A New Enantioselective Approach to the Bicyclo[4.4.0]decane and Bicyclo[4.3.0]nonane Systems

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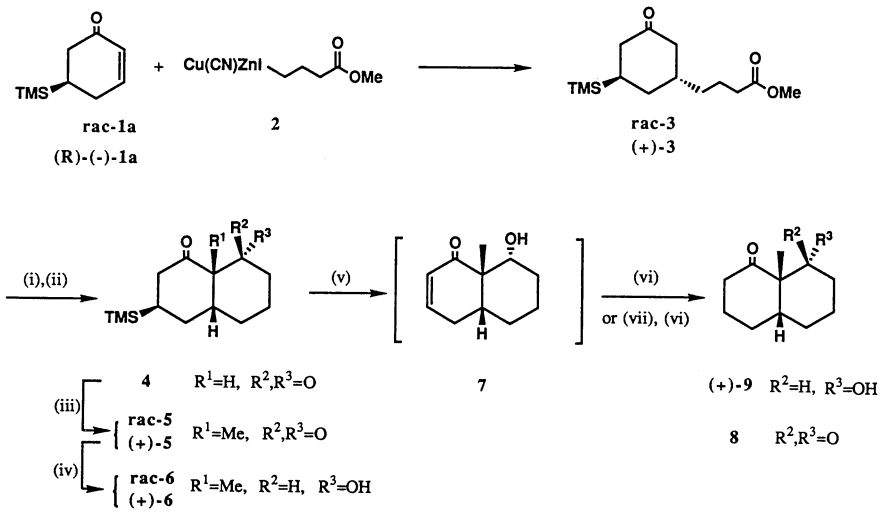
Highly diastereoselective routes to cis-fused bicyclo[4.4.0]decane-2,10-diones and bicyclo[4.3.0]nonane-2,9-diones from 5-trimethylsilyl-2-cyclohexen-1-one (**1a**) and its 3-methyl derivative were established by utilizing an annulation with ω-(alkoxycarbonyl)alkylzinc reagents. Bicyclo[4.4.0]decane-2,8-dione was obtained diastereoselectively by the double Michael reaction of **1a** with dienol silyl ether. The diastereoselective Diels-Alder reaction of **1a** with cyclopentadiene gave an endo adduct, which can be regarded as a new chiral cyclohexenone synthon, with a high optical purity.

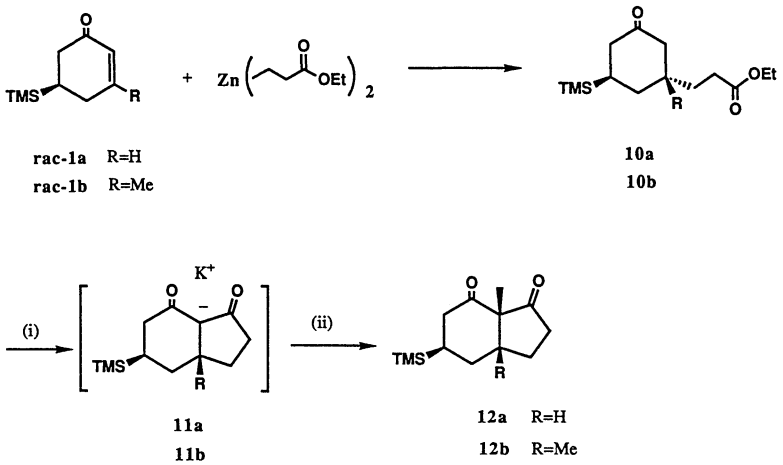
Recently we reported the preparation of enantiomerically pure (*R*)- and (*S*)-5-trimethylsilyl-2-cyclohexen-1-one (**1a**)[1] as a new cyclohexenone-type chiral synthon. As part of our continuing study to utilize **1a** for asymmetric natural-product synthesis, we were interested in establishing stereocontrolled enantioselective routes to polyfunctionalized bicyclo[4.4.0]decane and bicyclo[4.3.0]nonane derivatives starting with **1a** and **1b**, since optically active bicyclic synthons are scarcely known except for the Wieland-Mischer ketone and its homologues which are prepared by asymmetric Robinson's annulation.[2]

Two questions should be answered for our purpose: 1) as we already reported,[1] the stereospecificity of the 1,4-addition of Grignard reagents to **1a** is extremely high, but, the degree of stereoselectivity for other reagents such as zinc and zinc-copper reagents which can be used for annulation is still obscure; 2) the effect of trimethylsilyl group on the stereochemistry of the ring junctions, which depends on the substituted pattern of the bicyclic systems,[3] is not explored.

