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Organoaluminum-Promoted Cyclization of Olefinic Epoxides. A New and Stereoselective Approach to Cyclohexane Frameworks

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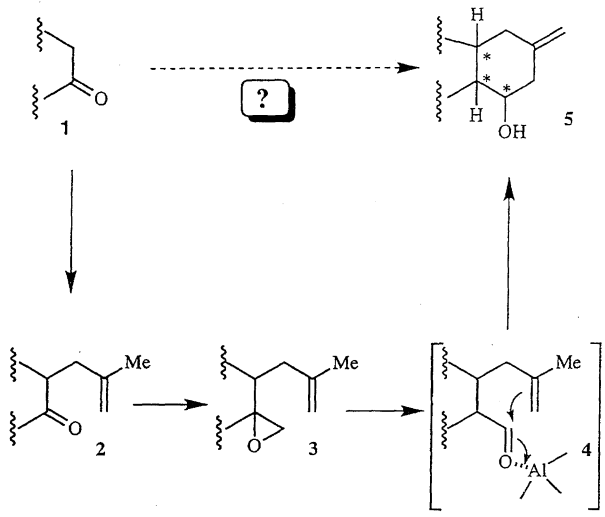
A new, general synthetic method of six-membered carbocycles has been demonstrated, which involves the stereocontrolled cyclization of olefinic epoxides with methylaluminum bis(4-bromo-2,6-di-*t*-butylphenoxide) (MABR) via the epoxide rearrangement and subsequent intramolecular ene reaction with high stereoselectivity. This strategy is shown to be highly useful in the stereoselective synthesis of the basic skeleton of various terpenes.

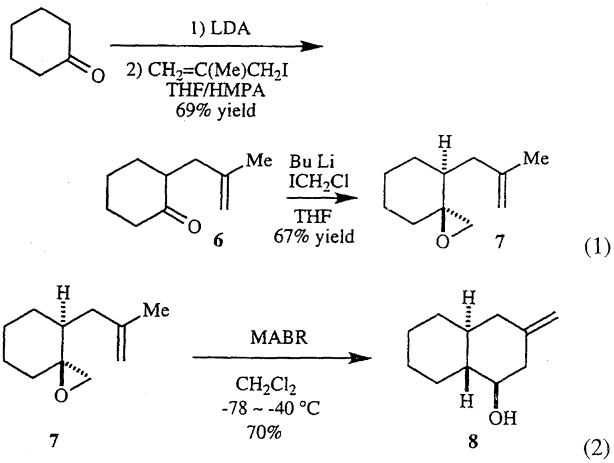
The synthesis of six-membered carbocycles has traditionally been one of the most important endeavors of synthetic chemists, leading to the development of a number of methodologies for the formation of cyclohexane frameworks.[1] The most widely utilized approach is undoutedly the Robinson annulation, which involves the Michael addition of an enolate to an alkyl vinyl ketone followed by aldol condensation of the resulting 1,4-dione. Many modifications of the tandem Michael/aldol reactions have been made, all of which lead to carbocycles with comparable regiochemistry. The conjugate addition/intramolecular Wittig approaches to cyclohexenone annulation allows somewhat greater variation in the carbocyclic products.[2,3] The thermal cyclization of enolates derived from acyclic dienones enabled a new synthesis of cyclohexenones.[4] More recently, palladium-catalyzed cyclization of siloxy-substituted hexatrienes leading to cyclohexenones has appeared.[5] In addition to these existing methodologies, we report a new and synthetically useful six-membered ring-forming procedure with high stereoselectivity.[6]

Results and Discussion

The overall transformations are outlined in Scheme 1. The requisite olefinic epoxide **3** is readily prepared from ketone **1** by the α-methallylation and the subsequent epoxide formation of the resulting ketone **2**.[7] The key cyclization is consummated by the initial rearrangement of olefinic epoxide **3** to intermediary olefinic aldehyde **4** and subsequent intramolecular ene reaction leading to the stereodefined six-membered carbocycles **5**. Both of these reaction sequences can be readily accomplished by effective use of our recently devised, exceptionally bulky organoaluminum reagent, methylaluminum bis(4-bromo-2,6-di-*t*-butylphenoxide) (MABR) under mild conditions (Fig. 1).[8,9]



Scheme 1.



