CHEMISTRY
A EUROPEAN JOURNAL

DOI: 10.1002/chem.200802340

# Highly Diastereoselective Addition of Allyltitanocenes to Ketones

**Yasutaka Yatsumonji,[a] Takuya Nishimura,[a] Akira Tsubouchi,[a] Keiichi Noguchi,[b] and Takeshi Takeda*[a]**

**Abstract:** The reaction of allyltitanocenes, generated by the reductive titanation of allylic sulfides or allylic alcohol derivatives with a titanocene(II) species, with phenyl and sterically hindered alkyl methyl ketones produced *anti* tertiary homoallylic alcohols with complete diastereoselectivity. Even when sterically less congested methyl ethyl ketone and methyl vinyl ketone were employed, the *anti* homoallylic alcohols were obtained with unprecedented high diastereoselectivity. The observed *anti* selectivity suggests that the reaction proceeds by the addition of primary (*E*)-σ-allyltitanocenes to ketones through chairlike cyclic transition states.

**Keywords:** allylation · allylic compounds · diastereoselectivity · ketones · titanium

## Introduction

The stereocontrolled construction of two adjacent stereogenic centers is one of the most important processes in organic synthesis. The addition of allyl metal species to carbonyl compounds has been extensively studied as a useful tool for such processes.[1] It is well known that reactions of allyl metals with aldehydes generally produce secondary homoallylic alcohols with high diastereoselectivity, but the selectivity seriously decreases when ketones are employed. In this context, much attention has recently been paid to the diastereoselective addition of allyl metals to ketones.[2,3] Although the reactions of γ-substituted allylzinc[2a,b] and allyltin[2c] reagents with aryl and sterically hindered alkyl methyl ketones produce tertiary homoallylic alcohols with high diastereoselectivity in certain cases, only moderate or low diastereoselectivity is observed in the reactions with sterically less congested alkyl methyl ketones, such as methyl ethyl ketone.[2a,g,4,5] Thus, a significant difference in bulkiness between the two alkyl groups of the ketones is of crucial importance for the conventional diastereoselective addition of allyl metals. Recently, we reported that tertiary homopropargyl alcohols were produced with high diastereoselectivity by a titanocene(II)-promoted one-pot multistep reaction involving thioacetals, alkynyl sulfones, and carbonyl compounds, in which allenyltitanocenes were produced as the active species.[6] The results prompted us to investigate the preparation of tertiary homoallylic alcohols by using allyltitanocenes **1**, generated by the reductive titanation of allylic substrates **2**–**4**. Herein, we describe the preparation of *anti* tertiary homoallylic alcohols **5** with high diastereoselectivity by the reaction of **1** with a variety of ketones **6** (Scheme 1).

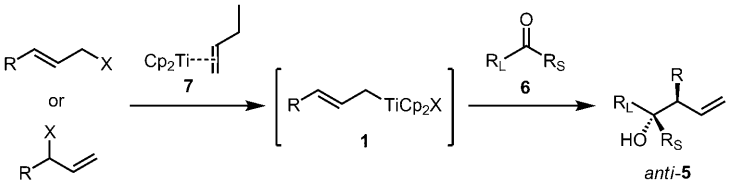
[a] Y. Yatsumonji, T. Nishimura, Dr. A. Tsubouchi, Prof. T. Takeda
Department of Applied Chemistry, Graduate School of Engineering
Tokyo University of Agriculture and Technology
Koganei, Tokyo 184-8588 (Japan)
Fax: (+81) 42-388-7034
E-mail: takeda-t@cc.tuat.ac.jp

[b] Prof. K. Noguchi
Instrumentation Analysis Center
Tokyo University of Agriculture and Technology
Koganei, Tokyo 184-8588 (Japan)

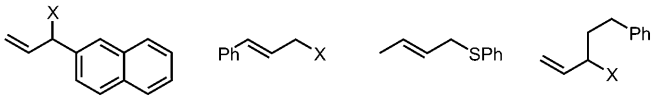
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.200802340.

## Results and Discussion

**Reductive titanation of allylic substrates**: Previously, we reported the diastereoselective preparation of *anti* secondary homoallylic alcohols by the reaction of aldehydes with allyltitanocenes **1**, generated by the desulfurizative titanation of allylic sulfides **2** with titanocene-1-butene complex (**7**).[7] On the basis of these results, we first examined the reaction conditions for the reductive titanation of allylic sulfides and allylic alcohol derivatives with **7**. After treatment of sulfide **2a** with **7** at −78 °C for 15 min and then at 0 °C for 45 min, the reaction mixture was treated with 1 M NaOH to produce a quantitative mixture of alkenes **8** and **8′** (Scheme 2; Table 1, entry 1). Upon quenching of the reaction with $D_2O$, deuterated alkenes **9** and **9′** were produced (87%, **9**/**9′** = 79:21, *E*/*Z* ratio of **9′** = 94:6). These results indicate that the




allylic substrates



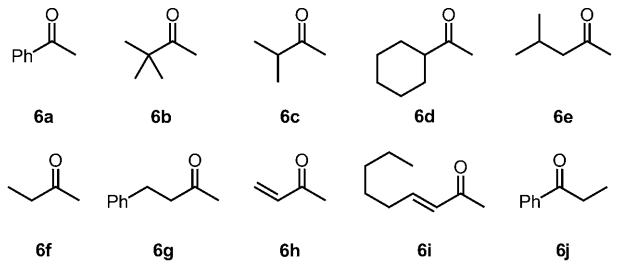
**2a**: X = SPh
**3a**: X = OMe
**4a**: X = O(CO)*t*Bu

**2b**: X=SPh
**3b**: X=OMe
**4b**: X= O(CO)*t*Bu

**2c** (*E*/*Z*=88:12)

**2d**: X=SPh
**3c**: X=OMe

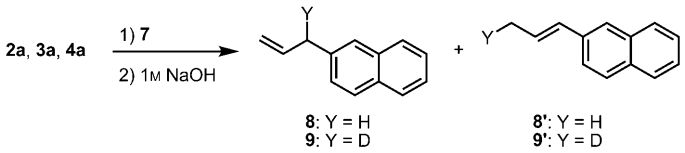
ketones



**6a** **6b** **6c** **6d** **6e**

**6f** **6g** **6h** **6i** **6j**

Scheme 1. Diastereoselective addition of allyltitanocenes **1** to ketones **6**. Cp: cyclopentadienyl.




Scheme 2. Reduction of allylic substrates with the titanocene(II) reagent **7**.

Table 1. Reduction of allylic substrates with the titanocene(II) reagent **7**.

| Entry | Substrate | *T* [°C][a] | *t* [min][a] | Yield [%][b] | **8**/**8′**[c] | *E*/*Z* ratio of **8′**[c] |
|---|---|---|---|---|---|---|
| 1 | **2a** | 0 | 45 | quant | 90:10 | 93:7 |
| 2 | **3a** | 0 | 45 | 80 | 90:10 | 77:23 |
| 3 | **3a** | 25 | 20 | 92 | 88:12 | 85:15 |
| 4 | **4a** | 25 | 20 | 89 | 81:19 | 97:3 |

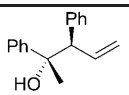
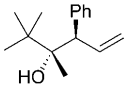
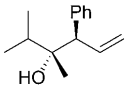
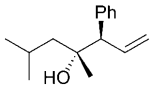
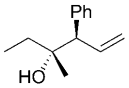
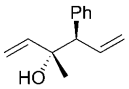
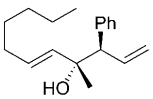
[a] Reaction conditions after the allylic substrate was treated with **7** at −78 °C for 15 min. [b] Yield of isolated product. [c] Determined by GLC analysis.

corresponding allyltitanocene **1** is produced by reductive titanation of **2a**. A similar treatment of allylic ether **3a** with **7** gave alkenes **8** and **8′** in 80% combined yield, and a small amount of the starting material was also recovered (Table 1, entry 2). When the reaction was carried out at 25 °C, however, the reductive titanation was almost complete within 20 min and the alkenes were obtained in better combined yield after hydrolysis (Table 1, entry 3). The allylic pivalate **4a** was also reduced with the titanocene(II) species **7** under the same reaction conditions to produce alkenes **8** and **8′** with a comparable combined yield (Table 1, entry 4).

