Novel Access to Neopentyl-Type Halogenated Cyclopentanoids *via* Olefinic Cyclobutanols

Hideo Nemoto, Motohiro Shiraki, and Keiichiro Fukumoto*

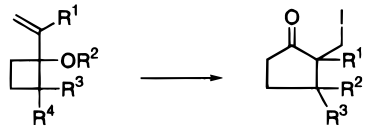
Pharmaceutical Institute, Tohoku University, Aobayama, Sendai 980-77, Japan

Received October 4, 1995[⊗]

The iodonium ion-mediated ring expansion of olefinic cyclobutanols **20**, **21**, and **25** gave mixtures of iodoalkylated cyclopentanones **33a**−**c** and **34a**−**c**. On the other hand, the same reaction of **29**, **30**, and **32** stereoselectively afforded iodoalkylated cyclopentanones **33d** and **33e**. The stereochemical course of this reaction is also discussed.

Cyclopentane rings constitute a basic structural unit of many natural products[1] thereby prompting the recent activity[2] of organic chemists in the synthesis of mono- as well as polycyclic cyclopentanoid derivatives. Of these, cyclopentanoids containing iodoalkyl substituents are particularly attractive since iodides play an important role in organic synthesis as sources of organometallics[3] and radicals.[4] We now report a novel strategy for the synthesis of iodoalkylated cyclopentanones **B** (difficult to prepare because of the neopentyl type iodide) based on

Chart 1



A **B**

iodonium ion-mediated ring expansion of olefinic cyclobutanols **A** (Chart 1).

The syntheses of olefinic cyclobutanols **20**, **21**, **25**, **29**, **30**, and **32**, substrates for ring expansion, were straightforward (Scheme 1). Alcohol **3**, prepared by silylation (100%) of 4-pentenol (**1**) followed by hydroboration−oxidation (83%) was first converted to aldehyde **5** by Swern oxidation and then to the cyclopropylidene ether **9** by the Wittig reaction with cyclopropylidenetriphenylphosphorane using a modification of the conditions described by McMurry (76% from **3**).[5] Aldehydes **6** and **7**, and ketone **8**, obtained by the Grignard reaction (95%) of hydroxamate **4**,[6] were also converted to cyclopropylidene derivatives **10** (88%), **11** (75%), and **12** (95%) by the procedure described above. Cyclobutanones **14**, **15**, and **16**, prepared by the oxidation of **9** (67%), **10** (34%), and **11** (35%) with MCPBA presumably *via* the oxaspiropentanes as intermediates, were subjected to the Grignard reaction to give cyclobutanols **19** (71%), **20** (79%), and **21** (63%). Cyclopropylidene alcohol **13**, derived by desilylation of **12** (100%), was also oxidized to give cyclobutanone **17** (53%), which was converted to the silyl ether **18** (94%) and subsequently converted to cyclobutanols **22** (76%) and **23** (19%).[7] The desilylation of **19** afforded alcohol **24** (95%), from which the Swern oxidation and Wittig reaction gave the unsaturated ester **25** (56%). Aldehyde **28**, obtained *via* **26** and **27** by silylation (100%) and hydroboration−oxidation (78%) of cyclobutanol **22** followed by the Swern oxidation (44%) of the resulting alcohol, was subjected to the Wittig reaction to give the unsaturated ester **29** (93%). The unsaturated ester **30**

[⊗] Abstract published in *Advance ACS Abstracts,* February 1, 1996.

(1) For naturally occurring cyclopentanoids: (a) Devon, T. K.; Scott, A. I. *Handbook of Naturally Occurring Compounds*; Academic Press: New York, 1972, Vols. I and II. (b) Nakanishi, K.; Goto, T.; Ito, S.; Nozoe, S. *Natural Products Chemistry*; Kodansha Scientific, Tokyo, 1974, Vol. I. (c) Comer, F. W.; McCapra, F.; Qureshi, I. H.; Scott, A. I. *Tetrahedron* **1967**, *23*, 4761. (d) Seto, H.; Yonehara, H. *J. Antibiot.* **1980**, *33*, 92. (e) Cane, D. E.; Oliver, J. S.; Harrison, P. H. M.; Abell, C.; Hubbard, B. R; Kane, C. T.; Lattman, R. *J. Am. Chem. Soc.* **1990**, *112*, 4513. For Carbocyclic nucleosides: (f) Marquez, V. E.; Lim, M.-I. *Med Res. Rev.* **1986**, 611. (g) Borthwick, A. D.; Biggadike, K. *Tetrahedron* **1992**, *48*, 571. (h) Niitsuma, S.; Ichikawa, Y.-I.; Takita, T. *Studies in Natural Products Chemistry*; Elsevier Science BV Amsterdam, 1992; p 585.

(2) For reviews in this area, see: (a) *The Total Synthesis of Natural Products* ApSimon, J. W. Ed., John Wiley & Sons: New York: 1973; Vol. 1, p 81; 1973, Vol. 2, p 1, p 197; 1981, Vol. 4, p 353, p 451; 1983, Vol. 5, p 1; 1983, Vol. 7, p 275. (b) Mitra, A. *The Synthesis of Prostaglandins*; John Wiley & Sons: New York, 1977. (c) Trost, B. M. *Chem. Soc. Rev.* **1982**, *11*, 141. (d) Paquette, L. A.; Doherty, A. M. *Polyquinane Chemistry*; Springer Verlag: Berlin, 1987. (e) Ramaiah, M. *Synthesis* **1984**, 529. (f) Paquette, L. A. *Top. Curr. Chem.* **1984**, *119*, 1. (g) Curran, D. P. *Synthesis* **1988**, *417*, 489. (h) Shore. N. E. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, p 1037. For some recent studies on this area, see: (i) Trost, B. M.; Hashmi, A. S. K. *J. Am. Chem. Soc.* **1994**, *116*, 2183. (j) Negishi, E.; Jensen, M. D.; Kondakov, D. Y.; Wang, S. *J. Am. Chem. Soc.* **1994**, *116*, 8404. (k) Lee, B. Y.; Chung, Y. K. *J. Am. Chem. Soc.* **1994**, *116*, 8793. (l) Sturino, C. F.; Fallis, A. G. *J. Am. Chem. Soc.* **1994**, *116*, 7447. (m) Feldman, K. S.; Schildknegt, K. *J. Org. Chem.* **1994**, *59*, 1129. (n) Wu, Y.-J.; Zhu, Y.-Y.; Burnell, D. J. *J. Org. Chem.* **1994**, *59*, 104. (o) Zora, M.; Herndon, J. W. *J. Org. Chem.* **1994**, *59*, 699. (p) Liebeskind, L. S.; Bombrun, A. *J. Org. Chem.* **1994**, *59*, 1149 and referenced cited therein.

(3) For reviews in this area, see: (a) Gilman, H.; Jones, R. G. *Org. React.* (N.Y.) **1951**, *6*, 339. (b) Sheverdina, N. T.; Kocheshkov, K. A. In *The Organic Compounds of Zinc and Cadmium in Methods of Element-Organic Chemistry*; Newsmeyanov, A. N.; Kocheshkov, K. A., Eds., North-Holland Publishing Co.: Amsterdam, 1967. (d) Boersma, J. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: Oxford, 1982; Vol. 2, p 823. (e) Erdik, E. *Tetrahedron* **1987**, *43*, 2203. (f) Knochel, P. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 1, p 211. (g) Noyori, R.; Kitamura, M. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 49. (h) Niwa, S. *Chem. Rev.* **1992**, *92*, 833. (i) Erdik, E. *Tetrahedron* **1992**, *48*, 9577. (j) Knochel, P.; Singer, R. D. *Chem. Rev.* **1993**, *93*, 2117. For some recent studies in this area, see: (k) Bailey, W. F.; Punzalan, E. R. *J. Org. Chem.* **1990**, *55*, 5404. (l) Negishi, E.; Swanson, D. R.; Rousset, C. J. *J. Org. Chem.* **1990**, *55*, 5406. (m) Stadtmüller, H.; Lentz, R.; Tucker, C. E.; Stüdemann, T.; Dörner, W.; Knochel, P. *J. Am. Chem. Soc.* **1993**, *115*, 7027. (n) Gao, Y.; Urabe, H.; Sato, F. *J. Org. Chem.* **1994**, *59*, 5521 and references cited therein.

