CHCl_3$).

The enantiomeric excesses of **10a** were determined by ^1H NMR and ^{13}C NMR spectra of the acetals derived from (*R*,*R*)-2,3-butandiol. (*R*,*R*)-2,3-Butanediol acetal of (+)-**10a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 145.54, 115.31, 111.13, 78.21, 78.21, 53.57, 47.19, 44.62, 35.91, 19.06, 17.91, 16.93, 16.88; (*R*,*R*)-2,3-Butanediol acetal of (−)-**10a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 145.72, 115.42, 111.03, 78.33, 78.29, 53.36, 47.00, 44.41, 35.76, 19.08, 18.31, 17.35, 17.30. The ^1H NMR spectrum of the butanediol acetal of (+)-**10a** showed the methyl proton signal at δ 0.924 (d, J = 6.6 Hz, 3H), while the corresponding signal from (−)-**10a** was observed at δ 0.935 (d, J = 6.3 Hz, 3H).

***cis*-4-Phenyl-3-(1-phenylvinyl)cyclopentanone (9b).** Cyclization of **4b** by neutral Rh[(*R*)-BINAP]Cl (0.50 equiv) afforded (3*S*,4*R*)-(+)-**9b** (25% yield, *cis*/*trans* = >99/0) as a colorless oil. $[\alpha]^{23}_D$ + 57.2° (*c* 0.75, $CHCl_3$); IR (neat) 1740, 1630 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 7.03−7.40 (m, 8H), 6.68−6.77 (m, 2H), 5.12 (s, 1H), 4.66 (br s, 1H), 3.93 (m, 1H), 3.76 (br q, J = 6.2 Hz, 1H), 2.66−2.85 (m, 3H), 2.52 (dd, J = 7.6,

18.5 Hz, 1H); EIMS *m*/*z* 262 (M^+, 37), 130 (100); HRMS calcd for $C_{19}H_{18}O_1$ (M^+) 262.1358, found 262.1396. Cyclization of **4b** by the neutral Rh[(*S*)-BINAP]Cl (0.50 equiv) afforded (3*R*,4*S*)-(−)-**9b** (30% yield, *cis*/*trans* = >99/0) as a colorless oil. $[\alpha]^{23}_D$ −65.4° (*c* 0.75, $CHCl_3$).

The enantiomeric excesses of **9b** were determined by ^{1}H NMR spectra of acetals derived from (*R*,*R*)-2,3-butandiol. The ^{1}H NMR (270 MHz) spectrum of the butanediol acetal of (±)-**9b** showed the olefin proton signals at δ 5.01 (s, 0.5H), 4.99 (s, 0.5H) in the ratio of 1 to 1, and also 4.76 (br s, 0.5H), 4.69 (br s, 0.5H) in the ratio of 1 to 1, while the corresponding signals from (+)-**9b** were only observed at δ 4.99 (s, 1H) and 4.69 (br s, 1H), and those from (−)-**9b** were observed at δ 5.01 (s, 1H) and 4.76 (br s, 1H), only. The enantiomeric excesses were also supported by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (+)-**9b**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 148.0, 142.9, 142.0, 128.8−125.7 (aromatic-C_{10}), 115.7, 112.9, 78.7, 78.4, 46.1, 45.9, 45.0, 41.2, 17.2, 16.8; (*R*,*R*)-2,3-Butanediol acetal of (−)-**9b**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 148.5, 142.9, 142.1, 128.7−125.7 (aromatic-C_{10}), 115.6, 112.9, 79.0, 78.3, 45.8, 45.5, 45.0, 41.8, 17.3, 17.2.