First, we prepared 1-oxa-4-methallyspiro[2.5]octane **7** as a model substrate to examine the efficiency of the MABR-promoted rearrangement-cyclization sequence. The synthesis of olefinic epoxide **7** is straightforward: Alkylation of

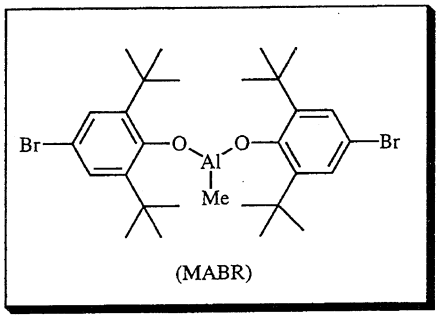
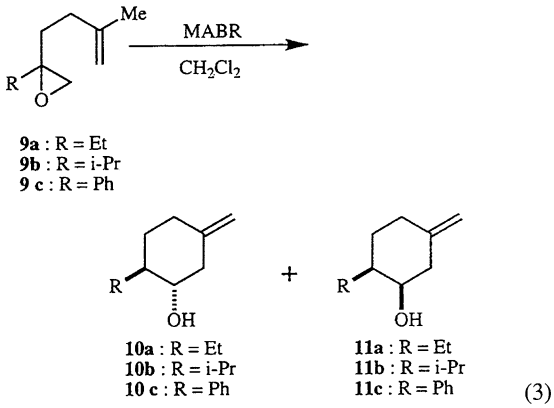


Fig. 1.

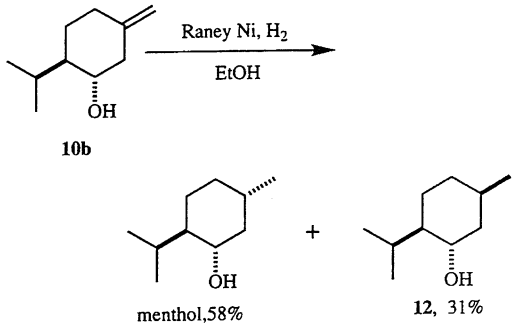
cyclohexanone with LDA (1.1 molar amount) and methallyl iodide in THF–HMPA (volume ratio, 10 : 1) at −78——20 °C furnished 2-methallylcyclohexanone **6** (69% yield) which was allowed to exposure to BuLi (1.1 molar amount) and chloroiodomethane (1.1 molar amount) in THF at −78—25 °C giving the 1-oxa-4-methallylspiro[2.5]octane **7** in 67% yield.[7,10] Treatment of the olefinic epoxide **7** with MABR (2 molar amount) in CH_2Cl_2 at −78——40 °C afforded *trans*-decalin-1-ol (OH is located trans to C-8) **8** as a sole isolable product with rigorous stereochemistry in 70% yield. It should be noted that other Lewis acids gave less satisfactory results. For example, dimethylaluminum chloride gave rise to the same *trans*-compound **8** with 90% selectivity, and boron trifluoride etherate led to the formation of several side-reaction products.



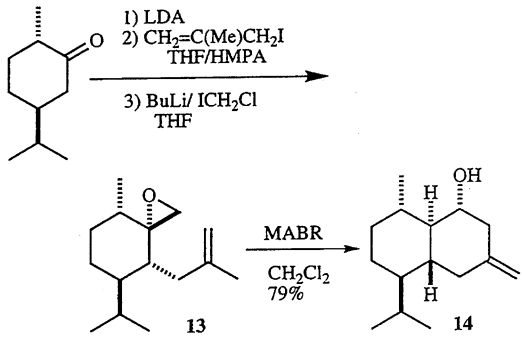
(3)

In a similar manner, olefinic epoxides **9a** and **9c** were converted stereoselectively to *trans*-alcohols **10a** (92%; **10a** : **11a**=97 : 3), and **10c** (91%; **10c** : **11c**=98 : 2), respectively. However, reaction of **9b** under the similar reaction conditions resulted in low stereoselectivity (92%); **10b** : **11b**=83 : 17. In fact, a profound solvent effect is observed in this particular case, as revealed in Table 1.