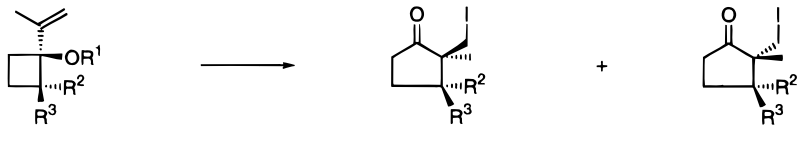
(4) For reviews in this area, see: (a) Giese, B. *Radicals in Organic Synthesis*: *Formation of Carbon*−*Carbon Bonds*, Pergamon Press: New York, 1986. (b) Curran, D. P. *Synthesis* **1988**, 417 and 489. (c) Jasperse, C. P.; Curran, D. P.; Fevig, T. L. *Chem. Rev.* **1991**, *91*, 1237. (d) Porter, N. A.; Giese, B.; Curran, D. P. *Acc. Chem. Res.* **1991**, *24*, 296. (e) Smadja, W. *Synlett* **1994**, 1. For some recent studies in this area, see: (f) Nishida, M.; Ueyama, E.; Hayashi, H.; Ohtake, Y.; Yamaura, Y.; Yanaginuma, E.; Yonemitsu, O.; Nishida, A.; Kawahara, N. *J. Am. Chem. Soc.* **1994**, *116*, 6455. (g) Curran, D. P.; Qi, H.; DeMello, N. C.; Lin, C.-H. *J. Am. Chem. Soc.* **1994**, *116*, 8430 and references cited therein.

(5) Stafford, J. A.; McMurry, J. E. *Tetrahedron Lett.* **1988**, *29*, 2531.

(6) Nemoto, H.; Nagamochi, M.; Ishibashi, H.; Fukumoto, K. *J. Org. Chem.* **1994**, *59*, 74.

0022-3263/96/1961-1347$12.00/0

Table 1.[a] Iodonium Ion-Mediated Ring Expansion of Olefinic Cyclobutanols

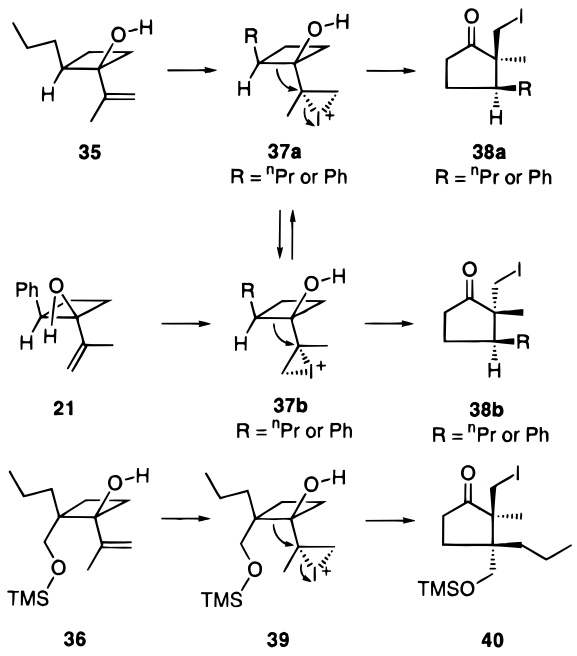


33 **34**

entry	substrate	R^1	R^2	R^3	product (%)b			
1	**20**	H	H	$(CH_2)_6Me$	**33a**	39	**34a**	39
2	**21**	H	H	Ph	**33b**	47	**34b**	47
3	**25**	H	H	$(CH_2)_3CH{=}CHCO_2Me$	**33c**	36	**34c**	36
4	**29**	H	CH_2OTBS	$(CH_2)_3CH{=}CHCO_2Me$	**33d**	88	**34d**	–
5	**30**	TES	CH_2OTBS	$(CH_2)_3CH{=}CHCO_2Me$	**33d**	96	**34d**	–
6	**32**	TES	CH_2OTBS	$(CH_2)_3C{\equiv}CCO_2Me$	**33e**	59	**34e**	–
7	**32**	TES	CH_2OTBS	$(CH_2)_3C{\equiv}CCO_2Me$	**33e**	100	**34e**	–

[a] All the reactions were carried out in ether at 0 °C in the presence of iodine and $NaHCO_3$ except for entry **7** in which iodine and $NaHCO_3$ were replaced with *N*-iodosuccinimide. [b] All were the isolated yields.

Chart 2



35 **37a** R = ^{n}Pr or Ph **38a** R = ^{n}Pr or Ph

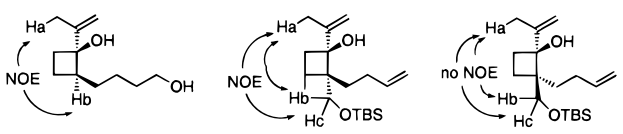
21 **37b** R = ^{n}Pr or Ph **38b** R = ^{n}Pr or Ph

36 **39** **40**

was also obtained (94%) by the successive Swern oxidation and Wittig reaction on **27**. The acetylenic ester **32** was prepared *via* the dibromo olefin **31** (88%) by the successive Swern oxidation and Wittig reaction on **27** followed by methoxycarbonylation (92%) of the *in situ*-generated acetylide by the base treatment of **31**.

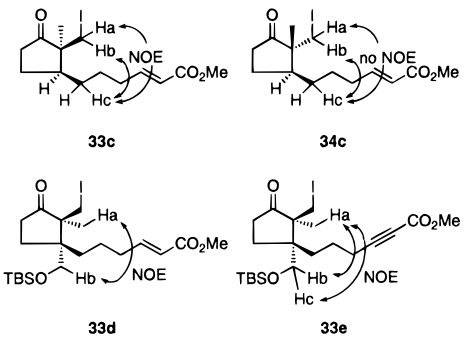
The iodonium ion-mediated ring expansion of olefinic cyclobutanols **20**, **21**, **25**, **29**, **30** and **32** was examined using iodine in the presence of $NaHCO_3$ or *N*-iodosuccinimide (Table 1). In all cases, the reaction proceeded in moderate to high yields, and the silyl ether (entry 5) gave a slightly better result than the corresponding alcohol (entry 4). Although no stereoselectivity was found in the cases of monosubstituted substrates (entries 1−3) giving the mixture of diastereomers **33a**−**c** and **34a**−**c**, complete stereoselectivity was observed in the cases of geminally substituted substrates (entries 4−7) to afford **33d**,**e** as the sole product.[8] This stereochemical outcome could be rationalized as follows: GMMX calculations[9] of **35** (model for monosubstituted aliphatic case), **21**, and **36** (model for geminally substituted case) were carried out to find the most stable conformers. Those are shown in Figure 1. In these conformers, the β face of the olefins was shielded by the alcoholic hydrogen, suggesting α face (the opposite site of the alcoholic hydrogen) approach of the iodonium ion. Iodonium intermediates **37a** and **37b** thus derived from **35** and **21** could be readily interconverted, giving iodides **38a** and **38b** (Chart 2). On the other hand, iodonium intermediate **39** derived from **36** could not be readily interconverted with the other conformer because of steric congestion of the silyloxymethyl group at the vicinal position. Hence, a single product, **40**, was obtained.

(7) The structure of **19**, **22**, and **23** was determined mainly by ^1H NMR (500 MHz) studies as follows. Namely, the definite NOE enhancement between methyl (Ha) (1.73 ppm) and hydrogen (Hb) (2.34−2.44 ppm) of **24** showed the isopropenyl group and hydrogen (Hb) to be *cis*. The observation of NOE between methyl (Ha) (1.77 ppm) and methylene (Hb and Hc) (3.36 and 3.52 ppm) of the siloxymethyl group of **22** confirmed these two groups to be *cis*. On the other hand, no such enhancement between methyl (Ha) (1.76 ppm) and methylene (Hb and Hc) (3.68 and 3.93 ppm) of **23** showed these two groups to be *trans*. The structure of **20** and **21** was deduced by the analogous reaction of **15** and **16** as for **14**.