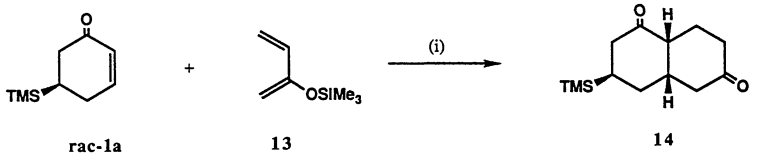
The diastereoselective synthesis of the bicyclo[4.4.0]decane system starting with **1a** was examined by using the 1,4-addition of the zinc-copper reagent **2**[4] to *rac*-**1a**. The reaction proceeded diastereoselectively to give the trans-adduct **3** as an exclusive diastereoisomer in 83% yield, which in turn gave bicyclodecane-2,10-dione **4** in 72% yield by an intramolecular condensation. ^{1}H NMR, ^{13}C NMR, and IR spectra revealed that one of the carbonyl groups of **4** is present mostly as an enol form. Methylation of **4** with base and methyl iodide gave **5** in 80% yield as a single diastereoisomer. Compound **5** was also obtained in good overall yield (75% from **3**) by one-pot treatment of **3** with *t*-butoxide and methyl iodide. The diastereomeric homogeneity of **3** and **5** was confirmed by their ^{13}C NMR spectra, and the cis junction of **5** was confirmed by the transformation into the known cis-dione **8**.[5] It should be noted that in the absence of trimethylsilyl group, methylation of the bicyclodecane-2,10-dione was reported to give a mixture of diastereoisomers (cis/trans=54/33).[5] Therefore, in this sequential transformation, the trimethylsilyl group plays a very important role in controlling both of the newly formed chiral centers. Furthermore, the diastereoselective reduction of **5** with diisobutylalumi-



Scheme 1. (i) *t*-BuOK; (ii) H^+; (iii) *t*-BuOK, MeI; (iv) DIBAH; (v) $CuCl_2$; (vi) Pd-C; (vii) PCC.



Scheme 2. (i) *t*-BuOK; (ii) MeI.



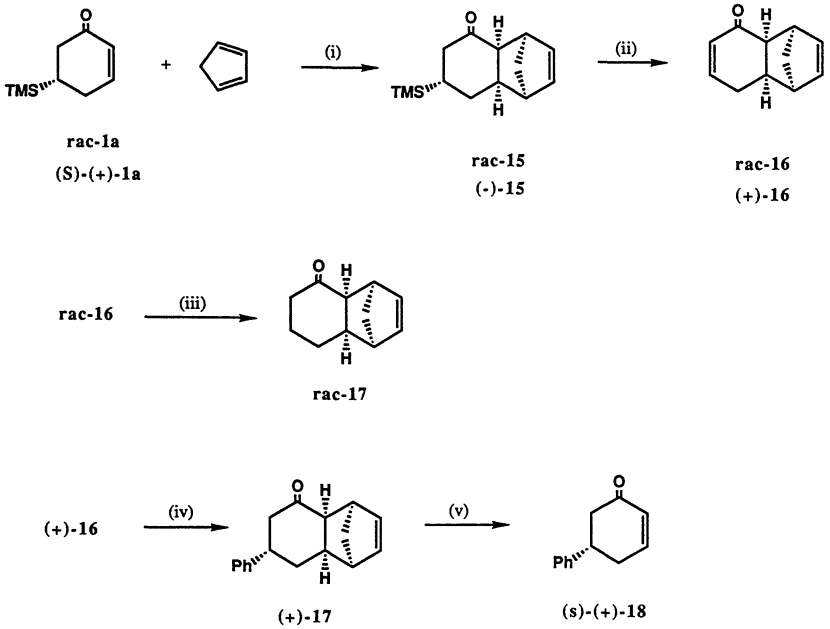
Scheme 3. (i) Lewis acid.

