Anal. Calcd for $C_{18}H_{15}NO_4$: C, 69.89; H, 4.89; N, 4.53. Found: C, 70.13; H, 4.75; N, 4.56.

10-Hydroxy-2,5,6,7-tetramethoxy-9-anthracenecarbonitrile (3i): yield 1.52 g (45%); yellow crystals (EtOAc), mp 186–187 °C; IR ($CHCl_3$) 3278 (OH), 2201 (CN) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.98 (s, 3 H), 4.03 (s, 3 H), 4.09 (s, 3 H), 4.26 (s, 3 H), 7.08 (dd, J = 2.1 and 9.4 Hz, 1 H), 7.33 (m, 2 H), 8.29 (d, J = 9.4 Hz, 1 H), 11.00 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 55.48, 56.15, 61.33, 62.58, 91.06, 99.68, 101.03, 106.87, 114.65, 118.33, 119.09, 125.19, 133.91, 137.06, 138.50, 148.83, 155.79, 155.88, 161.00. Anal. Calcd for $C_{19}H_{17}NO_5$: C, 67.25; H, 5.05; N, 4.13. Found: C, 67.37; H, 5.15; N, 4.26.

10-Hydroxy-2-methoxy-9-anthracenecarbonitrile (3k): yield 1.62 g (65%); yellow crystals (EtOAc), mp 233–235 °C; IR ($CHCl_3$) 3248 (OH), 2206 (CN) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.88 (s, 3 H), 6.96 (d, J = 2.3 Hz, 1 H), 7.3 (m, 2 H), 7.5 (m, 1 H), 8.09 (d, J = 8.5 Hz, 1 H), 8.35 (m, 2 H), 10.60 (br s, 1 H). Anal. Calcd for $C_{16}H_{11}NO_2$: C, 77.10; H, 4.45; N, 5.62. Found: C, 77.24; H, 4.39; N; 5.64.

General Procedure for the Preparation of Anthraquinones 12a–i,k. To a solution of the nitrile **3** (1 mmol), prepared in ethanol (60 mL) at 75 °C, was added in one portion an aqueous solution containing 10% NaOH (6 mL) and 30% H_2O_2 (10 mL), and the resulting solution was stirred for 5 h at 75 °C and then for 12 h at room temperature. Upon cooling the reaction mixture to 10–15 °C, the precipitated anthraquinone was filtered, washed with water, and dried to give an essentially pure product. Yields and the characterizations of anthraquinones **12a–k** follow.

1,8-Dimethoxyanthraquinone (12a): yield 224 mg (91%); yellow crystals (EtOH), mp 226–227 °C (lit.[14] mp 223–224 °C.

1,2,7,8-Tetramethoxyanthraquinone (12b): yield 311 mg (95%), yellow crystals (EtOH), mp 159–160 °C; IR ($CHCl_3$) 1679, 1574 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.98 (s, 1 H), 4.01 (s, 3 H), 7.20 (d, J = 8.6 Hz, 2 H), 8.05 (d, J = 8.6 Hz, 2 H); ^{13}C NMR ($CDCl_3$) 56.92, 62.35, 116.25, 124.72, 149.56, 159.32, 181.41, 182.30. Anal. Calcd for $C_{18}H_{16}O_6$: C, 65.85; H, 4.91. Found: C, 65.97; H, 4.98.

1-Methoxyanthraquinone (12c): yield 311 mg (95%); yellow crystals (EtOH), mp 173–175 °C (lit.[15] mp 170 °C).

(14) Morton, R. A.; Earlam, W. T. *J. Chem. Soc.* **1941**, 159.

1,2-Dimethoxyanthraquinone (12d): yield 244 mg (91%); yellow crystals (EtOH), mp 215–217 °C (lit.[15] mp 211–212 °C).

1,2,3-Trimethoxyanthraquinone (12e): yield 280 mg (91%); yellow crystals (EtOH), mp 175–177 °C (lit.[16] mp 171–172 °C).

1,4-Dimethoxyanthraquinone (12f): yield 258 mg (93%); yellow crystals (EtOH), mp 175–176 °C (lit.[17] mp 171 °C).