24 **22** **23**

(8) In entries 1 and 2, the isomers **33a** and **34a**, and **33b** and **34b**, could not be separated, and the product ratio was tentatively determined by the integration of methyl group (0.97 and 1.15 ppm for **33a** and **34a**, and 0.78 and 1.27 ppm for **33b** and **34b**) in these ^1H NMR (300 MHz) spectra. The structures of products **33c**−**e** and **33c**−**e** were determined by ^1H NMR (500 MHz) studies of these pure samples as follows: an NOE enhancement between Ha and Hb (3.06 and 3.46 ppm) and Hc (1.22−1.33 ppm) of **33c** and no such effect between Ha and Hb (3.07 and 3.19 ppm) and Hc (1.20−1.34 ppm) of **34c** were observed, showing iodomethyl and side chain of **33c** and **34c** to be *cis* and *trans*, respectively. The definite NOE enhancement between Ha (1.06 ppm) and Hb (3.66 ppm) of **33d** and between Ha (1.08 ppm) and Hb and Hc (3.64 and 3.69 ppm) of **33e** confirmed that the methyl and siloxymethyl groups of these compounds were *cis*.

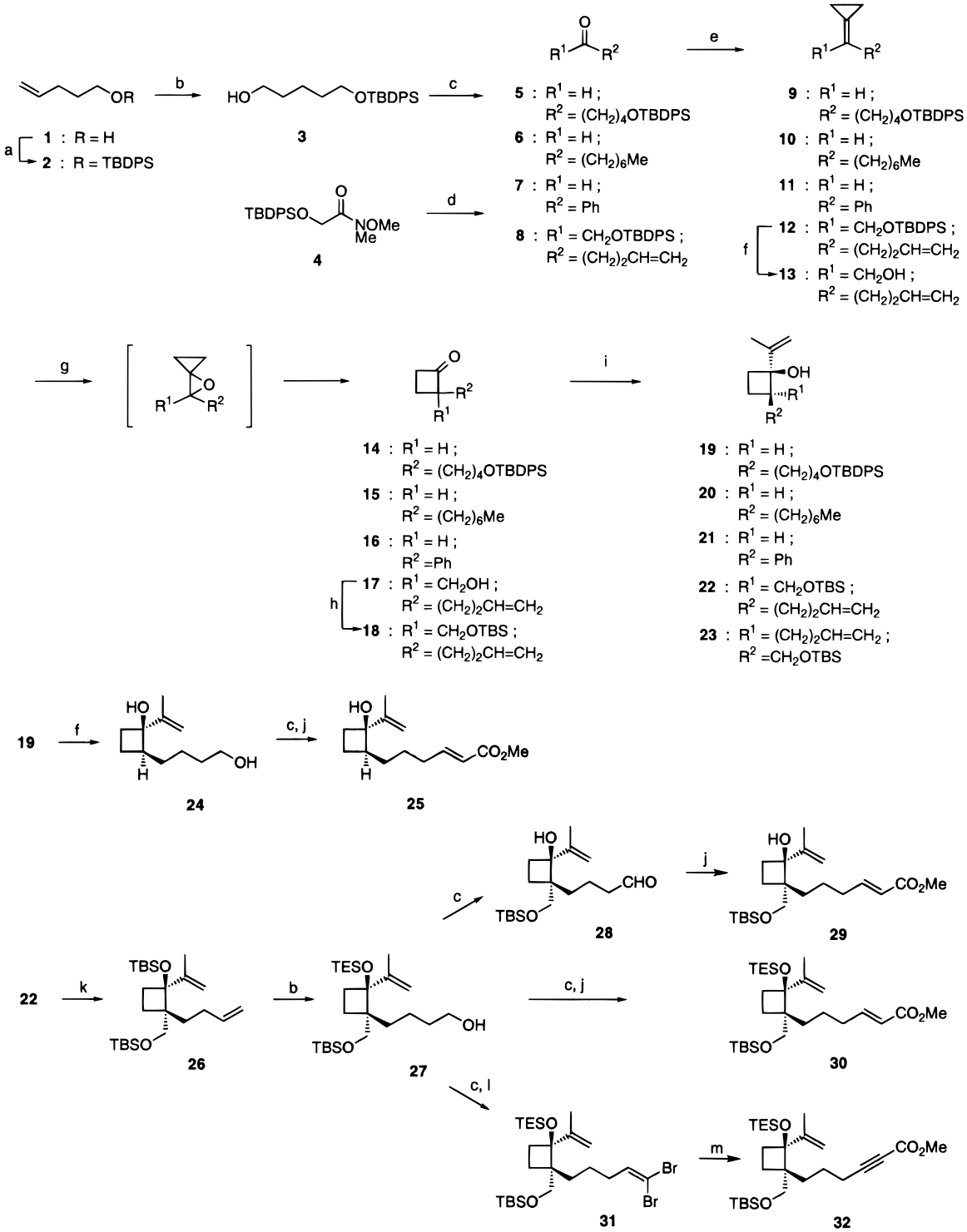


33c **34c**

33d **33e**

(9) GMMX (version 1.0), Serena Software, P. O. Box 3076, Bloomington, IN.

Scheme 1[a]

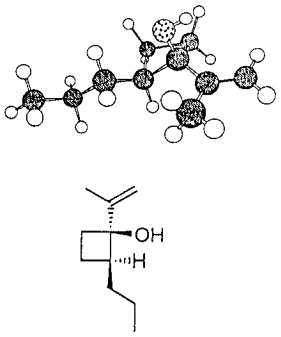


[a] Steps: (a) TBDPSCl, DMAP, imidazole, DMF, rt, 19 h; (b) $BH_3{\cdot}SMe_2$, THF, rt, 2 h, then H_2O_2, NaOH, THF, rt, 1 h; (c) DMSO, $(COCl)_2$, CH_2Cl_2, -78 °C, 30 min, then Et_3N, -78 °C→0 °C; (d) $BrMgCH_2CH_2CH{=}CH_2$, THF, 0 °C, 1.5 h; (e) cyclopropyltriphenylphosphonium bromide, NaH, THF, 62 °C, 10 h, then **5**-**8**, TDA-1, 62 °C, 4 h; (f) TBAF, THF, rt, 3.5 h; (g) MCPBA, CH_2Cl_2, 0 °C, 17 h; (h) TBSCl, DMAP, imidazole, DMF, rt, 1.5 h; (i) isopropenylmagnesium bromide, $CeCl_3$, THF, rt, 3 h; (j) $Ph_3P{=}CHCO_2Me$, MeCN, reflux, 1 h; (k) TESOTf, 2,6-lutidine, CH_2Cl_2, rt, 1 h, (l) CBr_4, PPh_3, CH_2Cl_2, rt, 10 h; (m) ^nBuLi, THF, –78 °C, 20 min, then $ClCO_2Me$, -78 °C, 10 min.

Thus, we disclosed a new strategy for the synthesis of iodoalkylated cyclopentanoids based on the iodonium ion-mediated ring expansion of olefinic cyclobutanols. We are now continuing to explore the usefulness of the iodoalkylated cyclopentanoids for the synthesis of biologically important compounds.

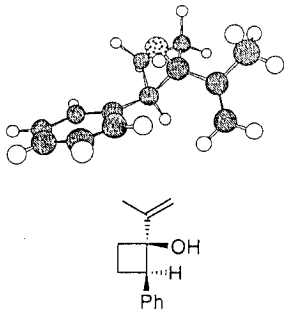
Experimental Section

General Procedure. All reactions were carried out under positive atmosphere of dry N_2 unless indicated otherwise. Solvents were freshly distilled prior to use: THF and Et_2O were distilled from sodium benzophenone, and DMSO, DMF, CH_2Cl_2, and Et_3N were distilled from CaH_2 and kept over 4 Å



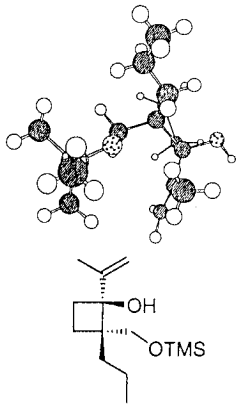
35

ΔE strain 34.11 Kcal/mol



21

ΔE strain 42.78 Kcal/mol



36

ΔE strain 35.21 Kcal/mol

Figure 1. Global minimum energy conformation of **35**, **21**, and **36** as determined by molecular mechanics calculations (Chem-3D output).

molecular sieves. The phrase "residue upon workup" refers to the residue obtained when the organic layer was separated and dried over anhydrous Na_2SO_4, and the solvent was evaporated under reduced pressure. Silica gel column chromatography was carried out with Wako gel C-200, while Merck Kieselgel 60 Art. 9385 was used for flash chromatography.