***trans*-4-Phenyl-3-(1-phenylvinyl)cyclopentanone (10b).** Cyclization of **4b** by the cationic Rh[(*R*)-BINAP]ClO_4 (0.05 equiv) mainly afforded (3*S*,4*S*)-(+)-**10b** (70% yield, *cis*/*trans* = 17/83, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ +50.1° (*c* 1.14, $CHCl_3$); IR (neat) 1740, 1630 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 6.69−7.38 (m, 10H), 5.22 (s, 0.83H), 5.14 (s, 0.83H), 5.12 (s, 0.17H), 4.66 (s, 0.17H), 3.93 (m, 0.17H), 3.76 (br q, *J* = 6.2 Hz, 0.17H), 3.40−3.58 (m, 1.66H), 2.66−2.86 (m, 2H), 2.25−2.57 (m, 2H); EIMS *m*/*z* 262 (M^+, 38), 220 (3), 205 (6), 130 (100). Purification by HPLC afforded (3*S*,4*S*)-(+)-**10b** as colorless crystals. mp 78.0−80.0 °C (recryst. from hexane). Anal. Calcd for $C_{19}H_{18}O_1$: C, 86.99; H, 6.92. Found: C, 86.70; H, 6.90. Cyclization of **4a** by the cationic Rh[(*S*)-BINAP]ClO_4 (0.05 equiv) mainly afforded (3*R*,4*R*)-(−)-**10b** (76% yield, *cis*/*trans* = 16/84, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ − 51.1° (*c* 1.30, $CHCl_3$).

The enantiomeric excesses of **10b** were determined by ^{1}H NMR and ^{13}C NMR spectra of the acetals derived from (*R*,*R*)-2,3-butandiol. The 270 MHz ^{1}H NMR spectrum of the (*R*,*R*)-butanediol acetal derived from (+)-**10b** showed the olefin proton signals at δ 5.131 (s, 1H) and 5.100 (s, 1H), while those from (−)-**10b** showed the signals at δ 5.136 (s, 1H) and 5.113 (s, 1H). The enantiomeric excesses were also conformed by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (+)-**10b**: ^{13}C NMR (125.8 MHz, $CDCl_3$) δ 149.9, 142.9, 142.4, 128.7−125.9 (aromatic-C_{10}), 114.3, 113.0, 78.4, 78.3, 49.4, 48.5, 48.2, 46.7, 16.9, 16.9; (*R*,*R*)-2,3-Butanediol acetal of (−)-**10b**: ^{13}C NMR (125.8 MHz, $CDCl_3$) δ 150.2, 143.3, 142.3, 128.8−125.7 (aromatic-C_{10}), 114.5, 112.9, 78.4, 78.4, 49.5, 48.3, 47.8, 46.4, 17.2, 17.2.

***cis*-4-Isobutyl-3-(1-isobutylvinyl)cyclopentanone (9c).** Cyclization of **4c** by Wilkinson complex (0.50 equiv) afforded (±)-**9c** (67% yield, *cis*/*trans* = 98/2) as a colorless oil. IR (neat) 1740, 1640 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.92 (s, 1H), 4.71 (s, 1H), 2.86 (m, 1H), 2.48 (m, 1H), 2.15−2.40 (m, 4H), 2.05 (m, 1H), 1.74−1.92 (m, 2H), 1.41−1.67 (m, 2H), 1.10 (m, 1H), 0.80−1.00 (m, 12H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 219.0, 146.8, 111.5, 45.4, 45.0, 44.7, 40.5, 37.5, 35.5, 26.3, 25.9, 24.1, 23.4, 21.9, 21.3; EIMS *m*/*z* 222 (M^+, 11), 139 (39), 111 (65), 95 (100), 83 (88), 68 (91); HRMS calcd for $C_{15}H_{26}O_1$ (M^+) 222.1984, found 222.1980.

