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Lewis Acid-Activated Chiral Leaving Group: Enantioselective Electrophilic Addition to Prochiral Olefins

Hiroko Nakamura, Kazuaki Ishihara, and Hisashi Yamamoto*

Graduate School of Engineering, Nagoya University, SORST, Japan Science and Technology Corporation (JST), Chikusa, Nagoya 464-8603, Japan

yamamoto@cc.nagoya-u.ac.jp

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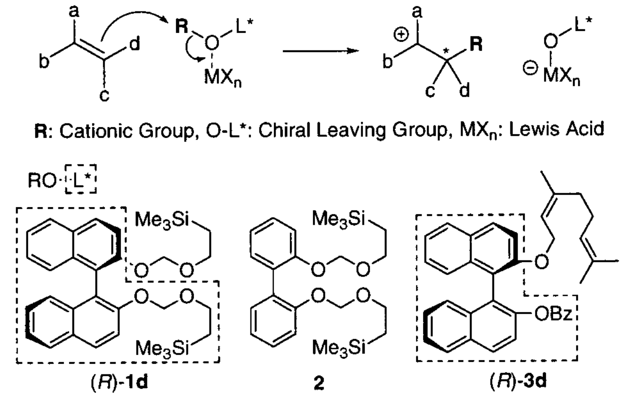
A new strategy using a BINOL derivative as a chiral leaving group and Lewis acid has been developed for enantioselective alkylation of prochiral olefins. (*R*)-2,2′-Bis[2-(trimethylsilyl)ethoxymethyl]-1,1′-binaphthol is demonstrated to be an effective reagent for enantioselective hydroxymethylation of silyl enol ethers and trisubstituted alkenes. Electrophilic addition to prochiral olefins is accompanied by cleavage of an acetal that is dual activated by $SnCl_4$ and the δ-effect of silicon through the S_N2 substitution process. Enantioselective synthesis of cyclic terpenes is also described using this strategy.

Introduction

Enantioselective alkylation of prochiral olefins is an effective way to construct stereogenic carbons, especially quaternary carbon centers. Numerous examples have been presented:[1] using a chiral leaving group is one of the most attractive methods since it does not require the additional steps for removal of a chiral auxiliary and affords the desired enantiomer directly. However, chiral leaving group-induced enantioselective alkylation has been less investigated than other methods, which include chiral ligand/metal-catalyzed reactions and chiral auxiliary-induced diastereoselective reactions. One difficulty of the system using a chiral leaving group is that a leaving group should not be released before asymmetric addition, but simultaneous cleavage of a leaving group after addition is required. Fuji et al. presented highly enantioselective nitroolefination of prochiral enolates derived from α-substituted lactones with chiral nitro enamines based on the addition−elimination strategy,[2h,i] and this is one of the few successful examples[2] that overcame this difficulty. The addition−elimination strategy, which was first introduced by Wilson and Cram,[2c,f] is an effective method for high asymmetric induction because initial enantioselective addition and the following elimination proceed completely stepwise manner. Tamura et al. developed asymmetric synthesis of 3-substituted 2-*exo*-methylenecyclohexanones via allylic S_N2' substitution of chiral amine auxiliary by organocuprates.[2j,l] Denmark and Marble also reported asymmetric S_N2' substitution of chiral carbamates derived from an achiral allylic alcohol.[2k] In these S_N2' reactions, alkylation occurred on one of the two possible diastereotopic faces to give an enantiomer. An example of the S_N2 substitution process, which is the asymmetric synthesis of monocyclic terpenes, was developed in our laboratory.[2e,g]

SCHEME 1



We have developed a new and effective method of enantiotopic face-selective alkylation of prochiral olefins using BINOL derivatives as a chiral leaving group under acidic conditions. In our strategy, a Lewis acid-activated O−C bond is cleaved at the moment of electrophilic addition and the chiral auxiliary is released (Scheme 1). This reaction should proceed by an S_N2 mechanism to construct a chiral center on an achiral olefin. The reagent

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(1) (a) Seyden-Penen, J. *Chiral Auxiliaries and Ligands in Asymmetric Synthesis*; John Wiley: New York, 1995. (b) *Comprehensive Asymmetric Catalysis*, Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds; Springer-Verlag: New York, 1999; Vol. 3.

(2) (a) Duggan, P. G.; Murphy, W. S. *J. Chem. Soc., Chem. Commun.* **1974**, 263. (b) Duggan, P. G.; Murphy, W. S. *J. Chem. Soc., Perkin Trans. 1* **1976**, 634. (c) Wilson, J. M.; Cram, D. J. *J. Am. Chem. Soc.* **1982**, *104*, 881. (d) Duhamel, P.; Valnet, J. Y.; Eddine, J. J. *Tetrahedron Lett.* **1982**, *23*, 2863. (e) Sakane, S.; Fujiwara, J.; Maruoka, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1983**, *105*, 6154. (f) Wilson, J. M.; Cram, D. J. *J. Org. Chem.* **1984**, *49*, 4930. (g) Sakane, S.; Fujiwara, J.; Maruoka, K.; Yamamoto, H. *Tetrahedron* **1986**, *42*, 2193. (h) Fuji, K.; Node, M.; Nagasawa, H.; Naniwa, Y.; Terada, S. *J. Am. Chem. Soc.* **1986**, *108*, 3855. (i) Fuji, K.; Node, M.; Abe, H.; Ito, A.; Masaki, Y.; Shiro, M. *Tetrahedron Lett.* **1990**, *31*, 2419. (j) Tamura, R.; Watabe, K.; Katayama, H.; Suzuki, H.; Yamamoto, Y. *J. Org. Chem.* **1990**, *55*, 408. (k) Denmark, S. E.; Marble, L. K. *J. Org. Chem.* **1990**, *55*, 1984. (l) Tamura, R.; Watabe, K.; Ono, N.; Yamamoto, Y. *J. Org. Chem.* **1992**, *57*, 4895. (m) Baker, R. W.; Pocock, G. R.; Sargent, M. V. *J. Chem. Soc., Chem. Commun.* **1993**, 1489. (n) Ogata, M.; Yoshimura, T.; Fujii, H.; Ito, Y.; Katsuki, T. *Synlett* **1993**, 728. (o) Yanagisawa, A.; Nomura, N.; Yamada, Y.; Hibino, H.; Yamamoto, H. *Synlett*, **1995**, 841. (p) Yang, X.; Wang, R. *Tetrahedron*: *Asymmetry* **1997**, *31*, 3275.

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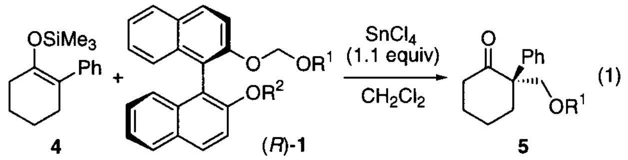
could be thought of as a cation synthon, which has a chiral atmosphere. The idea of a Lewis acid-activated cationic alkyl group took a hint from Lewis acid-assisted chiral Brønsted acid (LBA), which is a reagent developed in our laboratory for enantioselective protonation prepared from $SnCl_4$ and an optically pure BINOL derivative.[3] On the basis of this concept, an intermolecular hydroxymethylating reagent (*R*)-**1d**,[4a,b] an achiral derivative **2**, and a reagent for intramolecular cyclization (*R*)-**3d**[4c] have been developed. Herein we report three topics based on the new concept in which a chiral leaving group is used: (1) alkoxymethylation of silyl enol ethers; (2) alkoxymethylation of trisubstituted alkenes; (3) and intramolecular cyclization of terpenes.

Results and Discussion

Enantioselective Alkoxymethylation of Silyl Enol Ethers. First, we chose to investigate the enantioselective alkylation of silyl enol ethers using a chiral leaving group (eq 1).[5,6] Silyl enol ethers, which are synthetic equivalents of enols or enolates, are more stable than the corresponding metal enolates and can be isolated. Shown in Table 1 are results from the reaction of various alkyl ethers of BINOL with the trimethylsilyl enol ether derived from 2-phenylcyclohexanone in the presence of $SnCl_4$. *p*-Methoxybenzyl ether of BINOL gave the racemic product, methoxymethyl or benzyloxymethyl ether of BINOL, while **1a** or **1b** gave products in moderate yields and ees (Table 1, entries 1 and 2). These reactions proceeded in toluene more slowly than in dichloromethane, and addition of excess $SnCl_4$ or an increase in the reaction temperature promoted the decomposition of substrate. When the trimethylsilylethoxymethyl (SEM) ether of BINOL **1d** was used, the product was obtained in much better yield, 91%, and with 75% ee (Table 1, entry 4). This result can be explained by assuming an interaction between silicon and a γ-positive charge (the γ-effect).[7] The terminal silyl group would stabilize the γ-oxonium cation, and therefore, the cleavage of acetal would be accelerated. The disubstituted, C_2-symmetric reagent (**1d**), only one alkyl group of which was transferred to a substrate, was more reactive than the monomethyl substituted reagent (**1c**). This reagent seems uneconomical at first sight; however, **1d** can be synthesized in one step from optically pure BINOL and SEMCl. Furthermore, mono(SEM)-protected BINOL can be collected and recycled. The corresponding racemic products could be synthesized in the reaction of silyl enol ethers with SEMCl and $SnCl_4$ (Table 1, entry 7).[8] While other terminal silyl groups were examined, they did not give significantly better reactivity or enantioselectivity (Table 1, entries 5 and 6). This result indicated that there was no appreciable steric effect from bulkiness of terminal silyl groups and the increase in enantioselectivity could be due to the increase in reactivity by an electronic effect of the silyl groups.



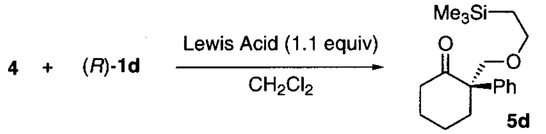
a: $CH_2OR^1 = R^2 = CH_2OMe$ (MOM)
b: $CH_2OR^1 = R^2 = CH_2OCH_2Bn$ (BOM)
c: $CH_2OR^1 = CH_2OCH_2CH_2SiMe_3$ (SEM), $R^2 = Me$
d: $CH_2OR^1 = R^2 = CH_2OCH_2CH_2SiMe_3$ (SEM)
e: $CH_2OR^1 = R^2 = CH_2OCH_2CH_2SiBu^tMe_2$ (TBSEM)
f: $CH_2OR^1 = R^2 = CH_2OCH_2CH_2SiPhMe_2$ (DMPSEM)

TABLE 1. Enantioselective Alkoxymethylation of 4 with 1 and $SnCl_4$[a]

entry	reagent (CH_2OR^1, R^2)[b]	*T*, time (°C, h)	yield (%)	ee[c,d] (%)
1[e]	**1a** (MOM, MOM)	−78, 3	56	51
2	**1b** (BOM, BOM)	−78, 3	55	43
3	**1c** (SEM, Me)	−78, 2	79	71
4	**1d** (SEM, SEM)	−78, 1	91	75
5	**1e** (TBSEM, TBSEM)	−78, 1	79	76
6	**1f** (DMPSEM, DMPSEM)	−78, 1	90	68
7	SEMCl[f]	−78, 0.5	90	

[a] For details, see the Experimental Section. [b] 1.1 equiv of reagent was used. [c] Determined by HPLC analysis. [d] Configuration was all (*R*)-(+). [e] Reaction was run in toluene. [f] SEMCl was used in place of **1**.

TABLE 2. Effects of Lewis Acids on SEM Addition of 4 with (*R*)-1d[a,b]



entry	Lewis acid	yield (%)	ee[c,d] (%)
1	$ZrCl_4$	49	42
2	$HfCl_4$	84	55
3	$TiCl_4$	59	28
4	$GaCl_3$	26	58
5	$B(C_6F_5)_3$	34	0

[a] Reactions were carried out at −78 °C for 1 h. [b] 1.1 equiv of (*R*)-**1d** was used. [c] Determined by HPLC analysis. [d] Configuration was all (*R*)-(+).

Different kinds of Lewis acids were then examined in place of $SnCl_4$ (Table 2). $ZrCl_4$ and $HfCl_4$ acted similarly to $SnCl_4$, but they did not exceed $SnCl_4$ in enantioselec-

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(3) (a) Yanagisawa, A.; Ishihara, K.; Yamamoto, H. *Synlett* **1997**, 411 and references therein. (b) Taniguchi, T.; Ogasawara, K. *Tetrahedron Lett.* **1997**, *38*, 6429. (c) Ishihara, K.; Ishida, Y.; Nakamura, S.; Yamamoto, H. *Synlett* **1997**, 758. (d) Ishihara, K.; Nakamura, H.; Nakamura, S.; Yamamoto, H. *J. Org. Chem.* **1998**, *63*, 6444. (e) Ishihara, K.; Nakamura, S.; Yamamoto, H. *J. Am. Chem. Soc.* **1999**, *121*, 4906. (f) Nakamura, S.; Kaneeda, M.; Ishihara, K.; Yamamoto, H. *J. Am. Chem. Soc.* **2000**, *122*, 8120. (g) Nakamura, S.; Ishihara K.; Yamamoto, H. *J. Am. Chem. Soc.* **2000**, *122*, 8131. (h) Ishihara, K.; Ishibashi, H.; Yamamoto, H. *J. Am. Chem. Soc.* **2001**, *123*, 1505.

(4) (a) Ishihara, K.; Nakamura, H.; Yamamoto, H. *J. Am. Chem. Soc.* **1999**, *121*, 7720. (b) Ishihara, K.; Nakamura, H.; Yamamoto, H. *Synlett* **2000**, 1245. (c) Ishihara, K.; Nakamura, H.; Yamamoto, H. *Synlett* **2001**, 1113.

(5) While far from efficient, there is nevertheless a report on the enantioselective hydroxymethylation. Fujii, M.; Sato, Y.; Aida, T.; Yoshihara, M. *Chem. Express* **1992**, *7*, 309.

(6) For the diastereoselective aldol-type reactions of chiral enolates with SEMCl, see: Suzuki, S.; Narita, H.; Harada, K. *J. Chem. Soc., Chem. Commun.* **1979**, 29.

(7) Lambert, J. B. *Tetrahedron* **1990**, *46*, 2677.

(8) Lithium enolates/SEMCl: (a) Crich, D.; Davies, J. W. *J. Chem. Soc., Chem. Commun.* **1989**, 1418. (b) Crich, D.; Lim, L. B. L. *Synlett* **1990**, 117. (c) Paquette, L. A.; Ra, C. S., Silvestri, T. W. *Tetrahedron* **1989**, *45*, 3099. Lithium enolates/BOMCl: (d) Wägner, J.; Vogel, P. *J. Chem. Soc., Chem. Commun.* **1989**, 1634. Trialkylsilyl enol ethers/$MOMCl/B(C_6F_5)_3$: (e) Ishihara, K.; Hanaki, N.; Yamamoto, H. *Synlett* **1993**, 577. Trialkylsilyl enol ethers/$RSCH_2Cl/TiCl_4$ or $ZnBr_2$: Paterson, I. *Tetrahedron* **1988**, *44*, 4207, and references therein.