nium hydride (DIBAH) gave a keto alcohol **6**. Thus, the diastereocontrolled conversion of *rac*-**1a** to **4**, **5**, and **6** promises an enantioselective access from the optically pure **1a** to these compound, which are indispensable intermediates in the synthesis of bicyclic sesquiterpenes such as fukinone and ligularone.[6] To demonstrate this, (1*S*,4*R*,6*R*)-**5** was synthesized starting with (*R*)-(−)-**1a**. The 1,4-addition of the zinc reagent **2** afforded the trans-adduct (3*S*,5*R*)-(+)-**3** (78%), which was in turn converted to (1*S*,4*R*,6*R*)-**5** in 58% yield by a one-pot procedure. The absolute configuration was confirmed by the conversion to the known hydroxy ketone **9**[5] by DIBAH reduction, oxidative desilylation, and hydrogenation.

A similar strategy was used for the diastereoselective construction of the bicyclo[4.3.0]nonane system. The 1,4-addition of zinc homoenolate[7] to *rac*-**1a** and *rac*-**1b** gave adducts **10a** and **10b** in 79 and 78% yields as a single diastereoisomer, respectively. A sequential treatment of **10a** and **10b** with *t*-BuOK and methyl iodide gave the expected bicyclo[4.3.0]nonane derivatives **12a** and **12b** in 49 and 50% overall yields from **10a** and **10b**, respectively. The diastereoselective homogeneity of **12a** and **12b** was confirmed by their ^{13}C NMR spectra before recrystallization, and an NOE measurement of **12b** by 500 MHz NMR revealed a cis relationship of the two angular methyl groups. Thus, diketone **12b** may be a valuable intermediate for the synthesis of cis-fused hydrindane derivatives such as pinguisone.[8] Though the structure of **12a** was not directly confirmed, it was tentatively assigned as shown in the scheme on the analogy of **12b**.

The double Michael reaction of a dienol silyl ether[9] **13**[10] to *rac*-**1a** was examined for a synthesis of differently functionalized bicyclo[4.4.0]decane synthons. In this reaction, the experimental procedure was found to be crucial. For example, an addition of a Lewis acid such as $SnCl_4$, $TiCl_4$, $TiCl_4$-$Ti(OPr^i)_4$,[11] $SnCl_4$-TMSCl,[12] or $ZnCl_2$-TrCl[13] to a mixture of *rac*-**1a** and **13** in dichloromethane at −78 °C gave the desired bicyclic derivative in less than 10% yield. After some trials, the addition of **13** to a mixture of *rac*-**1a** and $SnCl_4$ in dichloromethane at −78 °C over a period of 1 h was found to be an appropriate choice to furnish the bicyclo[4.4.0]decanedione **14** (66%) as a single diastereoisomer. Though the stereochemistry was not confirmed, the structure was tentatively assigned as depicted in the scheme from the mechanistic aspects of the same type of reactions.[9]

As a typical example of [4+2]-cycloaddition reaction of **1a**, a Diels-Alder reaction with cyclopentadiene was carried out. The Diels-Alder reaction of *rac*-**1a** with cyclopentadiene catalyzed by aluminium chloride at room temperature smoothly gave the adduct as a diastereomeric mixture (13.5/1), which was separable by careful flash column chromatography, in 83% combined yield. On the analogy of the Diels-Alder reaction of 2-cyclohexen-1-one with cyclopentadiene,[14] the major isomer was assumed to have an endo adduct structure and a trans relationship



Scheme 4. (i) Lewis acid; (ii) $CuCl_2$, $Cu(OAc)_2$; (iii) K-selectride; (iv) PhMgBr; (v) BF_3-Et_2O.

with respect to the trimethylsilyl group. The endo stereochemistry was confirmed by the transformation of *rac*-**15** into the known compound *rac*-**17** by an oxidative desilylation with $CuCl_2$ followed by a conjugate reduction with K-selectride.[15] The optically active (−)-**15** and (+)-**16** were synthesized similarly from the optically pure (*S*)-(+)-**1** in 93 and 78% yields, respectively. Enone (+)-**16** can be an alternative chiral cyclohexenone synthon since the anchor, the cycloadduct part, can easily be removed by retro Diels-Alder reaction. To realize this concept, the copper(I) catalyzed 1,4-addition of phenylmagnesium bromide to (+)-**16** was examined. The reaction proceeded smoothly at −78 °C to give (+)-**17** in 76% yield. The retro Diels-Alder reaction catalyzed by BF_3 etherate[16] gave (*S*)-(+)-5-phenyl-2-cyclohexen-1-one (**18**) (72%).