***trans*-4-Isobutyl-3-(1-isobutylvinyl)cyclopentanone (10c).** Cyclization of **4c** by the cationic Rh[(*R*)-BINAP]ClO_4 (0.05 equiv) afforded (3*S*,4*S*)-(+)-**10c** (74% yield, *cis*/*trans* = 2/98, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ +141.5° (*c* 1.07, $CHCl_3$); IR (neat) 1740, 1640 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.91 (s, 1H), 4.86 (br s, 1H), 2.31−2.61 (m, 3H), 2.04−2.30 (m, 2H), 1.71−1.95 (m, 4H), 1.41−1.66 (m, 2H), 1.11 (m, 1H), 0.80−1.00 (m, 12H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 217.9, 148.1, 110.9, 49.4, 45.5, 45.1, 44.4, 43.6, 38.6, 26.7, 26.3, 23.9, 22.6, 22.5, 21.5; EIMS *m*/*z* 222 (M^+, 23), 165 (14), 139 (29), 110 (77), 95 (100), 83 (87), 68 (81); HRMS calcd for $C_{15}H_{26}O_1$ (M^+) 222.1984, found 222.1986. Cyclization of **4c** by the cationic Rh[(*S*)-BINAP]ClO_4 (0.05 equiv) afforded (3*R*,4*R*)-(−)-**10c** (77% yield, *cis*/*trans* = 2/98, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ −132.1° (*c* 1.11, $CHCl_3$).

The enantiomeric excesses of **10c** were determined by ^{1}H NMR and ^{13}C NMR spectra of the acetals derived from (*R*,*R*)-2,3-butandiol. The 270 MHz ^{1}H NMR spectrum of the butanediol acetal derived from (+)-**10c** showed the olefin proton signals at δ 4.843 (br s, 1H) and 4.745 (br s, 1H), while those from (−)-**10c** showed the signals at δ 4.851 (br s, 1H) and 4.741 (br s, 1H). The enantiomeric excesses were also conformed by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (+)-**10c**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 149.0, 115.4, 110.1, 78.2, 78.2, 51.3, 46.0, 45.3, 44.5, 43.4, 39.7, 26.8, 26.2, 24.2, 22.7, 22.5, 21.5, 16.9, 16.9; (*R*,*R*)-2,3-Butanediol acetal of (−)-**10c**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 149.2, 115.5, 110.1, 78.3, 78.2, 51.1, 45.6, 45.0, 44.3, 43.8, 39.4, 26.8, 26.2, 24.1, 22.6, 22.5, 21.6, 17.3, 17.3.

***cis*-3,4-Dimethyl-3-isopropenylcyclopentanone (17a).** Cyclization of **8a** by the neutral Rh[(*R*)-BINAP]Cl (0.50 equiv) afforded (3*S*,4*R*)-(+)-**17a** (5% yield, *cis*/*trans* = 95/5, 87% ee) as a colorless oil. $[\alpha]^{23}_D$ +13.1° (*c* 0.61, $CHCl_3$); IR (neat) 1740, 1640 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.84 (m, 1H), 4.66 (s, 1H), 2.62 (m, 1H), 2.55 (m, 1H), 2.26 (m, 1H), 2.04 (m, 1H), 1.98 (m, 1H), 1.78 (br s, 3H), 1.17 (s, 3H), 0.88 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 219.0, 148.5, 110.6, 47.9, 47.8, 45.0, 38.1, 26.2, 19.6, 17.4; EIMS *m*/*z* 153 (M^+ + 1, 3), 152 (M^+, 21), 110 (9), 96 (14), 82 (100); HRMS calcd for $C_{10}H_{16}O_1$ (M^+) 152.1201, found 152.1197. Cyclization of **8a** by the neutral Rh[(*S*)-BINAP]Cl (0.50 equiv) afforded (3*R*,4*S*)-(−)-**17a** (5% yield, *cis*/*trans* = 95/5, 88% ee) as a colorless oil. $[\alpha]^{23}_D$ −15.0° (*c* 0.53, $CHCl_3$).