5-(*tert*-Butyldiphenylsiloxy)-1-pentene (2). To a stirred solution of 4-penten-1-ol (**1**) (2.50 mL, 24.2 mmol), imidazole (1.98 g, 29.0 mmol), and a catalytic amount of DMAP in DMF (25 mL) was added TBDPSCl (6.61 mL, 25.4 mmol) at 0 °C, and stirring was continued for 19 h at rt. The reaction mixture was diluted with Et_2O and washed with 10% HCl, saturated aqueous $NaHCO_3$, and NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (95:5 v/v) as eluant to give silyl ether **2** (7.85 g, 100%) as a colorless oil: IR (neat) 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.05 (9H, s), 1.60−1.70 (2H, m), 2.08−2.22 (2H, m), 3.67 (2H, t, J = 6.2 Hz), 4.93 (1H, dd, J = 1.8 and 10.3 Hz), 5.00 (1H, dd, J = 1.8 and 17.2 Hz), 5.88−6.99 (1H, m), 7.26−7.71 (10H, m); MS m/z 267 (M^+ − 57); HRMS calcd for $C_{17}H_{19}OSi$ 267.1205 (M^+ − 57), found 267.1197.

5-(*tert*-Butyldiphenylsiloxy)-1-pentanol (3). To a stirred solution of the silyl ether **2** (8.9 g, 27.4 mmol) in THF (50 mL) was added 2.0 M solution of $BH_3{\cdot}SMe_2$ in THF (5.48 mL, 11.0 mmol) at 0 °C, and stirring was continued for 2 h at rt. The reaction mixture was treated with 3 N aqueous solution of NaOH (36.5 mL, 110 mmol) and 30% aqueous solution of H_2O_2 (12.5 mL, 110 mmol), stirred for 1 h at rt, and extracted with AcOEt. The combined extracts were washed with saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (85:15 v/v) as eluant to give alcohol **3** (7.82 g, 83%) as a colorless oil: IR (neat) 3340 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.05 (9H, s), 1.27 (1H, br s), 1.34−1.71 (6H, m), 3.55−3.68 (2H, m), 3.67 (2H, t, J = 6.2 Hz), 7.31−7.73 (10H, m); MS m/z 285 (M^+ − 57). Anal. Calcd for $C_{21}H_{30}O_2Si$: C, 73.63; H, 8.83. Found: C, 73.65; H, 8.77.

1-(*tert*-Butyldiphenylsiloxy)-5-cyclopropylidenepentane (9). To a stirred solution of DMSO (4.39 mL, 61.8 mmol) in CH_2Cl_2 (30 mL) was added $(COCl)_2$ (5.23 mL, 41.2 mmol), and then the solution of alcohol **3** (7.06 g, 20.6 mmol) in CH_2Cl_2 (30 mL) was added at −78 °C. After stirring was continued for 30 min at the same temperature, the reaction mixture was treated with Et_3N (20.1 mL, 144 mmol), stirred for 5 min at 0 °C, treated with 10% HCl aqueous solution, and extracted with CH_2Cl_2. The combined extracts were washed with saturated aqueous $NaHCO_3$ and NaCl. Workup of the organic layer afforded aldehyde **5**. To a stirred suspension of NaH (1.65 g, 60% oil suspension, 41.2 mmol) in THF (70 mL) was added cyclopropyltriphenylphosphonium bromide (15.8 g, 41.2 mmol) at rt. After the mixture had been stirred for 10 h at 62 °C, a solution of aldehyde **5** obtained above and TDA-1 {tris[2-(2-methoxyethoxy)ethyl]amine} (0.5 mL, 1.56 mmol) in THF (40 mL) was added in 30 min, and stirring was continued for 4 h at the same temperature. The reaction mixture was diluted with water and extracted with Et_2O. The combined extracts were washed with saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane as eluant to give cyclopropylidene silyl ether **9** (5.67 g, 76% from **3**) as a colorless oil: IR (neat) 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.92−1.10 (4H, m), 1.05 (9H, s), 1.43−1.67 (4H, m), 2.09−2.25 (2H, m), 3.67 (2H, t, J = 5.9 Hz), 5.67−5.79 (1H, m), 7.31−7.73 (10H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ 2.0, 2.2, 19.3, 25.6, 27.0, 31.6, 32.3, 63.9, 118.3, 121.2, 127.7, 129.6, 134.2, 135.7; MS m/z 364 (M^+). Anal. Calcd for $C_{24}H_{32}OSi$: C, 79.06; H, 8.85. Found: C, 78.98; H, 8.93.

1-(*tert*-Butyldiphenylsiloxy)hex-5-en-2-one (8). To a stirred solution of hydroxamate **4**[6] (10.9 g, 30.6 mmol) in THF (40 mL) was added a solution of 3-butenylmagnesium bromide [prepared from magnesium (4.46 g, 183 mmol) and 1-bromo-3-butene (9.31 mL, 91.7 mmol)] in THF (45 mL) at −78 °C, and stirring was continued for 1.5 h at 0 °C. The reaction mixture was treated with 10% HCl solution and extracted with Et_2O. The combined extracts were washed with saturated aqueous $NaHCO_3$ and NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (98:2 v/v) as eluant to give ketone **8** (10.2 g, 95%) as a colorless oil: IR (neat) 1733, 1715 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.10 (9H, s), 2.26−2.37 (2H, m), 2.63 (2H, t, J = 6.9 Hz), 4.18 (2H, s), 4.96 (1H, dd, J = 1.5 and 9.0 Hz), 5.01 (1H, dd, J = 1.5 and 17.3 Hz), 5.70−5.87 (1H, m), 7.33−7.68 (15H, m); MS m/z 295 (M^+ − 57); HRMS calcd for $C_{18}H_{19}O_2Si$ 295.1154 (M^+ − 57), found 295.1141. Anal. Calcd for $C_{22}H_{28}O_2Si$: C, 74.95; H, 8.01. Found: C, 75.02; H, 8.05.

General Procedure for the Preparation of Cyclopropylidene Derivatives. Preparation of 1-Cyclopropylideneoctane (10). To a stirred suspension of NaH (1.37 g, of 60% oil suspension, 34.3 mmol) in THF (60 mL) was added cyclopropyltriphenylphosphonium bromide (13.1 g, 34.3 mmol) at rt. After the mixture had been stirred for 10 h at 62 °C, a solution of octyl aldehyde **6** (2.0 g, 15.6 mmol) and TDA-1 (0.5 mL, 1.56 mmol) in THF (30 mL) was added in 30 min, and stirring was continued for 4 h at the same temperature. The reaction mixture was diluted with water and extracted with Et_2O. The combined extracts were washed with saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane as eluant to give cyclopropylidene derivative **10** (2.09 g, 88%) as a colorless oil: IR (neat) 1650 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.88 (3H, t, J = 6.2 Hz), 0.93−1.12 (4H, m), 1.15−1.50 (10H, m), 2.09−2.22 (2H, m), 5.70−5.79 (1H, m); MS m/z 152 (M^+); HRMS calcd for $C_{11}H_{20}$ 152.1565 (M^+), found 152.1541.

Cyclopropylidenemethylbenzene (11): yield 75%; colorless oil; IR (neat) 1590 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.11−1.24 (2H, m), 1.36−1.48 (2H, m), 6.71−6.80 (1H, m), 7.13−7.59 (5H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ 0.5, 4.2, 118.3, 124.0, 126.6, 128.3, 138.2; MS m/z 130 (M^+); HRMS calcd for $C_{10}H_{10}$ 130.0782 (M^+), found 130.0783.

1-(*tert*-Butyldiphenylsiloxy)-2-cyclopropylidene-5-hexene (12): yield 95%; colorless oil; IR (neat) 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.78−1.10 (4H, m), 1.05 (9H, s), 2.25−2.34 (2H, m), 2.41 (2H, t, J = 8.1 Hz), 4.30 (2H, s), 4.93 (1H, dd, J = 1.8 and 10.2 Hz), 5.01 (1H, dd, J = 1.8 and 17.2 Hz),

5.76−5.96 (1H, m), 7.30−7.75 (10H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ 1.5, 2.2, 19.4, 27.0, 31.5, 32.0, 66.9, 114.2, 118.1, 126.8, 127.6, 129.5, 134.0, 135.7, 139.2; MS *m*/*z* 319 ($M^+ - 57$); HRMS calcd for $C_{21}H_{23}OSi$ 319.1518 ($M^+ - 57$). found 319.1501.