**Reaction of cinnamyltitanocenes 1 with ketones 6**: After the reductive titanation of cinnamyl phenyl sulfide (**2b**) with the titanocene(II) reagent **7** (2.0 equiv) at 0 °C for 45 min, the resulting cinnamyltitanocene **1** was treated with acetophenone (**6a**; 1.2 equiv) in tetrahydrofuran (THF) at 0 °C for 1 h to produce homoallylic alcohol **5a** as a single diastereomer in 88% yield (Table 2, entry 1). Unlike the *syn*-selective addition of allenyltitanocenes to **6a**,[6] the reaction of the allyltitanocene proceeded with complete *anti* selectivity. Similarly, the reaction of the allyltitanocene generated from **2b** with *tert*-butyl methyl ketone (**6b**) and isopropyl methyl ketone (**6c**) at −78 °C for 18 h gave the single isomers **5b** and **5c** in good to high yields (Table 2, entries 3 and 4).

What is striking is that high *anti* selectivity was observed even in the reaction of **2b** with methyl ethyl ketone (**6f**;

Table 2. *anti*-Selective preparation of homoallylic alcohols **5** by the reaction of cinnamyltitanocenes **1** with ketones **6**.

| Entry | Substrate | Ketone | Procedure[a] | Product | Yield [%][b] | *anti*/*syn*[c] |
|---|---|---|---|---|---|---|
| 1 | **2b** | **6a** | A[d] |  **5a**[e] | 88 | 100:0 |
| 2 | **3b** | **6a** | B | **5a** | 79 | 100:0 |
| 3 | **2b** | **6b** | A |  **5b** | 72 | 100:0 |
| 4 | **2b** | **6c** | A |  **5c**[f] | 85 | 100:0 |
| 5 | **2b** | **6e** | A |  **5d** | 68 | 96:4 |
| 6[g] | **2b** | **6f** | A |  **5e**[h] | 88 | 90:10 |
| 7[g] | **3b** | **6f** | B | **5e** | 80 | 90:10 |
| 8[g] | **4b** | **6f** | B | **5e** | 73 | 90:10 |
| 9[g] | **2b** | **6h** | A |  **5f** | 72 | 88:12 |
| 10 | **2b** | **6i** | A |  **5g** | 67 | 77:23[i] |

[a] Described in the Experimental Section. [b] Yield of isolated product. [c] Determined by NMR analysis. [d] The reaction of allyltitanocene with **6a** was carried out at 0 °C for 1 h. [e] See reference [2c]. [f] See reference [2b]. [g] 3 equiv of **6** were used. [h] See reference [2a]. [i] Determined by GLC analysis.

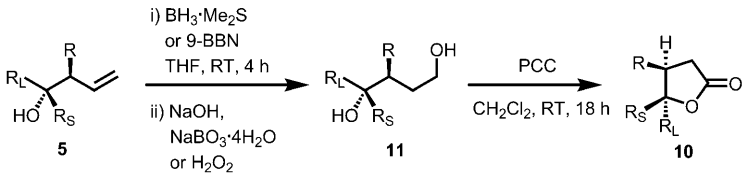
Table 2, entry 6). Despite extensive studies on the reactivity of allyl metal reagents toward carbonyl compounds, only a few reactions with enones have been reported so far: for example, reactions of allylic Grignard reagents with enones afford the corresponding homoallylic alcohols with poor diastereoselectivity.[8] By contrast, treatment of the allyltitanocene generated from **2b** with methyl vinyl ketone (**6h**) and 3-nonen-2-one (**6i**) gave alcohols **5f** and **5g**, respectively, in good yields and with satisfactory diastereoselectivity (Table 2, entries 9 and 10). The similar *anti*-selective allylation of ketones also proceeded when the allylic methyl ether **3b** and allylic pivalate **4b** were employed for the preparation of the corresponding cinnamyltitanocenes **1** (Table 2, entries 2, 7, and 8).

**Reaction of 2-alkenyltitanocenes 1 with ketones 6**: It is well known that the reactions of crotyl metal reagents with carbonyl compounds generally afford the homoallylic alcohols with lower diastereoselectivities than the reactions with cinnamyl metal reagents.[2c,4,5,9] By contrast, the reaction of crotyltitanocene **1**, prepared by the reductive titanation of **2c**, with **6a** gave the single isomer *anti*-**5h** in high yield (Table 3, entry 1). Even in the case of propiophenone (**6j**), the alcohol **5k** was obtained with almost complete diastereoselectivity (Table 3, entry 4).

Allyltitanocenes **1** were also prepared by the reductive titanation of α-substituted allylic sulfides and allylic methyl ethers. Thus, the successive treatment of **2d** and **3c** with **7** and acetophenone (**6a**) gave the tertiary homoallylic alcohol **5l**, also with complete diastereoselectivity (Table 3, entries 5 and 6). A variety of α-substituted allylic sulfides are readily prepared by the regioselective alkylation of allyl sulfide,[10] and allylic ethers are also easily obtained by the addition of vinylmagnesium bromide to aldehydes[11] followed by methylation. Therefore, the allylation of ketones with these allylic substrates is a versatile tool for the *anti*-selective preparation of homoallylic alcohols.

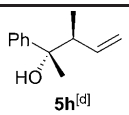
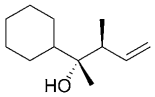
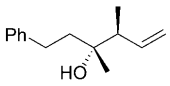
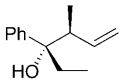
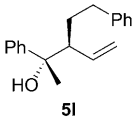
**Determination of stereochemistry of homoallylic alcohols 5**: The *anti* stereochemistry of the major isomers of the new compounds **5b**, **5d**, **5g**, **5j**, and **5l** was determined by X-ray single-crystal structure analysis or NOESY experiments after the homoallylic alcohols **5** were transformed into γ-butyrolactones **10**. The transformation was performed by the hydroboration–oxidation of **5** and subsequent oxidation of the resulting diols **11** with pyridinium chlorochromate (PCC; Scheme 3 and Table 4).

The structures of the lactones **10a** and **10e** were unequivocally confirmed through single-crystal X-ray analysis. The ORTEP drawings of **10a** and **10e** are shown in Figure 1 and Figure 2.




Scheme 3. Transformation of allylic alcohols **5** into γ-butyrolactones **10**. 9-BBN: 9-borabicyclo[3.3.1]nonane.

Table 3. *anti*-Selective preparation of homoallylic alcohols **5** by the reaction of 2-alkenyltitanocenes **1** with ketones **6**.

| Entry | Substrate | Ketone | Procedure[a] | Product | Yield [%][b] | *anti*/*syn*[c] |
|---|---|---|---|---|---|---|
| 1 | **2c** | **6a** | A |  **5h**[d] | 79 | 100:0 |
| 2 | **2c** | **6d** | A |  **5i**[d] | 82 | 100:0 |
| 3 | **2c** | **6g** | A |  **5j** | 85 | 88:12 |
| 4 | **2c** | **6j** | A |  **5k**[d] | 85 | 99:1 |
| 5 | **2d** | **6a** | A |  **5l** | 80 | 100:0 |
| 6 | **3c** | **6a** | B | **5l** | 70 | 100:0 |

[a] Described in the Experimental Section. [b] Yield of isolated product. [c] Determined by NMR analysis. [d] See reference [5].