With this improved procedure at hand, our new approach serves as a new route to the stereoselective synthesis of the basic skeleton of various terpenes from simple carbonyl precursors. Thus, the cyclization product **10b** is easily transformed to naturally occurring menthol by the simple hydrogenation. Similarly, perhydrocarvone is converted via olefinic epoxide **13** to cadinane skeleton **14**[11] as a bicyclic sesquiterpene.



(4)



(5)

Experimental

General. Infrared (IR) spectra were recorded on a Hitachi 260-10 and FT-IR 8100 spectrometer. ^{1}H NMR spectra were measured on a Varian Gemini-200 (200 MHz) spectrometer. Analytical gas-liquid phase chromatography (GLC) was performed on Gasukuro Kogyo Model 370 and Shimadzu GC-8A instruments equipped

Table 1. Rearrangement-Cyclization Sequence of Olefinic Epoxide **9b**[a]

Entry	Solvent	Condition (°C, h)	% yield[b]	Ratio[c] of **10b** : **11b**
1	CH_2Cl_2	−78, 1.3; −40, 4	92	83 : 17
2		−78, 1; −40, 3.5	91	82 : 18
3		−78, 48	84	77 : 23
4		0, 0.5	99	57 : 43
5	Toluene	−78, 1; −40, 1; −20, 2	94	83 : 17
6	CH_2Cl_2/ether[d]	−20, 48; 0, 0.5	37	84 : 16
7		−78, 0.3; −20, 60	99	88 : 12
8	$ClCH_2CH_2Cl$	−40, 1; −20, 0.5	99	93 : 7

a) Unless otherwise noted, the reaction was carried out using 2 molar amount of MABR under the given reaction conditions. b) Isolated yield. c) Determined by ^{1}H NMR analysis. d) Volume ratio=1 : 1.

with a flame ionization detector and a capillary column of PEG-HT (0.25×25000 mm) using nitrogen as carrier gas. All experiments were carried out under an atmosphere of dry argon. For thin layer-chromatography (TLC) analysis throughout this work, Merck precoated TLC plates (silica gel $60F_{254}$, 0.25 mm) were used. The products were purified by preparative column chromatography on silica gel 60 (E. Merck 9385, 230—400 mesh). Microanalyses were accomplished at the Institute of Agriculture, Nagoya University.

In experiments requiring dry solvents, ether and tetrahydrofuran (THF) were freshly distilled from sodium metal using benzophenone ketyl as indicator. Benzene, hexane, and toluene were dried over sodium metal. Dichloromethane and DMF were stored over 4A molecular sieves. Trimethylaluminum was obtained from Toso-Akzo Chem. Co., Ltd., Japan. Other simple chemicals were purchased and used as such.

Preparation of Methallyl Iodide. To a mixture of NaI (5.62 g, 37.5 mmol) in acetone (38 ml) was added methallyl chloride (2.96 ml, 30 mmol) at room temperature. The reaction mixture was stirred at room temperature for 4 h. This was poured into water and the crude product was extracted with pentane. The organic layer was dried over Na_2SO_4 and concentrated to give the crude methallyl iodide almost quantitatively. This was used for further experiment without purification.

Preparation of Olefinic Epoxides. 1-Oxa-4-methallylspiro[2.5]octane 7. To a solution of LDA (17 mmol) prepared from *i*-Pr_2NH (1.92 g, 19 mmol) and a 1.57 M hexane solution (1 M=1 mol dm^{-3}) of BuLi (10.8 ml, 17 mmol) in THF (20 ml) was added cyclohexanone (1.55 ml, 15 mmol) at −78 °C under an argon atmosphre. After 10 min of stirring, crude methallyl iodide prepared as above was added and the resulting solution was treated with HMPA (2 ml) at −78 °C. The whole mixture was then poured into ice water, and extracted with ether. The combined organic extracts were dried over Na_2SO_4. Evaporation of solvents and purification of the residual oil by column chromatography (ehter/hexane=1 : 9 to 1 : 6 as eluants) gave 2-methallylcyclohexanone **6** (1.57 g, 69% yield) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ=4.73 (1H, s, CH=) 4.62 (1H, s, CH=), 2.28—2.60 (3H, m, CH_2–C(=O)–CH–), 2.00—2.15 (2H, m, CH_2–C=), 1.65 (3H, s, CH_3), 1.20—1.95 (6H, m, $3CH_2$).