TABLE 3. Effects of Solvents on SEM Addition of 4 with (*R*)-1d and SnCl$_4$[a]

entry	solvent	*T*, time (°C, h)	yield (%)	ee[b,c] (%)
1	hexane	−78, 1	*d*	
2	toluene	−78, 1	65	56
3	Et$_2$O	−78, 1	*d*	
4	*t*BuOMe	−78 to −40, 1	71	55
5	EtNO$_2$	−78, 1	38	52
6	chlorobenzene	−40, 0.5	91	45
7	CHCl$_3$	−50, 0.5	82	69
8	1,2-dichloropropane	−78, 1	76	77
9	1,2-dichloropropane	−100, 3	82	81
10	1,3-dichloropropane	−78, 1	97	66
11	1-chloropropane	−78, 2.5	78	73
12	1-chloropropane	−125, 1 to −78, 1	94	81
13	1-chloropropane	−125, 47	55	94
14	2-chloropropane	−78, 1	85	70
15	CH$_2$BrCl	−78, 1	94	70
(16	CH$_2$Cl$_2$	−78, 1	91	75)[e]

[a] 1.1 equiv of (*R*)-**1d** and SnCl$_4$ were used. [b] Determined by HPLC analysis. [c] Configuration was all (*R*)-(+). [d] No reaction was observed. [e] These data appear in Table 1 (entry 4).

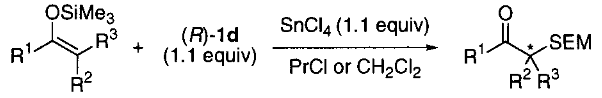
tivity (Table 2, entries 1 and 2). We considered their low solubility in dichloromethane to be the reason that ZrCl$_4$ and HfCl$_4$ did not lead to better results than SnCl$_4$. While GaCl$_3$ and TiCl$_4$ had high solubility in dichloromethane, they did not afford satisfactory results (Table 2, entries 3 and 4).

We next examined the solvent effects on the reaction of **4** with (*R*)-**1d** and SnCl$_4$ (Table 3). No reaction was observed in hexane, because of its low solubility, and diethyl ether promoted the decomposition of SnCl$_4$. Halogenated solvents tended to give the product with high enantiomeric excess, with 1,2-dichloropropane, 1-chloropropane, and dichloromethane showing the best results. Although enantioselectivity in 1,2-dichloropropane at −78 °C was higher than that in 1-chloropropane at −78 °C, the latter is cheaper and can be cooled to lower temperature than the former, and the highest ee value was achieved by performing the reaction in 1-chloropropane at −125 °C for an extended time (Table 3, entry 13). The reaction of 1 equiv of **4** and **1d** with 0.5 equiv of SnCl$_4$ or 0.5 equiv of **1d** with 1 equiv of **4** and SnCl$_4$ afforded **5d** in 50% yield. These results led us to understand that SnCl$_4$ does not act as a catalyst, probably due to formation of a stable complex with a released chiral auxiliary, and the second SEM group on **1d** is not consumed. It should be added that *tert*-butyldimethylsilyl enol ether and dimethylhydrosilyl enol ether derived from 2-phenylcyclohexanone treated with **1d** and SnCl$_4$ in CH$_2$Cl$_2$ at −78 °C led to the adducts in quantitative yields with 32% and 69% ee, respectively.

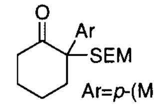
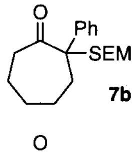
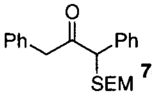
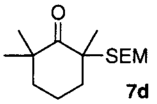
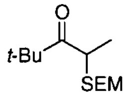
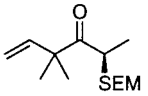
In view of these results, we believe that the highly enantioselective S$_N$2 SEM-addition mechanism could be materialized with an exquisite balance between the nucleophilicity of a trimethylsilyl enol ether and the electrophilicity of acetal dual activated by SnCl$_4$ and the γ-effect of silicon.[7]

The generality and scope of the SnCl$_4$-mediated SEM addition explored using several trimethylsilyl enol ethers are shown in Table 4. Good enantioselectivities were observed in the reaction of aromatic silyl enol ethers (Table 4, entries 1−4) and aliphatic silyl enol ethers (Table 4, entries 5−7), whereas low enantioselectivities were observed in the reaction of silyl enol ethers derived from 2-phenylcyclopentanone and 2-alkylcyclohexanones. Notice that the absolute stereochemical course in the case of **4** is opposite that in **6f**, and reactions proceeded smoothly in 1-chloropropane in the case of aromatic silyl enol ethers including **4**, while no desired reaction was observed in the aliphatic silyl enol ethers including **6f**. The 2-(trimethylsilyl)ethyl group was easily removed in quantitative yield without racemization by treatment with hydrogen fluoride-pyridine at room temperature (eq 2).

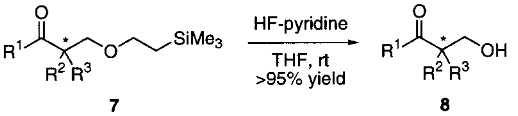
TABLE 4. Enantioselective 2-(Trimethylsilyl)ethoxymethylation[a]



6 7

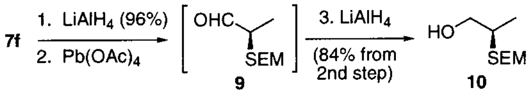
entry	silyl enol ether	temp., time (°C, h)[b]	product	yield (%), ee (%)[b] (conf)-(rotn)
1[c]	**6a**	−125, 1 to −78, 1	 Ar=*p*-(MeO)C$_6$H$_4$ **7a**	91, 82, (+)
2[c]	**6b**	−125, 1 to −78, 1		76, 77, (+)
3[c]		−125, 108		57, 86, (+)
4[d]	**6c**[e]	−78, 17		75, 64, (+)
5[d]	**6d**	−97, 3		78, 71, (+)
6[d]	**6e**[f]	−97, 6		87, 74, (+)
7[d]	**6f**	−97, 6		80, 79, (*R*)-(+)

[a] For details, see the Experimental Section. [b] Determined by HPLC or GC analysis. [c] 1-Chloropropane was used. [d] Dichloromethane was used. [e] *E*/*Z* = 83:17. [f] >99% *Z*.



(2)

To demonstrate the effectiveness of the present reaction, optically active ketone **7f** obtained in the reaction of Heathcock's silyl enol ether **6f**[6] (Table 4, entry 7) was converted to synthetically more useful aldehyde **9** in high yield according to their protocol (eq 3).



(3)

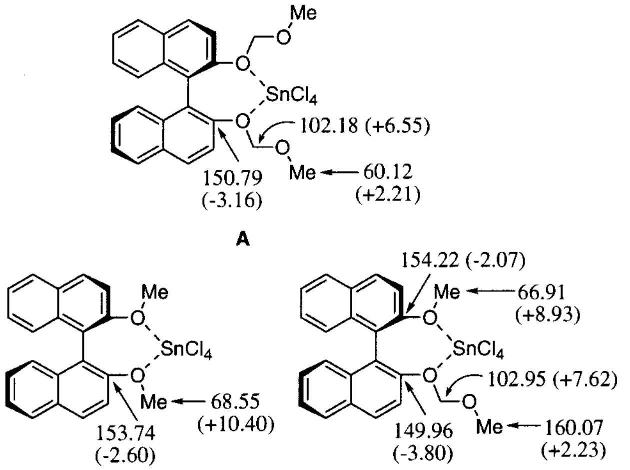


FIGURE 1. Changes in the chemical shifts of the chiral reagents **1**. ^{13}C NMR (75 MHz, CD_2Cl_2, −78 °C) assignments (δ (ppm)) for a 1:1 **1**−$SnCl_4$ complex.

Structure of 1−SnCl$_4$ Complex. While the chiral reagent **1** has four oxygens that could be coordinated by $SnCl_4$, we believe that the bidentate complex **A** is probably formed of **1** and $SnCl_4$ (Figure 1). Because an amount of $SnCl_4$ equivalent to a chiral reagent gave the best result in these transformations, a *n*:*n* complex[10] of reagent and $SnCl_4$ would be the most effective species. The regioselective cleavage of acetals in these transformations indicates that $SnCl_4$ predominantly coordinates with the OAr oxygen atoms. In addition, a ^{13}C NMR study established that the addition of 1 equiv of $SnCl_4$ to **1a** gave rise to a symmetrical complex, and changes in the chemical shifts also supported the existence of complex **A**.[11]

A stable conformation of complex **A** was predicted by theoretical calculations of a 2,2′-di(methoxymethoxy)-1,1′-biphenyl and $SnCl_4$ complex **B**, which was optimized at the partial PM3 calculation of the MOM units on the basis of a 2,2′-dimethyl-1,1′-biphenyl and $SnCl_4$ complex optimized at the B3LYP/LANL2DZ level[12] using Gaussian 98[13] (Figure 2).[4a] These calculations indicated that the di(MOM) ether with $SnCl_4$ occurs at an equatorial site on tin. It is noteworthy that the C5−O4 bond is almost perpendicular to the C1−C3 axis, presumably due to the steric repulsive interactions with apical and equatorial chlorines. Also of interest is the finding that the C5−O6 bond is shorter than the O4−C5 bond which is perpendicular to the C5−O6−C7 plane. This indicates that the C5−O6 bond has a partial double-bond character due to the stereoelectronic effect.[14] From these studies, we assumed that a stable conformation of the reagent was **C** (Figure 3).

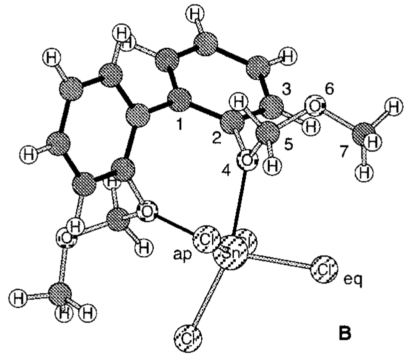


FIGURE 2. Optimized geometry of a 2,2′-dimethoxy-1,1′-diphenyl-$SnCl_4$ complex. Selected bond distances (Å), bond angles (deg), and dihedral angles (deg): O4−C5 = 1.456, C5−O6 = 1.386, Sn−Cl_{ap} = 2.397, Sn−Cl_{eq} = 2.376, O4−Sn = 2.328, C2−O4−C5 = 111.4, Sn−O4−C5 = 122.1, C5−O6−C7 = 116.4, C1−C2−O4−C5 = −85.7, C3−C2−O4−C5 = 92.4, Cl_{ap}−Sn−O4−C5 = 33.0, Cl_{eq}−Sn−O4−C5 = −61.5, C2−O4−C5−O6 = −64.0, O4−C5−O6−C7 = −90.6.

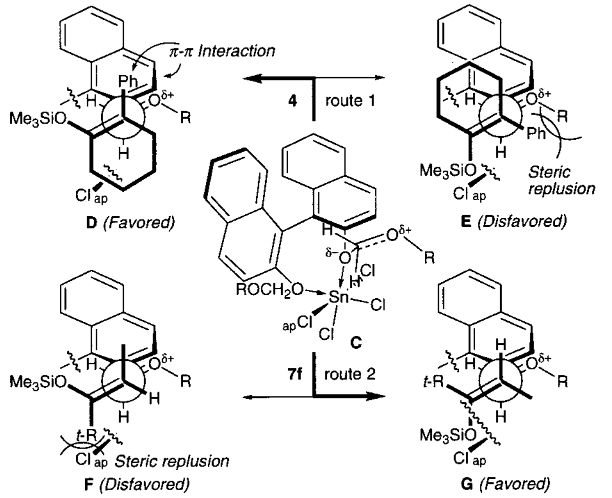


FIGURE 3. Proposed extended transition states for the enantioselective SEM addition to silyl enol ethers. (R: $CH_2CH_2SiMe_3$).

The observed absolute stereochemistries are explained in terms of the acyclic extended transition-state mechanism that was a kind postulated by Noyori et al.[15] We considered that there could be two different routes (Figure 3). First in the reaction of **4**, TS **D**, which is stabilized by $\pi-\pi$ attractive interaction between phenyl and naphthyl groups, is favored over the alternative TS **E**, which is destabilized due to steric repulsion between

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(9) Mori, I.; Ishihara, K.; Heathcock, C. H. *J. Org. Chem.* **1990**, *55*, 1114.

(10) We have no evidence that the complex is consisted of one chiral reagent and one $SnCl_4$. There is a possibility that a 2:2, 4:4, or *n*:*n* complex exists.

(11) The possibility of an unsymmetrical structure, in which two oxygen atoms in a single MOM group of **2a** are coordinated to the tin atom, was clearly denied. Santelli, M.; Pons, J.-M. *Lewis Acids and Selectivity in Organic Synthesis*; CRC Press: Boca Raton, 1996; Chapter 4.

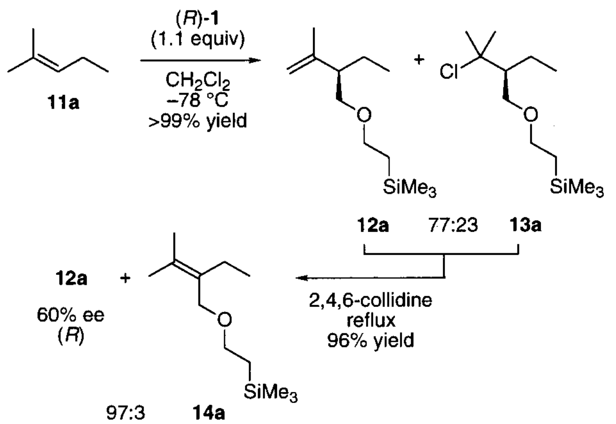
(12) (a)Dunning, T. H., Jr. *J. Chem. Phys.* **1970**, *53*, 2823. (b) Wadt, W. R.; Hay, P. J. *J. Chem. Phys.* **1985**, *82*, 284.

(13) Gaussian 98 (Revision A.6): Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. Gaussian, Inc., Pittsburgh, PA, 1998.

(14) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon Press: Oxford, 1983.

(15) Murata, S.; Suzuki, M.; Noyori, R. *J. Am. Chem. Soc.* **1980**, *102*, 3248.

SCHEME 2



2-(trimethylsilyl)ethyl and phenyl groups. Second in the reaction of **7f**, TS **G** is preferable to TS **F**, which is destabilized due to steric repulsion between the *tert*-alkyl group and an apical chlorine. In other words, **4** favored TS **D** because of the positive cause while **7f** disfavored TS **F** because of the negative cause. The stereoselection observed for other silyl enol ethers can also be understood in a similar fashion. These two different mechanisms can explain the observed difference between aromatic and aliphatic substrates in stereochemistry and solvent effects, which has been described above.

Enantioselective Hydroxymethylation of Trisubstituted Alkenes. We have demonstrated above an enantioselective SEM addition to silyl enol ethers using **1d** and $SnCl_4$. The chiral reagent **1d** and $SnCl_4$-induced enantioselective Prins-type reaction[16] of trisubstituted alkenes was then developed.[17,18] Simple olefins are common and easily available substrates; however, with them it is harder than with silyl enol ethers to control regioselection and enantioselection because they have two or more possible reacting points and no heteroatom that can interact with reagents and metals. First, we examined an enantioselective SEM addition to 2-methyl-2-pentene with **1d** and $SnCl_4$ (Scheme 2). Electrophilic SEM addition occurred rapidly and site selectively at the less substituted carbon of the double bond in olefin **11a** at −78 °C in dichloromethane, and a mixture of the desired product **12a** and the 3-chloroalkyl ether **13a** was obtained. Although it was difficult to separate the product mixture by column chromatography on silica gel,[19] the chlorinated byproduct **13a** could be converted into the desired product by regioselective dehydrochlorination. No reaction was observed when the mixture of **12a** and **13a** was treated with a bulky anionic base such as triphenylmethyllithium,[20] and KO(*t*-Bu)/*t*-BuLi resulted in decomposition of substrate, whereas the mixture could be transformed into **12a** and **14a** by heating in amines (Table 5). Especially in 2,4,6-collidine was the product **12a** obtained in high regioselectivity (Table 5, entry 5) and with 60% ee. The enantiomeric excess of **12a** was improved to 81% by carrying out the SEM addition at −97 °C in dichloromethane. The higher concentration of the reaction mixture raised the reactivity without reducing the enantioselectivity. The reaction of **11a** in toluene at −78 °C and 1-chloropropane at −125 to −78 °C led to **12a** with 54% and 74% ee, respectively.