The $^1$H–$^1$H NOESY spectrum of lactone **10d** is shown in Figure 3. A clear cross-peak between the two methyl protons of lactone **10d** confirms that the two methyl groups are *cis* relative to each other. The relative configurations of **10b** and **10c** were assigned in a similar manner by NOESY experiments (see the Supporting Information).

The stereochemistry of lactones **10** thus determined clearly indicates the *anti* selectivity of the addition of allyltitanocenes **1**, generated by the reductive titanation of the allylic substrates **2**–**4**, to ketones **6**.

In addition, the *anti* stereochemistry of the major isomer of **5f** was confirmed after the compound was transformed into the saturated tertiary alcohol **12** by reduction of the double bonds. The $^1$H NMR spectrum of the major isomer of **12** thus obtained was completely identical to that of **12** obtained by reduction of the known *anti* homoallylic alcohol **5e**[2a] (Scheme 4).

**Stereochemical pathway**: The observed *anti* selectivity suggests that the most thermodynamically stable primary (*E*)-σ-allyltitanocenes **1** are produced by the reductive titanation of both the primary and secondary allylic substrates **2**–**4** and that their reaction with ketones **6** proceeds via the chairlike

Table 4. Transformation of allylic alcohols **5** into γ-butyrolactones **10**.

| Entry | R | $R_L$ | $R_S$ | Intermediate | Yield [%][a] | Product | Yield [%][a] |
|---|---|---|---|---|---|---|---|
| 1 | Ph | *t*Bu | Me | **11a** | 61 | **10a** | 80 |
| 2 | Ph | *i*Bu | Me | **11b** | 57 | **10b** | 50 |
| 3 | Ph | (*E*)-$C_5H_{11}CH{=}CH$ | Me | **11c** | 55 | **10c** | 39 |
| 4 | Me | $PhCH_2CH_2$ | Me | **11d** | 69 | **10d** | 60 |
| 5 | $PhCH_2CH_2$ | Ph | Me | **11e** | 65 | **10e** | 74 |

[a] Yield after isolation.

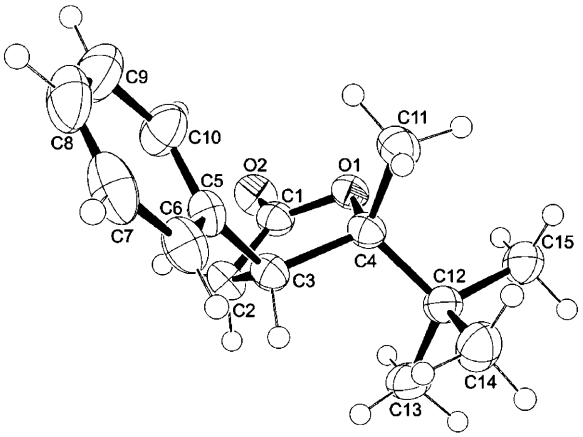



Figure 1. Molecular structure of compound **10a**.

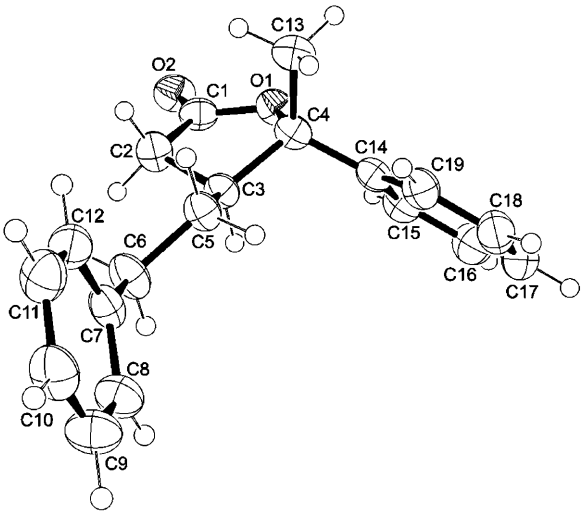



Figure 2. Molecular structure of compound **10e**.

six-membered transition state **13** (Scheme 5).[1a] The high degree of diastereoselectivity in the present reaction would be attributable to the Cp ligands of **1**: it is assumed that the unfavorable steric repulsion between the bulky Cp ring on the titanium atom and the larger alkyl group ($R_L$) of the ketone in transition state **13b** suppresses the formation of the *syn* isomer (Scheme 5).

## Conclusion

We have established a practical method for the highly diastereoselective preparation of *anti* tertiary homoallylic alcohols by utilizing allyltitanocenes that are readily prepared by the reductive titanation of a variety of allylic substrates with the titanocene(II) species. The addition of allyltitanium reagents bearing $Et_2N$,[4] *i*PrO,[4] and PhO[5] ligands with acetophenone and isopropyl methyl ketone tends to produce the *anti* tertiary homoallylic alcohols with high diastereoselectivity. The reactions of these allylic titanium reagents with alkyl methyl ketones such as 2-octanone and 2-heptanone, however, show only moderate selectivity. Therefore, allyltitanocene species **1**, generated by the reductive titanation of allyl-

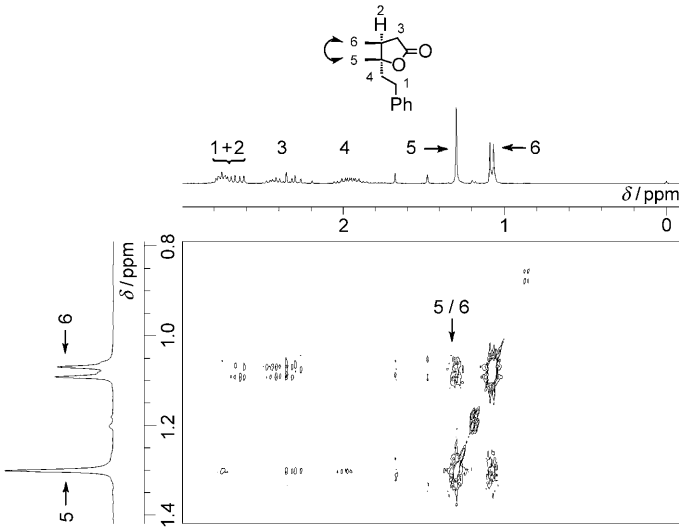
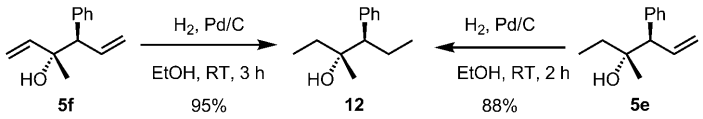
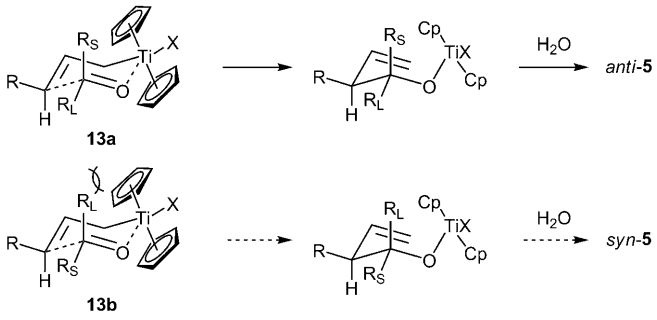



Figure 3. $^1H$–$^1H$ NOESY spectrum of **10d**.




Scheme 4. Transformation of **5e** and **5f** into the tertiary alcohol **12**.




Scheme 5. Stereochemical pathway for the addition of allyltitanocenes **1** to ketones **6**.

ic substrates, are the reagents of choice for the preparation of a variety of *anti* homoallylic alcohols. Further studies on the stereoselective reactions of these organotitanium species are currently underway.