1,7-Dimethoxyanthraquinone (12g): yield 292 mg (98%); yellow crystals (EtOH), mp 195–197 °C (lit.[18] mp 185 °C).

1,2,7-Trimethoxyanthraquinone (12h): yield 299 mg (97%); yellow crystals (EtOH), mp 232–235 °C (lit.[19] mp 225–226 °C).

2,5,6,7-Tetramethoxyanthraquinone (12i): yield 289 mg (88%); yellow crystals (EtOH), mp 199–200 °C; IR ($CHCl_3$) 1666, 1598 cm^{-1}; ^1H NMR δ 3.98 (s, 3 H), 4.01 (s, 6 H), 4.06 (s, 3 H), 7.27 (m, 1 H), 7.65 (d, J = 2.6 Hz, 1 H), 7.69 (s, 1 H), 8.21 (d, J = 8.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 55.81, 56.34, 61.27, 61.58, 105.65, 106.48, 109.34, 120.99, 121.25, 128.59, 129.50, 134.44, 157.17, 163.56, 181.52, 182.67. Anal. Calcd for $C_{18}H_{16}O_6$: C, 65.85; H, 4.91. Found: C, 65.90; H, 4.98.

Anthraquinone (12j): yield 1.53 g (70%); yellow crystals (EtOH), mp 282–283 °C (lit.[20] mp 283–285 °C).

2-Methoxyanthraquinone (12k): yield 223 mg (90%); yellow crystals (EtOH), mp 198–199 °C (lit.[21] mp 195–197 °C).

Acknowledgment. We thank the Welch Foundation and the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this work.

Supplementary Material Available: X-ray data for 4,5-dimethoxy-10-hydroxy-9-anthracenecarbonitrile (**3a**) (9 pages); observed and calculated structure factors for **3a** (5 pages). Ordering information is given on any current masthead page.

(15) Zahn, K.; Koch, H. *Chem. Ber.* **1938**, *71*, 172.
(16) Briggs, L. H.; Nicholls, G. A. *J. Chem. Soc.* **1949**, 1241.
(17) Dufraisse, C.; Velluz, L. *Bull. Soc. Chim. Fr.* **1942**, *9*, 171.
(18) Huber, A. *Chem. Zentralblatt* **1906**, I, 1070.
(19) Bistrzycki, A.; Yessel de Schepper, D. W. *Chem. Ber.* **1898**, *31*, 2799.
(20) Sammes, P. G.; Dodsworth, D. *J. Chem. Soc., Chem. Commun.* **1979**, 33.
(21) Attree, G. F.; Perkin, A. G. *J. Chem. Soc.* **1931**, *144*, 153.

Tandem Radical Cyclization of Acyclic Homoallylic Xanthates: Cyclopentannulated γ-Thionolactone and γ-Lactones

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The first tandem radical cyclization of linear homoallylic xanthates was explored. Homoallylic xanthates prepared from α,β-unsaturated esters were easily cyclized by tin hydride with an radical initiator to give the corresponding thionolactone annulated cyclopentane skeleton in a high yield. The stereochemistry of cyclized products was also discussed. Thionolactones obtained were oxidized chemoselectivity with *m*-CPBA under neutral condition to afford γ-lactones in a high yield.

Radical chemistry has advanced rapidly through the discovery of novel radical species, the synthetic utility of radical chain reactions, and investigation of radical reaction mechanisms.[1] Intramolecular serial radical cyclizations provide a useful method for the synthesis of multifused compounds. Because of the mild reaction conditions, protection of functional groups may not be necessary.[2] Relatively few reports of successful tandem radical cyclizations of functionalized radical species have been published,[3] although many examples of radical cyclizations[4]

(1) For reviews, see: (a) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon–Carbon Bonds*; Permagon Press: Oxford, 1986. (b) Hart, D. J. *Science* **1984**, *223*, 883. (c) Neumann, W. P. *Synthesis* **1987**, 665. (d) Curran, D. P. *Synthesis* **1988**, 417 and 489 and references therein.

(2) (a) Giese, B.; Groninger, K. *Tetrahedron Lett.* **1984**, *25*, 2743. (b) Stork, G.; Baine, N. H. *J. Am. Chem. Soc.* **1982**, *104*, 41.