To a solution of ketone **6** (1.52 g, 10 mmol) and ICH_2Cl (1.94 g, 11 mmol) in THF (12 ml) was added a 1.57 M hexane solution of BuLi (7 ml, 11 mmol) slowly at −78 °C under Ar. The reaction mixture was allowed to warm to room temperature over a period of 3 h. The solution was poured into aqueous NH_4Cl and extracted with ether. The combined ethereal extracts were dried over Na_2SO_4. Evaporation of solvents and purification of residual oil by column chromatography (ether/hexane=1 : 10 as eluant) afforded the title epoxide **7** (1.11 g, 67% yield) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ=4.72 (1H, s, CH=), 4.65 (1H, s, CH=), 2.73 (1H, d, J=5 Hz, CH–O), 2.49 (1H, d, J=5 Hz, CH–O), 1.98—2.07 (2H, m, CH_2–C=), 1.67 (3H, s, CH_3–), 1.35—1.80 (9H, m, $4CH_2$ and CH); IR (liquid film) 3073, 3042, 2934, 2856, 1649, 1446, 1375, 1157, 1101, 953, 887, 816 cm^{-1}. Found: C, 79.47; H, 10.95%. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91%.

2-Ehtyl-2-methallyloxirane 9a. The epoxide **9a** was prepared in 18% overall yield starting from 2-butanone in a similar manner to that described for the preparation of 1-oxa-4-methallylspiro[2.5]octane **7**: ^{1}H NMR ($CDCl_3$) δ=4.69 (2H, d, J=5 Hz, CH_2=), 2.58 (2H, s, CH_2–O), 2.02 (2H, t, J=8 Hz, CH_2–C=), 1.70 (3H, s, CH_3), 1.55—1.75 (4H, m, $2CH_2$), 0.92 (3H, t, J=7 Hz, CH_3); IR (liquid film) 3074, 3040, 2970, 2909, 2882, 1651, 1455, 1375, 889, 821, 760 cm^{-1}. Found: C, 77.09; H, 11.53%. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50%.

2-Isopropyl-2-methallyloxirane 9b. The epoxide **9b** was prepared in 41% overall yield starting from 3-methyl-2-butanone in a similar manner to that described for the preparation of 1-oxa-4-methallylspiro[2.5]octane **7**: ^{1}H NMR ($CDCl_3$) δ=4.67 (2H, d, J=5 Hz, CH_2=), 2.55 (2H, s, CH_2–O), 1.92—2.00 (2H, m, CH_2–C=), 1.71 (3H, s, CH_3–), 1.65—1.82 (3H, m, CH and CH_2), 0.91 (6H, dd, J=10, 7 Hz, $2CH_3$); IR (liquid film) 3079, 3052, 2989, 2880, 1651, 1411, 1372, 889, 752 cm^{-1}. Found: C, 77.84; H, 11.76%. Calcd for $C_{10}H_{18}O$: C, 77.86; H, 11.76%.

2-Methallyl-2-phenyloxirane 9c. The epoxide **9c** was prepared in 27% overall yield starting from acetophenone in a similar manner to that described for the preparation of 1-oxa-4-methallylspiro[2.5]octane **7**: ^{1}H NMR ($CDCl_3$) δ=7.2—7.40 (5H, m, Ph), 4.68 (1H, s, CH=), 4.63 (1H, s, CH=), 2.98 (1H, d, J=5 Hz, CH–O), 2.72 (1H, d, J=5 Hz, CH–O), 1.80—2.38 (4H, m, $2CH_2$), 1.68 (3H, s, CH_3); IR (liquid film) 3098, 3052, 2937, 2856, 1724, 1651, 1605, 1496, 1448, 1375, 1026, 928, 887, 762, 700 cm^{-1}. Found: C, 82.90; H, 8.56%. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57%.