In conclusion, since the optically pure (*R*)- and (*S*)-**1** are available, the above routes offer a ready access to both the enantiomers of each of the bicyclo[4.4.0]decane and bicyclo[4.3.0]nonane systems with a structural variety not previously available in such types of compounds.

Experimental

^{1}H NMR spectra were taken in $CDCl_3$ on a Hitachi R-24B (60 MHz) and ^{13}C NMR spectra were taken in $CDCl_3$ on a JEOL FX-90Q. The NOE of **12b** was measured on a JEOL JNM-GX-500. IR spectra were recorded on a Hitachi 260-50 spectrophotometer. Optical rotations were measured on a Horiba SEPA-200 automatic polarimeter.

(3*S*,5*R*)-3-[3-(Methoxycarbonyl)propyl]-5-(trimethylsilyl)-cyclohexanone (3). A suspension of activated zinc (1.7 g, 26 mmol) in 2 ml of THF containing 1,2-dibromoethane (190 mg, 1.0 mmol) was heated at 65 °C for 1 min and then cooled to 25 °C. Then, chlorotrimethylsilane (0.1 ml, 0.8 mmol) was added. After 15 min at 25 °C, a solution of methyl 4-iodobutyrate (5.7 g, 25 mmol) in THF (10 ml) was slowly added at 30 °C. After the addition was completed, the reaction mixture was stirred overnight at 40 °C. To the cooled (−10 °C) solution was rapidly added a mixture of CuCN (1.98 g, 22 mmol) and LiCl (1.9 g, 44 mmol, dried at 150 °C for 1 h) in THF (22 ml). The mixture was stirred at 0 °C for 10 min and then cooled to −78 °C. A solution of **1a** (1.6 g, 10 mmol) and chlorotrimethylsilane (5.5 ml, 43 mmol) in dry ether (10 ml) was added dropwise over a period of 30 min to the solution of the copper reagent prepared above. After 3 h of stirring at −78 °C, the reaction mixture was allowed to warm to rt overnight. Then, the mixture was poured into aq NH_4Cl and extracted with ether. The organic layer was washed with brine, dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by column chromatography (hexane/ethyl acetate=300/25—300/75) to give **3**. (3*S**,5*R**)-**3**: 83%; oil. (3*S*,5*R*)-(+)-**3**: 78%; oil; $[\alpha]_D^{21}$ +68.2° (*c* 1.06, $CHCl_3$); ^{1}H NMR δ=0.00 (9H, s), 0.9—1.95 (8H, m), 1.95—2.65 (6H, m), and 3.66 (3H, s); ^{13}C NMR δ=−3.5, 21.5, 22.6, 29.8, 32.5, 33.9, 37.6, 42.0, 46.6, 51.4, 173.68, and 212.5; IR(neat) 1715 and 1740 cm^{-1} (C=O). Found: C, 62.14; H, 9.76%. Calcd for $C_{14}H_{26}O_3Si$: C, 62.18; H, 9.69%.

4-(Trimethylsilyl)bicyclo[4.4.0]decane-2,10-dione (4). Potassium *t*-butoxide (1 g, 9 mmol) prepared from freshly distilled *t*-butyl alcohol was dissolved in dry THF (80 ml), and **3** (1.22 g, 4.5 mmol) was added to the cooled (0 °C) mixture. After stirred for 1 h at 0 °C, the mixture was poured into 2 M (1 M=1 mol dm^{-3}) aq HCl and extracted with hexane. The organic layer was dried over anhydrous $MgSO_4$ and concentrated in vacuo. The residue was purified by flash column chromatography (hexane) to give **4** (0.71 g, 72% yield). *rac*-**4**: oil; ^{1}H NMR δ=0.0 (9H, s), 0.85—2.65 (13H, m), and 15.38 (1H, s); ^{13}C NMR δ=−3.3, 18.3, 20.8, 30.3, 30.7, 31.5, 32.3,

34.4, 109.2, 185.3, and 194.6; IR (neat) 1630 (C=O) and 1595 cm^{-1} (C=C). Found: C, 65.82; H, 9.75%. Calcd for $C_{14}H_{24}O_2Si$: C, 65.49; H, 9.30%.