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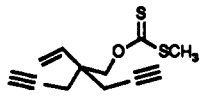
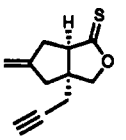
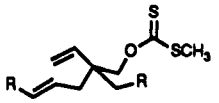
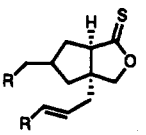
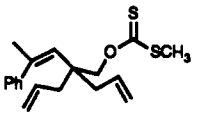
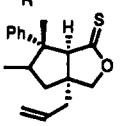
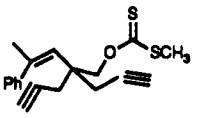
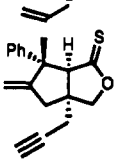
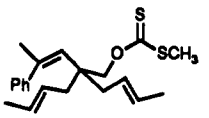
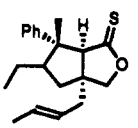
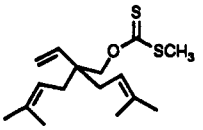
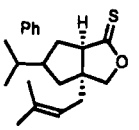
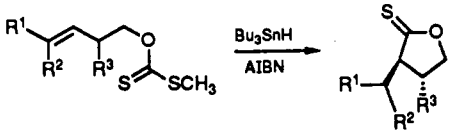
Table I. Tandem Radical Cyclization of Homoallylic Xanthates

entry	xanthate	no.	product	no.	yield (%)[a]	isomer ratio[b]
1		1		9	44	-
2		2 (R = H)		10 (R = H)	76	(76:24)
3		3 (R = Me)		11 (R = Me)	67	(86:14)
4		4 (R = Ph)		12 (R = Ph)	53	(58:42)
5		5		13	71	(>99:1)
6		6		14	61	(>99:1)
7		7		15	58	(90:10)
8		8		16	78	(73:27)

[a] Isolated yield. [b] Diastereomer ratio at C-5 H (α/β). The ratio was determined by ^{1}H NMR (270 MHz, 400 MHz) based on the integration values of the γ-proton.

have been reported. We have been studying the radical cyclization of homoallylic xanthates (dithiocarbonates) with tri-*n*-butyltin hydride and previously reported the highly regio- and stereoselective monocyclizations leading to γ-thionolactones (eq 1).[5] As an extension of this new

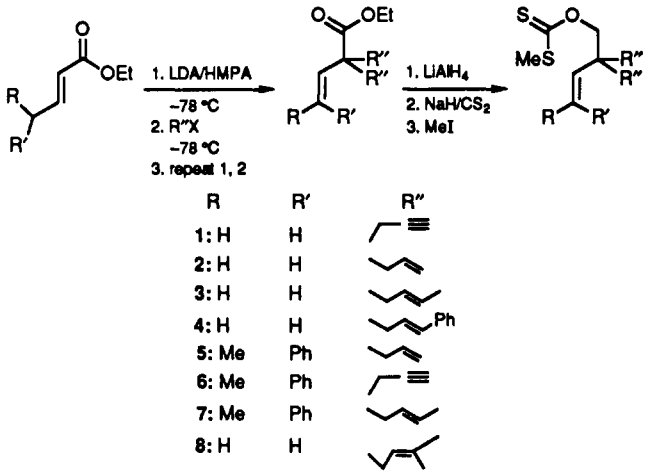


(1)

methodology, our efforts have been focused on serial radical cyclizations such as tandem, triple, and further cyclizations. We report herein the first examples of such a tandem radical cyclization applied to the synthesis of ring-fused lactones using thionolactone formation as a key step (eq 1).