Preparation of Methylaluminum Bis(4-bromo-2,6-di-*t*-butylphenoxide) (MABR). To a solution of 4-bromo-2,6-di-*t*-butylphenol (2 mmol) in CH_2Cl_2 (5 ml) was added at room temperature a 2 M hexane solution of Me_3Al (0.5 ml, 1 mmol). The methane gas evolved immediately. The resulting colorless solution was stirred at room temperature for 1 h and used as a solution of MABR in CH_2Cl_2 without any purification.

General Method for the Rearrangement-Cyclization Sequence of Olefinic Epoxides. To a solution of MABR (1 mmol) in CH_2Cl_2 (5 ml) was added olefinic epoxide **3** (0.5 mmol) at −78 °C under an argon atmosphere. The resulting mixture was stirred at −78—−40 °C for several hours. The solution was poured into diluted HCl and extracted with CH_2Cl_2. The combined CH_2Cl_2 extracts were dried over Na_2SO_4. Evaporation of solvents and purification of the residue by column chromatography on silica gel (ether/hexane as eluant) gave methylenecyclohexanol **5** with high stereoselectivity. The *cis*/*trans* ratio of the cyclization product **5** was determined by ^{1}H NMR or capillary GLC analysis.

General Method for the Rearrangement-Cyclization Sequence with Conventional Lewis Acids. To a solution of olefinic **3** in CH_2Cl_2 was added 1.2—2 molar amount of a Lewis acid at −78 °C under an argon; the reaction solution was stirred at −78 °C for several hours. Usual work up and purification gave ene-products. The stereoselectivity was determined as mentioned above.

3-Methylenedecahydronaphthalen-1-ol 8.[8c] The reaction was carried out at −78 °C for 1 h and at −40 °C for 1 h. The crude products were purified by column chromatography (ether/hexane=2 : 3 as eluant) to furnish a bicyclic alcohol **8** in 70% yield: ^{1}H NMR ($CDCl_3$) δ=4.70 (2H, s, CH_2=), 3.70—3.85 (1H, s, CH–O), 2.51 (1H, dd, J=4, 13 Hz, O–C–CH–C=); IR (liquid film) 3550, 2924, 2859, 1653, 1449, 1339, 1043, 991, 887 cm^{-1}. Found: C, 79.49; H, 10.90%. Calcd for $C_{11}H_{18}O$: C, 79.47; H, 10.91%.

***trans*- and *cis*-2-Ethyl-5-methylenecyclohexanol 10a, 11a.**[8c] The reaction was carried out at −78 °C for 1 h and at −40 °C for 1.5 h. The crude products were purified by column chromatography (ether/hexane=1 : 7 to 3 : 2 as eluants) to furnish a mixture of *trans*- and *cis*-2-ethyl-5-methylenecyclohexanol **10a** and **11a**, in 92% yield. The isomeric ratio was determined by ^{1}H NMR.

***trans*-2-Ethyl-5-methylenecyclohexanol 10a:** ^{1}H NMR ($CDCl_3$) δ=4.70 (2H, br, s, CH_2=), 3.32 (1H, ddd, J=5, 9, 14 Hz, CH–O), 2.59 (1H, dd, J=5, 12.5 Hz, O–C–CH–C=), 2.25 (1H, m, O–C–CH–C=), 1.67—2.12 (4H, m, C–CH_2–C= and C–CH_2–C–C=),

0.98—1.41 (3H, m, C–CH_2–C and CH), 0.92 (3H, t, J=7.5 Hz, CH_3); IR (liquid film) 3300, 2968, 1655, 1449, 1045, 955, 889, 855 cm^{-1}. Found: C, 77.11; H, 11.56%. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50%.