## Experimental Section

**General**: THF was distilled from sodium and benzophenone. Preparative thin-layer chromatography (PTLC) was carried out by using Wakogel B-5F. $^1$H (300 MHz) and $^{13}$C (75 MHz) NMR spectra were recorded in $CDCl_3$, and chemical shifts ($\delta$) are quoted in parts per million relative to tetramethylsilane (TMS) for $^1$H NMR spectroscopy and relative to $CDCl_3$ for $^{13}$C NMR spectroscopy. IR absorptions are reported in cm$^{-1}$. GC analysis was carried out with nitrogen as the carrier gas on a TC-FFAP column (GL Science, 0.32 mm × 30 m).

**Reduction of the allylic sulfide 2a**: A 1.59 M hexane solution of BuLi (1.3 mL, 2.0 mmol) was added to a THF (3 mL) suspension of $Cp_2TiCl_2$ (249 mg, 1.0 mmol) at −78 °C under argon. After 1 h, a THF (2 mL) solution of **2a** (138 mg, 0.5 mmol) was added to the mixture dropwise over a period of 5 min. Stirring was continued for 15 min at the same temperature and then at 0 °C for 45 min. The reaction was quenched by addition of 1 M NaOH, and insoluble materials were filtered off through celite and washed with diethyl ether. The organic materials were extracted with diethyl ether and dried over $Na_2SO_4$. After removal of the solvent, the residue was purified by PTLC (hexane) to give a mixture of 2-allylnaphthalene (**8**) and 2-(prop-1-enyl)naphthalene (**8′**;[12] combined yield = 84 mg, quantitative, **8**/**8′** = 90:10, *E*/*Z* ratio of **8′** = 93:7): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 1.90–2.00 (m, 0.3H), 3.54 (d, $J$ = 6.6 Hz, 1.8H), 5.08–5.18 (m, 1.8H), 6.04 (ddt, $J$ = 16.9, 10.3, 6.6 Hz, 0.9H), 6.35 (dq, $J$ = 15.8, 6.6 Hz, 0.1H), 6.55 (d, $J$ = 16.2 Hz, 0.1H), 7.21–7.82 ppm (m, 7H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$ = 40.3, 116.0, 125.2, 125.9, 126.6, 127.4, 127.5, 127.6, 127.9, 132.1, 133.6, 137.3, 137.5 ppm; IR (neat): $\tilde{\nu}$ = 3054, 2977, 2908, 1636, 1600, 1508, 1432, 994, 960, 914, 851, 815, 752, 606 cm$^{-1}$.

**Reduction of the allylic ether 3a**: A 1.59 M hexane solution of BuLi (5.0 mL, 8.0 mmol) was added to a THF (12 mL) suspension of $Cp_2TiCl_2$ (996 mg, 4.0 mmol) at −78 °C under argon. After 1 h, a THF (8 mL) solution of **3a** (536 mg, 2.0 mmol) was added to the mixture dropwise over a period of 5 min. Stirring was continued for 15 min at the same temperature and then at 25 °C for 20 min. The reaction was quenched by addition of 1 M NaOH, and insoluble materials were filtered off through celite and washed with diethyl ether. The organic materials were extracted with diethyl ether and dried over $Na_2SO_4$. After removal of the solvent, the residue was purified by PTLC (hexane) to give a mixture of **8** and **8′** (311 mg, 92%, **8**/**8′** = 90:10, *E*/*Z* ratio of **8′** = 77:23).

**Reduction of the allylic pivalate 4a**: The reduction of **4a** (536 mg, 2.0 mmol) under the above conditions produced a mixture of **8** and **8′** (299 mg, 89%, **8**/**8′** = 81:19, *E*/*Z* ratio of **8′** = 97:3).

**Preparation of *anti*-homoallylic alcohols 5**

**Typical procedure A**: **(3*S**,4*R**)-2,2,3-trimethyl-4-phenylhex-5-en-3-ol (5b)**: A 1.54 M hexane solution of BuLi (5.2 mL, 8.0 mmol) was added to a THF (12 mL) suspension of $Cp_2TiCl_2$ (996 mg, 4.0 mmol) at −78 °C under argon. After 1 h, a THF (8 mL) solution of **2b** (453 mg, 2.0 mmol) was added to the mixture dropwise over a period of 5 min. Stirring was continued for 15 min at the same temperature and then at 0 °C for 45 min. After the reaction mixture had been stirred at −78 °C for 15 min, **6b** (240 mg, 2.4 mmol) in THF (4 mL) was added dropwise over a period of 10 min; the reaction mixture was then stirred for a further 18 h. The reaction was quenched by addition of 1 M NaOH, and insoluble materials were filtered off through celite and washed with diethyl ether. The organic materials were extracted with diethyl ether and dried over $Na_2SO_4$. After removal of the solvent, the residue was purified by PTLC (hexane/AcOEt 95:5) to give (3*S**,4*R**)-2,2,3-trimethyl-4-phenylhex-5-en-3-ol (**5b**; 314 mg, 72%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.93 (s, 9H), 1.16 (s, 3H), 1.70 (s, 1H), 3.62 (d, $J$ = 9.5 Hz, 1H), 5.02–5.13 (m, 2H), 6.37 (ddd, $J$ = 16.9, 9.9, 9.9 Hz, 1H), 7.15–7.32 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$ = 21.6, 26.6, 39.2, 58.0, 77.8, 116.6, 126.3, 128.4, 129.0, 140.7, 143.3 ppm; IR (neat): $\tilde{\nu}$ = 3568, 3062, 3026, 2959, 2875, 1632, 1601, 1483, 1454, 1395, 1374, 1329, 1211, 1099, 1004, 906, 728, 703 cm$^{-1}$; elemental analysis: calcd (%) for $C_{15}H_{22}O$: C 82.52, H 10.16; found: C 82.50, H 9.96.

The following homoallylic alcohols **5** were obtained in a similar fashion. In the case of the preparation of **5a**, the reaction of allyltitanocene **1**, generated from **2b**, with **6a** was carried out at 0 °C for 1 h.

**(2*S**,3*R**)-2,3-diphenylpent-4-en-2-ol (5a)**:[2c] The reaction was carried out by using **2b** (453 mg, 2.0 mmol) and **6a** (288 mg, 2.4 mmol) to produce **5a** (420 mg, 88%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 1.45 (s, 3H), 2.02 (s, 1H), 3.64 (d, $J$ = 8.6 Hz, 1H), 4.94 (d, $J$ = 17.0 Hz, 1H), 5.06 (d, $J$ = 10.3 Hz, 1H), 6.13 (ddd, $J$ = 17.0, 10.3, 8.6 Hz, 1H), 7.10–7.37 ppm (m, 10H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$ = 28.5, 61.8, 76.3, 118.0, 125.5, 126.5, 126.8, 127.7, 128.1, 129.6, 137.3, 140.1, 146.3 ppm; IR (neat): $\tilde{\nu}$ = 3562, 3470, 3060, 3027, 2977, 1494, 1446, 1374, 1066, 1029, 917, 759, 737, 700 cm$^{-1}$.

**(3*S**,4*S**)-2,3-Dimethyl-4-phenylhex-5-en-3-ol (5c)**:[2b] The reaction was carried out by using **2b** (453 mg, 2.0 mmol) and **6c** (176 mg, 2.4 mmol) to produce **5c** (347 mg, 85%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.87 (s, 3H), 0.91 (d, $J$ = 6.8 Hz, 3H), 0.98 (d, $J$ = 6.8 Hz, 3H), 1.37 (s, 1H), 1.96 (septet, $J$ = 6.8 Hz, 1H), 3.42 (d, $J$ = 9.7 Hz, 1H), 5.09 (ddd, $J$ = 17.2, 1.9, 0.7 Hz, 1H), 5.14 (dd, $J$ = 10.3, 2.0 Hz, 1H), 6.35 (dt, $J$ = 17.2, 10.0 Hz, 1H), 7.18–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$ = 16.8, 17.5, 20.1, 34.0, 57.6, 76.1, 116.8, 126.4, 128.2, 129.3, 137.9, 141.8 ppm; IR (neat): $\tilde{\nu}$ = 3483, 3074, 3027, 2961, 2876, 1635, 1601, 1491, 1470, 1454, 1387, 1156, 1081, 1005, 917, 736, 702 cm$^{-1}$.