(1*S*,4*R*,6*R*)-1-Methyl-4-(trimethylsilyl)bicyclo[4.4.0]decane-2,10-dione (5). A solution of *t*-BuOK (5 g, 45 mmol) in dry THF (80 ml) was cooled to 0 °C. Keto ester **3** (3.79 g, 14 mmol) was added to the solution, and the reaction mixture was stirred for 1 h. Methyl iodide (4.4 ml, 70 mmol) was added and the mixture was stirred for another 1 h. The reaction was quenched with 2 M aq HCl and extracted with hexane. The organic layer was washed with aq Na_2SO_3, dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by flash column chromatography (hexane/ethyl acetate=30/1—6/1) to give **5**. (1*S**,4*R**,6*R**)-**5**: 75%; mp 69—72 °C (pentane). (1*S*,4*R*,6*R*)-(+)-**5**: 58% [from (3*R*,5*R*)-(+)-**3**]; mp 69—70 °C (pentane); $[\alpha]_D^{21}$ +222.9° (*c* 1.01, $CHCl_3$); ^1H NMR δ=0.0 (9H, s), 1.36 (3H, s), and 0.5—2.6 (12H, m); ^{13}C NMR δ=−3.9, 19.4, 22.0, 25.0, 27.1, 28.4, 38.2, 40.5, 49.3, 63.8, 209.7, and 213.5; IR (KBr) 1692 and 1715 cm^{-1} (C=O). Found: C, 66.85; H, 9.74%. Calcd for $C_{14}H_{24}O_2Si$: C, 66.61; H, 9.58%.

(1*S*,4*R*,6*R*,10*R*)-10-Hydroxy-1-methyl-4-(trimethylsilyl)bicyclo[4.4.0]decan-2-one (6). To a solution of **5** (762 mg, 3 mmol) in toluene (10 ml) was added a solution of 3.6 ml of DIBAH (1 mol l^{-1} in hexane) at −78°C, and the mixture was stirred for 10 min at that temperature. The reaction was quenched by an addition of saturated aq Na_2SO_4 until a white precipitate appeared. The solution was filtered through Celite, and concentrated in vacuo. The residue was purified by flash column chromatography (hexane/ethyl acetate=10/1—2/1) to give **6**. (1*S**,4*R**,6*R**,10*R**)-**6**: quant; oil. (1*S*,4*R*,6*R*,10*R*)-**6**: 67%;[17] mp 65 °C (pentane); $[\alpha]_D^{21}$ +159.5° (*c* 1.02, $CHCl_3$); ^1H NMR δ=0.03 (9H, s), 0.8—2.6 (12H, m), 1.45 (3H, s), 2.8—3.2 (1H, m), and 3.45 (1H, br d); ^{13}C NMR δ=−4.0, 21.3, 23.3, 24.0, 26.7, 28.8, 32.2, 39.0, 47.2, 53.3, 78.4, and 216.8; IR (KBr) 3550 (OH) and 1690 cm^{-1} (C=O). Found: C, 65.80; H, 10.44%. Calcd for $C_{14}H_{26}O_2Si$: C, 66.09; H, 10.30%.