***cis*-2-Ethyl-5-methylenecyclohexanol 11a:** ^{1}H NMR ($CDCl_3$) δ=4.80 (1H, s, CH=), 4.72 (1H, s, CH=), 3.91 (1H, br, s, CH–O), 1.87—2.42 (4H, m, $2CH_2$=), 1.09—1.70 (6H, m, $2CH_2$, CH and OH), 0.88 (3H, t, J=3.8 Hz, CH_3); IR (liquid film) 3440, 2961, 2936, 1653, 1460, 1198, 1017, 889, 868 cm^{-1}. Found: C, 77.20; H, 11.68%. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50%.

***trans*- and *cis*-2-Isopropyl-5-methylenecyclohexanol 10b and 11b.**[8c] The reaction was carried out at −78 °C for 1.3 h and at −40 °C for 4 h. The crude products were purified by column chromatography (ether/hexane=1 : 3 as eluant) to furnish a mixture of *trans*- and *cis*-2-isopropyl-5-methylenecyclohexanol **10b** and **11b**, in 92% yield. The isomeric ratio was determined by ^{1}H NMR.

***trans*-2-Isopropyl-5-methylenecyclohexanol 10b:** ^{1}H NMR ($CDCl_3$) δ=4.66 (2H, s, CH_2=), 3.44 (1H, br, CH–O), 2.58 (1H, dd, J=2.5, 6.0 Hz, CHC=), 0.96—2.33 (8H, m, $2CH_2$, 3CH and OH), 0.92 (3H, d, J=3.3 Hz, CH_3C), 0.79 (3H, d, J=3.3 Hz, CH_3C); IR (liquid film) 3310, 2957, 2872, 1655, 1466, 1387, 1370, 1051, 1032, 980, 891 cm^{-1}. Found: C, 77.80; H, 11.86%. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76%.

***cis*-2-Isopropyl-5-methylenecyclohexanol 11b:** ^{1}H NMR ($CDCl_3$) δ=4.81 (1H, s, CH=), 4.72 (1H, s, CH=), 4.10 (1H, br s, CH–O), 2.30 (3H, m, CH_2C–O and CHC=), 1.97 (1H, ddd, J=2.5, 6.6, 9.0 Hz, CHC=), 1.78 (1H, m, CH), 1.53 (1H, oct, J=3 Hz, CH), 1.01—1.37 (3H, m, CH_2 and OH), 0.95 (3H, d, J=3 Hz, CH_3), 0.88 (3H, d, J=3 Hz, CH_3); IR (liquid film) 3460, 2942, 2870, 1655, 1475, 1385, 1197, 993, 967, 889, 874 cm^{-1}. Found: C, 77.87; H, 11.91%. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76%.

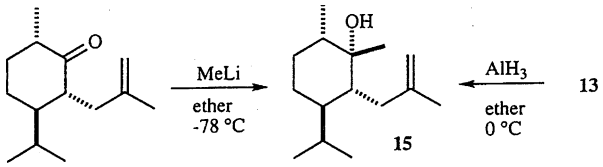
***trans*- and *cis*-5-Methylene-2-phenylcyclohexanol 10c and 11c.**[8c] The reaction was carried out at −78 °C for 1 h and at −40 °C for 1 h. The crude products were purified by column chromatography (ether/hexane=2 : 3 as eluant) to furnish a mixture of *trans*- and *cis*-2-phenyl-5-methylenecyclohexanol, **11c** and **12c**, in 91% yield. The isomeric ratio was determined by ^{1}H NMR.

***trans*-5-Methylene-2-phenylcyclohexanol 10c:** ^{1}H NMR ($CDCl_3$) δ=7.22—7.39 (5H, m, Ph), 4.70 (2H, s, CH_2=), 3.68 (1H, dt, J=2.8, 11.5 Hz, CH–O), 2.73 (1H, m, PhCH), 2.57 (1H, m, O–C–CH–C–CH=), 2.38 (1H, m, O–C–CH–C=), 1.87—2.28 (3H, m, C–CH_2–C= and C–CH–C), 1.50—1.71 (2H, m, CH and OH); IR (liquid film) 3551, 3028, 2936, 2840, 1653, 1495, 1454, 1342, 1065, 1048, 957, 893, 758, 700 cm^{-1}. Found: C, 82.92; H, 8.50%. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57%.