2-Cyclopropylidene-5-hexenol (13). To a stirred solution of silyl ether **12** (4.29 g, 11.4 mmol) in THF (10 mL) was added 1 M solution of ^{n}Bu$_4$NF in THF (20.0 mL, 20.0 mmol) at rt, and stirring was continued for 3.5 h at the same temperature. The reaction mixture was diluted with water and extracted with CH_2Cl_2. The combined extracts were washed with saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (95:5 v/v) as eluant to give alcohol **13** (1.57 g 100%) as a colorless oil: IR (neat) 3320, 1635 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.01−1.19 (4H, m), 1.55 (1H, t, J = 6.0 Hz), 2.24−2.41 (4H, m), 4.24 (2H, d, J = 6.0 Hz), 4.95 (1H, dd, J = 1.5 and 9.9 Hz), 5.03 (1H, dd, J = 1.5 and 17.3 Hz), 5.76−5.94 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ 1.3, 1.4, 31.8, 32.0, 65.8, 114.5, 117.8, 127.3, 138.7; MS *m*/*z* 137 ($M^+ - 1$); HRMS calcd for $C_9H_{13}O$ 137.0966 ($M^+ - 1$), found 137.0962.

General Procedure for the Preparation of Cyclobutanone Derivatives. Preparation of 2-[4-(*tert*-Butyldiphenylsiloxy)butyl]cyclobutanone (14). To a stirred solution of cyclopropylidene **9** (4.3 g, 11.8 mmol) in CH_2Cl_2 (40 mL) was added *m*-CPBA (3.31 g, of 80% active, 15.3 mmol) at 0 °C, and stirring was continued for 17 h at rt. The reaction mixture was diluted with CH_2Cl_2 and washed with 10% NaOH and saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (99:1 v/v) as eluant to give cyclobutanone **14** (3.01 g, 67%) as a colorless oil: IR (neat) 1770 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.05 (9H, s), 1.32−1.79 (7H, m), 2.05−2.23 (1H, m), 2.81−3.09 (2H, m), 3.16−3.32 (1H, m), 3.65 (2H, t, J = 5.9 Hz), 7.33−7.73 (10H, m); MS *m*/*z* 323 ($M^+ - 57$). Anal. Calcd for $C_{24}H_{32}O_2Si$: C, 75.74; H, 8.47. Found: C, 75.48; H, 8.47.

2-Heptylcyclobutanone (15): yield 34%; colorless oil; IR (neat) 1780 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.88 (3H, t, J = 7.3 Hz), 1.12−1.82 (13H, m), 2.08−2.29 (1H, m), 2.80−3.11 (2H, m), 3.19−3.35 (1H, m); MS *m*/*z* 168 (M^+); HRMS calcd for $C_{11}H_{20}O$ 168.1514 (M^+), found 168.1541.

2-Phenylcyclobutanone (16): yield 35%; colorless oil; IR (neat) 1785 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.16−2.34 (1H, m), 2.45−2.63 (1H, m), 2.74−3.11 (1H, m), 3.13−3.33 (1H, m), 4.47−4.60 (1H, m), 7.19−7.44 (5H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ 17.7, 44.9, 64.6, 127.0, 128.6, 136.5, 207.7; MS *m*/*z* 146 (M^+); HRMS calcd for $C_{10}H_{10}O$ 146.0732 (M^+), found 146.0713.

2-(3-Butenyl)-2-(hydroxymethyl)cyclobutanone (17): yield 53%; colorless oil; IR (neat) 3430, 1765, 1635 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.58−2.30 (7H, m), 2.92−3.04 (2H, m), 3.65 and 3.79 (each 1H, each dd, J = 5.1 and 10.8 Hz), 4.97 (1H, dd, J = 1.5 and 8.8 Hz), 5.04 (1H, dd, J = 1.5 and 16.9 Hz), 5.71−5.93 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.9, 28.4, 30.5, 43.3, 64.0, 69.9, 114.9, 137.8, 215.7; MS *m*/*z* 154 (M^+); HRMS calcd for $C_9H_{14}O_2$ 154.0994, found 154.1012.

2-(3-Butenyl)-2-[(*tert*-butyldimethylsiloxy)methyl]cyclobutanone (18). To a stirred solution of alcohol **17** (1.7 g, 11.1 mmol), imidazole (1.28 g, 18.9 mmol), and a catalytic amount of DMAP in DMF (12 mL) was added TBSCl (2.5 g, 16.6 mmol) at 0 °C, and stirring was continued for 1.5 h at rt. The reaction mixture was diluted with Et_2O and washed with 10% HCl and saturated aqueous $NaHCO_3$ and NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (98:2 v/v) as eluant to give silyl ether **18** (2.78 g, 94%) as a colorless oil: IR (neat) 1770, 1635 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.03 (3H, s), 0.05 (3H, s), 0.88 (9H, s), 1.45−2.27 (6H, m), 2.77−2.98 (2H, m), 3.52 and 3.75 (each 1H, each d, J = 9.5 Hz), 4.96 (1H, dd, J = 1.5 and 10.3 Hz), 5.02 (1H, dd, J = 1.5 and 17.2 Hz), 5.68−5.88 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.5, 18.3, 19.3, 25.9, 28.8, 30.9, 43.9, 65.0, 70.1, 114.9, 138.1, 214.8; MS *m*/*z* 268 (M^+). Anal. Calcd for $C_{15}H_{28}O_2Si$: C, 67.11; H, 10.51. Found: C, 66.88; H, 10.57.

General Procedure for the Preparation of Isopropenylcyclobutanol Derivatives. Preparation of (1*R*,2*S*)-2-[4-(*tert*-Butyldiphenylsiloxy)butyl]-1-isopropenylcyclobutanol (19). To a stirred suspension of cerium chloride (6.63 g, 26.9 mmol) in THF (80 mL) was added a solution of isopropenylmagnesium bromide [prepared from magnesium (1.44 g, 19.1 mmol) and 2-bromopropene (2.39 mL, 26.9 mmol)] in THF (40 mL) at −78 °C. After stirring had been continued for 1 h, a solution of cyclobutanone **14** (3.01 g, 7.90 mmol) in Et_2O (20 mL) was added dropwise to this reaction mixture at the same temperature, and the temperature was then raised to rt in 3 h. The reaction mixture was treated with saturated aqueous NH_4Cl and extracted with Et_2O. The combined extracts were washed with saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (97:3 v/v) as eluant to give isopropenylcyclobutanol **19** (2.35 g, 71%) as a colorless oil: IR (neat) 3450 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.04 (9H, s), 1.21−1.93 (10H, m), 1.77 (3H, s), 2.10−2.24 (1H, m), 2.33−2.47 (1H, m), 3.66 (2H, t, J = 6.2 Hz), 4.79 and 4.90 (each 1H, each br s), 7.30−7.71 (10H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ 18.2, 19.3, 21.5, 23.4, 27.0, 29.3, 31.6, 32.8, 42.8, 63.9, 79.7, 109.2, 127.8, 129.5, 134.2, 135.7, 149.4; MS *m*/*z* 365 ($M^+ - 57$); HRMS calcd for $C_{23}H_{29}O_2Si$ 365.1937 ($M^+ - 57$), found 365.1935.

(1*R*,2*S*)-2-Heptyl-1-isopropenylcyclobtanol (20): yield 79%; colorless oil; IR (neat) 3480 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.88 (3H, t, J = 5.9 Hz), 1.13−1.94 (16H, m), 1.78 (3H, s), 2.11−2.26 (1H, m), 2.35−2.48 (1H, m), 4.80 and 4.92 (each 1H, each br s); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.0, 17.9, 21.3, 22.6, 27.1, 29.3, 29.4, 29.8, 31.4, 32.0, 42.8, 79.4, 108.8, 149.4; MS *m*/*z* 210 (M^+); HRMS calcd for $C_{14}H_{26}O$ 210.1984 (M^+), found 210.1955.