***cis*-1-Methylbicyclo[4.4.0]decane-2,10-dione (8).** A solution of **6** (635 mg, 2.5 mmol) and anhydrous $CuCl_2$ (1.6 g, 12 mmol) in DMF (20 ml) was heated to 90—100 °C. After 2.5 h, the solution was filtered through a short pad of silica gel, and to the filtrate was added aq $NaHCO_3$. The solution was extracted with ether, and the organic layer was washed with aq NH_4Cl, dried over $MgSO_4$, and concentrated. The residue was purified by flash column chromatography (hexane/ethyl acetate=10/1—1/1) to give (1*S**,6*R**,10*R**)-10-hydroxy-1-methylbicyclo[4.4.0]dec-3-en-2-one (**7**, 216 mg, 48%) (though this compound was found to contain a small amount of impurities, it was used for the next reaction without further purification): oil; ^1H NMR δ=1.42 (3H, s), 0.6—3.5 (9H, m), 4.22 (1H, d, *J*=10 Hz), 5,71 (1H, dd, *J*=10 and 3 Hz), and 6.5—7.0 (1H, m); IR (neat) 1670 (C=O) and 3100—3650 cm^{-1} (OH). A solution of **7** (1 mmol, 180 mg) and PCC (1.1 g, 5 mmol) in dry dichloromethane (20 ml) was stirred at rt overnight. After addition of dry ether (20 ml), the solution was filtered through a short pad of silica gel and concentrated in vacuo. The residue was purified by TLC (hexane/ether=1/1) to give (1*S**,6*R**)-1-methylbicyclo-[4.4.0]dec-3-ene-2,10-dione (91 mg, 51%). The dione (40 mg, 0.22 mmol) in ethyl acetate was stirred in the presence of a catalytic amount of Pd-C under H_2 for 2.5 h. The reaction mixture was filtered through Celite and concentrated under reduced pressure. The residue was purified by TLC (hexane/ether=2/1) to give cis-dione **8** (26 mg, 64%) and 6.5 mg of the starting material. *cis*-**8**: mp 27.5—29.5 °C (pentane); ^1H NMR δ=1.39 (3H, s) and 0.5—2.5 (13H, m); IR (CCl_4) 2997, 2870, 1724, 1701, 1550, 1446, 1377, 1315, 1261, 1238, 1099, 1005, 987, and 979 cm^{-1}. Found: C, 73.09; H, 8.73%. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95%.

(1*S*,6*R*,10*R*)-10-Hydroxy-1-methylbicyclo[4.4.0]decan-2-one (9). An oxidative desilylation of (1*S*,4*R*,6*R*,10*R*)-**6** was carried out as mentioned above, and a slightly impure **7**, obtained by chromatographical purification was, hydrogenated in ethyl acetate at rt for 1 h with Pd/C catalyst to give (1*S*,6*R*,10*R*)-**9** in 48% yield: mp 53.4—55 °C (pentane); $[\alpha]_D^{21}$ +121.6° (*c* 0.96, $CHCl_3$); lit,[4] mp 55 °C (pentane) $[\alpha]_D^{21}$ +128.3° (*c* 2.09, $CHCl_3$); ^1H NMR δ=1.15—2.7 (13H, m), 1.50 (3H, s), 2.8—3.2 (1H, m), and 3.55 (1H, br d); ^{13}C NMR δ=21.7, 23.3, 24.1, 25.7, 28.7, 32.3, 38.7, 45.6, 53.5, 78.4, and 219.6; IR (KBr) 3520 (OH) and 1665 cm^{-1} (C=O).

Conjugate Addition of Zinc Homoenolate to 1a and 1b. This reaction was carried out according to the method of Nakamura and Kuwajima.[7] (3*S**,5*R**)-3-[2-(Ethoxycarbonyl)ethyl]-5-(trimethylsilyl)cyclohexanone (**10a**): 79%; oil; ^1H NMR δ=0.0 (9H, s), 1.25 (3H, t, *J*=7 Hz), 0.8—2.5 (12H, m), and 4.08 (2H, q, *J*=7 Hz); ^{13}C NMR δ=−3.5, 14.2, 21.5, 28.2, 29.9, 32.0, 37.3, 41.9, 46.3, 60.4, 173.2, and 212.1; IR (neat) 1710 and 1739 cm^{-1} (C=O). (3*S**,5*R**)-3-[2-(Ethoxycarbonyl)ethyl]-3-methyl-5-(trimethylsilyl)cyclohexanone (**10b**): 78%; oil; ^1H NMR δ=0.0 (9H, s), 0.98 (3H, s), 1.22 (3H, t, *J*=7 Hz), 0.9—2.5 (11H, m), and 4.11 (2H, q, *J*=7 Hz); ^{13}C NMR δ=−3.7. 14.3, 21.7, 28.1, 29.0, 31.8, 37.1, 39.9, 41.3, 53.5, 60.5, 173.5, and 211.9; IR (neat) 1710 and 1740 cm^{-1} (C=O).