***cis*-5-Methylene-2-phenylcyclohexanol 11c:** ^{1}H NMR ($CDCl_3$) δ=7.17—7.38 (5H, m, Ph), 4.90 (1H, s, CH=), 4.79 (1H, s, CH=), 4.07 (1H, br, s, CH–O), 2.86 (1H, m, PhCH), 2.40—2.53 (3H, m, O–C–CH_2–C= and O–C–CH–C=), 1.90—2.29 (2H, m, O–C–CH–C= and C–CH–C), 1.69—1.73 (1H, m, C–CH–C), 1.40 (1H, d, J=5 Hz, OH); IR (KBr) 3330, 3061, 2914, 2898, 1647, 1495, 1443, 1306, 1194, 1086, 982, 895, 760 cm^{-1}. Found: C, 82.90; H, 8.35%. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57%.

Menthol and Stereoisomeric Alcohol 12.[8c] To a solution of *trans*-2-isopropyl-5-methylenecyclohexanol **10b** (30.9 mg; 0.2 mmol) in EtOH (2 ml) was added 10 mg of Raney Ni at room temperature. The reaction mixture was stirred vigorously at room temperature for 2 h under H_2 atmosphere. After filtration, solvents were evaporated and purification of the residual oil by column chromatography (ether/hexane=1 : 2 as eluant) gave 2-isopropyl-5-methylcyclohexanol (27.6 mg, 0.18 mmol) in 89% yield (menthol/**12**=65 : 35). The stereochemistry was confirmed in comparison with a retention time of *l*-menthol by GLC analysis: *tR* (*l*-menthol)=8.03 min at the column temperature of 120 °C.

Olefinic Epoxide 13. The epoxide **13** was prepared in 42% overall yield starting from perhydrocarvone in a similar manner to that described for the preparation of **7**: ^{1}H NMR δ=4.72 (1H, s, HC=), 4.62 (1H, s, HC=), 2.63 (1H, d, J=5 Hz, CH–O), 2.57 (1H, d, J=5 Hz, CH–O), 1.65 (3H, s, CH_3–C=), 1.20—2.10 (10H, m, $2CH_2$, 4CH and CH_2–C=), 0.89 (3H, d, J=8.2 Hz, CH_3–), 0.78 (6H, dd, J=7, 8 Hz, $C\underline{H}_3$–CH–$C\underline{H}_3$). Found: C, 81.01; H, 11.79%. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.78%. The stereochemistry of olefinic epoxide **13** was determined by correlation to tertiary alcohol **15**, an authentic sample of which was prepared by methylation of α-methallylperhydrocarvone with methyllithium.



(6)

Tertiary Alcohol 15. To a solution of MeLi (1 M ether solution, 0.4 ml, 0.4 mmol) in ether was added α-methallylperhydrocarvone dropwise at −78 °C under an argon atmosphere. After stirring for 5 min, the reaction solution was quenched with H_2O and extracted with ether. The combined ethereal extracts were dried over Na_2SO_4. Evaporation of solvents and purification of residual oil by column chromatography (ether/hexane=1 : 9 as eluant) afforded the tertiary alcohol **15** (52.3 mg, 78% yield). The reduction of olefinic epoxide **13** to tertiary alcohol **15** was carried out as follows; To a suspension of $AlCl_3$ (16 mg, 0.12 mmol) in ether (3 ml) was added $LiAlH_4$ (13.3 mg, 0.35 mmol) at 0 °C under an argon atmosphere, and the suspension was stirred at 0 °C for 30 min. To the resulting suspension was added olefinic epoxide **15** (78 mg, 0.35 mmol) and the mixture was stirred for 1 h. Then it was quenched carefully with dilute HCl and extracted with ether. The combined ethereal extracts were dried over Na_2SO_4. Evaporation of solvents and purification of residual oil by column chromatography (ether/hexane=1 : 9 as eluant) afforded the tertiary alcohol. The product was identical with **15** (47 mg, 60% yield).