(1*R*,2*R*)-1-Isopropenyl-2-phenylcyclobutanol (21): yield 63%; colorless oil; IR (neat) 3450 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.46 (1H, s), 1.82 (3H, s), 1.87−2.03 (1H, m), 2.04−2.18 (1H, m), 2.21−2.59 (2H, m), 3.80 (1H, t, J = 8.4 Hz), 4.86 and 5.03 (each 1H, each br s), 7.17−7.38 (5H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.5, 20.7, 31.1, 47.3, 80.8, 109.9, 126.7, 128.4, 138.7, 148.9; MS *m*/*z* 188 (M^+); HRMS calcd for $C_{13}H_{16}O$ 188.1201, found 188.1224.

[(1*S*,2*S*) and (1*R*,2*S*)]-2-(3-Butenyl)-2-[(*tert*-butyldimethylsiloxy)methyl]-1-isopropenylcyclobutanol (22 and 23). 22: yield 76%; colorless oil; IR (neat) 3440, 1630 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ −0.01 (3H, s), 0.00 (3H, s), 0.85 (9H, s), 1.25−1.33 (1H, m), 1.56 (1H, s), 1.65−1.84 (4H, m), 1.77 (3H, s), 1.86−1.96 (1H, m), 1.97−2.06 (1H, m), 2.32−2.45 (1H, m), 3.36 and 3.52 (each 1H, each d, J = 10.4 Hz), 4.84 and 4.87 (each 1H, each d, J = 1.2 Hz), 4.91 (1H, dd, J = 1.2 and 9.8 Hz), 5.00 (1H, dd, J = 1.2 and 17.1 Hz), 5.77−5.91 (1H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.8, −5.7, 18.3, 19.8, 23.1, 25.9, 28.5, 28.9, 29.4, 50.8, 64.6, 81.7, 111.0, 114.0, 139.6, 147.3; MS *m*/*z* 253 ($M^+ - 57$); HRMS calcd for $C_{14}H_{25}O_2Si$ 253.1624 ($M^+ - 57$), found 253.1630.

23: yield 19%; colorless oil; IR (neat) 3460, 1630 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.09 (3H, s), 0.10 (3H, s), 0.91 (9H, s), 1.34−1.46 (2H, m), 1.50−1.57 (1H, m), 1.57−1.67 (1H, m), 1.76 (3H, s), 1.78−1.90 (2H, m), 1.92−2.02 (1H, m), 2.35−2.44 (1H, m), 3.68 and 3.93 (each 1H, each d, J = 10.4 Hz), 4.07 (1H, s), 4.85−5.01 (4H, m), 5.69−5.80 (1H, m); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.6, −5.5, 18.1, 19.9, 21.2, 25.8, 28.4, 30.0, 31.2, 50.5, 65.5, 82.0, 111.3, 114.2, 139.1, 146.9; MS *m*/*z* 253 ($M^+ - 57$). Anal. Calcd for $C_{18}H_{34}O_2Si$: C, 69.62; H, 11.04. Found: C, 69.79; H, 11.02.

(1*R*,2*S*)-2-(4-Hydroxybutyl)-1-isopropenylcyclobutanol (24). By following the same procedure described for **13**, **24** was prepared: yield 95%; colorless needles; mp 52−53 °C (from hexane−Et_2O); IR ($CHCl_3$) 3450, 1640 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.18−1.35 (2H, m), 1.36−1.47 (1H, m), 1.48−1.58 (3H, m), 1.58−1.63 (2H, m), 1.73 (3H, s), 1.74−1.89 (2H, m), 1.95−2.07 (2H, m), 2.07−2.20 (1H, m), 2.34−2.44 (1H, m), 3.51−3.67 (2H, m), 4.75 and 4.88 (each 1H, each d, each J = 1.2 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 18.2, 21.4, 23.3, 29.3, 31.6, 32.8, 42.6, 62.6, 79.7, 109.2, 149.4; MS *m*/*z* 184 (M^+); HRMS calcd for $C_{11}H_{20}O_2$ 184.1463 (M^+), found 184.1466.

(1*R*,2*S*)-1-Isopropenyl-2-[(*E*)-5-(methoxycarbonyl)-4-pentenyl]cyclobutanol (25). To a stirred solution of DMSO (1.11 mL, 15.7 mmol) in CH_2Cl_2 (10 mL) was added $(COCl)_2$ (1.14 mL, 13.1 mmol), and then the solution of alcohol **24** (480 mg, 2.61 mmol) in CH_2Cl_2 (5 mL) at −78 °C. After stirring

had been continued for 30 min at the same temperature, the reaction mixture was treated with Et_3N (3.46 mL, 24.8 mmol), stirred for 5 min at 0 °C, treated with 10% HCl, and extracted with CH_2Cl_2. The combined extracts were washed with saturated aqueous $NaHCO_3$ and NaCl. Workup of the organic layer afforded the corresponding aldehyde. A solution of the aldehyde obtained above and methyl triphenylphosphoranylideneacetate (1.05 g, 3.13 mmol) in CH_3CN (15 mL) was refluxed for 1 h. The residue upon evaporation of the solvent was chromatographed on silica gel with hexane-AcOEt (99:1 v/v) as eluant to give ester **25** (348 mg, 56% from **24**) as a colorless oil: IR (neat) 3470, 1720, 1650, 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.25−1.98 (7H, m), 1.77 (3H, s), 2.09−2.29 (3H, m), 2.33−2.49 (1H, m), 2.85 (1H, s), 3.72 (3H, s), 4.80 and 4.91 (each 1H, each br s), 5.82 (1H, dt, J = 1.1 and 15.7 Hz), 6.96 (1H, dt, J = 6.6 and 15.7 Hz); MS m/z 238 (M^+); HRMS calcd for $C_{14}H_{22}O_3$ 238.1569 (M^+), found 238.1604.

(1*S*,2*S*)-2-(3-Butenyl)-2-[(*tert*-butyldimethylsiloxy)methyl]-1-isopropenyl-1-(triethylsiloxy)cyclobutane (26). To a stirred solution of alcohol **22** (1.3 g, 4.18 mmol) and 2,6-lutidine (1.95 mL, 16.7 mmol) in CH_2Cl_2 (15 mL) was added triethylsilyl trifluoromethanesulfonate (TESOTf) (1.89 mL, 8.35 mmol) at 0 °C, and stirring was continued for 1 h at rt. The reaction mixture was treated with water and extracted with CH_2Cl_2. The combined extracts were washed with saturated aqueous $NaHCO_3$ and NaCl. The residue upon workup was chromatographed on silica gel with hexane as eluant to give silyl ether **26** (1.77 g, 100%) as a colorless oil: IR (neat) 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ −0.01 (3H, s), 0.00 (3H, s), 0.58 (6H, q, J = 8.1 Hz), 0.86 (9H, s), 0.95 (9H, t, J = 8.1 Hz), 1.21−1.33 (1H, m), 1.52−2.14 (6H, m), 1.72 (3H, s), 2.31−2.44 (1H, m), 3.31 and 3.50 (each 1H, each d, each J = 10.3 Hz), 4.78 and 4.86 (each 1H, each br s), 4.90 (1H, dd, J = 1.1 and 10.3 Hz), 5.00 (1H, dd, J = 1.1 and 16.9 Hz), 5.78−5.95 (1H, m); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.7, −5.5, 6.4, 7.2, 18.4, 20.5, 23.6, 26.0, 28.7, 29.0, 30.2, 52.0, 64.8, 83.2, 111.4, 113.4, 140.4, 148.2; MS m/z 424 (M^+). Anal Calcd for $C_{24}H_{48}O_2Si_2$: C, 67.86; H, 11.39. Found: C, 67.86; H, 11.11.

(1*S*,2*S*)-2-[(*tert*-Butyldimethylsiloxy)methyl]-2-(4-hydroxybutyl)-1-isopropenyl-1-(triethylsiloxy)cyclobutane (27). By following the same procedure described for **3**, compound **27** was prepared from **26**: yield 78%; colorless oil; IR (neat) 3350, 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ −0.02 (3H, s), −0.01 (3H, s), 0.58 (6H, q, J = 8.1 Hz), 0.86 (9H, s), 0.95 (9H, t, J = 8.1 Hz), 1.16−1.90 (10H, m), 1.71 (3H, s), 2.32−2.43 (1H, m), 3.30 and 3.49 (each 1H, each d, J = 10.3 Hz), 3.59−3.72 (2H, m), 4.79 and 4.86 (each 1H, each br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.9, −5.7, 6.3, 7.2, 18.3, 20.4, 20.5, 23.5, 25.9, 28.6, 30.4, 34.0, 52.1, 63.3, 64.7, 83.2, 110.3, 148.2; MS m/z 442 (M^+). Anal. Calcd for $C_{24}H_{50}O_3Si_2$: C, 65.10; H, 11.38. Found: C, 65.00; H, 11.38.