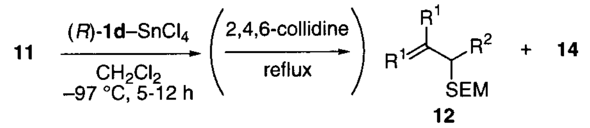
TABLE 5. Regioselective Dehydrochlorination of 13a to 12a

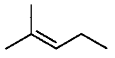
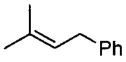
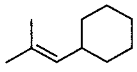
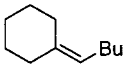
$$\underset{77\,:\,23}{\mathbf{12a} + \mathbf{13a}} \xrightarrow{\text{base}} \mathbf{12a} + \mathbf{14a}$$

entry	base	*T* (°C), time (h)[a]	yield[b] (%)	(**12a**/**14a**)[c]
1	Ph_3CLi	40, 1[d]	*e*	
2	DBU	130, 3	84	89:11
3	DBN	120, 1	87	86:14
4	*i*-Pr_2EtN	170, 3	*e*	
5	2,4,6-collidine	180, 3	96	97:3

[a] Unless otherwise noted, the reaction was carried out under reflux conditions using a base as a solvent. [b] Isolated yield. [c] Determined by ^1H NMR analysis. [d] Diethyl ether was used as a solvent. [e] No reaction.

TABLE 6. Enantioselective Prins Reaction of Prochiral Alkenes with (*R*)-1d and $SnCl_4$[a]



entry	Alkene	product	% yield[b] (**12**:**14**)[c]	% ee,[d] rotn
1[e,f]	 **11a**	**12a**	85[g,h] (97:3)	81, (−)-(*R*)
2[e,i]	 **11b**	**12b**	78[g] (99:1)	84, (−)
3[j]	 **11c**	**12c**	75	77, (−)
4[j]	 **11d**	**12d**	92[k]	73, (−)

[a] Reactions were run with 1.1 equiv of **1d** and $SnCl_4$ at −97 °C for 12 h in dichloromethane. [b] Isolated yield. [c] Determined by GC analysis. [d] Determined by GC or HPLC analysis. [e] The mixture of **12** and **13**, which was obtained by SEM addition, was treated with 2,4,6-collidine. [f] The ratio of **12**/**13** was 74:26 (^1H NMR analysis). [g] Total yield in two steps. [h] 3 equiv of **11a** was used. Isolated yield based on (*R*)-**1d**. [i] The ratio of **12**:**13** was 85:15 (^1H NMR analysis). [j] **13** was not detected by ^1H NMR analysis. [k] Stirred for 5 h.

The representative results are summarized in Table 6. For acyclic or exocyclic trisubstituted alkenes **11a**−**d**, the reaction with **1d** proceeded smoothly even at −97 °C and afforded the corresponding homoallylic ethers **12a**−**d** in good enantioselectivities and good yields. The dehydrochlorination condition using collidine was applied to **11b** in 99% regioselectivity. Other substrates did not give significant amounts of chlorinated byproduct. In one particular case, cyclization occurred with SEM addition

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(16) For reviews on the Prins reaction, see: (a) Adams, D. R.; Bhatnagar, S. P. *Synthesis* **1977**, 661. (b) Snyder, B. B. *Compr. Org. Synth.* **1991**, *2*, 527.

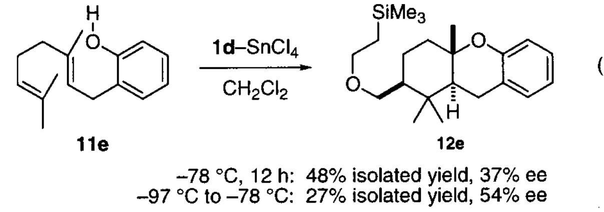
(17) Enantioselective reaction of prochiral alkenes with formaldehyde: Mikami, K.; Yoshida, A. *Synlett* **1995**, 29.

(18) For the diastereoselective Prins reaction of chiral acetals, see: Snider, B. B.; Burbaum, B. W. *Synth. Commun.* **1986**, *16*, 1451.

(19) The % ee of chloride **5a** could not be determined by chiral HPLC and GC analyses.

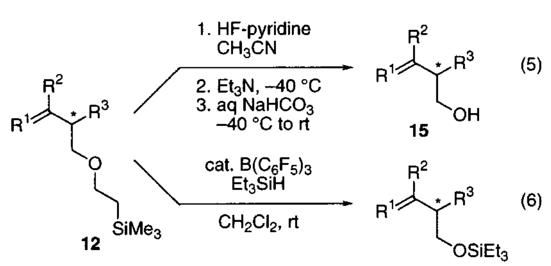
(20) For the successful use of triphenylmethyllithium, see: Kenneth, J. B.; Grundon, M. F.*J. Chem. Soc., Perkin Trans. 1* **1980**, 1820.

(eq 4).[21,22,4e,g,h] One additional remark should be made: A Prins-type SEM addition generally did not proceed well



when SEMCl$-$$SnCl_4$ or SEM phenyl ether$-$$SnCl_4$ was used instead of the chiral reagent **1d**, in contrast with the case of a SEM addition to silyl enol ethers. Racemic homoallylic ethers **12a**$-$**d**, which were required as authentic samples, were quantitatively prepared according to the SEM-addition to **11a**$-$**d** with **2** (Scheme 1) at -78 °C. Therefore, a bidentate chelation system is necessary and would be particularly effective for introducing SEM to alkenes.

The 2-(trimethylsilyl)ethyl group of **12** was cleanly removed by treatment of hydrogen fluoride-pyridine in acetonitrile in most cases (eq 5). A careful quench at low



temperature was required to avoid decomposition of substrates. The $HSiEt_3$/catalytic $B(C_6F_5)_3$ system[23] was also effective for the site-selective reductive cleavage of **12**, especially in the case of unstable substrates, to afford the corresponding homoallylic triethylsilyl ether (eq 6). The subsequent deprotection of alkoxysilanes was unnecessary in the reductive cleavage with $HSiEtMe_2$/cat-$B(C_6F_5)_3$ to give the corresponding homoallylic alcohol directly after mild acidic quench.

The absolute stereochemistry observed in the Prins reaction can be explained in terms of the acyclic extended transition-state (TS) mechanism, which has been postulated in the enantioselective SEM addition to silyl enol ethers with **1d** (Figure 4). In the reaction of **11a** with **1d**, TS **H** is preferable to TS **I**, which is destabilized due to steric repulsion between the ethyl group of **11a** and the adjacent naphthyl group of **1d**.

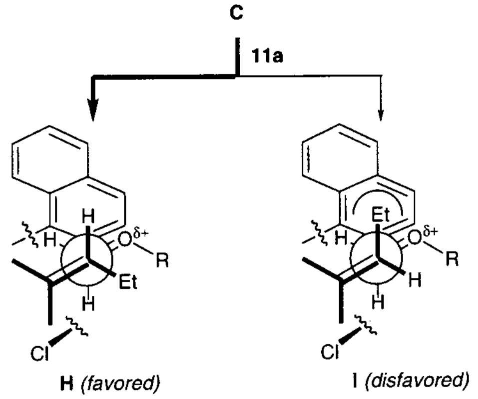
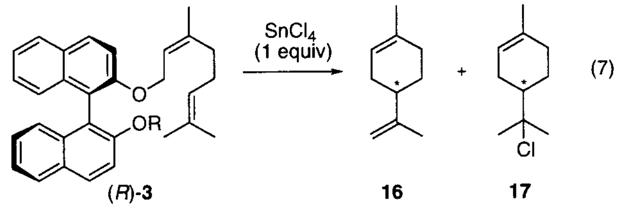


FIGURE 4. Proposed transition-state assemblies of enantioselective Prins-type SEM addition.

Enantioselective Intramolecular Cyclization of Terpenes. In 1983, we reported the first biomimetic asymmetric synthesis of (*R*)-(+)-limonene (up to 77% ee) from (*R*)-BINOL mononeryl ether with bulky organoaluminum reagents.[2e,g] This was one of the successful examples of a chiral leaving group inducing intramolecular cyclization of terpenes.[24] We decided to apply our strategy using BINOL derivatives as a chiral leaving group and $SnCl_4$ to synthesis of cyclic terpenes (eq 7).



(*R*)-**3** **16** **17**

3a: R = H **3d**: R = Bz
3b: R = Me **3e**: R = *p*-CF₃Bz
3c: R = Ts

To investigate effects of leaving groups on enantioselectivity, various neryl-protected (*R*)-BINOL derivatives (*R*)-**3a**$-$**e** were treated with $SnCl_4$ in toluene (Table 7). The reactions of **3a**$-$**c** gave (*S*)-($-$)-limonene with only moderate asymmetric induction (Table 7, entries 1$-$3), whereas the reaction of **3d** gave (*R*)-(+)-limonene with 87% ee (Table 7, entry 4). This remarkable change could be explained as follows: In the case of **3e** and **3f**, $SnCl_4$ probably coordinates to the carbonyl oxygen predominantly, thus the conformation of a **3**$-$$SnCl_4$ complex would be quite different from that in the case of **3a**$-$**c**. While the reactivity in toluene at -78 °C was very low, cyclization completed within 12h in dichloromethane even at -97 °C and (*R*)-(+)-limonene was obtained in 93$-$94% ee (Table 7, entries 5 and 10). Enantioselectivity observed in 1-chloropropane at -78 °C was equal to that in dichloromethane at -97 °C (Table 7, entry 6). Compound **3d** led to results similar to those of **3e** except for the generation of α-terpinene in 1-chloropropane (Table 7, entry 6). α-Terpinyl chloride (**17**) was obtained together with **16** as a single byproduct regardless of reaction

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[21] For the nonasymmetric cyclization of polyprenoids using chloromethyl methyl ether and $AgBF_4$, see: Krimer, M. Z.; Smit, V. A.; Semenovskii, A. V.; Kucherov, V. F. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1968**, 1352; *Chem. Abstr.* **1968**, *69*, 87212s.

[22] For examples of bicyclic sesquiterpenes including chiral tertiary methyl group, see: (a) Goldsmith, D. J.; Deshpande, R. *Synlett* **1995**, 495. (b) San Feliciano, A.; Gordaliza, M.; Miguel del Corral, J. M.; de la Puente, M. L. García-Granda, S.; Salvado, M. A. *Tetrahedron* **1993**, *49*, 9067. (c) Tokoroyama, T.; Kanazawa, R.; Yamamoto, S.; Kakikawa, T.; Suenaga, H.; Miyabe, M. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 1720. (d) Kushlan, D. M.; Faulkner, D. J.; Parkanyi, L.; Clardy, J. *Tetrahedron* **1989**, *45*, 3307. (e) Capon, R. J.; Macleod, J. K.; Coote, S. J.; Davies, S. G.; Gravatt, G. L.; Dordor-Hedgecock, I. M.; Whittaker, M. *Tetrahedron* **1988**, *44*, 1637. (f) Piers, E.; Wai, J. S. M. *J. Chem. Soc., Chem. Commun.* **1987**, 1342.

[23] (a) Gevorgyan, V.; Liu, J.-X.; Rubin, M.; Benson, S.; Yamamoto, Y. *Tetrahedron Lett.* **1999**, *40*, 8919. (b) Blackwell, J. M.; Foster, K. L.; Beck, V. H.; Piers, W. E. *J. Org. Chem.* **1999**, *64*, 4887.

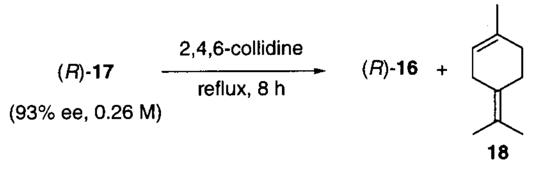
[24] For the intermolecular version in terpene biosynthesis, see: (a) Coates, R. M. *Fortschr. Chem. Org. Naturst.* **1976**, *33*, 73. (b) Poulter, C. D.; Rilling, H. C. *Acc. Chem. Res.* **1978**, *11*, 307. (c) Poulter, C. D.; Rilling, H. C. In *Biosynthesis of Isoprenoid Compounds*; Porter, J. W., Ed.; Wiley: New York, 1981; Vol. 1, p 161.

TABLE 7. Intramolecular Cyclization of 3 Promoted by Lewis Acid[a]

entry	**3**	solvent	*T*, time (°C, h)	ee[b] (%) (config)	yield[c] (%) **16**/**17**[d]
1	**3a**	toluene	−78, 12	18 (*S*)	
2	**3b**	toulene	−78, 12	52 (*S*)	
3	**3c**	toluene	−78, 12	25 (*S*)	*e*
4	**3d**	toluene	−78, 6	87 (*R*)	
5	**3d**	CH_2Cl_2	−97, 4	93 (*R*)	40:51
6	**3d**	PrCl	−78, 12	92 (*R*)	37[f]:47
7[g]	**3d**	toluene	−78, 12	48 (*R*)	
8	**3e**	toluene	−78, 12	89 (*R*)	24:33
9	**3e**	toluene	−97, 6	92 (*R*)	*e*
10	**3e**	CH_2Cl_2	−97, 6	94 (*R*)	38:62
11	**3e**	PrCl	−78, 12	92 (*R*)	40:48

[a] Unless otherwise noted, the reaction proceeded with >99% conversion. [b] Ee of **16**. Determined by GC analysis. [c] Isolated yields. [d] The ratio was estimated by GC and ^{1}H NMR spectral analyses. [e] Some of the starting material **3** remained. [f] α-Terpinene was produced in 6% yield. [g] $TiCl_4$ was used in place of $SnCl_4$.

conditions (see the Experimental Section); nonetheless, desired product **16** could be isolated by column chromatography on silica gel. **17** was transformed to an 81:19 mixture of **16** and terpinolene (**18**) in 90% yield by heating in 2,4,6-collidine under reflux conditions without reducing the optical purity (eq 8). Therefore, (*R*)-**16** was obtained with 93% ee in 77% overall yield from **3d** in two steps (entry 5, Table 7 → eq 8).



(8)

16+**18**: 90% yield, **16**:**18**=81:19, **16**: 93% ee

As described previously, we believe that the chiral auxiliary could discriminate one of two possible enantiotopic faces in enantioselective SEM addition. In the case of intramolecular cyclization, the mechanism could, however, be a little different from the previous case because a new chiral center is constructed on a chiral compound. Shown in Figure 5 is a proposed transition-state model. The isoprenyl group can approach the activated carbon center from two possible faces, *anti-endo* **J** and *anti-exo* **K** without chiral auxiliary. The topologically related linalyl system is known to cyclize preferentially from an *anti-endo* conformation,[25] and a similar preference is expected for its allylic isomer.[26] Then, *anti-endo* **J** has two possible enantiomeric transition-state structures, **L** and **M**, the former of which is sterically more favorable than the latter. The complex **3** has a cavity between binaphthyl group and $SnCl_4$, and six-membered limonene seems to fit in there.