**A mixture of (3*S**,4*S**)- and (3*S**,4*R**)-4,6-dimethyl-3-phenylhept-1-en-4-ol (5d)**: The reaction was carried out by using **2b** (453 mg, 2.0 mmol) and **6e** (240 mg, 2.4 mmol) to produce **5d** (297 mg, 68%; 3*S**,4*S**/3*S**,4*R** = 96:4): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.92 (d, $J$ = 6.6 Hz, 3H), 0.96 (d, $J$ = 6.6 Hz, 3H), 1.11 (s, 2.88H), 1.18 (s, 0.12H), 1.36–1.40 (m, 2H), 1.45 (s, 1H), 1.72–1.94 (m, 1H), 3.27 (d, $J$ = 9.7 Hz, 0.96H), 3.31 (d, $J$ = 9.7 Hz, 0.04H), 5.07–5.21 (m, 2H), 6.20–6.38 (m, 1H), 7.17–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$ = 24.0, 24.3, 24.9, 25.1, 48.2, 61.8, 74.5, 117.7, 126.5, 128.2, 129.2, 137.8, 141.1 ppm; IR (neat): $\tilde{\nu}$ = 3569, 3482, 3077, 3028, 2954, 2870, 1493, 1453, 1376, 1157, 1082, 918, 746, 703 cm$^{-1}$; elemental analysis: calcd (%) for $C_{15}H_{22}O$: C 82.52, H 10.16; found: C 82.72, H 9.93.

**A mixture of (3*S**,4*S**)- and (3*S**,4*R**)-3-methyl-4-phenylhex-5-en-3-ol (5e)**:[2a] The reaction was carried out by using **2b** (453 mg, 2.0 mmol) and **6f** (433 mg, 6.0 mmol) to produce **5e** (384 mg, 88%; 3*S**,4*S**/3*S**,4*R** = 90:10): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.91 (t, $J$ = 7.3 Hz, 0.3H), 0.93 (t, $J$ = 7.5 Hz, 2.7H), 1.06 (s, 2.7H), 1.15 (s, 0.3H), 1.45 (s, 1H), 1.53 (q, $J$ = 7.5 Hz, 2H), 3.30 (d, $J$ = 9.5 Hz, 0.9H), 3.31 (d, $J$ = 9.5 Hz, 0.1H), 5.06–5.22 (m, 2H), 6.33 (dt, $J$ = 16.9, 9.9 Hz, 1H), 7.19–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$ = 7.9, 24.2, 32.5, 60.0, 74.1, 117.5, 126.5, 128.2, 129.2, 137.8, 141.2 ppm; IR (neat): $\tilde{\nu}$ = 3464, 3076, 3028, 2972, 2937, 2881, 1636, 1601, 1492, 1453, 1416, 1377, 1282, 1157, 1114, 1072, 1048, 1032, 997, 916, 741, 702 cm$^{-1}$.

**A mixture of (3*S**,4*S**)- and (3*S**,4*R**)-3-methyl-4-phenylhexa-1,5-dien-3-ol (5f)**: The reaction was carried out by using **2b** (453 mg, 2.0 mmol) and **6h** (421 mg, 6.0 mmol) to produce **5f** (271 mg, 72%; 3*S**,4*S**/3*S**,4*R** = 88:12): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 1.25 (s, 3H), 1.61 (s, 0.88H), 1.84 (s, 0.12H), 3.36 (d, $J$ = 8.8 Hz, 1H), 5.04–5.25 (m, 4H), 5.93 (dd, $J$ = 17.2, 10.8 Hz, 0.12H), 5.97 (dd, $J$ = 17.3, 10.7 Hz, 0.88H), 6.22 (ddd, $J$ = 17.0, 10.3, 9.0 Hz, 0.88H), 6.18–6.30 (m, 0.12H), 7.20–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$ = 26.5, 61.0, 74.8, 112.8, 117.8, 126.8, 128.1, 129.5, 137.4, 139.9, 143.3 ppm; IR (neat): $\tilde{\nu}$ = 3567, 3462, 3083, 3028, 2979, 2930, 1454, 1372, 1173, 995, 921, 702 cm$^{-1}$; elemental analysis: calcd (%) for $C_{13}H_{16}O$: C 82.94, H 8.57; found: C 83.01, H 8.78.

**A mixture of (*E*)-(3*S**,4*S**)- and (*E*)-(3*S**,4*R**)-4-methyl-3-phenylundeca-1,5-dien-4-ol (5g)**: The reaction was carried out by using **2b** (543 mg, 2.4 mmol) and **6i** (280 mg, 2.0 mmol) to produce **5g** (345 mg, 67%; 3*S**,4*S**/3*S**,4*R** = 77:23): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.85–0.93 (m, 1H), 1.17–1.42 (m, 9H), 1.58 (s, 0.77H), 1.80 (s, 0.23H), 1.97–2.07 (m, 2H), 3.30–3.37 (m, 1H), 5.05–5.23 (m, 2H), 5.46–5.60 (m, 2H), 6.15–6.31

(m, 1H), 7.18–7.33 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$=14.0, 22.5, 29.0, 31.3, 32.3, 61.6, 74.3, 117.7, 126.7, 128.1, 129.3, 129.6, 134.8, 137.7, 140.3 ppm; IR (neat): $\tilde{\nu}$=3463, 3062, 3028, 2926, 2856, 1454, 1373, 975, 917, 702 cm$^{-1}$; elemental analysis: calcd (%) for $C_{18}H_{26}O$: C 83.67, H 10.14; found: C 84.09, H 10.48.

**(2*S**,3*S**)-3-Methyl-2-phenylpent-4-en-2-ol (5h)**:[5] The reaction was carried out by using **2c** (329 mg, 2.0 mmol) and **6a** (288 mg, 2.4 mmol) to produce **5h** (278 mg, 79%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=0.97 (d, $J$=6.9 Hz, 3H), 1.53 (s, 3H), 1.95 (s, 1H), 2.60 (dq, $J$=6.9, 7.1 Hz, 1H), 5.06–5.22 (m, 2H), 5.65–5.77 (m, 1H), 7.19–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$=14.1, 25.8, 48.7, 75.6, 116.6, 125.4, 126.6, 127.8, 139.9, 147.0 ppm; IR (neat): $\tilde{\nu}$=3458, 3061, 3026, 2977, 2934, 2877, 1446, 1373, 1071, 1028, 912, 701 cm$^{-1}$.

**(2*S**,3*R**)-2-Cyclohexyl-3-methylpent-4-en-2-ol (5i)**:[5] The reaction was carried out by using **2c** (329 mg, 2.0 mmol) and **6d** (303 mg, 2.4 mmol) to produce **5i** (299 mg, 82%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=1.00 (d, $J$=7.0 Hz, 3H), 1.03 (s, 3H), 1.05–1.25 (m, 4H), 1.26 (s, 1H), 1.35–1.47 (m, 1H), 1.60–1.87 (m, 6H), 2.42 (dq, $J$=7.1, 7.2 Hz, 1H), 5.06 (d, $J$=15.4 Hz, 1H), 5.10 (d, $J$=9.9 Hz, 1H), 5.90 (ddd, $J$=17.2, 10.3, 8.4 Hz, 2H), 7.19–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$=14.6, 20.1, 26.2, 26.6, 26.7, 26.8, 27.3, 44.2, 45.0, 75.2, 115.8, 140.6 ppm; IR (neat): $\tilde{\nu}$=3482, 3073, 2926, 2853, 1636, 1450, 1378, 1120, 1074, 909 cm$^{-1}$.