(1*S*,2*S*)-2-[(*tert*-Butyldimethylsiloxy)methyl]-1-isopropenyl-2-(4-oxobutyl)cyclobutanol (28). To a stirred solution of DMSO (0.18 mL, 2.53 mmol) in CH_2Cl_2 (10 mL) was added $(COCl)_2$ (0.184 mL, 2.11 mmol), the solution of alcohol **27** (18.6 mg, 0.422 mmol) in CH_2Cl_2 (5 mL) was added at the same temperature, and the reaction mixture was treated with Et_3N (0.55 mL, 4.01 mmol), stirred for 5 min at 0 °C, treated with 10% HCl, and extracted with CH_2Cl_2. The combined extracts were washed with saturated aqueous $NaHCO_3$ and NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (85:15 v/v) as eluant to give aldehyde **28** (61.5 mg, 44%) as a colorless oil: IR (neat) 3450, 1720, 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.00 (3H, s), 0.01 (3H, s), 0.86 (9H, s), 1.30−1.94 (8H, m), 1.78 (3H, s), 2.36−2.54 (3H, m), 3.39 and 3.54 (each 1H, each d, J = 10.3 Hz), 4.80 and 4.96 (each 1H, each br s), 9.78 (1H, t, J = 1.5 Hz); MS m/z 269 (M^+ − 57); HRMS calcd for $C_{14}H_{25}O_3Si$ 269.1573 (M^+ − 57), found 269.1570.

(1*S*,2*S*)-2-[(*tert*-Butyldimethylsiloxy)methyl]-1-isopropenyl-2-[(*E*)-5-(methoxycarbonyl)-4-pentenyl]cyclobutanol (29). A solution of aldehyde **28** (48.7 mg, 0.149 mmol) and methyl triphenylphosphoranylideneacetate (124 mg, 0.371 mmol) in CH_3CN (3 mL) was refluxed for 1 h. The residue upon evaporation of the solvent was chromatographed on silica gel with hexane−AcOEt (93:7 v/v) as eluant to give ester **29** (51.6 mg, 93%) as a colorless oil: IR (neat) 3500, 1730, 1650, 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ −0.01 (3H, s), 0.00 (3H, s), 0.86 (9H, s), 1.23−1.82 (8H, m), 1.78 (3H, s), 2.15−2.27 (2H, m), 2.33−2.45 (1H, m), 3.35 and 3.52 (each 1H, each d, J = 10.3 Hz), 3.72 (3H, s), 4.82 and 4.92 (each 1H, each br s), 5.83 (1H, d, J = 15.4 Hz), 6.98 (1H, dt, J = 7.0 and 15.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.6, 18.4, 19.9, 22.8, 23.2, 25.8, 29.0, 29.9, 33.2, 50.9, 51.4, 64.8, 81.7, 111.0, 121.0, 147.3, 149.7, 167.1; MS m/z 325 (M^+ − 57); HRMS calcd for $C_{17}H_{29}O_4Si$ 325.1835 (M^+ − 57). found 325.1809.

(1*S*,2*S*)-2-[(*tert*-Butyldimethylsiloxy)methyl]-1-isopropenyl-2-[(*E*)-5-(methoxycarbonyl)-4-pentenyl]-1-(triethylsiloxy)cyclobutane (30). By following the same procedure described for **25**, ester **30** was prepared from **27**: yield 94% from **27**; colorless oil; IR (neat) 1720, 1650, 1640 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ −0.06 (3H, s), −0.02 (3H, s), 0.58 (6H, q, J = 7.5 Hz), 0.85 (9H, s), 0.94 (9H, t, J = 7.5 Hz), 1.20−1.90 (7H, m), 1.71 (3H, s), 2.12−2.26 (2H, m), 2.32−2.43 (1H, m), 3.28 and 3.48 (each 1H, each d, J = 10.2 Hz), 3.72 (3H, s), 4.78 and 4.91 (each 1H, each br s), 5.82 (1H, d, J = 15.6 Hz), 6.99 (1H, dt, J = 6.9 and 15.6 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.6, 6.4, 7.2, 18.3, 20.4, 23.0, 23.5, 25.9, 28.7, 30.5, 33.4, 51.4, 52.0, 64.7, 83.1, 110.5, 120.8, 148.0, 150.2, 167.3; MS m/z 496 (M^+). Anal. Calcd for $C_{27}H_{52}O_4Si_2$: C, 65.27; H, 10.55. Found: C, 64.98; H, 10.63.

(1*S*,2*S*)-2-[(*tert*-Butyldimethylsiloxy)methyl]-2-(5,5-dibromo-4-pentenyl)-1-isopropenyl-1-(triethylsiloxy)cyclobutane (31). To a stirred solution of DMSO (0.913 mL, 12.9 mmol) in CH_2Cl_2 (30 mL) was added $(COCl)_2$ (0.936 mL, 10.7 mmol), and then the solution of alcohol **27** (1.90 g, 4.29 mmol) in CH_2Cl_2 (30 mL) was added at −78 °C. After stirring had been continued for 30 min at the same temperature, the reaction mixture was treated with Et_3N (2.69 mL, 19.3 mmol), stirred for 5 min at 0 °C, treated with 10% HCl, and extracted with CH_2Cl_2. The combined extracts were washed with saturated aqueous $NaHCO_3$ and NaCl. Workup of the organic layer afforded the corresponding aldehyde. To a stirred solution of CBr_4 (5.69 g, 17.2 mmol) in CH_2Cl_2 (30 mL) was added PPh_3 (9.0 g, 34.3 mmol) at 0 °C. After stirring had been continued for 30 min at the same temperature, a solution of the aldehyde obtained above in CH_2Cl_2 (20 mL) was added to this reaction mixture, and stirring was continued for 10 h at rt. The reaction mixture was diluted with hexane and filtered. The residue upon evaporation of the filtrate was chromatographed on silica gel with hexane as eluant to give dibromo olefin **31** (2.25 g, 88% from **27**) as a colorless oil: IR (neat) 1650 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ −0.01 (3H, s), 0.00 (3H, s), 0.59 (6H, q, J = 8.1 Hz), 0.87 (9H, s), 0.96 (9H, t, J = 8.1 Hz), 1.21−1.94 (7H, m), 1.71 (3H, s), 2.05−2.16 (2H, m), 2.32−2.45 (1H, m), 3.28 and 3.48 (each 1H, each d, J = 10.3 Hz), 4.79 and 4.93 (each 1H, each br s), 6.41 (1H, t, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.6, −5.5, 6.4, 7.3, 18.4, 20.5, 22.9, 23.6, 26.1, 28.7, 30.3, 34.1, 52.0, 64.7, 83.1, 88.5, 110.5, 139.1, 148.0; MS m/z 594 (M^+); HRMS calcd for $C_{25}H_{48}Br_2O_2Si_2$ 594.1560 (M^+), found 594.1582.

(1*S*,2*S*)-2-[(*tert*-Butyldimethylsiloxy)methyl]-1-isopropenyl-2-[5-(methoxycarbonyl)-4-pentynyl]-1-(triethylsiloxy)cyclobutane (32). To a stirred solution of dibromo olefin **31** (265 mg, 0.443 mmol) in THF (3 mL) was added 1.5 M solution of n-BuLi in hexane (0.62 mL, 0.93 mmol) at −78 °C. After stirring had been continued for 20 min at the same temperature, the reaction mixture was treated with methyl chlorocarbonate (0.171 mL, 2.22 mmol) and stirred for 10 min at the same temperature. The reaction mixture was treated with water and extracted with Et_2O. The combined extracts were washed with saturated aqueous NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (98:2 v/v) as eluant to give acetylene **32** (202 mg, 92%) as a colorless oil: IR (neat) 2250, 1720, 1650 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ −0.01 (3H, s), 0.00 (3H, s), 0.58 (6H, q, J = 8.4 Hz), 0.85 (9H, s), 0.94 (9H, t, J = 8.4 Hz), 1.24−1.93 (7H, m), 1.70 (3H, s), 2.25−2.45 (3H, m), 3.29 and 3.48 (each 1H, each d, J = 10.6 Hz), 3.75 (3H, s), 4.79 and 4.87 (each 1H, each br s); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.8, −5.6, 6.3, 7.1, 18.2, 19.7, 20.4, 22.9, 23.4, 25.8, 28.5, 30.3, 51.8, 52.3, 64.7,

72.8, 83.0, 90.0, 110.5, 147.8, 154.2; MS *m/z* 496 (M^+). Anal. Calcd for $C_{27}H_{52}O_4Si_2$: C, 65.53; H, 10.18. Found: C, 65.23; H, 10.44.