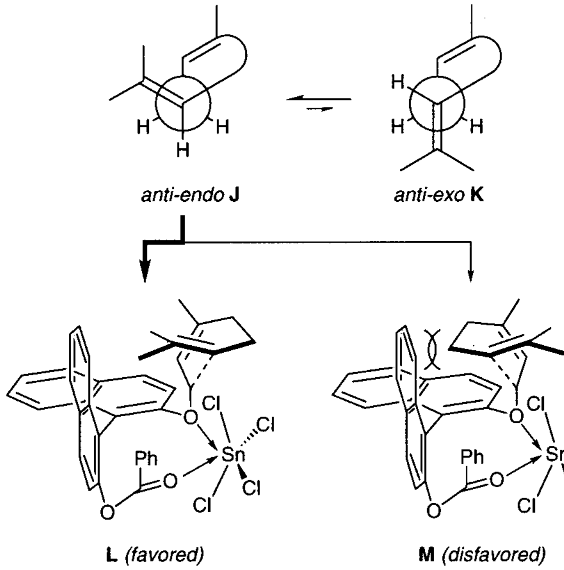
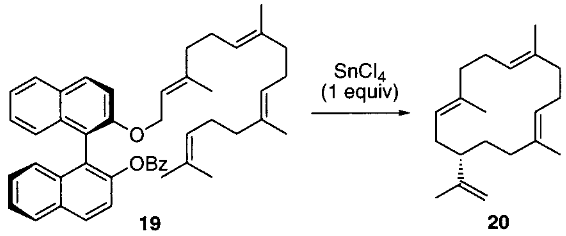


FIGURE 5. Proposed transition-state model for the enantioselective intramolecular cyclization of (*R*)-**3d**.

We next examined synthesis of a 14-membered cyclic diterpene, cembrene A (**20**) by macrocyclization of *all-E*-geranylgeranyl ether **19** derived from monobenzoate of (*R*)-BINOL (eq 9). A cembranoid **20**, which has been isolated from termite,[27] tree[28a] and soft coral,[29] has been shown to be a highly active trail pheromone of the Australian termite *Nasuititermis exitiosus*. The geometrical structure of **20** has been confirmed to be 3*E*,7*E*,-11*E*, and the absolute configuration has been determined to be 1*R*. Attempts to synthesize **20** have used a variety of methodologies;[30] however, as far as we know, there has been only one report on its enantioselective synthesis.[30e] The reaction of (*R*)-**19** in the presence of 1 equiv of $SnCl_4$ gave the desired cyclic compound **20** with many isomers and byproducts that were generated by intermolecular reaction. The ratio of **20** and other byproducts was greatly



(9)

CH_2Cl_2, −78 °C, 3 h: ca. 10% yield, 32% ee (*S*)
PrCl, −78 °C, 60 h: 7% isolated yield (>95% purity), 19% ee (*S*)

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[25] Godtfredsen, S.; Obrecht, J. P.; Arigoni, D. *Chimia* **1977**, *31*, 62.

[26] Poulter, C. D.; King, C.-H. R. *J. Am. Chem. Soc.* **1982**, *104*, 1420, 1422.

[27] (a) Moore, B. P. *Nature (London)* **1966**, *211*, 746. (b) Birch, A. J.; Brown, M. W. V.; Corrie, J. E. T.; Moore, B. P. *J. Chem. Soc., Perkin Trans. 1* **1972**, 2653.

[28] (a)Patil, V. D.; Nayak, V. R.; Dev, S. *Tetrahedron* **1973**, *29*, 341. (b) Kato, T.; Suzuki, M.; Kobayashi, T.; Moore, B. P. *J. Org. Chem.* **1980**, *45*, 1126.

[29] (a) Patil, V. D.; Nayak, V. R.; Dev, S. *Tetrahedron* **1972**, *28*, 2341. (b) Vanderah, D. J.; Rutedge, N.; Schnitz, F. J.; Cierezko, L. S. *J. Org. Chem.* **1978**, *43*, 1614.

[30] (a) Kodama, M.; Matsuki, Y.; Ito, S. *Tetrahedron Lett.* **1975**, *16*, 3065. (b) Kitahara, Y.; Kato, T.; Kobayashi, T. *Chem. Lett.* **1976**, 219. (c) Vig, O. P.; Nanda, R.; Cauba, R.; Puri, S. K. *Ind. J. Chem.* **1985**, *24B*, 918. (d) Schwabe, R.; Farkas, I.; Pfander, H. *Helv. Chim. Acta* **1988**, *71*, 292. (e) Farkas, I.; Pfander, H. *Helv. Chim. Acta* **1990**, *73*, 1980. (f) Pattenden, G.; Smithies, A. J. *Synlett* **1992**, 577. (g) Li, W. D.; Li, Y.; Li, Y. L. *Chin. J. Chem.* **1992**, *10*, 92. (h) Li, W. D.; Li, Y.; Li, Y. L. *Science in China* **1993**, *36*, 1161; *Chem. Abstr.* **1994**, *120*, 218236z. (i) Yue, X. J.; Li, Y. L. *Bull. Soc. Chim. Belg.* **1995**, *104*, 69. (j) Pattenden, G.; Smithies, A. J. *J. Chem. Soc., Perkin Trans. 1* **1995**, 57. (k) Yue, X.; Li, Y. *Synthesis* **1996**, 736.

influenced by the solvent effect. Toluene, dichloromethane, chlorobenzene, and other solvents were examined, use of 1-chloropropane resulted in the best purity in these solvents, and **20** could be isolated with >95% purity. When the reaction was carried out in dichloromethane, **20** was obtained with better ee, 32%. The absolute configuration of its major enantiomer was determined to be 1*S* by comparing the specific rotation with data for natural (*R*)-**20**. The absolute stereochemistry of **20** was opposite to that of **16**, although the same chiral leaving group derived from (*R*)-BINOL was used for both reactions. Limitations of yield and ee in this reaction are believed to be due to a disproportion between the 14-membered ring and reacting space on the complex of **19** and $SnCl_4$. Although six-membered limonene could fit in a cavity between the binaphthyl group and $SnCl_4$, the 14-membered ring was too big to fit in. Despite the low optical yield and low chemical yield of **20**, the macrocyclization is a very attractive alternative to the multistep synthesis from naturally occurring chiral synthons.

Conclusions

We have developed a new chiral hydroxymethylation reagent that has a chiral leaving group and demonstrated that this reagent can introduce a functionalized carbon directly to prochiral silyl enol ethers and trisubstituted alkenes with high enantioselectivities. The electrophilic addition proceeds through the S_N2 substitution mechanism with cleavage of an acetal, which is dual activated by $SnCl_4$ and the γ-effect of silicon. The present protocol is highly effective for the asymmetric construction of not only tertiary but also quaternary carbon stereocenters. Our chiral leaving group−Lewis acid system is also effective for enantioselective synthesis of cyclic terpenes, which has no remarkable functional group.

Experimental Section

(*R*)-2,2′-Bis[2-(trimethylsilyl)ethoxymethoxy]-1,1′-binaphthyl (1d). To a solution of (*R*)-2,2′-dihydroxy-1,1′-binaphthyl (2.86 g, 10 mmol) in dry THF (100 mL) was added sodium hydride (60% dispersion in mineral oil, 880 mg, 22 mmol) portionwise at 0 °C. After being stirred for 1 h, 2-(trimethylsilyl)ethoxymethyl chloride (3.89 mL, 22 mmol) was added dropwise, and the reaction mixture was allowed to warm to room temperature. After being stirred for 2 h at the same temperature, the mixture was quenched with brine and extracted with ether. The combined organic layers were dried over anhydrous $MgSO_4$, concentrated, and purified by column chromatography on silica gel using hexanes−ethyl acetate (50:1 to 35:1) as eluent to give **1d** (5.45 g, >99% yield) as a viscous oil: TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.56$; IR (film) 2953, 1509, 1248, 1034, 1015, 860, 835 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ −0.11 (s, 18H), 0.65−0.82 (m, 4H), 3.29−3.42 (m, 4H), 5.00 (d, J = 6.9 Hz, 2H), 5.15 (d, J = 6.9 Hz, 2H), 7.11−7.35 (m, 6H), 7.59 (d, J = 9.0 Hz, 2H), 7.59 (d, J = 7.8 Hz, 2H), 7.94 (d, J = 8.7 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ −1.2, 18.2, 66.3, 94.0, 117.8, 121.6, 124.3, 125.9, 126.6, 128.2, 129.6, 130.1, 134.3, 153.1; $[\alpha]^{31.0}_D = +71.5$ (c = 1.86, $CHCl_3$). Anal. Calcd for $C_{32}H_{42}O_4Si_2$: C, 70.28; H, 7.74. Found: C, 70.32; H, 7.69.

(*R*)-2,2′-Di(methoxymethoxy)-1,1′-binaphthyl (1a).[31] Compound **1a** was prepared from chloromethyl methyl ether and (*R*)-BINOL as described above for the preparation of **1d**.

(*R*)-2,2′-Di(benzyloxymethoxy)-1,1′-binaphthyl (1b). Compound **1b** was prepared from benzyloxymethyl chloride and (*R*)-BINOL as described above for the preparation of **1d**: TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.38$; IR (KBr) 2835, 1622, 1510, 1381, 1148, 756 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 4.34 (s, 4H), 5.10 (d, J = 7.2 Hz, 2H), 5.20 (d, J = 7.2 Hz, 2H), 7.05−7.38 (m, 16H), 7.66 (d, J = 9.0 Hz, 2H), 7.90 (d, J = 8.2 Hz, 2H), 7.98 (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 69.7, 92.7, 117.1, 121.1, 124.2, 125.6, 126.5, 127.7, 127.9, 128.0 (2C), 128.4 (2C), 129.5, 129.9, 134.1, 137.3, 152.6; $[\alpha]^{24.5}_D = +39.8$ (c = 3.44, $CHCl_3$). Anal. Calcd for $C_{36}H_{30}O_4$: C, 82.11; H, 5.74. Found: C, 82.10; H, 5.76.

(*R*)-2-Methoxy-2′-[2-(trimethylsilyl)ethoxymethoxy]-1,1′-binaphthyl (1c). Compound **1c** was prepared from 2-(trimethylsilyl)ethoxymethyl chloride and (*R*)-BINOL-Me[32] as described above for the preparation of **1d**: TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.50$; IR (KBr) 2951, 1593, 1509, 1252, 1084, 1017, 810 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ −0.10 (s, 9H), 0.72−0.80 (m, 2H), 3.35−3.42 (m, 2H), 3.77 (s, 3H), 5.03 (d, J = 7.0 Hz, 1H), 5.14 (d, J = 7.0 Hz, 1H), 7.10−7.38 (m, 6H), 7.46 (d, J = 9.0 Hz, 1H), 7.60 (d, J = 9.0 Hz, 1H), 7.87 (dd, J = 3.6, 8.2 Hz, 2H), 7.96 (t, J = 9.3 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ −1.3, 18.0, 56.9, 66.0, 93.7, 114.1, 117.6, 123.6, 124.0, 125.5, 125.6, 126.3, 126.5, 128.0, 128.1, 128.3, 129.2, 129.4, 129.5, 130.0, 134.1, 152.9, 155.0; $[\alpha]^{24.2}_D = +54.7$ (c = 3.06, $CHCl_3$). Anal. Calcd for $C_{27}H_{30}O_3Si$: C, 75.31; H, 7.02. Found: C, 75.37; H, 7.05.

(*R*)-2,2′-Bis[2-(*tert*-butyldimethylsilyl)ethoxymethoxy]-1,1′-binaphthyl (1e). (a) To a stirred solution of ethylvinyl ether (8.8 mL, 92 mmol) in THF (35 mL) was added a 1.59 M solution of *tert*-butyllithium (48 mL, 77 mmol) in pentane dropwise under argon atmosphere at −78 °C. The mixture was slowly warmed to 0 °C by removal of the solid dry ice from the bath and then cooled to −78 °C again, and *tert*-butyldimethylsilyl trifluoromethanesulfonate (13.8 mL, 60 mmol) was added to the mixture. After being stirred for 1 h at room temperature, the mixture was quenched with ice and a saturated $NaHCO_3$ solution, extracted with pentane, and washed with water six times. The combined organic layers were dried over anhydrous $MgSO_4$, concentrated, and distilled. Obtained *tert*-butyldimethyl(α-ethoxyvinyl)silane (6.3 g, 33.6 mmol) was then added to a 1.06 M solution of $BH_3{\cdot}THF$ (78 mL, 83 mmol) in dry THF. After 2 h at reflux temperature, NaOH solution was added followed by the dropwise addition of 30% H_2O_2 (30 mL), and the mixture was refluxed for 1.5 h. The aqueous phase was extracted with ether, and the combined organic layers were washed with water, dried with K_2CO_3, concentrated, and distilled to give 2-(*tert*-butyldimethylsilyl)ethanol.[33] (b) Compound **1e** was prepared as described above for the preparation of **1d** from (*R*)-BINOL and 2-(*tert*-butyldimethylsilyl)ethoxymethyl chloride, which was prepared from 2-(*tert*-butyldimethylsilyl)ethanol with paraformaldehyde and gaseous hydrogen chloride:[34] TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.57$; IR (film) 2953, 1509, 1472, 1235, 1015, 828, 758 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ −0.19 (s, 12H), 0.79 (s, 18H), 0.87−1.08 (m, 4H), 3.51−3.57 (m, 4H), 5.19 (d, J = 7.1 Hz, 2H), 5.35 (d, J = 7.1 Hz, 2H), 7.30−7.54 (m, 6H), 7.78 (d, J = 9.0 Hz, 2H), 8.05 (d, J = 8.1 Hz, 2H), 8.14 (d, J = 9.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ −6.0 (2C), 13.9, 16.4, 26.5, 66.3, 93.7, 117.6, 121.4, 124.1, 125.7, 126.4, 128.0, 129.4, 129.9, 134.1, 152.9; $[\alpha]^{26.6}_D = +56.5$ (c = 4.30, $CHCl_3$). Anal. Calcd for $C_{42}H_{46}O_4Si_2$: C, 75.18; H, 6.91. Found: C, 75.18; H, 7.10.

(*R*)-2,2′-Bis[2-(dimethylphenylsilyl)ethoxymethoxy]-1,1′-binaphthyl (1f). (a) Ethyl triphenylsilyl acetate, which was prepared following the procedure described by Fessenden,[35] was reduced by lithium aluminum hydride to give

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2-(dimethylphenylsilyl)ethanol. (b) Compound **1f** was prepared as described above for the preparation of **1d** from (*R*)-BINOL and 2-(dimethylphenylsilyl)ethoxymethyl chloride, which was prepared from 2-(dimethylphenylsilyl)ethanol with paraformaldehyde and gaseous hydrogen chloride:[34] TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.49$; IR (film) 2955, 1507, 1235, 1034, 820, 752 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.16 (s, 12H), 0.88−1.06 (m, 4H), 3.32−3.38 (m, 4H), 4.91 (d, J = 6.9 Hz, 2H), 5.08 (d, J = 6.9 Hz, 2H), 7.08−7.40 (m, 16H), 7.53 (d, J = 8.7 Hz, 2H), 7.85 (d, J = 7.8 Hz, 2H), 7.91 (d, J = 9.3 Hz, 2H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −2.7, −2.6, 17.1, 65.8, 93.7, 117.5, 121.3, 124.0, 125.7, 126.3, 127.9, 128.0, 129.1, 129.4, 129.9, 133.5, 134.1, 138.6, 152.9; $[\alpha]^{26.8}_{D}$ = +48.1 (*c* = 4.27, CHCl$_3$). Anal. Calcd for $C_{38}H_{54}O_4Si_2$: C, 72.33; H, 8.63. Found: C, 72.45; H, 8.79.

^{13}C NMR Assignments for a 1:1 2a−SnCl$_4$ Complex.

(*R*)-2,2′-Bis(methoxymethoxy)-1,1′-binaphthyl (1a): ^{13}C NMR (75 MHz, CD$_2$Cl$_2$, −78 °C) δ 57.9, 95.6, 117.7, 121.5, 126.1, 126.9, 128.6, 130.1, 131.2, 131.4, 135.5, 154.0.

1a−SnCl$_4$: ^{13}C NMR (75 MHz, CD$_2$Cl$_2$, −78 °C) δ 60.1, 102.2 (br), 123.3 (br), 126.0 (br), 128.2 (2C), 129.3, 130.4, 132.6, 133.2, 134.7, 150.8 (br).