For an efficient second cyclization of the homoallylic xanthates, alkenes, or alkynes were substituted at the β-position as proximal radical acceptors. Precursors for the tandem radical cyclization were prepared as follows: α,β-unsaturated ethyl esters were treated with lithium diisopropylamide (LDA)/hexamethylphosphoramide (HMPA) complex at −78 °C followed by addition of allyl halides (Scheme I). Repetition of the above procedure gave α,α'-disubstituted β,γ-unsaturated esters[6] which were

Scheme I. Preparation of Tandem Radical Cyclization Precursors



	R	R′	R″
1:	H	H	
2:	H	H	
3:	H	H	
4:	H	H	Ph
5:	Me	Ph	
6:	Me	Ph	
7:	Me	Ph	
8:	H	H	

reduced with $LiAlH_4$ to homoallylic alcohols. The alcohols were treated with NaH, CS_2, and MeI to afford the desired homoallylic xanthates in a high yield (Scheme II).[7] In order to satisfy the topological requirement for the second cyclization, β-allylic or propargyl substituents should be syn to the resulting radical of the first cyclization.

The xanthates were treated with tri-*n*-butyltin hydride (1.2 equiv) in thiophene-free, degassed dry toluene and heated at 80 °C for 1–2 h with portionwise addition of 10% azobisisobutyronitrile (AIBN) under argon to give cyclo-

(3) (a) Stork, G.; Mook, R., Jr. *J. Am. Chem. Soc.* **1983**, *105*, 3721. (b) Curran, D. P.; Kuo, C.-C. *Ibid.* **1986**, *108*, 1106. (c) Tsang, R.; Fraser-Reid, B. *Ibid.* **1986**, *108*, 2116. (d) Curran, D. P.; Rakiewicz, D. M. *Ibid.* **1985**, *107*, 1448. (e) Reutrakul, V.; Poolsanong, C.; Pohmakotr, M. *Tetrahedron Lett.* **1989**, *30*, 6913.

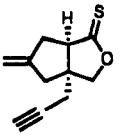
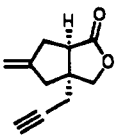
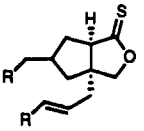
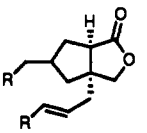
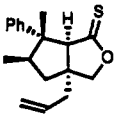
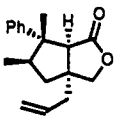
(4) For reviews, see: (a) Thebtaranonth, C.; Thebtaranonth, Y. *Tetrahedron* **1990**, *46*, 1385. (b) References 1.

(5) (a) Yamamoto, M.; Uruma, T.; Iwasa, S.; Kohmoto, S.; Yamada, K. *J. Chem. Soc., Chem. Commun.* **1989**, 1265. (b) For reviews, see: Crich, D. Quintero, L. *Chem. Rev.* **1989**, *89*, 1413 and references therein.

(6) Herrmann, J. L.; Kieczykowski, G. R.; Schlessinger, R. H. *Tetrahedron Lett.* **1973**, 2433.

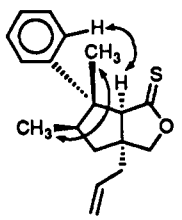
(7) Barton, D. H. R.; McCombie, S. W. *J. Chem. Soc., Perkin Trans. 1* **1975**, 1574.

Table II. Oxidation of Thionolactones

entry	thionolactone	no.	product	no.	yield (%)[a]
1		9[b]		17[b]	85
2		10 (R = H)		18	80
3		11 (R = Me)		19	82
4		13		20	85

[a] Isolated yield. [b] Reference 5a.