The enantiomeric excesses of **17a** were determined by ^{1}H NMR spectra of acetals derived from (*R*,*R*)-2,3-butandiol. The ^{1}H NMR spectrum of the butanediol acetal of (±)-**17a** showed the olefin proton signals at δ 4.76 (m, 0.5H), 4.73 (m, 0.5H) in the ratio of 1 to 1, and also 4.69 (s, 0.5H), 4.66 (s, 0.5H) in the ratio of 1 to 1, while the corresponding signals from (+)-**17a** cyclized by Rh[(*R*)-BINAP]Cl were observed at δ 4.73 (m, 0.94H) and 4.66 (s, 0.94H), and also at δ 4.76 (m, 0.06H) and 4.69 (s, 0.06H). The signals derived from (−)-**17a** cyclized by Rh[(*S*)-BINAP]Cl were observed at δ 4.76 (m, 0.94H) and 4.69 (s, 0.94H), and also at δ 4.73 (m, 0.06H) and 4.66 (s, 0.06H). The enantiomeric excesses were also supported by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (+)-**17a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 150.4, 116.7, 109.5, 78.0, 77.9, 49.6, 47.2, 45.9, 40.2, 26.1, 19.9, 17.3, 17.1, 17.0; (*R*,*R*)-2,3-Butanediol acetal of (−)-**17a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 150.2, 116.5, 110.0, 78.3, 78.3, 49.3, 48.5, 46.0, 40.8, 26.4, 20.4, 17.4, 17.4, 17.0.

***trans*-3,4-Dimethyl-3-isopropenylcyclopentanone (18a).** Cyclization of **8a** by the cationic Rh[(*R*)-BINAP]ClO_4 (0.05 equiv) afforded (3*S*,4*S*)-(+)-**18a** (83% yield, *cis*/*trans* = 2/98, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ +104.0° (*c* 1.30, $CHCl_3$); IR (neat) 1740, 1630 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.89 (m, 1H), 4.84 (br s, 1H), 2.45−2.52 (m, 2H), 2.43 (d, *J* = 18.8 Hz, 1H), 2.12 (d, *J* = 18.8 Hz, 1H), 1.98 (m, 1H), 1.79 (br s, 3H), 1.05 (s, 3H), 0.99 (d, *J* = 6.6 Hz, 3H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 218.0, 148.7, 111.2, 52.3, 46.7, 44.3, 36.3, 19.9, 18.8, 14.4; EIMS *m*/*z* 152 (M^+, 7), 110 (3), 96 (19), 82 (100); HRMS calcd for $C_{10}H_{16}O_1$ (M^+) 152.1201, found 152.1204. Cyclization of **8a** by the cationic Rh[(*S*)-BINAP]ClO_4 (0.05 equiv) afforded (3*R*,4*R*)-(−)-**18a** (75% yield, *cis*/*trans* = 2/98, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ −111.0° (*c* 1.30, $CHCl_3$).

The enantiomeric excesses of **18a** were determined by ^{1}H NMR spectra of acetals derived from (*R*,*R*)-2,3-butandiol. The ^{1}H NMR spectrum of the butanediol acetal of (+)-**18a** cyclized by Rh[(*R*)-BINAP]Cl showed the olefin proton signals at δ 4.79 (m, 1H) and 4.77 (br s, 1H), and methyl proton signal at δ 1.03 (s, 3H), while those from (−)-**18a** cyclized by Rh[(*S*)-BINAP]Cl were observed at δ 4.77−4.78 (m, 2H) and methyl proton signal at δ 1.04 (s, 3H). The enantiomeric excesses were also supported by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (+)-**18a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 150.6, 115.2, 109.8, 78.3, 77.8, 52.1, 47.7, 46.0, 38.0, 20.0, 18.6, 17.1, 16.9, 13.6; (*R*,*R*)-2,3-Butanediol acetal of (−)-**18a**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 150.7, 115.2, 109.7, 78.6, 77.9, 52.0, 47.5, 45.9, 38.0, 20.0, 19.3, 17.4, 17.3, 13.7.