(*R*)-2-Methoxy-2′-methoxymethoxy-1,1′-binaphthyl (1g): ^{13}C NMR (75 MHz, CD2Cl2, −78 °C) δ 57.8, 58.0, 95.3, 114.7, 117.7, 119.7, 121.6, 125.5, 126.1, 126.7, 126.9, 128.5, 128.6, 130.1, 130.5, 131.2, 131.3, 131.5, 135.5, 135.6, 153.8, 156.3.

1g−SnCl$_4$: ^{13}C NMR (75 MHz, CD$_2$Cl$_2$, −78 °C) δ 60.1, 66.9 (br), 103.0 (br), 122.7 (br), 123.7 (br), 124.9 (br), 126.3 (br), 128.1, 128.3, 129.4, 130.4, 130.5, 132.5, 133.0, 133.2, 133.3, 134.5 134.7 150.0 (br), 154.2.

(*R*)-2,2′-Dimethoxy-1,1′-binaphthyl (1h): ^{13}C NMR (75 MHz, CD$_2$Cl$_2$, −78 °C) δ 58.2, 114.8, 119.8, 125.5, 126.6, 128.5, 130.1, 130.5, 131.5, 135.4, 156.3.

1h−SnCl$_4$: ^{13}C NMR (75 MHz, CD$_2$Cl$_2$, −78 °C) δ 68.6, 124.6, 125.3, 128.6, 128.9, 129.6, 130.6, 133.3, 133.9, 134.3, 153.7.

Preparation of Silyl Enol Ethers 4 and 6a−f. Compounds **4**, **6a**, and **6b** were prepared as described in the literature.[3f] Compounds **6c**,[36] **6d**,[37] **6e**,[38] and **6f**[6] were prepared by treating the corresponding ketones with LDA in THF, followed by silylation (TMSCl, Et$_3$N).

Representative Procedure for the Enantioselective 2-(Trimethylsilyl)ethoxymethylation of Silyl Enol Ethers with (*R*)-1d in the Presence of Tin Tetrachloride and the Subsequent Deprotection of the 2-(Trimethylsilyl)-ethyl Group. To a solution of a silyl enol ether (0.5 mmol) and (*R*)-**1d** (0.55 mmol) in dichloromethane or 1-chloropropane (2.5 mL) was added a 1 M solution of SnCl$_4$ (0.55 mmol) in dichloromethane over 30 min under argon atmosphere at the temperature indicated in Table 1 or 3 (a pentane−nitrogen liquid bath, −125 °C; a hexane−nitrogen liquid bath, −97 °C; an acetone−dry ice bath, −78 °C). After being stirred under the conditions indicated in Table 1 or 3, the reaction was quenched with triethylamine (0.55 mmol) and a saturated NaHCO$_3$ solution. Then the mixture was warmed to room temperature and extracted with ether. The combined organic layers were dried over anhydrous MgSO$_4$, concentrated, and purified by column chromatography on silica gel to give the desired a-[2-(trimethylsilyl)ethoxymethyl] ketone. The ee of the ketone was determined by HPLC or GC analysis or by subsequent conversion to the corresponding a-hydroxymethyl ketone or its trifluoroacetate and GC analysis.

To a solution of α-[2-(trimethylsilyl)ethoxymethyl] ketone (0.5 mmol), obtained in the above reaction, in THF (1.5 mL) was added hydrogen fluoride (70%)−pyridine (1.5 mL) at −78 °C. The reaction mixture was allowed to warm to room temperature. After being stirred for 2−3 h, the solution was quenched with water and extracted with ether twice, and the combined extracts were dried over MgSO$_4$, filtered, and concentrated. The crude product was purified by column chromatography on silica gel to give the desired α-hydroxymethyl ketone in quantitative yield.

The physical properties and analytical data of α-[2-(trimethylsilyl)ethoxymethyl] ketones and α-hydroxymethyl ketones thus are listed below.

(*R*)-(+)-2-Phenyl-2-methoxymethylcyclohexanone (5a): TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.46$; HPLC (Chiralpak AD, hexane−*i*-PrOH = 200:1, flow rate = 1.0 mL/min) t_R = 7.76 (minor), 9.36 (major) min; IR (film) 2938, 1705, 1449, 1105, 702 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.68−1.80 (m, 3H), 1.90−2.09 (m, 2H), 2.26−2.32 (m, 2H), 2.70−2.78 (m, 1H), 3.24 (s, 3H), 3.29 (d, J = 9.4 Hz, 1H), 3.74 (d, J = 9.4 Hz, 1H), 7.22−7.39 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 21.3, 27.8, 32.2, 40.3, 58.4, 59.6, 79.1, 127.1 (2C), 127.2, 129.0 (2C), 138.8, 212.2; $[\alpha]^{26.0}_{D}$ = +52.3 (*c* = 0.34, CHCl$_3$) for 23% ee. Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 76.91; H, 8.43.

(*R*)-(+)-2-Phenyl-2-benzyloxymethylcyclohexanone (5b): TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.48$; HPLC (Chiralpak AD, hexane−*i*-PrOH = 200:1, flow rate = 1.0 mL/min) t_R = 9.86 (minor), 10.98 (major) min; IR (film) 2938, 1705, 1453, 1100, 700 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.68−1.80 (m, 3H), 1.84−2.10 (m, 2H), 2.24−2.32 (m, 2H), 2.77−2.84 (m, 1H), 3.41 (d, J = 9.2 Hz, 1H), 3.81 (d, J = 9.2 Hz, 1H), 4.35 (d, J = 12.3 Hz, 1H), 4.46 (d, J = 12.3 Hz, 1H), 7.17−7.36 (m, 10H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 21.3, 27.8, 32.4, 40.2, 58.5, 73.3, 76.5, 127.1, 127.2 (2C), 127.3, 127.4 (2C), 128.3, 128.9, 138.7 (2C), 138.9 (2C), 212.3; $[\alpha]^{26.0}_{D}$ = +34.8 (*c* = 1.30, CHCl$_3$) for 18% ee. Anal. Calcd for $C_{20}H_{22}O_2$: C, 81.60; H, 7.53. Found: C, 81.56; H, 7.64.

(*R*)-(+)-2-Phenyl-2-[2-(trimethylsilyl)ethoxymethyl]cyclohexanone (5d). TLC (hexane−diethyl ether = 10:1) R_f = 0.25; HPLC (Chiralpak AD, hexane−*i*-PrOH = 100:1, flow rate = 0.25 mL/min) t_R = 17.29 (minor), 18.19 (major) min; IR (film) 2951, 1709, 1105, 860, 837, 702 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.07 (s, 9H), 0.82 (t, J = 8.1 Hz, 2H), 1.65−1.80 (m, 3H), 1.88−2.10 (m, 2H), 2.25−2.32 (m, 2H), 2.75 (dd, J = 3.0, 15.0 Hz, 1H), 3.26−3.35 (m, 1H), 3.30 (d, J = 9.3 Hz, 1H), 3.38−3.50 (m, 1H), 3.75 (d, J = 9.3 Hz, 1H), 7.20−7.36 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.1 (3C), 18.1, 21.6, 28.0, 32.5, 40.5, 58.6, 69.1, 76.8, 127.3, 127.4 (2C), 129.1 (2C), 139.3, 212.5; $[\alpha]^{26.1}_{D}$ = +163.1 (*c* = 3.09, CHCl$_3$) for 93% ee. Anal. Calcd for $C_{18}H_{28}O_2Si$: C, 71.00; H, 9.27. Found: C, 70.93; H, 9.28. This compound was converted to (*R*)-2-hydroxymethyl-2-phenylcyclohexanone: TLC (hexanes−ethyl acetate = 4:1) R_f = 0.18; HPLC (Chiralpak OD-H, hexane−*i*-PrOH = 9:1, flow rate = 1.0 mL/min) t_R = 6.51 (major), 7.28 (minor) min; IR (film) 3400 (br), 2938, 1701, 1032, 702 cm^{-1};Å@^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.63−1.83 (m, 3H), 1.92−2.03 (m, 1H), 2.13−2.47 (4H), 2.54−2.64 (m, 1H), 3.36 (dd, J = 8.7, 11.4 Hz, 1H), 3.88 (dd, J = 6.3, 11.4 Hz, 1H), 7.17−7.42 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 21.4, 28.6, 32.2, 40.7, 60.3, 70.4, 127.2 (2C), 127.7, 129.4 (2C), 138.5, 216.2. Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.89. Found: C, 76.47; H, 7.88.

(*R*)-(+)-2-Phenyl-2-[2-(*tert*-butyldimethylsilyl)ethoxymethyl]cyclohexanone (5e): TLC (hexane−diethyl ether = 20:1) R_f = 0.20; IR (film) 2951, 1709, 1125, 828, 702 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.15 (s, 3H), −0.13 (s, 3H), 0.81 (s, 9H), 0.82−0.90 (m, 2H), 1.69−1.79 (m, 3H), 1.88−2.10 (m, 2H), 2.26−2.31 (m, 2H), 2.72−2.78 (m, 1H), 3.25−3.48 (m, 2H), 3.30 (d, J = 9.6 Hz, 1H), 3.76 (d, J = 9.6 Hz, 1H), 7.22−7.39 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −6.0, −5.9, 13.9, 16.5, 21.3, 26.5 (3C), 27.7, 32.3, 40.3, 58.4, 69.1, 76.6, 127.1 (2C), 127.1, 128.9 (2C), 139.0, 212.2; $[\alpha]^{26.8}_{D}$ = +109.58 (*c* = 3.45, CHCl$_3$) for 76% ee. Anal. Calcd for $C_{21}H_{34}O_2Si$: C, 72.78; H, 9.89. Found: C, 72.68; H, 10.03.

(*R*)-(+)-2-Phenyl-2-[2-(dimethylphenylsilyl)ethoxymethyl]cyclohexanone (5f): TLC (hexanes−ethyl acetate =

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4:1) R_f = 0.51; IR (film) 2951, 1709, 1118, 822, 758, 702 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.20 (s, 3H), 0.21 (s, 3H), 1.06 (t, J = 8.0 Hz, 2H), 1.67−1.76 (m, 3H), 1.86−2.03 (m, 2H), 2.24−2.30 (m, 2H), 2.67−2.74 (m, 1H), 3.26−3.36 (m, 1H), 3.28 (d, J = 9.4 Hz, 1H), 3.42−3.51 (m, 1H), 3.72 (d, J = 9.4 Hz, 1H), 7.20−7.47 (m, 10H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −2.7 (2C), 17.0, 21.2, 27.6, 32.2, 40.1, 58.2, 68.5, 76.7, 127.0, 127.1 (2C), 127.7 (2C), 128.7 (2C), 128.8, 133.5 (2C), 138.9, 139.0, 212.0; $[\alpha]^{23.6}_{D}$ = +93.7 (c = 2.77, CHCl$_3$) for 67% ee. Anal. Calcd for $C_{23}H_{30}O_2Si$: C, 75.36; H, 8.25. Found: C, 75.36; H, 8.44.

(+)-2-(4-Methoxyphenyl)-2-[2-(trimethylsilyl)ethoxymethyl]cyclohexanone (7a). TLC (hexane-diethyl ether = 10:1) R_f = 0.23; HPLC (Chiralpak AD, hexane−i-PrOH = 40:1, flow rate = 0.5 mL/min) t_R = 10.2 (minor), 11.1 (major) min; IR (film) 2951, 1707, 1512, 1250, 860, 831 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.06 (s, 9H), 0.83 (t, J = 8.4 Hz, 2H), 1.64−1.79 (m, 3H), 1.86−2.09 (m, 2H), 2.28 (t, J = 5.2 Hz, 2H), 2.67 (dd, J = 3.4, 15.2 Hz, 1H), 3.25 (d, J = 9.4 Hz, 1H), 3.28−3.37, (m, 1H), 3.40−3.50 (m, 1H), 3.73 (d, J = 9.4 Hz, 1H), 3.80 (s, 3H), 6.88 (d, J = 8.7 Hz, 2H), 7.15 (d, J = 8.7 Hz, 2H); $[\alpha]^{27.1}_{D}$ = +163.0 (c = 1.68, CHCl$_3$) for 82% ee. Anal. Calcd for $C_{19}H_{30}O_3Si$: C, 68.22; H, 9.04. Found: C, 68.19; H, 9.07.

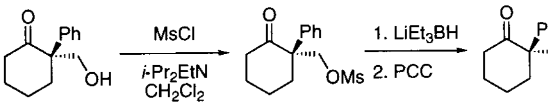
(+)-2-Phenyl-2-[2-(trimethylsilyl)ethoxymethyl]cycloheptanone (7b): TLC (hexane−diethyl ether = 10:1) R_f = 0.38; IR (film) 2951, 1701, 1107, 860, 837, 700 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.10 (s, 9H), 0.78 (t, J = 8.4 Hz, 2H), 1.34−1.58 (m, 3H), 1.75−2.04 (m, 4H), 2.27−2.34 (m, 1H), 2.46−2.54 (m, 1H), 2.72 (dd, J = 9.2, 14.7 Hz, 1H), 3.22−3.44 (m, 2H), 3.62 (d, J = 10.4 Hz, 1H), 3.70 (d, J = 10.4 Hz, 1H), 7.20−7.35 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.1 (3C), 18.1, 24.7, 27.1, 31.1 (2C), 42.1, 60.2, 69.1, 75.0, 127.2, 127.4 (2C), 128.7 (2C), 141.6, 214.5; $[\alpha]^{27.5}_{D}$ = +103.4 (c = 1.58, CHCl$_3$) for 86% ee. Anal. Calcd for $C_{19}H_{30}O_2Si$: C, 71.64; H, 9.49. Found: C, 71.73; H, 9.47. The ee was determined by conversion to 2-(hydroxymethyl)-2-phenylcycloheptanone and HPLC analysis: HPLC (Chiralcel OD-H, hexane−i-PrOH = 9:1, flow rate = 0.5 mL/min) t_R = 15.25 (major), 17.12 (minor) min; IR (film) 3400 (br), 2932, 1698, 1057, 700 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.36−1.60 (m, 3H), 1.76−1.86 (m, 2H), 1.95−2.11 (m, 2H), 2.33−3.57 (m, 4H), 3.69 (dd, J = 5.7, 10.8 Hz, 1H), 3.82 (d, J = 10.8 Hz, 1H), 7.15−7.39 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 25.2, 26.9, 30.9, 32.6, 42.3, 61.0, 70.3, 127.2 (2C), 127.6, 129.1 (2C), 140.9, 217.2. Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 77.06; H, 8.30.

(+)-2,4-Diphenyl-1-[2-(trimethylsilyl)ethoxy]-3-butanone (7c): TLC (hexane−diethyl ether = 10:1) R_f = 0.25; HPLC (Chiralcel OB−H, hexane−i-PrOH = 50:1, flow rate = 0.5 mL/min) t_R = 13.2 (major), 18.5 (minor) min; IR (film) 1717, 1248, 1103, 860, 837, 700 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.04 (s, 9H), 0.86 (t, J = 8.4 Hz, 2H), 3.38−3.55 (m, 3H), 3.71 (s, 2H), 4.01 (t, J = 8.6 Hz, 1H), 4.06−4.11 (m, 1H), 7.05−7.35 (m, 10H); ^{13}C NMR (CDCl$_3$, 300 MHz) δ −1.1 (3C), 18.3, 49.9, 58.1, 68.8, 71.7, 127.2, 127.9, 128.8 (4C), 129.2 (2C), 130.0 (2C), 134.1, 136.1, 206.8; $[\alpha]^{29.6}_{D}$ = +60.7 (c = 1.00, CHCl$_3$) for 64% ee. Anal. Calcd for $C_{21}H_{28}O_2Si$: C, 74.07; H, 8.29. Found: C, 74.02; H, 8.31.