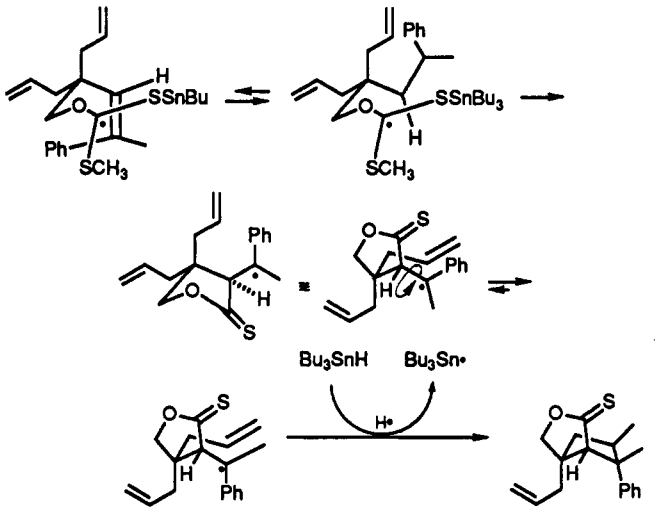
pentannulated thionolactones in 44–78% yield. The results are summarized in Table I. In each case, the tandem cyclization of the homoallylic xanthates proceeded with high regioselectivity to afford 5-*exo-trig* or 5-*exo-dig* cyclized thionolactones annulated with the cyclopentane ring without any other byproducts from 5-exo/6-endo, 5-endo/5-exo, or triple cyclization. The tri-*n*-butyltin radical ($Bu_3Sn^{\bullet}$) would chemoselectively attack the thiocarbonyl group to form a thioacyl radical, which would then cyclize onto the double or triple bonds (entries 1, 6).[8] In entries 2, 3, 4, 5, 7, and 8, the cyclization products were obtained as inseparable diastereomeric mixtures. In all cases, 5-exo cyclized products were obtained. In entries 2–8, the α-isomers (at C-5) were favored, presumably via chair form intermediates[9] (Scheme II). The introduction of a methyl and a phenyl group at C-4 improved the stereoselectivity of the reaction. The stereochemistry of the diastereomers was determined by detailed ^1H NMR, ^{13}C NMR, and NOESY spectroscopic studies. NOE cross peaks between the C-5 methyl protons and C-4 methyl protons and also the proton at ring junction and aromatic protons in the NOESY spectrum of **13** provides the basis for the stereo-



13

chemical assignment shown. All thionolactones obtained were unstable upon storage. Although thionolactones have not been discovered as natural products, γ-lactones are one of the most common ring structures to occur naturally.[10] Conversion of the thionolactones to the corresponding γ-lactones was accomplished efficiently by employing 1.3 equiv of *m*-chloroperoxybenzoic acid (*m*-CPBA) in dry CH_2Cl_2. These results are summarized in Table II. In conclusion, the tandem radical cyclizations of homoallylic

Scheme II



xanthates has proven to be an effective method for the synthesis of linearly fused thionolactones in one step. The easy conversion of these compounds to γ-lactones increases the utility of this methodology.

Experimental Section

Melting point are uncorrected. Mass spectra were taken at 70 eV. Column chromatography was performed on Merck Art 7734, Wako gel C-200, Fujigel BW-200 and BW-820MH. All solvents were freshly distilled and stored under nitrogen atmosphere. Tetrahydrofuran (THF) was distilled over $LiAlH_4$ and stored over molecular sieves (5A). Ether, benzene, and *n*-hexane were dried over sodium wire. Unless otherwise noted, other solvents were used after simple distillation. The purity of all new compounds was demonstrated to be >95% by ^1H NMR and ^{13}C NMR spectra.

General Procedure for the Synthesis of Dithiocarbonates. To a suspension of 1.1 equiv of LDA/HMPA complex in 10 mL of THF was added a solution of 20 mmol of ethyl crotonate in 2 mL of THF with stirring at −78 °C under N_2. The resulting mixture was stirred for 15 min, after which 1.3 equiv of alkyl halide in 2 mL of THF was added. Stirring was continued for 20 min. Saturated NH_4Cl solution (20 mL) and ether (20 mL) were added to the reddish solution and warmed to room temperature. The organic layer was separated, washed (brine), and dried ($MgSO_4$). The solvent was removed on a rotary evaporator, and the residue was purified by flash column chromatography on silica gel (benzene) to give monosubstituted β,γ-unsaturated ester in 85–90% yield. Without further purification, the above procedure was repeated and α,α'-disubstituted β,γ-unsaturated esters were obtained in 80–85% isolated yield. The esters were reduced with

(8) Barton, D. H. R.; Jang, D. O.; Jaszberenyi, J. Cs. *Tetrahedron Lett.* **1990**, *31*, 3991.
(9) Abramovitch, R. A. *Reactive Intermediates*; Plenum Press: New York, 1982; Vol 2, Chapter 3.
(10) (a) ApSimon, J. *The Total Synthesis of Natural Products*; John Wiley & Sons; Inc.: New York, 1988. (b) Fischer, H. D.; Fischer, N. H.; Franck, R. W.; Oliver, E. J. *Progress in the Chemistry of Organic Natural Products*; Springer-Verlag: Wien, 1979.