Bicyclic Sesquiterpene 14. The reaction was carried out at −78 °C for 1.5 h, at −20 °C for 5.5 h. The crude products were purified by column chromatography (ether/hexane=1 : 7 to 3 : 2 as eluants) to furnish a mixture of bicyclic alcohols **14** in 79% yield: ^{1}H NMR δ=4.70 (1H, m, HC=), 4.60 (1H, m, HC=), 4.09 (1H, C$\underline{H}$–OH), 2.60 (1H, m, CH–C=), 2.40 (1H, m, CH–C=), 1.2—2.05 (11H, m, $3CH_2$ and 5CH), 1.15 (3H, d, J=7 Hz, CH_3). The relative stereochemistry of **14** was established by 500 MHz ^{1}H NMR analysis (Fig. 2).

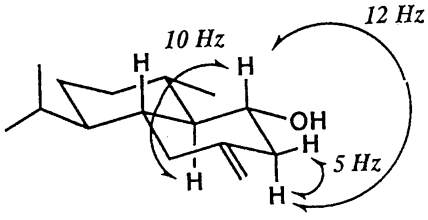


Fig. 2.

References

1) Reviews of ring-forming reactions and annulations: a) H. O. House, "Modern Synthetic Reactions," 2nd ed, Benjamin, Menlo Park (1972); b) P. T. Lansbury, *Chem. Res.*, **5**, 311 (1972); c) B. P. Mundy, *J. Chem. Educ.*, **50**, 110 (1973); d) M. E. Jung, *Tetrahedron*, **32**, 3 (1976); e) R. E. Gawley, *Synthesis*, **1976**, 777; f) B. Giese, *Angew. Chem., Int. Ed. Engl.*, **28**, 969 (1989); g) B. M. Trost, *Angew. Chem., Int. Ed. Engl.*, **28**, 1173 (1989); h) L. A. Paquette, *Angew. Chem., Int. Ed. Engl.*, **29**, 609 (1990).

2) a) S. F. Martin and S. R. Desai, *J. Org. Chem.*, **42**, 1664 (1977); b) S. F. Martin and S. R. Desai, *J. Org. Chem.*, **43**, 4673 (1978).

3) R. J. Pariza and P. L. Fuchs, *J. Org. Chem.*, **48**, 2304 (1983).

4) P. Magnus, *Nouv. J. Chim.*, **2**, 555 (1978).

5) C. M. Hettrick and W. J. Scott, *J. Am. Chem. Soc.*, **113**, 4903 (1991).

6) K. Maruoka, N. Murase, T. Ooi, and H. Yamamoto, *Synlett*, **1991**, 857.

7) K. M. Sadhu and D. S. Matteson, *Tetrahedron Lett.*, **27**, 795 (1986).

8) Intramolecular ene reaction with MABR: a) K. Maruoka, T. Ooi, and H. Yamamoto, *J. Am. Chem. Soc.*, **111**, 6431 (1989); b) K. Maruoka, S. Saito, T. Ooi, and H. Yamamoto, *Tetrahedron Lett.*, **30**, 5607 (1989); c) T. Ooi, K. Maruoka, and H. Yamamoto, *Tetrahedron*, **50**, 6505 (1994).

9) For other synthetic applications of MABR, see: a) K. Maruoka, K. Nonoshita, H. Banno, and H. Yamamoto, *J. Am. Chem. Soc.*, **110**, 7922 (1988); b) K. Maruoka, H. Banno, K. Nonoshita, and H. Yamamoto, *Tetrahedron Lett.*, **30**, 1265 (1989); c) K. Nonoshita, H. Banno, K. Maruoka, and H. Yamamoto, *J. Am. Chem. Soc.*, **112**, 316 (1990); d) K. Maruoka, J. Sato, H. Banno, and H. Yamamoto, *Tetrahedron Lett.*, **31**, 377 (1990).

10) The isomeric purity of **7** is ca. 96% by capillary GLC analysis.

11) T. K. Devon and A. I. Scott, "Handbook of Naturally Occurring Compounds—Volume II, Terpenes," Academic Press, New York (1972).