(+)-2,6,6-Trimethyl-2-[2-(trimethylsilyl)ethoxymethyl]cyclohexanone (7d): TLC (hexane-diethyl ether = 10:1) R_f = 0.30; IR (film) 2951, 1701, 1109, 860, 839 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.87 (t, J = 7.8 Hz, 2H), 1.07 (s, 3H), 1.08 (s, 3H), 1.12 (s, 3H), 1.55−1.86 (m, 5H), 2.00−2.09 (m, 1H), 3.10 (d, J = 8.9 Hz, 1H), 3.41−3.53 (m, 2H), 3.57 (d, J = 8.9 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.0 (3C), 18.1, 18.2, 23.7, 27.3, 28.1, 35.0, 29.7, 44.7, 49.0, 68.8, 77.1, 219.4; $[\alpha]^{28.5}_{D}$ = +4.25 (c = 2.84, CHCl$_3$) for 71% ee. Anal. Calcd for $C_{15}H_{30}O_2Si$: C, 66.61; H, 11.18. Found: C, 66.59; H, 11.21. The ee was determined by conversion to 2,6,6-trimethyl-2-(hydroxymethyl)cyclohexanone, trifluoroacetylation, and GC analysis. **2,6,6-Trimethyl-2-(hydroxymethyl)cyclohexanone:** TLC (hexanes−ethyl acetate = 4:1) R_f = 0.18; IR (film) 3500 (br), 2932, 1692, 1466, 1051 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.07 (s, 3H), 1.18 (s, 3H), 1.19 (s, 3H), 1.51−1.97 (m, 6H), 2.64 (br, 1H), 3.78 (d, J = 11.1 Hz, 1H), 3.51 (d, J = 11.1 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 17.8, 22.7, 27.3, 27.4, 35.1, 40.0, 45.3, 49.6, 70.7, 223.3. The trifluoroacetate: GC (γ-TA, column temperature = 100 °C, 50 kPa) t_R = 11.31 (minor), 12.01 (major) min; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.08 (s, 3H), 1.18 (s, 3H), 1.20 (s, 3H), 1.62−1.80 (m, 4H), 1.84−1.96 (m, 2H), 4.03 (d, J = 10.2 Hz, 1H), 4.62 (d, J = 10.2 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 17.6, 22.8, 27.4, 27.7, 34.6, 39.5, 44.9, 48.0, 73.3, 112.9, 217.3. Other resonances for the trifluoroacetate could not be discerned. Anal. Calcd for $C_{10}H_{18}O_2$: C, 70.55; H, 10.66. Found: C, 70.61; H, 10.63.

(+)-2,4,4-Trimethyl-1-[2-(trimethylsilyl)ethoxymethoxy]pentan-3-one (7e): TLC (hexane−diethyl ether = 10:1) R_f = 0.38; GC (γ-TA, column temperature = 100 °C, 50 kPa) t_R = 18.55 (minor), 19.35 (major) min; IR (film) 2957, 1707, 11250, 1107, 860, 837 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.86 (t, J = 8.4 Hz, 2H), 1.01 (d, J = 6.6 Hz, 3H), 1.15 (s, 9H), 3.24−3.38 (m, 2H), 3.42 (t, J = 8.4 Hz, 2H), 3.52 (t, J = 7.6 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.1 (3C), 15.8, 18.4, 16.3 (3C), 40.4, 45.0, 68.6, 73.6, 218.7; $[\alpha]^{27.6}_{D}$ = +20.0 (c = 3.00, CHCl$_3$) for 74% ee. Anal. Calcd for $C_{13}H_{28}O_2Si$: C, 63.88; H, 11.54. Found: C, 63.89; H, 11.51. This compound was converted to 1-hydroxy-2,4,4-trimethylpentan-3-one: TLC (hexanes−ethyl acetate = 4:1) R_f = 0.08; IR (film) 3400 (br), 2973, 1701, 1030, 992 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.09 (d, J = 7.2 Hz, 3H), 1.18 (s, 9H), 2.10 (s, 1H), 3.21−3.31 (m, 1H), 3.58−3.62 (m, 1H), 3.71−3.78 (m, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 15.3, 26.2 (3C), 42.0, 45.1, 65.7, 220.7. Anal. Calcd for $C_8H_{16}O_2$: C, 66.63; H, 11.18. Found: C, 66.71; H, 11.11.

(R)-(+)-3,3,5-Trimethyl-6-[2-(trimethylsilyl)ethoxy]hex-1-en-4-one (7f): TLC (hexane−diethyl ether = 10:1) R_f = 0.38; IR (film) 2973, 1713, 1250, 1107, 860, 837 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.87 (t, J = 8.4, 2H), 0.98 (d, J = 6.3 Hz, 3H), 1.22 (s, 6H), 3.19−3.32 (m, 2H), 3.42 (t, J = 8.4 Hz, 2H), 3.42−3.53 (m, 1H), 5.13−5.24 (m, 2H), 5.95 (dd, J = 10.5, 17.7 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.1 (3C), 16.0, 18.4, 23.3 (2C), 41.2, 51.6, 68.6, 73.4, 114.9, 142.2, 215.8; $[\alpha]^{28.1}_{D}$ = +35.6 (c = 2.79, CHCl$_3$) for 79% ee. Anal. Calcd for $C_{14}H_{28}O_2Si$: C, 65.57; H, 11.00. Found: C, 65.52; H, 11.04. The ee was determined by conversion to 6-hydroxy-3,3,5-trimethylhex-1-en-4-one, trifluoroacetylation, and GC analysis. 6-Hydroxy-3,3,5-trimethylhex-1-en-4-one: IR (film) 3400 (br), 2977, 1710, 1011, 992 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.05 (d, J = 7.2 Hz, 3H), 1.24 (s, 3H), 1.25 (s, 3H), 1.90 (br, 1H), 3.13−3.24 (m, 1H), 3.56 (dd, J = 3.9, 10.8 Hz, 1H), 3.64−3.73 (m, 1H), 51.8−5.24 (m, 2H), 5.93 (dd, J = 10.5, 17.4 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 15.4, 23.3, 23.4, 42.8, 51.7, 65.5, 115.3, 141.8, 217.5. Anal. Calcd for $C_9H_{16}O_2$: C, 69.19; H, 10.32. Found: C, 69.21; H, 10.29. The trifluoroacetate: GC (γ-TA, column temperature = 80 °C, 100 kPa) t_R = 6.13 (minor), 7.05 (major) min; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.07 (d, J = 6.9 Hz, 3H), 1.23 (s, 3H), 1.26 (s, 3H), 3.37−3.51 (m, 1H), 4.24 (dd, J = 5.4, 10.2 Hz, 1H), 4.45 (t, J = 10.2 Hz, 1H), 5.22−5.28 (m, 2H), 5.88 (dd, J = 10.5, 17.4 Hz, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ 15.5, 23.0, 23.1, 49.3, 51.7, 69.8, 114.7 (q, J_{CF} = 284 Hz), 116.1, 141.2, 213.3. Other resonances for the trifluoroacetate could not be discerned.

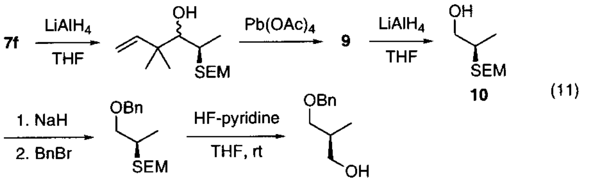


(10)

Determination of the Absolute Configuration of 2-Phenyl-2-[(2-trimethylsilyl)ethoxymethyl]cyclohexanone (5d). To a solution of 2-hydroxymethyl-2-phenylcyclohexanone (122.6 mg, 0.6 mmol, 81% ee) derived from **5d** and N,N-diisopropylethylamine (127 mL, 0.73 mmol) in dichloromethane (5 mL) was added methanesulfonyl chloride (57 mL, 0.73 mmol) at −78 °C, and the reaction mixture was allowed to warm to room temperature. After being stirred for 2 h, the reaction mixture was quenched with saturated ammonium chloride and extracted with ether twice, and the combined extracts were dried over $MgSO_4$, filtered, and concentrated. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (4:1) as eluent to give the corresponding methanesulfonate (168.7 mg, 0.54 mmol, 90% yield): TLC (hexanes−ethyl acetate = 4:1) R_f = 0.11; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.65−1.87 (m, 3H), 1.93−2.13 (m, 2H), 2.28−2.40 (m, 2H), 2.73−2.82 (m, 1H), 2.84 (s, 3H), 4.07 (d, J = 10.5 Hz, 1H), 4.49 (d, J = 10.5 Hz, 1H), 7.22−7.45 (m, 5H).

To a solution of the methanesulfonate (156.2 mg, 0.5 mmol) in dry THF (1 mL) was added Superhydride (0.75 mL, 0.75 mmol, 1 M in THF). After being stirred at room temperature for 6 h, the reaction mixture was quenched with ice−1 N HCl, extracted with ether twice, and the combined extracts were dried over $MgSO_4$, filtered, and concentrated. The crude product was purified by column chromatography on silica gel using hexane−diethyl ether (10:1) as eluent to give a diastereomeric mixture of 2-methyl-2-phenylcyclohexanol (87.5 mg, 0.46 mmol, 92% yield): TLC (hexanes−ethyl acetate = 4:1) R_f = 0.43; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.00−1.04 (m, 1H), 1.27 (s, 3H), 1.36−1.92 (m, 7H), 2.12−2.29 (m, 1H), 3.91−4.14 (m, 1H), 7.19−7.50 (m, 5H).

To a solution of 2-methyl-2-phenylcyclohexanol (78.7 mg, 0.41 mmol) in dichloromethane were added pyridinium chlorochromate (221 mg, 1.03 mmol) and sodium acetate (202 mg, 2.46 mmol) at room temperature. After the mixture was stirred for 7 h, magnesium sulfate (500 mg) was added. After being stirred for 0.5 h, the reaction mixture was filtered and concentrated. The crude product was purified by column chromatography on silica gel using hexane−diethyl ether (30:1−25:1) as eluent to give 2-methyl-2-phenylcyclohexanone (70.2 mg, 0.37 mmol, 91% yield): TLC (hexanes−ethyl acetate = 4:1) R_f = 0.50; $[\alpha]_D$ = +155.9 (c = 2.16, cyclohexane) [lit.[39] $[\alpha]_D$ = −163 (cyclohexane) for the (S)-enantiomer];^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.27 (s, 3H), 1.61−1.82 (m, 4H), 1.89−2.01 (m, 1H), 2.25−2.43 (m, 2H), 2.61−2.76 (m, 1H), 7.14−7.40 (m, 5H).



(11)

Determination of the Absolute Configuration of (+)-7f.[10] To a solution of (+)-**6f** (197 mg, 0.77 mmol, 79% ee) in dry THF (1 mL) was added lithium aluminum hydride (35.1 mg, 0.92 mmol) at 0 °C, and the reaction mixture was allowed to warm to room temperature. After being stirred for 2 h, the reaction mixture was quenched with ice−1 N HCl and extracted with ether twice, and the combined extracts were dried over $MgSO_4$, filtered, and concentrated. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (20:1) as eluent to give a diastereomeric mixture of 4,4-dimethyl-2-[(2-trimethylsilyl)ethoxymethyl]hex-5-en-3-ol (191 mg, 0.74 mmol, 96% yield). Minor diastereomer: TLC (hexanes−ethyl acetate = 4:1) R_f = 0.52; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.00 (s, 9H), 0.80−1.00 (m, 2H), 1.03 (s, 3H), 1.04 (d, J = 6.9 Hz, 3H), 1.06 (s, 3H), 1.85−1.95 (m, 1H), 3.23 (dd, J = 4.6, 6.9 Hz, 1H), 3.32−3.53 (m, 3H), 3.59 (dd, J = 4.6, 9.2 Hz, 1H), 3.75 (d, J = 6.9 Hz, 1H), 4.95−4.99 (m, 1H), 4.99−5.04 (m, 1H), 5.98 (dd, J = 10.0, 16.7 Hz, 1H); Major diastereomer: TLC (hexanes−ethyl acetate = 4:1) R_f = 0.48; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.01 (s, 9H), 0.90−0.10 (m, 2H), 0.95 (d, J = 6.9 Hz, 3H), 1.05 (s, 3H), 1.07 (s, 3H), 1.90−2.02 (m, 1H), 2.44 (d, J = 4.4 Hz, 1H), 3.37 (d, J = 5.7 Hz, 2H), 3.40−3.58 (m, 3H), 4.98−5.05 (m, 2H), 5.98 (dd, J = 10.2, 18.1 Hz, 1H).

To a solution of a diastereomeric mixture (191 mg, 0.74 mmol) of 4,4-dimethyl-2-[(2-trimethylsilyl)ethoxymethyl]hex-5-en-3-ol in dichloromethane (5 mL) was added lead tetraacetate (443.4 mg, 1 mmol) at −78 °C. The reaction mixture was allowed to warm to room temperature. After being stirred at room temperature for 2 h, ca. 0.5 g of silica gel was added (for filtration aid), the mixture was filtered, and the filtrate was concentrated to obtain 2-[2-(trimethylsilyl)ethoxymethyl]-propionaldehyde (**9**) as an oil. The crude aldehyde was used in the next step without purification. **9**: TLC (hexanes−ethyl acetate = 4:1) R_f = 0.29; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.01 (s, 9H), 0.85−0.95 (m, 2H), 1.11 (d, J = 6.9 Hz, 3H), 2.54−2.67 (m, 1H), 3.45−3.60 (m, 4H), 9.71 (s, 1H).

The crude aldehyde **9** was dissolved in dry THF (1 mL) was added lithium aluminum hydride (34.2 mg, 0.90 mmol) at 0 °C, and the reaction mixture was allowed to warm to room temperature. After being stirred for 2 h, the reaction mixture was quenched with ice−1 N HCl, extracted with ether twice, and the combined extracts were dried over $MgSO_4$, filtered, and concentrated. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (20:1) as eluent to give 2-[(2-trimethylsilyl)ethoxymethyl]-1-propanol (**10**) (121.6 mg, 0.64 mmol, 84% yield). **10**: TLC (hexanes−ethyl acetate = 4:1) R_f = 0.23; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.02 (s, 9H), 0.86 (d, J = 6.9 Hz, 3H), 0.94 (t, J = 8.3 Hz, 2H), 1.97−2.12 (m, 1H), 2.87 (dd, J = 4.6, 8.1 Hz, 1H), 3.34 (t, J = 8.1 Hz, 1H), 3.46−3.68 (m, 5H).

To a solution of **10** (118.3 mg, 0.62 mmol) in dry THF (1.4 mL) and DMF (0.5 mL) was added sodium hydride (60% dispersion in mineral oil, 32 mg, 0.80 mmol) portionwise at 0 °C, and the reaction mixture was allowed to warm to room temperature. After being stirred for 1 h, benzyl bromide (80 mL, 0.65 mmol) was added. After being stirred for 1 h, the reaction mixture was quenched with brine and extracted with ether, and the combined extracts were dried over $MgSO_4$, filtered, and concentrated. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (50:1) as eluent to give 1-benzyloxy-2-methyl-3-[(2-trimethylsilyl)ethoxy]propane (158.3 mg, 0.56 mmol, 91% yield): TLC (hexanes−ethyl acetate = 4:1) R_f = 0.60; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.01 (s, 9H), 0.92 (t, J = 7.9 Hz, 2H), 0.97 (d, J = 6.9 Hz, 3H), 2.06 (octet, J = 6.8 Hz, 1H), 3.23−3.53 (m, 6H), 4.51 (s, 2H), 7.22−7.39 (m, 5H).