**A mixture of (3*S**,4*R**)- and (3*S**,4*S**)-3,4-dimethyl-1-phenylhex-5-en-3-ol (5j)**:[2g] The reaction was carried out by using **2c** (329 mg, 2.0 mmol) and **6g** (356 mg, 2.4 mmol) to produce **5j** (347 mg, 85%; 3*S**,4*R**/3*S**,4*S**=88:12): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=1.05 (d, $J$=7.0 Hz, 3H), 1.17 (s, 2.64H), 1.21 (s, 0.36H), 1.43 (s, 0.12H), 1.56 (s, 0.88H), 1.68–1.89 (m, 2H), 2.34 (dq, $J$=7.0, 7.3 Hz, 1H), 2.59–2.83 (m, 2H), 5.06–5.21 (m, 2H), 5.72–5.95 (m, 2H), 7.13–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$=15.0, 23.5, 29.8, 42.1, 47.5, 73.6, 116.7, 125.7, 128.4, 140.1, 142.8 ppm; IR (neat): $\tilde{\nu}$=3447, 3063, 3026, 2974, 2874, 1455, 1375, 1059, 911, 699 cm$^{-1}$.

**A mixture of (3*S**,4*S**)- and (3*S**,4*R**)-4-methyl-3-phenylhex-5-en-3-ol (5k)**:[5] The reaction was carried out by using **2c** (329 mg, 2.0 mmol) and **6j** (322 mg, 2.4 mmol) to produce **5k** (323 mg, 85%; 3*S**,4*S**/3*S**,4*R**=99:1): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=0.72 (t, $J$=7.4 Hz, 3H), 0.81 (d, $J$=6.8 Hz, 0.01H), 1.02 (d, $J$=6.8 Hz, 0.99H), 1.81 (s, 1H), 1.83 (dq, $J$=14.3, 7.2 Hz, 1H), 1.97 (dq, $J$=14.5, 7.3 Hz, 1H), 2.65 (dq, $J$=14.1, 6.9 Hz, 1H), 5.03 (d, $J$=11.2 Hz, 1H), 5.05 (d, $J$=17.6 Hz, 1H), 5.55–5.69 (m, 1H), 7.18–7.41 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$=7.8, 13.4, 31.4, 47.6, 78.2, 116.2, 126.1, 126.3, 127.7, 140.0, 144.6 ppm; IR (neat): $\tilde{\nu}$=3488, 3061, 3026, 2974, 2937, 2879, 1494, 1446, 1376, 1139, 1058, 1005, 969, 913, 759, 702 cm$^{-1}$.

**(2*S**,3*S**)-3-Phenylethyl-2-phenylpent-4-en-2-ol (5l)**: The reaction was carried out by using **2d** (509 mg, 2.0 mmol) and **6a** (288 mg, 2.4 mmol) to produce **5l** (426 mg, 80%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=1.35 (dddd, $J$=13.3, 11.0, 9.6, 4.8 Hz, 1H), 1.54 (s, 3H), 1.78 (dddd, $J$=13.1, 8.6, 7.3, 2.6 Hz, 1H), 2.01 (s, 1H), 2.24–2.36 (m, 2H), 2.60 (ddd, $J$=14.0, 10.0, 4.3 Hz, 1H), 5.17 (dd, $J$=17.1, 2.1 Hz, 1H), 5.27 (dd, $J$=10.3, 2.0 Hz, 1H), 5.63 (ddd, $J$=17.0, 8.5, 8.5 Hz, 1H), 6.98–7.05 (m, 2H), 7.09–7.42 ppm (m, 8H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$=25.7, 30.4, 33.9, 56.0, 75.4, 119.4, 125.6, 125.9, 126.7, 127.8, 128.2, 128.3, 138.5, 142.2, 146.1 ppm; IR (neat): $\tilde{\nu}$=3456, 3061, 3026, 2976, 2926, 1495, 1446, 1063, 1029, 918, 754, 700 cm$^{-1}$; elemental analysis: calcd (%) for $C_{19}H_{22}O$: C 85.67, H 8.32; found: C 85.78, H 8.52.

**Typical procedure B**: A 1.54M hexane solution of BuLi (5.2 mL, 8.0 mmol) was added to a THF (12 mL) suspension of $Cp_2TiCl_2$ (996 mg, 4.0 mmol) at −78°C under argon. After 1 h, a THF (8 mL) solution of **3b** (296 mg, 2.0 mmol) was added to the mixture dropwise over a period of 5 min. Stirring was continued for 15 min at the same temperature and then at 25°C for 20 min. After the reaction mixture had been stirred at −78°C for 15 min, **6a** (288 mg, 2.4 mmol) in THF (4 mL) was added dropwise over a period of 10 min, and the reaction mixture was stirred for a further 18 h. The workup used in procedure A afforded **5a** (377 mg, 79%).

In a similar fashion, the homoallylic alcohols **5e** (349 mg, 80%) and **5l** (373 mg, 70%) were obtained by using **3b** (296 mg, 2.0 mmol) with **6f** (433 mg, 6.0 mmol) and **3c** (353 mg, 2.0 mmol) with **6a** (288 mg, 2.4 mmol), respectively. The homoallylic alcohol **5e** (377 mg, 73%) was also obtained by using **4b** (437 mg, 2.0 mmol) and **6f** (433 mg, 6.0 mmol).

**Transformation of homoallylic alcohols 5 into γ-butyrolactones 10**

**Transformation of 5 into 10 by using $BH_3$·$Me_2S$: Typical procedure**: A 2M diethyl ether solution of $BH_3$·$Me_2S$ (0.6 mL, 1.2 mmol) was added to a THF (5.6 mL) solution of the homoallylic alcohol **5j** (isomeric ratio=88:12; 377 mg, 1.85 mmol) at room temperature under argon. The mixture was stirred for 4 h, and the reaction was then quenched by addition of water at 0°C. Sodium perborate (2.6 g, 17 mmol) and NaOH (67 mg, 17 mmol) were subsequently added at 0°C, and the mixture was heated at 50°C for 4 h. After the mixture had cooled to room temperature, the organic materials were extracted with diethyl ether and dried over $Na_2SO_4$. After removal of the solvent under reduced pressure, the residue was purified by PTLC (hexane/AcOEt 2:1) to give **11d** (284 mg, 69%). A $CH_2Cl_2$ (3 mL) solution of **11d** (267 mg, 1.2 mmol) was added to PCC (1.13 g, 4.5 mmol) in $CH_2Cl_2$ (15 mL), and the mixture was stirred for 18 h at room temperature under argon. Purification of the reaction mixture by column chromatography (Kanto silica gel 60N, eluted with AcOEt) gave the crude product, which was further purified by PTLC (hexane/AcOEt 2:1) to give a mixture of (3*S**,4*R**)- and (3*S**,4*S**)-3,4-dimethyl-4-(phenylethyl)butyrolactone (**10d**; 157 mg, 60%; 3*S**,4*R**/3*S**,4*S**=91:9): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=1.04–1.12 (m, 3H), 1.30 (s, 2.73H), 1.48 (s, 0.27H), 1.68–2.07 (m, 2H), 2.18–2.51 (m, 2H), 2.60–2.85 (m, 3H), 7.16–7.33 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$=14.4, 19.6, 30.0, 36.5, 38.3, 42.1, 88.5, 126.0, 128.2, 128.5, 141.4, 175.8 ppm; IR (neat): $\tilde{\nu}$=3027, 2974, 2937, 2879, 1766, 1496, 1455, 1422, 1385, 1244, 1198, 1171, 1122, 1081, 1052, 962, 945, 924, 754, 701, 634 cm$^{-1}$; elemental analysis: calcd (%) for $C_{14}H_{18}O_2$: C 77.03, H 8.31; found: C 77.02, H 8.63.

In a similar fashion, the following γ-butyrolactones **10** were obtained.