General Procedure for the Ring Expansion of Olefinic Cyclobutanols by Iodine. Preparation of [(2*R*,3*S*) and (2*S*,3*S*)]-3-Heptyl-2-(iodomethyl)-2-methylcyclopentanone (33a and 34a). To a stirred solution of olefinic alcohol **20** (80.1 mg, 0.381 mmol) in Et_2O (1 mL) and water (1 mL) were added $NaHCO_3$ (48 mg, 0.571 mmol) and iodine (145 mg, 0.571 mmol), and stirring was continued for 1 h at rt. The reaction mixture was extracted with Et_2O. The combined extracts were washed with saturated aqueous $Na_2S_2O_3$ and NaCl. The residue upon workup was chromatographed on silica gel with hexane−EtOAc (95:5 v/v) as eluant to give iodides **33a** and **34a** (100 mg, 78%) as a colorless oil: IR (neat) 1740 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.81−0.96 (3H, m), 0.97 (1.5H, s), 1.15 (1.5H, s), 1.15−2.25 (15H, m), 2.25−2.42 (2H, m), 3.08 and 3.21 (each 0.5H, each d, J = 10.6 Hz), 3.09 and 3.45 (each 0.5 H, each d, J = 10.0 Hz); MS *m/z* 337 ($M^+ + 1$); HRMS calcd for $C_{14}H_{25}IO$ 337.1028 ($M^+ + 1$), found 337.1052.

[(2*R*,3*R*) and (2*S*,3*R*)]-2-(Iodomethyl)-2-methyl-3-phenylcyclopentanone (33b and 34b): yield 94%; colorless oil; IR (neat) 1740 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.78 (1.5H, s), 1.27 (1.5H, s), 2.14−2.71 (4H, m), 2.72 and 3.13 (each 0.5H, each d, J = 10.6 Hz), 2.93 and 3.51 (each 0.5H, each d, J = 10.3 Hz), 3.28 (0.5H, t, J = 8.4 Hz), 3.69−3.91 (0.5H, m), 7.29−7.42 (5H, m); MS *m/z* 314 (M^+); HRMS calcd for $C_{13}H_{15}IO$ 314.0168, found 314.0188.

[(2*R*,3*S*) and (2*S*,3*S*)]-2-(Iodomethyl)-3-[(*E*)-5-(methoxycarbonyl)-4-pentenyl]-2-methylcyclopentanone (33c and 34c). 33c: yield 36%; colorless oil; IR (neat) 1740, 1720 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 0.97 (3H, s), 1.22−1.33 (1H, m), 1.39−1.57 (3H, m), 1.58−1.70 (1H, m), 2.03−2.20 (2H, m), 2.21−2.42 (4H, m), 3.06 and 3.46 (each 1H, each d, J = 9.8 Hz), 3.74 (3H, s), 5.87 (1H, d, J = 15.9 Hz), 6.98 (1H, dt, J = 7.3 and 15.9 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 12.5, 17.4, 25.3, 26.0, 29.3, 32.4, 37.0, 43.7, 51.4, 51.5, 121.5, 148.9, 167.1, 219.8; MS *m/z* 364 (M^+); HRMS calcd for $C_{14}H_{21}IO_3$ 364.0536, found 364.0560.

34c: yield 36%; colorless oil; IR (neat) 1740, 1730 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 1.16 (3H, s), 1.20−1.34 (1H, m), 1.38−1.71 (3H, m), 1.73−1.82 (1H, m), 1.90−2.01 (1H, m), 2.02−2.12 (1H, m), 2.15−2.47 (4H, m), 3.07 and 3.19 (each 1H, each d, J = 10.4 Hz), 3.74 (3H, s), 5.86 (1H, d, J = 15.9 Hz), 6.97 (1H, dt, J = 6.7 and 15.9 Hz); ^{13}C NMR (125 Hz, $CDCl_3$) δ 9.1, 23.0, 24.3, 26.2, 28.4, 32.3, 35.7, 46.5, 51.2, 51.6, 121.5, 148.8, 167.1, 218.3; MS *m/z* 365 ($M^+ + 1$); HRMS calcd for $C_{14}H_{22}IO_3$ 365.0614 ($M^+ + 1$), found 365.0604.

(2*S*,3*R*)-3-[(*tert*-Butyldimethylsiloxy)methyl]-2-(iodomethyl)-3-[(*E*)-5-(methoxycarbonyl)-4-pentenyl]-2-methylcyclopentanone (33d): yield 88% (from **29**) and 96% (from **30**); colorless oil; IR (neat) 1730, 1720, 1650 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 0.04 (6H, s), 0.84 (9H, s), 1.06 (3H, s), 1.32−1.51 (3H, m), 1.74−1.85 (1H, m), 1.88−1.99 (2H, m), 2.12−2.30 (3H, m), 2.34−2.43 (1H, m), 3.40 and 3.50 (each 1H, each d, J = 11.0 Hz), 3.66 (2H, s), 3.73 (3H, s), 5.85 (1H, d, J = 15.3 Hz), 6.94 (1H dt, J = 7.0 and 15.3 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.9, −5.8, 11.0, 18.0, 21.6, 22.6, 25.7, 29.4, 33.2, 33.6, 34.0, 49.0, 51.3, 51.5, 68.7, 121.4, 148.7, 167.0, 217.7; MS *m/z* 451 ($M^+ - 57$); HRMS calcd for $C_{17}H_{28}IO_4Si$ 451.0802 ($M^+ - 57$), found 451.0800.

(2*S*,3*R*)-3-[(*tert*-Butyldimethylsiloxy)methyl]-2-(iodomethyl)-3-[5-(methoxycarbonyl)-4-pentynyl]-2-methylcyclopentanone (33e): yield 59%; colorless oil; IR (neat) 2250, 1740, 1720 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 0.04 (3H, s), 0.05 (3H, s), 0.85 (9H, s), 1.08 (3H, s), 1.42−1.52 (1H, m), 1.53−1.64 (2H, m), 1.77−1.85 (1H, m), 1.91−1.99 (1H, m), 2.00−2.08 (1H, m), 2.23−2.42 (4H, m), 3.41 and 3.51 (each 1H, each d, J = 11.0 Hz), 3.64 and 3.69 (each 1H, each d, J = 9.8 Hz), 3.77 (3H, s); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.9, −5.8, 10.8, 18.1, 19.8, 21.7, 22.5, 25.8, 29.5, 33.5, 34.1, 48.9, 51.4, 52.7, 68.7, 73.4, 88.9, 154.2, 217.6; MS *m/z* 449 ($M^+ - 57$); HRMS calcd for $C_{17}H_{26}IO_4Si$ 449.0645 ($M^+ - 57$), found 449.0625.

Preparation of (Iodomethyl)cyclopentanone 33e by *N*-Iodosuccinimide. To a stirred solution of olefinic cyclobutane **32** (505 mg, 1.02 mmol) in CCl_4 (10 mL) was added *N*-iodosuccinimide (NIS) (275 mg, 1.22 mmol) at rt, and stirring was continued for 1 h at the same temperature. The reaction mixture was diluted with CH_2Cl_2 and washed with saturated aqueous $Na_2S_2O_3$ and NaCl. The residue upon workup was chromatographed on silica gel with hexane−AcOEt (95:3 v/v) as eluant to give iodide **33e** (517 mg, 100%) as a colorless oil, which was identical with the sample obtained above in all aspects.

Supporting Information Available: ^1H NMR spectra of compounds **2**, **19**, **20**, **21**, **24**, **25**, **28**, **29**, **31**, **33a** and **34a**, **33b** and **34b**, **33c**, **34c**, **33d**, and **33e** (15 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JO951806Y