A Typical Procedure for Intramolecular Condensation and Methylation. To a solution of potassium *t*-butoxide (5 g, 45 mmol) in dry THF (80 ml) was added keto ester **10a** (3.78 g, 14 mmol), and the solution was refluxed for 1 h. Methyl iodide (4.4 ml, 70 mmol) was added and the reaction mixture was refluxed for another 1 h. The reaction was quenched with 2 M HCl and the aqueous layer was extracted with hexane. The organic layer was washed with aq Na_2SO_3, dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by column chromatography (hexane/AcOEt=20/1—10/1). (1*S**,4*R**,6*R**)-1-Methyl-4-(trimethylsilyl)bicyclo[4.3.0]nonane-2,9-dione (**12a**): 49%; mp 49—50 °C (pentane); ^1H NMR δ=0.03 (9H, s), 1.25 (3H, s), and 1.0—3.0 (10H, m); ^{13}C NMR δ=−4.0, 17.7, 22.9, 23.2, 24.8, 35.5, 38.2, 48.2, 63.2, 210.9, and 215.4; IR (KBr) 1690 and 1750 cm^{-1} (C=O). Found: C, 65.50; H, 9.49%. Calcd for $C_{13}H_{22}O_2Si$: C, 65.50; H, 9.30%. (1*S**,4*R**,6*R**)-1,6-Dimethyl-4-(trimethylsilyl)bicyclo[4.3.0]nonane-2,9-dione (**12b**): 50%; mp 39—40 °C (pentane); ^1H NMR δ=0.04 (9H, s), 0.87 (3H, s), 1.08 (3H, s), and 0.7—2.5(m); ^{13}C NMR δ=−3.8, 13.5, 22.5, 24.0, 29.2, 33.2, 33.5, 37.4, 47.3, 67.1, 212.4, and 215.8; IR (KBr) 1690 and 1748 cm^{-1} (C=O). Found: C, 66.39; H, 9.69%. Calcd for $C_{14}H_{24}O_2Si$: C, 66.61; H, 9.58%.

(1*R,4*R**,6*R**)-4-(Trimethylsilyl)bicyclo[4.4.0]decane-2,8-dione (14).** Enone **1a** (168 mg, 1 mmol) and tin(IV) chloride (0.14 ml, 1.2 mmol), dissolved in dry dichloromethane (60 ml), were cooled to −78 °C. To the solution was added dropwise 2-trimethylsiloxy-1,3-butadiene (284 mg, 2 mmol) in dichloromethane (10 ml) over a period of 1 h, and then the mixture was stirred at that temperature for 30 min. Aqueous $NaHCO_3$ was added and the aqueous layer was

extracted with dichloromethane. The organic layer was dried and concentrated in vacuo. The residue was purified by TLC (hexane/ether=1/1) to give **14** (155mg, 66%): oil; ^{1}H NMR δ=0.03 (9H, s) and 0.4—3.0 (13H m); ^{13}C NMR δ=−4.1, 22.0, 24.6, 30.8, 37.2, 41.8, 42.9, 43.4, 47.4, 210.9, and 211.6; IR (neat) 1725 cm^{-1} (C=O). Found: C, 65.03; H, 9.15%. Calcd for $C_{13}H_{22}O_2Si$: C, 65.50; H, 9.30%.

(1*R*,2*S*,5*S*,7*R*,8*S*)-5-(Trimethylsilyl)tricyclo[6.2.1.0^{2,7}]-undec-9-en-3-one (15). To a solution of **1a** (168 mg, 1 mmol) in toluene (4 ml) was added a solution of $AlCl_3$ (33 mg, 0.25 mmol) in toluene (4 ml), and the reaction mixture was stirred for 40 min under Ar. After an addition of freshly distilled cyclopentadiene (9.8 mmol) in toluene (2 ml), the mixture was stirred at rt for 1 h. The mixture was poured onto ice-water and extracted with ether. The organic layer was washed with aq $NaHCO_3$, dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by TLC (hexane/ether=10/1) to give **15**. (1*R**,2*S**,5*S**, 7*R**,8*S**)-**15**: 83%; mp 39—40 °C (ethanol). (1*R*,2*S*,5*S*,7*R*, 8*S*)-**15**: 93%; mp 48—50 °C; $[\alpha]_D^{21}$ −10.12° (*c* 1.09, $CHCl_3$); ^{1}H NMR δ=0.04 (9H, s), 0.7—3.5 (11H, m), and 6.13 (2H, d, *J*=2 Hz); ^{13}C NMR δ=−3.5, 19.1, 27.8, 38.7, 41.3, 46.7, 49.1, 49.3, 51.9, 134.6, 138.0, and 213.1; IR (neat) 1700 cm^{-1} (C=O). Found: C, 71.87; H, 9.71%. Calcd for $C_{14}H_{22}OSi$: C, 71.73; H, 9.46%.