**(3*S**,4*R**)-4-*tert*-Butyl-4-methyl-3-phenylbutyrolactone (10a)**: The hydroboration–oxidation of **5b** (283 mg, 1.3 mmol) was carried out by using $BH_3$·$Me_2S$ (2M in diethyl ether, 0.40 mL, 0.80 mmol), sodium perborate (2.0 g, 13 mmol), and NaOH (50 mg, 13 mmol) to produce **11a** (189 mg, 61%). The oxidation of **11a** (186 mg, 0.80 mmol) was carried out by using PCC (755 mg, 3.0 mmol) to produce **10a** (146 mg, 80%): m.p.=126–127°C; $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=1.06 (s, 9H), 1.07 (s, 3H), 2.87 (dd, $J$=18.7, 6.4 Hz, 1H), 3.09 (dd, $J$=18.7, 10.3 Hz, 1H), 3.82 (dd, $J$=10.3, 6.4 Hz, 1H), 7.17–7.38 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$=19.7, 25.4, 38.3, 39.1, 44.4, 94.1, 127.3, 128.5, 128.8, 140.5, 176.2 ppm; IR (KBr): $\tilde{\nu}$=3005, 2976, 2880, 1746, 1499, 1484, 1458, 1418, 1397, 1377, 1298, 1268, 1203, 1153, 1124, 1087, 960, 943, 750, 706 cm$^{-1}$; elemental analysis: calcd (%) for $C_{15}H_{20}O_2$: C 77.55, H 8.68; found: C 77.21, H 8.66.

**(3*S**,4*S**)-4-Isobutyl-4-methyl-3-phenylbutyrolactone (10b)**: The hydroboration–oxidation of **5d** (148 mg, 0.60 mmol) was carried out by using $BH_3$·$Me_2S$ (2M in diethyl ether, 0.20 mL, 0.40 mmol), sodium perborate (923 mg, 5.8 mmol), and NaOH (23 mg, 5.8 mmol) to produce **11b** (81 mg, 57%). The oxidation of **11b** (71 mg, 0.30 mmol) was carried out by using PCC (273 mg, 1.1 mmol) to produce **10b** (26 mg, 50%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=0.97 (d, $J$=6.6 Hz, 3H), 1.04 (d, $J$=6.6 Hz, 3H), 1.04 (s, 3H), 1.63 (dd, $J$=14.7, 7.5 Hz, 1H), 1.75 (dd, $J$=14.7, 5.1 Hz, 1H), 1.80–2.00 (m, 1H), 2.84 (dd, $J$=17.6, 8.6 Hz, 1H), 3.00 (dd, $J$=17.6, 10.8 Hz, 1H), 3.53 (dd, $J$=10.7, 8.7 Hz, 1H), 7.20–7.40 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$=21.1, 23.7, 24.2, 24.5, 34.0, 48.4, 50.4, 89.6, 127.7, 128.1, 128.6, 136.5, 175.6 ppm; IR (neat): $\tilde{\nu}$=3032, 2955, 2871, 1775, 1498, 1456, 1384, 1367, 1303, 1269, 1223, 1194, 1122, 1052, 1030, 968, 939, 743, 702, 619 cm$^{-1}$; elemental analysis: calcd (%) for $C_{15}H_{20}O_2$: C 77.55, H 8.68; found: C 77.95, H 8.84.

**(3*S**,4*S**)-4-Methyl-3-phenylethyl-4-phenylbutyrolactone (10e)**: The hydroboration–oxidation of **5l** (346 mg, 1.3 mmol) was carried out by using $BH_3$·$Me_2S$ (2M in diethyl ether, 0.40 mL, 0.80 mmol), sodium perborate (2.0 g, 13 mmol), and NaOH (50 mg, 13 mmol) to produce **11e** (240 mg, 65%). The oxidation of **11e** (228 mg, 0.80 mmol) was carried out by using PCC (745 mg, 3.0 mmol) to produce **10e** (166 mg, 74%): m.p.=109–110°C; $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=1.59 (s, 3H), 1.64–1.82 (m, 1H), 1.93–2.06 (m, 1H), 2.40 (dd, $J$=16.1, 9.5 Hz, 1H), 2.45–2.67 (m, 3H), 2.68 (dd, $J$=16.1, 7.3 Hz, 1H), 7.08–7.38 ppm (m, 10H); $^{13}$C NMR

(75 MHz, $CDCl_3$): $\delta$ = 21.7, 31.3, 34.1, 34.7, 46.5, 88.7, 124.3, 126.2, 127.7, 128.1, 128.4, 140.7, 143.9, 175.4 ppm; IR (KBr): $\tilde{\nu}$ = 3518, 3086, 3061, 3027, 2979, 2938, 2861, 1769, 1602, 1496, 1447, 1421, 1383, 1317, 1272, 1223, 1191, 1141, 1114, 1090, 1054, 1030, 1010, 970, 936, 767, 700, 661 $cm^{-1}$; elemental analysis: calcd (%) for $C_{19}H_{20}O_2$: C 81.40, H 7.19; found: C 81.22, H 7.24.

**Transformation of 5g into 10c by using 9-BBN**: A 0.5 M THF solution of 9-BBN (3.0 mL, 1.5 mmol) was added to a THF (1.4 mL) solution of the homoallylic alcohol **5g** (96 mg, 0.37 mmol) at room temperature under argon. The mixture was stirred for 1.5 h, and the reaction was then quenched by addition of 3 M NaOH (0.4 mL) at 0 °C. Hydrogen peroxide (30%, 1.5 mL) was subsequently added at 0 °C, and the mixture was stirred at 25 °C for 30 min. The organic materials were extracted with diethyl ether and dried over $Na_2SO_4$. After removal of the solvent under reduced pressure, the residue was purified by PTLC (hexane/AcOEt 2:1) to give **11c** (57 mg, 55%). A $CH_2Cl_2$ (3 mL) solution of **11c** (55 mg, 0.2 mmol) was added to PCC (199 mg, 0.8 mmol) in $CH_2Cl_2$ (3 mL), and the mixture was stirred for 18 h at room temperature under argon. The workup described above afforded (3*S**,4*S**)-4-((*E*)-hept-1-enyl)-4-methyl-3-phenylbutyrolactone (**10c**; 74 mg, 39%): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.90 (t, *J* = 6.8 Hz, 3H), 1.08 (s, 3H), 1.23–1.47 (m, 6H), 2.05–2.13 (m, 2H), 2.92 (d, *J* = 8.4 Hz, 1H), 3.56 (d, *J* = 8.4 Hz, 1H), 5.61–5.77 (m, 2H), 7.15–7.38 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$ = 13.9, 21.4, 22.3, 28.6, 31.2, 32.0, 34.2, 50.3, 87.9, 127.6, 127.7, 128.5, 131.4, 132.2, 136.9, 175.7 ppm; IR (neat): $\tilde{\nu}$ = 3524, 3032, 2927, 1778, 1498, 1455, 1379, 1222, 1061, 971, 700, 619 $cm^{-1}$; elemental analysis: calcd (%) for $C_{18}H_{24}O_2$: C 79.37, H 8.88; found: C 79.32, H 9.17.