***cis*-3-Ethyl-3-isopropenyl-4-methylcyclopentanone (17b).** Cyclization of **8b** by Wilkinson complex (0.50 equiv) afforded (±)-**17b** (74% yield, *cis*/*trans* = 94/6) as a colorless oil. IR (neat) 1740, 1635 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 4.95 (m, 1H), 4.62 (s, 1H), 2.57 (dd, J = 8.0, 18.3 Hz, 1H), 2.43 (d, J = 17.9 Hz, 1H), 2.23 (m, 1H), 2.11 (d, J = 17.9 Hz, 1H), 1.98 (br d, J = 18.3 Hz, 1H), 1.71 (br s, 3H), 1.64 (m, 1H), 1.33 (qd, J = 7.3, 14.4 Hz, 1H), 0.89 (d, J = 7.1 Hz, 3H), 0.71 (t, J = 7.3 Hz, 3H); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 219.0, 145.6, 112.8, 52.2, 44.9, 43.6, 38.1, 28.9, 19.2, 17.5, 8.7; EIMS *m*/*z* 167 (M^+ + 1, 2), 166 (M^+, 16), 124 (9), 110 (24), 96 (100), 81 (60); HRMS calcd for $C_{11}H_{18}O_1$ (M^+) 166.1358, found 166.1355.

***trans*-3-Ethyl-3-isopropenyl-4-methylcyclopentanone (18b).** Cyclization of **8b** by cationic Rh[(*R*)-BINAP]ClO_4 (0.05 equiv) afforded (3*S*,4*S*)-(−)-**18b** (75% yield, *cis*/*trans* = 3/97, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ −102.5° (*c* 1.30, $CHCl_3$); IR (neat) 1740, 1630 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 4.95 (s, 1H), 4.70 (s, 1H), 2.50 (d, J = 17.5 Hz, 1H), 2.50 (dd, J = 18.8, 7.3 Hz, 1H), 2.41 (m, 1H), 2.16 (d, J = 17.5 Hz, 1H), 1.86 (dd, J = 18.8, 3.0 Hz, 1H), 1.75 (br s, 3H), 1.67 (qt, J = 7.6, 14.7 Hz, 1H), 140 (qt, J = 7.6, 14.7 Hz, 1H), 1.04 (d, J = 7.1 Hz, 3H), 0.75 (t, J = 7.3 Hz, 3H); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 218.8, 147.0, 112.8, 50.9, 46.2, 45.1, 36.0, 25.5, 19.9, 16.1, 9.4; EIMS *m*/*z* 166 (M^+, 9), 148 (8), 137 (18), 124 (22), 110 (29), 96 (100), 95 (28), 81 (76), 67 (35); HRMS calcd for $C_{11}H_{18}O_1$ (M^+) 166.1358, found 166.1360 Cyclization of **8b** by cationic Rh[(*S*)-BINAP]ClO_4 (0.05 equiv) afforded (3*R*,4*R*)-(+)-**18b** (82% yield, *cis*/*trans* = 3/97, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ +100.6° (*c* 1.20, $CHCl_3$).

The enantiomeric excesses of **18b** were determined by ^1H NMR spectra of acetals derived from (*R*,*R*)-2,3-butandiol. The ^1H NMR spectrum of the butanediol acetal of (−)-**18b** cyclized by Rh[(*R*)-BINAP]Cl mainly showed the olefin proton signals at δ 4.865 (m, 1H) and 4.752 (br d, 1H), and methyl proton signal at δ 0.749 (t, J = 7.3 Hz, 3H), while those from (+)-**18b** cyclized by Rh[(*S*)-BINAP]Cl were mainly observed at δ 4.865 (m, 1H) and 4.783 (br s, 1H), and methyl proton signal at δ 0.736 (s, 3H). The enantiomeric excesses were supported by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (−)-**18b**: ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 148.3, 115.4, 111.1, 78.3, 77.9, 51.7, 46.6, 45.8, 39.6, 23.4, 20.8, 17.2, 17.1, 14.7, 9.2; (*R*,*R*)-2,3-Butanediol acetal of (+)-**18b**: ^{13}C NMR (68 MHz, $CDCl_3$) δ 148.3, 115.6, 111.3, 78.2, 77.9, 51.9, 46.4, 45.6, 39.1, 24.7, 20.5, 17.3, 17.2, 15.1, 9.2.