(1*R*,2*S*,7*R*,8*S*)-Tricyclo[6.2.1.0^{2,7}]undeca-4,9-dien-3-one (16). A solution of **15** (117 mg, 0.5 mmol), anhydrous $CuCl_2$ (203 mg, 1.5 mmol), and $Cu(OAc)_2$-H_2O (100 mg, 0.5 mmol) in DMF was heated to 85—90 °C for 3.5 h. After cooled to rt, the reaction was quenched with water and extracted with ether. The organic layer was dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by TLC (hexane/ether=3/1) to give **16**. (1*R**,2*S**, 7*R**,8*S**)-**16**: 63%; oil. (1*R*,2*S*,7*R*,8*S*)-**16**: 78%; oil; $[\alpha]_D^{18}$ +261.0° (*c* 1.01, $CHCl_3$); ^{1}H NMR δ=1.33 (2H, s), 1.6—3.1 (5H, m), 3.1—3.5 (1H, m), 5.73 (1H, dt, *J*=1 and 10 Hz), 6.05 (2H, d, *J*=1 Hz), and 6.4—6.7 (1H, m); ^{13}C NMR δ=27.3, 33.9, 48.3, 48.8, 49.1, 128.9, 134.7, 137.4, 149.4, and 200.2; IR (neat) 1660 cm^{-1} (C=O).

(*S*)-(+)-5-Phenyl-2-cyclohexen-1-one (18). A solution of (1*R*,2*S*,7*R*,8*S*)-**16** (544 mg, 3.4 mmol), HMPA (1.83 ml, 10.2 mmol), chlorotrimethylsilane (1.72 ml, 13.6 mmol), and CuBr/Me_2S (36 mg, 0.17 mmol) in THF (30 ml) was cooled to −78 °C. To the solution was added a THF solution of phenylmagnesium bromide (10.2 mmol). After stirred at that temperature for 30 min, the reaction mixture was quenched with aq NH_4Cl and extracted with ether. After removal of the solvent, the residue was dissolved in 30 ml of methanol and treated with potassium fluoride at rt for 30 min. Water was added to the reaction mixture, and the product was extracted with ether. The organic layer was dried and concentrated, and the residue was purified by TLC (hexane/ether=5/1) to give (1*R*,2*S*,5*S*,7*R*,8*S*)-5-phenyltricyclo[6.2.1.0^{2,7}]undec-9-en-3-one (**17**, 630 mg, 76%); oil; $[\alpha]_D^{21}$ +131.0° (*c* 1.05, $CHCl_3$); ^{1}H NMR δ=1.1—1.9 (3H, m), 1.9—3.5 (8H, m), 6.25 (2H, s), and 7.22 (5H, s), ^{13}C NMR δ=34.8, 36.9, 37.0, 45.1, 46.3, 47.7, 48.8, 50.9, 126.0, 126.4, 128.2, 135.1, 137.5, 144.0, and 213.4; IR (neat) 1690 cm^{-1} (C=O). To a solution of ketone **17** (630 mg, 2.6 mmol) in dichloromethane (6 ml) was added $BF_3 \cdot Et_2O$ (0.36 ml, 2.9 mmol) and the reaction mixture was stirred at rt for 1 h. The same operation, i.e. an addition of $BF_3 \cdot Et_2O$ (2.6 mmol) followed by a stirring at rt for 1 h, was repeated two more times. The reaction was quenched with aq $NaHCO_3$ and extracted with dichloromethane. After a usual work up, the residue was purified by TLC (hexane/ether=3/1) to give (*S*)-(+)-**18** [327 mg, 72%, $[\alpha]_D^{25}$ +44.4° (*c* 1.13, $CHCl_3$)] lit,[1] (*R*)-(−)-**18**: $[\alpha]_D$ −46.4° (*c* 5.00, $CHCl_3$)]; mp 60 °C (pentane); ^{1}H NMR δ=2.35—2.9 (4H, m), 3.0—3.6 (1H, m), 6.00 (1H, dt, *J*=2 and 10 Hz), 6.7—7.1 (1H, m), and 7.10 (5H, s); IR (KBr) 1680 cm^{-1} (C=O).

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