**Transformation of homoallylic alcohols 5 into the saturated alcohol 12**

**Reduction of the homoallylic alcohol 5f**: An EtOH (1.7 mL) solution of **5f** (94 mg, 0.50 mmol) was added to a flask charged with 10% Pd/C (18 mg) under hydrogen at room temperature, and the reaction mixture was stirred for 3 h. The insoluble materials were filtered off and washed with diethyl ether. The solvent was evaporated under reduced pressure, and the residue was purified by PTLC (hexane/AcOEt 95:5) to give a mixture of (3*S**,4*S**)- and (3*S**,4*R**)-3-methyl-4-phenylhexan-3-ol (**12**; 91 mg, 95%; 3*S**,4*S**/3*S**,4*R** = 88:12): $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 0.71 (t, *J* = 7.3 Hz, 3H), 0.90 (t, *J* = 7.4 Hz, 2.64H), 0.92 (t, *J* = 7.3 Hz, 0.36H), 1.06 (s, 2.64H), 1.13 (s, 0.36H), 1.20 (s, 1H), 1.38–1.56 (m, 2H), 1.66–1.82 (m, 1H), 1.82–1.99 (m, 1H), 2.50 (dd, *J* = 11.9, 3.3 Hz, 0.88H), 2.50–2.59 (m, 0.12H), 7.17–7.34 ppm (m, 5H); $^{13}$C NMR (75 MHz, $CDCl_3$; major isomer): $\delta$ = 8.0, 12.9, 21.8, 24.3, 32.5, 57.6, 74.7, 126.4, 128.0, 129.7, 141.3 ppm; IR (neat): $\tilde{\nu}$ = 3446, 3061, 3027, 2967, 2876, 1493, 1454, 1378, 1156, 702 $cm^{-1}$; elemental analysis: calcd (%) for $C_{13}H_{20}O$: C 81.20, H 10.48; found: C 81.66, H 10.01.

**Reduction of the homoallylic alcohol 5e**: The homoallylic alcohol **5e** (94 mg, 0.50 mmol) was reduced under the same reaction conditions for 2 h to give **12** (85 mg, 88%).

**Crystal data for compounds 10**: CCDC 708323 (**10a**) and CCDC 708322 (**10e**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

**10a**: $C_{15}H_{20}O_2$, $M_W$ = 232.31; crystal size 0.60 × 0.20 × 0.20 mm; monoclinic; space group $P2_1/c$; *a* = 11.1678(3), *b* = 11.6635(3), *c* = 10.7369(3) Å; $\beta$ = 110.922(2)°; *V* = 1306.33(6) Å$^3$; *Z* = 4; *T* = 193 K; $D_x$ = 1.181 g cm$^{-3}$; $\mu_{Cu\text{-}K\alpha}$ = 0.603 mm$^{-1}$; $R_{int}$ = 0.0270; number of measured/independent reflections = 22817/2385; *R* = 0.0399 and $wR(F^2)$ = 0.1152 (all data).

**10e**: $C_{19}H_{20}O_2$, $M_W$ = 280.35; crystal size 0.60 × 0.20 × 0.08 mm; monoclinic; space group $P2_1/c$; *a* = 10.42773(19), *b* = 12.0634(2), *c* = 12.3870(2) Å; $\beta$ = 96.5130(10)°; *V* = 1548.14(5) Å$^3$; *Z* = 4; *T* = 193 K; $D_x$ = 1.203 g cm$^{-3}$; $\mu_{Cu\text{-}K\alpha}$ = 0.602 mm$^{-1}$; $R_{int}$ = 0.0349; number of measured/independent reflections = 27683/2841; *R* = 0.0397 and $wR(F^2)$ = 0.1037 (all data).

## Acknowledgements

This work was supported by a Grant-in-Aid for Scientific Research (no. 18350018) and a Grant-in-Aid for Scientific Research on Priority Areas "Advanced Molecular Transformations of Carbon Resources" (no. 19020016) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

[1] a) S. E. Denmark, N. G. Almstead in *Modern Carbonyl Chemistry* (Ed.: J. Otera), Wiley-VCH, Weinheim, **2000**, chapter 10; b) S. R. Chemler, W. R. Roush in *Modern Carbonyl Chemistry* (Ed.: J. Otera), Wiley-VCH, Weinheim, **2000**, chapter 11; c) N. Risch, M. Arend in *Stereoselective Synthesis, Methods of Organic Chemistry, Vol. 3* (Eds.: G. Helmchen, R. Hoffmann, J. Mulzer, E. Schaumann), Thieme, Stuttgart, **1996**, pp. 1357–1602; d) J. Szymoniak, C. Moïse in *Titanium and Zirconium in Organic Synthesis* (Ed.: I. Marek), Wiley-VCH, Weinheim, **2002**, chapter 13; e) S. E. Denmark, J. Fu, *Chem. Rev.* **2003**, *103*, 2763–2793; f) I. Fleming, A. Barbaro, D. Walter, *Chem. Rev.* **1997**, *97*, 2063–2192; g) Y. Yamamoto, N. Asao, *Chem. Rev.* **1993**, *93*, 2207–2293.

[2] For recent examples of diastereoselective allylation of ketones, see: [Zn]: a) G. Dunet, P. Mayer, P. Knochel, *Org. Lett.* **2008**, *10*, 117–120; b) H. Ren, G. Dunet, P. Mayer, P. Knochel, *J. Am. Chem. Soc.* **2007**, *129*, 5376–5377; [Sn]: c) M. Yasuda, K. Hirata, M. Nishino, A. Yamamoto, A. Baba, *J. Am. Chem. Soc.* **2002**, *124*, 13442–13447; [Si]: d) L. F. Tietze, T. Kinzel, S. Schmatz, *J. Am. Chem. Soc.* **2006**, *128*, 11483–11495; [In]: e) S. A. Babu, M. Yasuda, A. Baba, *J. Org. Chem.* **2007**, *72*, 10264–10267; f) N. Hayashi, H. Honda, M. Yasuda, I. Shibata, A. Baba, *Org. Lett.* **2006**, *8*, 4553–4556; [V]: g) Y. Kataoka, I. Makihara, T. Yamahata, K. Tani, *Organometallics* **1997**, *16*, 4788–4795.

[3] For diastereoselective asymmetric allylation of ketones, see: a) M. Wadamoto, H. Yamamoto, *J. Am. Chem. Soc.* **2005**, *127*, 14556–14557; b) R. Wada, K. Oisaki, M. Kanai, M. Shibasaki, *J. Am. Chem. Soc.* **2004**, *126*, 8910–8911.

[4] M. T. Reetz, R. Steinbach, J. Westermann, R. Peter, B. Wenderoth, *Chem. Ber.* **1985**, *118*, 1441–1454.

[5] D. Seebach, L. Wildler, *Helv. Chim. Acta* **1982**, *65*, 1972–1981.

[6] T. Takeda, M. Ando, T. Sugita, A. Tsubouchi, *Org. Lett.* **2007**, *9*, 2875–2878.

[7] T. Takeda, I. Miura, Y. Horikawa, T. Fujiwara, *Tetrahedron Lett.* **1995**, *36*, 1495–1498.

[8] a) T. Zair, C. Santelli-Rouvier, M. Santelli, *J. Org. Chem.* **1993**, *58*, 2686–2693; b) M. El Idrissi, M. Santelli, *J. Org. Chem.* **1988**, *53*, 1010–1016.

[9] a) A. R. Katritzky, C. N. Fali, M. Qi, *Tetrahedron Lett.* **1998**, *39*, 363–366; b) H. Maeda, K. Shono, H. Ohmori, *Chem. Pharm. Bull.* **1994**, *42*, 1808–1812; c) Y. Rollin, S. Derien, E. Duñach, C. Gebehenne, J. Périchon, *Tetrahedron* **1993**, *49*, 7723–7732; d) H. Hebri, E. Duñach, J. Périchon, *Tetrahedron Lett.* **1993**, *34*, 1475–1478; e) R. E. Sjöholm, *Acta Chem. Scand.* **1990**, *44*, 82–89.

[10] E. Negishi, *Organometallics in Organic Synthesis, Vol. 1*, Wiley, New York, **1980**, pp. 136–178.

[11] R. G. Salomon, S. Ghosh, *Org. Synth.* **1990**, *Coll. Vol. VII*, 177–183.

[12] Y. Kayaki, T. Koda, T. Ikariya, *Eur. J. Org. Chem.* **2004**, 4989–4993.

Received: November 11, 2008
Published online: January 29, 2009