***cis*-3-Methyl-4-phenyl-3-(1-phenylvinyl)cyclopentanone (17c).** Cyclization of **8c** by Wilkinson complex (0.50 equiv) afforded (±)-**17c** (95% yield, *cis*/*trans* = >99/0) as a colorless oil. IR (neat) 1740 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.03−7.26 (m, 8H), 6.53−6.55 (m, 2H), 5.09 (br s, 1H), 5.02 (br s, 1H), 3.50 (dd, J = 4.7, 8.7 Hz, 1H), 2.85 (dd, J = 8.7, 18.7 Hz, 1H), 2.82 (d, J = 19.0 Hz, 1H), 2.64 (dd, J = 4.7, 18.7 Hz, 1H), 2.29 (d, J = 19.0 Hz, 1H), 1.53 (s, 3H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 218.0, 154.1, 142.7, 142.0, 128.7, 128.2, 128.0, 127.4, 126.7, 126.6, 116.9, 53.0, 52.2, 49.4, 44.6, 31.1; FABMS *m*/*z* 277 (M^+ + 1), 276 (M^+).

***trans*-3-Methyl-4-phenyl-3-(1-phenylvinyl)cyclopentanone (18c).** Cyclization of **8c** by the cationic Rh[(*R*)-BINAP]-ClO_4 (0.10 equiv) mainly afforded (3*S*,4*S*)-(+)-**18c** (80% yield, *cis*/*trans* = 21/79, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ +42.7° (*c* 0.27, $CHCl_3$); IR (neat) 1740 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 7.00−7.39 (m, 8.6H), 6.51−6.55 (m, 1.4H), 5.09 (br s, 0.3H), 5.04−5.06 (m, 1.4H), 5.02 (br s, 0.3H), 3.67 (t, J = 8.8 Hz, 0.7H), 3.50 (dd, J = 4.7, 8.8 Hz, 0.3H), 2.60−2.95 (m, 3H), 2.34 (d, J = 17.2 Hz, 0.7H), 2.29 (d, J = 19.0 Hz, 0.3H), 1.53 (s, 0.9H), 1.08 (s, 2.1H); EIMS *m*/*z* 276 (M^+, 16), 144 (45), 129 (100), 104 (67); HRMS calcd for $C_{20}H_{20}O_1$ (M^+) 276.1514, found 276.1456. Cyclization of **8c** by the cationic Rh[(*S*)-BINAP]ClO_4 (0.10 equiv) mainly afforded (3*R*,4*R*)-(−)-**18c** (80% yield, *cis*/*trans* = 21/79, >95% ee) as a colorless oil. $[\alpha]^{23}_D$ −42.5° (*c* 0.30, $CHCl_3$).

The enantiomeric excesses of **18c** were determined by ^1H NMR spectra of acetals derived from (*R*,*R*)-2,3-butandiol. The ^1H NMR spectrum of the butanediol acetal of (+)-**18c** cyclized by Rh[(*R*)-BINAP]ClO_4 mainly showed the methyl proton signals of C(3)-position at δ 1.070 (s, 1H), while those from (−)-**18c** cyclized by Rh[(*S*)-BINAP]ClO_4 were mainly observed at δ 1.105 (s, 1H). The enantiomeric excesses were also supported by ^{13}C NMR spectra. (*R*,*R*)-2,3-Butanediol acetal of (+)-**18c** (*cis*/*trans* = 21/79): ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 156.1, 143.2, 140.0, 130.8−125.9 (aromatic-C_{10}), 115.6, 114.4, 78.4, 77.9, 53.3, 50.4, 49.1, 43.7, 21.5, 17.1, 16.7; (*R*,*R*)-2,3-Butanediol acetal of (−)-**18c** (*cis*/*trans* = 21/79): ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 156.2, 143.4, 140.2, 129.3−126.0 (aromatic-C_{10}), 115.5, 114.5, 78.6, 77.9, 52.8, 50.0, 48.9, 43.5, 22.4, 17.3, 17.2.

Supporting Information Available: Experimental section for the determination of absolute configuration of (+)-**10a**. Copies of the ^1H NMR spectra of all compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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