Benzyloxy-2-methyl-3-[(2-trimethylsilyl)ethoxy]propane was converted to the known (−)-(S)-1-benzyloxy-3-hydroxy-2-methylpropane by treatment with hydrogen fluoride−pyridine in THF (see the above general procedure): >95% yield; TLC (hexanes−ethyl acetate = 4:1) R_f = 0.12; $[\alpha]^{31.0}_D$ = −15.6 (c = 2.21, $CHCl_3$) [lit.[40] $[\alpha]_D$ = +17.2 (c = 3.24, $CHCl_3$) for the (R)-enantiomer]; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.88 (d, J = 6.9 Hz, 3H), 2.00−2.17 (m, 1H), 2.55 (br, 1H), 3.43 (t, J = 8.4 Hz, 1H), 3.50−3.70 (m, 3H), 4.52 (s, 2H), 7.26−7.40 (m, 5H).

General Procedure for the Enantioselective SEM Addition to Prochiral Alkenes with (*R*)-1d and $SnCl_4$ (See Table 5 for Reaction Conditions). To a solution of (R)-**1d** (0.55 or 0.5 mmol) in dichloromethane (0.5 or 3 mL) was added a 1 M solution of $SnCl_4$ in dichloromethane (0.55 or 0.5 mL) dropwise at −78 °C. The solution was cooled to −97 °C, and then substrate **11** (0.5 or 2.5 mmol) was added dropwise. The reaction mixture was stirred at the same temperature for 5−12 h and quenched with excess triethylamine and saturated aqueous sodium hydrogen carbonate successively. After being allowed to warm to room temperature, the resultant mixture was extracted with hexane twice. The combined organic layers were dried over magnesium sulfate, filtered, and concentrated in vacuo to yield the crude product. Column chromatography of the crude product on silica gel (eluting with hexanes−ethyl acetate) gave **12** including 0−26% of **13** as a minor product.

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(39) Paquette, L. A.; Gilday, J. P.; Maynard, G. D. *J. Org. Chem.* **1983**, *48*, 422.

(40) Nagaoka, H.; Kishi, Y. *Tetrahedron* **1981**, *37*, 3873.

Regioselective Dehydrochlorination of 13. A mixed solution of **12** and **13** obtained in the above SEM addition in 2,4,6-collidine (0.5 mL) was heated with reflux conditions for 3 h. After being cooled to room temperature, the resultant mixture was washed with 1 M hydrogen chloride and brine andextracted with hexane. The combined organic layers were dried over magnesium sulfate, filtered, and concentrated in vacuo to yield the crude product. Column chromatography on silica gel (eluting with hexanes−ethyl acetate) gave **12** including with less than 3% of **14** in good yield. Enantiopurities of **12a**−**d** were determined by GC or HPLC analysis.

2-Ethyl-3-methyl-1-[2-(trimethylsilyl)ethoxy]-3-butene (12a): GC (PEG, column temperature = 80 °C, 100 kPa) t_R = 2.9 min; HPLC (Daicel OD-H column, hexane−*i*-PrOH = 9:1, flow rate = 1.0 mL/min) for the α-naphthylurethane of the corresponding homoallylic alcohol t_R = 18.2 (minor enantiomer), 21.6 (major enantiomer) min; TLC (hexanes−EtOAc = 15:1) R_f = 0.55; IR (neat) 2959, 1248, 1111, 860, 837 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.84 (t, *J* = 7.5 Hz, 3H), 0.92 (t, *J* = 8.3 Hz, 2H), 1.22−1.37 (m, 1H), 1.46−1.56 (m, 1H), 1.65 (s, 3H), 2.19−2.28 (m, 1H), 3.29 (dd, *J* = 6.8, 9.3 Hz, 1H), 3.37 (dd, *J* = 7.5, 9.3 Hz, 1H), 3.48 (t, *J* = 8.3 Hz, 2H), 4.73 (s, 1H), 4.81 (s, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.2 (3C), 11.8, 18.2, 19.5, 22.9, 49.0, 68.2, 73.1, 112.1, 145.8; $[\alpha]^{26.9}_D$ = -12.0 (*c* = 3.00, CHCl$_3$) for 81% ee. Anal. Calcd for $C_{17}H_{28}OSi$: C, 67.22; H, 12.22. Found: C, 67.10; H, 12.44.

The absolute configuration of **12a** was determined to be *R* by comparison of optical rotation values with data in the literature[41] after conversion to the known a-naphthylurethan with hydrogenation (Pd/C, H$_2$, EtOH, rt, 12 h), deprotection of 2-(trimethylsilyl)ethyl group (hydrogen fluoride-pyridine, CH$_3$CN, rt, 3 h), and addition of 1-naphthyl isocyanate (cat. DMAP, pentane, rt, 2 h): $[\alpha]^{25.7}_D$ = +1.6 (*c* = 2.42, CHCl$_3$) [lit.[41] $[\alpha]^{24}_D$ = −3.5 (CHCl$_3$) for the (*S*)-enantiomer]; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.91−0.97 (m, 9H), 1.24−1.54 (m, 3H), 1.74−1.92 (m, 1H), 4.14−4.26 (m, 2H), 6.91(s, 1H), 7.45−7.55 (m, 3H), 7.67 (d, *J* = 8.4 Hz, 1H), 7.84−7.92 (m, 3H); ^{13}C NMR (CDCl$_3$, 300 MHz) δ 12.2, 19.6 (2C), 21.0, 28.2, 45.3, 66.4, 119.2, 120.6, 125.1, 125.9, 126.0, 126.2, 128.8, 132.7, 134.2, 154.9.

The product of SEM addition reaction **12a** included 26% of **13a**: TLC (hexanes−EtOAc = 15:1) R_f = 0.55; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.92 (t, *J* = 8.1 Hz, 2H), 1.00 (t, *J* = 7.5 Hz, 3H), 1.25−1.54 (m, 2H), 1.60 (s, 3H), 1.62 (s, 3H), 1.65−1.75 (m, 1H), 3.42−3.58 (m, 4H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.3 (3C), 13.2, 18.3, 21.5, 31.2, 31.6, 53.2, 65.0, 68.2, 70.1. By the regioselective dehydrochlorination described above, the mixture of **12a** and **13a** was converted to **12a** and 3% of **14a**: GC (PEG, column temperature = 80 °C, 100 kPa) t_R = 3.5 min; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.70 (s, 3H), 1.73 (s, 3H), 2.13 (q, *J* = 5.6 Hz, 2H), 3.92 (s, 2H). Other resonances could not be discerned for this minor isomer.

2-Benzyl-3-methyl-1-[2-(trimethylsilyl)ethoxy]-3-butene (12b): GC (PEG, column temperature = 140 °C, 100 kPa) t_R = 6.3 min; HPLC (Daicel OD-H column, hexane−*i*-PrOH = 400:1, flow rate = 0.25 mL/min) t_R = 17.7 (major enantiomer), 20.2 (minor enantiomer) min; TLC (hexanes−EtOAc = 15:1, R_f = 0.50; HPLC (hexane−*i*-PrOH = 400:1, flow rate = 0.25 mL/min, Daicel OD-H column) t_R = 17.7 (major enantiomer), 20.2 (minor enantiomer) min; IR (neat) 2867, 1248, 1111, 837, 699 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.92 (t, *J* = 8.2 Hz, 2H), 1.69 (s, 3H), 2.58−2.67 (m, 2H), 2.79−2.88 (m, 1H), 3.30−3.39 (m, 2H), 3.47 (t, *J* = 8.2 Hz, 2H), 4.66 (s, 1H), 4.76 (s, 1H), 7.13−7.28 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.2 (3C), 18.2, 20.5, 37.0, 48.8, 68.3, 72.3, 112.3, 125.9, 128.2 (2C), 129.2 (2C), 140.7, 145.6; $[\alpha]^{27.6}_D$ = −13.5 (*c* = 3.19, CHCl$_3$) for 84% ee. Anal. Calcd for $C_{17}H_{28}OSi$: C, 73.85; H, 10.21. Found: C, 73.58; H, 10.50.

The product of SEM addition reaction **12b** included 15% of **13b**: ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.02 (s, 9H), 0.85 (t, *J* = 8.3 Hz, 2H), 1.68 (s, 3H), 1.70 (s, 3H), 2.05−2.11 (m, 1H), 2.68 (dd, *J* = 10.5, 13.5 Hz, 1H), 3.08 (dd, *J* = 3.0, 13.5 Hz, 1H), 3.28−3.42 (m, 4H), 7.13−7.31 (m, 5H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.2 (3C), 18.3, 31.0, 32.2, 34.2, 53.8, 66.1, 68.1, 68.7, 126.0, 128.4 (2C), 129.3 (2C), 141.4. By the regioselective dehydrochlorination described above, the mixture of **12b** and **13b** was converted to **12b** and 1% of **14b**: GC (PEG, column temperature = 140 °C, 100 kPa) t_R = 7.3 min; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.82 (s, 6H), 3.85 (s, 2H). Other resonances could not be discerned for this minor isomer.

2-Cyclohexyl-3-methyl-1-[2-(trimethylsilyl)ethoxy]-3-butene (12c): GC (γ-TA column, column temperature = 80 °C, 30 kPa) for the corresponding homoallyl trifluoroacetate t_R = 40.5 (minor enantiomer), 42.1 (major enantiomer) min; TLC (hexanes−EtOAc = 15:1, R_f = 0.46; IR (neat) 2923, 2853, 1248, 1111, 860 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.83−1.00 (m, 4H), 1.10−1.35 (m, 4H), 1.60−1.79 (m, 5H), 1.66 (s, 3H), 2.08 (dt, *J* = 5.1, 8.7 Hz, 1H), 3.39 (t, *J* = 8.7 Hz, 2H), 3.44−3.53 (m, 2H), 4.68 (s, 1H), 4.80 (s, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.3 (3C), 18.1, 20.2, 26.7 (2C), 26.8, 31.3, 31.5, 37.6, 53.0, 68.1, 71.0, 112.5, 146.1; $[\alpha]^{26.8}_D$ = -1.3 (*c* = 3.14, CHCl$_3$) for 77% ee. Anal. Calcd for $C_{16}H_{32}OSi$: C, 71.57; H, 12.01. Found: C, 71.34; H, 12.32.

1-[1-[[2-(Trimethylsilyl)ethoxy]methyl]pentyl]-1-cyclohexene (12d): GC (γ-TA column, column temperature = 80 °C, 50 kPa) for the corresponding homoallylic trifluoroacetate t_R = 42.3 (minor enantiomer), 45.0 (major enantiomer) min; TLC (hexanes−EtOAc = 15:1) R_f = 0.53; IR (neat) 2928, 2857, 1248, 1120, 858, 837 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.85−0.94 (m, 5H), 1.15−1.33 (m, 5H), 1.34−1.46 (m, 1H), 1.50−1.54 (m, 4H), 1.82−1.90 (m, 2H), 1.94−2.03 (m, 2H), 2.11−2.22 (m, 1H), 3.24 (dd, *J* = 7.1, 9.3 Hz, 1H), 3.33 (dd, *J* = 7.2, 9.3 Hz, 1H), 3.47 (dt, *J* = 2.1, 8.4 Hz, 2H), 5.42 (s, 1H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.2 (3C), 14.3, 18.2, 22.9, 23.0, 23.2, 25.4, 25.5, 29.7, 29.8, 47.7, 68.1, 73.6, 122.9, 138.0; $[\alpha]^{25.9}_D$ = -14.3 (*c* = 3.00, CHCl$_3$) for 73% ee. Anal. Calcd for $C_{17}H_{34}OSi$: C, 72.27; H, 12.13. Found: C, 72.04; H, 12.47.

***trans*-2,3,4,4a,9,9a-Hexahydro-1,1,4a-trimethyl-2-[2-(trimethylsilyl)ethoxymethyl]-1*H*-xanthene (12e):** HPLC (hexane−*i*-PrOH = 400:1, flow rate = 1.0 mL/min, Daicel OD-H column) t_R = 5.5 (major enantiomer), 7.6 (minor enantiomer) min; TLC (hexanes−EtOAc = 15:1) R_f = 0.33; IR (neat) 2867, 1586, 1489, 1456, 1248, 1100, 860, 837, 752 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ −0.01 (s, 9H), 0.77 (s, 3H), 0.95 (t, *J* = 8.3 Hz, 2H), 1.10 (s, 3H), 1.20 (s, 3H), 1.20−1.36 (m, 1H), 1.45−1.55 (m, 1H), 1.64−1.75 (m, 2H), 1.98−2.04 (m, 2H), 2.59−2.77 (m, 2H), 3.10 (t, *J* = 9.0 Hz, 1H), 3.41−3.54 (m, 2H), 3.61 (dd, *J* = 3.3, 9.0 Hz, 1H), 6.74−6.84 (m, 2H), 7.04−7.10 (m, 2H); ^{13}C NMR (CDCl$_3$, 75 MHz) δ −1.2 (3C), 16.4, 18.4, 19.9, 23.0, 24.1, 28.6, 35.7, 39.6, 48.1, 49.1, 68.4, 71.8, 77.1, 117.1, 119.8, 122.5, 127.3, 129.8, 153.2; $[\alpha]^{33.2}_D$ = +10.4 (*c* = 2.57, CHCl$_3$) for 54% ee. Anal. Calcd for $C_{22}H_{36}O_2Si$: C, 73.28; H, 10.06. Found: C, 73.30; H, 10.19.

General Procedure for the Deprotection of 2-(Trimethylsilyl)ethyl Group of 12a−d. To a solution of **12a**−**d** (0.4 mmol) in acetonitrile (0.8 mL) was added 70% hydrogen fluoride·pyridine (0.4 mL) dropwise at −40 °C, and the mixture was stirred at room temperature for 3 h. *After being cooled to −40 °C, the resultant mixture was carefully neutralized with triethylamine (3.5 mL) to prevent the decomposition of homoallyl alcohols with hydrogen fluoride aqueous solution,* and subsequently, the saturated aqueous sodium hydrogen carbonate was poured into the mixture. After being allowed to warm to room temperature, the mixture was extracted with ether, dried over magnesium sulfate, filtered, and concentrated in vacuo to yield the crude product. Column chromatography on silica gel (eluting with hexanes−ethyl acetate) gave the corresponding optically active homoallylic alcohol in good yield.

2-Ethyl-3-methyl-3-butenol (15a): ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.88 (t, *J* = 6.6 Hz, 3H), 1.20−1.50 (m, 3H), 1.67 (s, 3H), 2.14−2.24 (m, 1H), 3.45−3.56 (m, 2H), 4.83 (s, 1H), 4.95 (s, 1H). **The corresponding α-naphthylurethane:** TLC

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(41) (a) Fuji, K.; Tanaka, F.; Node, M. *Tetrahedron Lett.* **1991**, *32*, 7281. (b) Tsuda, K.; Kishida, Y.; Hayatsu, R. *J. Am. Chem. Soc.* **1960**, *82*, 3396.

(hexanes−EtOAc = 4:1) $R_f = 0.41$, HPLC (hexane−*i*-PrOH = 9:1, flow rate = 1.0 mL/min, Daicel OD-H) $t_R = 18.2$ (minor enantiomer), 21.6 (major enantiomer) min; IR (neat) 3312 (NH), 1710 (C=O), 1539, 1499, 1215, 772 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.88 (t, *J* = 7.4 Hz, 3H), 1.30−1.55 (m, 2H), 1.70 (s, 3H), 2.34−2.45 (m, 1H), 4.12−4.23 (m, 2H), 4.80 (s, 1H), 4.89 (s, 1H), 6.94 (s, 1H), 7.43−7.54 (m, 3H), 7.66 (d, *J* = 8.1 Hz, 1H), 7.84−7.87 (m, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 11.7, 19.2, 22.5, 48.2, 67.3, 113.3, 120.7, 125.1, 125.9, 126.1 (2C), 126.3 (2C), 128.8, 132.6, 134.2, 144.5, 154.6; $[\alpha]^{26.3}_D$ = -5.9 (*c* = 2.00, $CHCl_3$) for 73% ee; HRMS (EI+) calcd for $C_{18}H_{21}NO_2$ 283.1572, found 283.1570.

2-Benzyl-3-methyl-3-butenol (15b): TLC (hexanes−EtOAc = 4:1) $R_f = 0.22$; IR (neat) 3650−3300 (br, OH), 2928, 1456, 1040, 891, 698 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.40 (br, 1H), 1.73 (s, 3H), 2.50−2.63 (m, 1H), 2.71 (d, *J* = 6.9 Hz, 2H), 3.50−3.62 (m, 2H), 4.19 (s, 1H), 4.94 (s, 1H), 7.16−7.28 (m, 5H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.1, 36.3, 51.2, 63.2, 113.9, 126.2, 128.4 (2C), 129.0 (2C), 140.1, 145.0; HRMS (EI+) calcd for $C_{12}H_{14}$ (M − H_2O) 158.1096, found 158.1079.

2-Cyclohexyl-3-methyl-3-butenol (15c): TLC (hexanes−EtOAc = 4:1) $R_f = 0.20$; GC (80 °C (column temperature), 30 kPa, γ-TA) for the corresponding homoallylic trifluoroacetate $t_R = 40.5$ (minor enantiomer), 42.1 (major enantiomer) min; IR (neat) 3600−3200 (br, OH), 2924, 1449, 1089, 1067, 1053, 1013, 889 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.86−0.98 (m, 2H), 1.13−1.39 (m, 5H), 1.60−1.78 (m, 5H), 1.68 (s, 3H), 2.05 (dt, *J* = 4.5, 9.8 Hz, 1H), 3.46 (dt, *J* = 3.0, 10.2 Hz, 1H), 3.69−3.77 (m, 1H), 4.83 (s, 1H), 4.99 (s, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 19.2, 26.4, 26.5, 26.7, 31.0, 31.8, 36.9, 56.2, 61.6, 115.0, 145.0; $[\alpha]^{25.9}_D$ = −1.9 (*c* = 1.62, $CHCl_3$) for 77% ee; HRMS (EI+) calcd for $C_{11}H_{18}$ (M − H_2O) 150.1409, found 150.1404.

2-(Cyclohex-1-en-1-yl)hexan-1-ol (15d): TLC (hexanes−EtOAc = 4:1) $R_f = 0.30$, GC (80 °C (column temperature), 50 kPa, γ-TA) for the trifluoroacetate $t_R = 42.3$ (minor enantiomer), 45.0 (major enantiomer) min; IR (neat) 3550−3100 (br, OH), 2928, 1466, 1055, 1017 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.88 (t, *J* = 6.9 Hz, 3H), 1.16−1.37 (m, 7H), 1.54−1.67 (m, 4H), 1.84−1.90 (m, 2H), 2.01−2.08 (m, 2H), 2.09−2.18 (m, 1H), 3.39−3.51 (m, 2H), 5.55 (s, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 14.2, 22.8, 22.9, 23.0, 24.4, 25.4, 28.9, 29.7, 50.4, 64.1, 125.6, 137.1; HRMS (EI+) calcd for $C_{12}H_{22}NO$ 182.1671, found 182.1686.

Representative Procedure for the Enantioselective Intramolecular Cyclization of (*R*)-3 (or 19) and $SnCl_4$ (See Table 7 for Reaction Conditions). To a solution of (*R*)-**3** (or **19**) (0.5 mmol) in 1-chloropropane (2.5 mL) was added a 1 M solution of $SnCl_4$ in hexane (0.5 mL), which was distilled before preparation of its solution, dropwise at −78 °C. The reaction mixture was stirred at the same temperature for 4−12 h and quenched with a saturated $NaHCO_3$ solution. After being allowed to warm to room temperature, the resultant mixture was extracted with pentane twice. The combined organic layers were dried over magnesium sulfate, filtered, and concentrated in vacuo to yield the crude product. Column chromatography of the crude product on silica gel (eluting with pentane) gave limonene (**16**) including 30∼40% of **17**[42] as a minor product (or **20**). **16:** GC (CHIRALDEX B-DM, column temperature = 90 °C, 7 kPa) $t_R = 56.3$ [(*S*)-**16**], $t_R = 59.7$ [(*R*)-**16**] min; $[\alpha]^{30.8}_D$ = 103.5 (*c* = 0.87, pentane) for 92% ee [$[\alpha]^{20}_D$ = +123 (neat) for (*R*)-limonene]. **20:** GC (CHIRALDEX B-DM, column temperature = 150 °C, 25 kPa) $t_R = 42.1$ (major), $t_R = 43.1$ (minor) min; $[\alpha]^{26.4}_D$ = +4.9 (*c* = 0.86, $CHCl_3$) for 19% ee [lit.[28] $[\alpha]_D$ = −19.7 (*c* = 0.35) for natural (*R*)-neocembrene]; TLC (hexanes−ethyl acetate = 15:1) $R_f = 0.67$; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.31−1.42 (m, 1H), 1.57 (s, 6H), 1.59 (s, 3H), 1.66 (s, 3H), 1.75−2.30 (m, 14H), 4.65−4.66 (m, 1H), 4.70−4.72 (m, 1H), 4.98 (t, *J* = 5.9 Hz, 1H), 5.06 (t, *J* = 6.3 Hz, 1H), 5.19 (t, *J* = 7.5 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 15.5, 15.7, 18.2, 19.5, 23.9, 25.0, 28.3, 32.6, 34.1, 39.1, 39.6, 46.1, 110.3, 121.9, 124.2, 126.1, 133.6, 134.1, 135.0, 149.4.

(*R*)-2-Neryloxy-2′-hydroxy-1,1′-binaphthyl (3a). To a solution of (*R*)-2,2′-dihydroxy-1,1′-binaphthyl (8.59 g, 30 mmol), triphenylphosphine (7.87 g, 30 mmol), and nerol (7.9 mL, 45 mmol) in dry THF (240 mL) was added diethyl azodicarboxylate (14.5 mL, 33 mmol) dropwise. The reaction mixture was stirred for 12 h and then evaporated under reduced pressure. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (30:1) as eluent to give **3a** (7.76 g, 61% yield) as a viscous oil: TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.49$; IR (film) 2928, 1592, 1507, 1208, 814, 749 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.54 (s, 3H), 1.61 (s, 3H), 1.64 (s, 3H), 1.92 (s, 4H), 4.47−4.59 (m, 2H), 4.93−5.00 (m, 2H), 5.13−5.18 (m, 1H), 7.05 (d, *J* = 8.7 Hz, 1H), 7.14−7.39 (m, 6H), 7.46 (d, *J* = 9.0 Hz, 1H), 7.83−7.91 (m, 3H), 8.01 (d, *J* = 9.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 17.8, 23.4, 25.8, 26.4, 32.3, 66.5, 115.3, 116.6, 117.1, 117.7, 120.9, 123.2, 123.8, 124.3, 125.1, 125.2, 126.4, 127.2, 128.1, 128.2, 129.2, 129.7, 129.8, 130.7, 132.1, 133.9, 134.2, 141.0, 151.4, 155.3; $[\alpha]^{25.8}_D$ = −31.7 (*c* = 3.15, $CHCl_3$). Anal. Calcd for $C_{30}H_{30}O_2$: C, 85.27; H, 7.16. Found: C, 85.28; H, 7.29.

(*R*)-2-Neryloxy-2′-methoxy-1,1′-binaphthyl (3b). To a stirred suspension of potassium carbonate (415 mg, 3 mmol) in acetone were added **3a** (423 mg, 1 mmol) and iodomethane (190 mL, 3 mmol). The reaction mixture was heated at reflux for 12 h, quenched with saturated NH_4Cl in an ice bath, and concentrated in vacuo. The resulting residue was diluted with ether, washed with H_2O, dried over $MgSO_4$, and concentrated. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (35:1) as eluent to give **3b** (352 mg, 81% yield) as a viscous oil: TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.45$; IR (film) 2932, 1593, 1509, 1263, 806, 749 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.54 (s, 3H), 1.59 (s, 3H), 1.64 (s, 3H), 1.89 (s, 4H), 3.77 (s, 3H), 4.48 (d, *J* = 6.3 Hz, 2H), 4.93−5.00 (m, 1H), 5.10−5.15 (m, 1H), 7.09−7.46 (m, 8H), 7.86 (d, *J* = 8.4 Hz, 2H), 4.91−7.98 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 17.8, 23.4, 25.9, 26.5, 32.3, 56.9, 66.8, 114.1, 117.0, 119.7, 121.1, 121.7, 123.5, 123.7, 123.9, 125.5, 125.6, 126.2, 126.3, 127.9, 128.0, 129.2 (2C), 129.4, 129.5, 132.0, 134.1, 134.2, 139.9, 154.5, 155.0; $[\alpha]^{26.5}_D$ = +27.7 (*c* = 3.15, $CHCl_3$). Anal. Calcd for $C_{31}H_{32}O_2$: C, 85.28; H, 7.39. Found: C, 85.19; H, 7.46.

(*R*)-2-Neryloxy-(1,1′-binaphthalen)-2′-yl *p*-toluenesulfonate (3c). To a stirred solution of **3a** (423 mg, 1 mmol) and triethylamine (420 mL, 3 mmol) in ether at −78 °C was added tosyl chloride (190 mg, 1 mmol). The reaction mixture was allowed to warm to room temperature. After being stirred for 5 h, the mixture was poured into saturated $NaHCO_3$ solution, extracted with ether, dried over $MgSO_4$, and concentrated. The crude product was purified by column chromatography on silica gel using hexanes−ethyl acetate (15:1) as eluent to give **3c** (508 mg, 88% yield) as a viscous oil. TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.34$; IR (film) 1593, 1509, 1372, 1173, 967, 824 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.56 (s, 3H), 1.60 (s, 3H), 1.66 (s, 3H), 1.95 (s, 4H), 2.20 (s, 3H), 4.44−4.56 (m, 2H), 4.96−5.05 (m, 1H), 5.15−5.19 (m, 1H), 6.65−6.73 (m, 3H), 6.96−7.45 (m, 8H), 7.73−7.99 (m, 5H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 17.7, 21.6, 23.3, 25.8, 26.4, 32.3, 66.2, 115.5, 117.7, 121.3, 121.7, 123.2, 123.8, 125.6, 125.8, 125.9, 126.3, 126.6, 126.9, 127.2 (2C), 127.6, 128.1, 128.7, 128.9 (2C), 129.4, 129.8, 132.0, 132.1, 132.9, 133.5, 133.7, 140.1, 144.0, 145.8, 154.5; $[\alpha]^{27.3}_D$ = -0.53 (*c* = 2.50, $CHCl_3$). Anal. Calcd for $C_{37}H_{36}O_4S$: C, 77.05; H, 6.29. Found: C, 76.98; H, 6.37.

(*R*)-2-Neryloxy-(1,1′-binaphthalen)-2′-yl Benzoate (3d). Compound **3d** was prepared as previously described by use of benzoyl chloride (85% yield): TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.42$; IR (film) 1738, 1266, 1215, 1088, 750, 708 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.52 (s, 3H), 1.55 (s, 3H), 1.63 (s, 3H), 1.90 (s, 4H), 4.46(d, *J* = 6.6 Hz, 2H), 4.93−5.00 (m, 1H), 5.08−5.13 (m, 1H), 7.19−7.66 (m, 13H), 7.80 (d, *J* = 7.8 Hz, 1H), 7.87 (d, *J* = 9.0 Hz, 1H), 7.96 (d, *J* = 8.4 Hz, 1H), 8.03 (d, *J* = 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 17.7, 23.3, 25.8, 26.4, 32.3, 66.2, 115.5, 118.6, 121.4, 122.0, 123.6, 123.8, 125.2, 125.4 (2C), 126.3, 126.4, 126.5, 127.8, 128.1 (3C), 128.9, 129.0, 129.6, 129.7 (3C), 131.7, 131.9, 133.0, 133.8, 133.9, 139.8, 147.0, 154.3, 164.6; $[\alpha]^{27.4}{}_{D}$ = -2.79 (c = 3.79, $CHCl_3$). Anal. Calcd for $C_{37}H_{34}O_3$: C, 84.38; H, 6.51. Found: C, 84.40; H, 6.58.

(*R*)-2-Neryloxy-(1,1′-binaphthalen)-2′-yl *p*-Trifluoromethylbenzoate (3e). Compound **3e** was prepared as previously described by use of *p*-trifluoromethylbenzoyl chloride (85% yield): TLC (hexanes−ethyl acetate = 4:1) $R_f = 0.50$; IR (film) 1744, 1325, 1267, 1215, 1088, 1017, 806 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.52 (s, 3H), 1.54 (s, 3H), 1.62 (s, 3H), 1.90 (s, 4H), 4.45 (d, J = 6.3 Hz, 2H), 4.91−4.99 (m, 1H), 5.05−5.10 (m, 1H), 7.15−7.51 (m, 9H), 7.62−7.66 (m, 3H), 7.81 (d, J = 8.0 Hz, 1H), 7.88 (d, J = 8.8 Hz, 1H), 7.97 (d, J = 8.0 Hz, 1H), 8.04 (d, J = 8.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 17.7, 23.4, 25.8, 26.5, 32.4, 66.3, 115.6, 118.4, 121.3, 121.6, 123.8 (2C), 125.25, 125.30, 125.34, 125.4, 125.7, 126.6 (2C), 126.7, 128.0, 128.2, 129.0, 129.1, 130.0, 130.2 (2C), 131.9, 132.1, 133.0, 133.8, 133.9, 134.2, 134.7, 140.1, 146.8, 154.4, 163.6; $[\alpha]^{25.5}{}_{D} = -0.52$ (c = 3.85, $CHCl_3$). Anal. Calcd for $C_{38}H_{33}F_3O_3$: C, 76.75; H, 5.59. Found: C, 76.73; H, 5.77.

(*R*)-2-(*all-E*-geranylgeranyloxy)(1,1′-binaphthalen)-2′-yl Benzoate (19). Compound **19** was prepared using a method similar to that for **3d** by Mitsunobu reaction with (*E*,*E*,*E*)-geranylgeraniol[43] followed by esterification: TLC (hexanes−ethyl acetate = 15:1) R_f = 0.20; IR (film) 1740, 1266, 1215, 1088, 754, 708 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.46 (s, 3H), 1.53 (s, 3H), 1.57 (s, 3H), 1.59 (s, 3H), 1.67 (s, 3H), 1.81−2.09 (m, 12H), 4.40−4.54 (m, 2H), 4.94−5.15 (m, 4H), 7.20−7.66 (m, 13H), 7.79 (d, J = 7.5 Hz, 1H), 7.86 (d, J = 9.0 Hz, 1H), 7.96 (d, J = 8.1 Hz, 1H), 8.03 (d, J = 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.0, 16.1, 16.4, 17.7, 25.7, 26.1, 26.6, 26.8, 39.3, 39.7, 39.8, 66.3, 115.4, 118.4, 120.4, 122.0, 123.5, 123.8, 124.2, 124.4, 125.2, 125.4 (2C), 126.3, 126.4, 126.5, 127.8, 128.1 (3C), 128.8, 128.9, 129.5, 129.6 (3C), 131.1, 131.7, 132.9, 133.7, 133.9, 134.8, 135.1, 139.7, 147.0, 154.2, 164.5; $[\alpha]^{24.3}{}_{D} = +1.26$ (c = 3.39, $CHCl_3$). Anal. Calcd for $C_{47}H_{50}O_3$: C, 85.16; H, 7.60. Found: C,85.16; H, 7.72.

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