$LiAlH_4$ in dry ether to give the corresponding homoallylic alcohols in almost quantitative yield.

The homoallylic alcohols were treated with 1.3 equiv of NaH in THF with stirring at room temperature under N_2 atmosphere followed by addition of dry CS_2. The resulting reddish suspension was stirred for 1.5 h, and then 2 equiv of neat MeI was added. After 2 h, a saturated NH_4Cl solution and ether were added. The organic layer was separated, washed (brine), and dried ($MgSO_4$). The solvent was removed by evaporator, and the residue was purified by flash column chromatography on silica gel (*n*-hexane) to give the desired xanthates in high yield.

***O*-2-Ethenyl-2-(2-propynyl)-4-pentynyl *S*-methyl dithiocarbonates (1)**: pale yellow oil, 1.145 g (77%) from 0.912 g of the alcohol.

***O*-2-Ethenyl-2-(2-propenyl)-4-pentenyl *S*-methyl dithiocarbonate (2)**: pale yellow oil, 0.340 g (93%) from 0.273 g of the alcohol.

***O*-2-Ethenyl-2-(2(*E*)-butenyl)-4-hexenyl *S*-methyl dithiocarbonate (3)**: pale yellow oil, 0.973 g (86%) from 0.761 g of the alcohol.

***O*-2-Ethenyl-5-phenyl-2-(3-phenyl-2(*E*)-propenyl)-4-(*E*)-pentenyl *S*-methyl dithiocarbonate (4)**: pale yellow oil, 0.920 g (86%) from 0.821 g of the alcohol. Spectral characterization data for xanthates 1–4 and 8 are included in the supplementary material.

***O*-4-Phenyl-2,2-di(2-propenyl)-3(*Z*)-pentenyl *S*-methyl dithiocarbonate (5)**: yellow oil, 0.305 g (84%) from 0.256 g of the alcohol; IR (neat) 3075, 1225, 1080 cm^{-1}; 400-MHz ^1H NMR ($CDCl_3$) δ 2.17 (d, 3 H, J = 1.2 Hz), 2.47 (br d, 4 H, J = 6.7 Hz), 2.57 (s, 3 H), 4.61 (s, 2 H), 5.08 (br s, 2 H), 5.20 (m, 2 H), 5.77–5.88 (m, 2 H), 7.20–7.35 (m, 5 H); 100-MHz ^{13}C NMR ($CDCl_3$) INEPT δ 18.39 (CH_3), 18.89 (CH_3), 40.81 (CH_2), 77.22 (CH_2), 118.37 (CH_2), 126.12 (CH), 126.92 (CH), 128.19 (CH), 130.37 (CH), 133.85 (CH), 138.26 (CH), 145.76 (CH), 215.60 (C); HRMS (m/z) calcd for $C_{19}H_{24}OS_2$ M^+ 332.1262, found M^+ 332.1267.

***O*-2-(2-Phenyl-1(*Z*)-propenyl)-2-(2-propynyl)-4-pentynyl *S*-methyl dithiocarbonate (6)**: pale yellow oil, 1.045 g (91%) from 0.818 g of the alcohol; IR (neat) 3300, 3050, 2225, 1220, 1080 cm^{-1}; 400-MHz ^1H NMR ($CDCl_3$) δ 2.04 (t, 2 H, J = 2.40 Hz), 2.21 (d, 3 H, J = 1.44 Hz), 2.57 (s, 3 H), 2.73 (d, 4 H, J = 2.40 Hz), 4.85 (s, 2 H), 5.62 (q, 1 H, J = 1.44 Hz), 7.25–7.38 (m, 5 H); 67.8-MHz ^{13}C NMR ($CDCl_3$) INEPT δ 18.27 (CH_3), 19.05 (CH_3), 26.29 (CH_2), 42.81 (C), 71.27 (C), 76.27 (CH_2), 80.07 (CH), 126.32 (CH), 127.12 (CH), 128.20 (CH), 128.46 (CH), 139.66 (C), 145.60 (C), 215.64 (C); HRMS (m/z) calcd for $C_{19}H_{20}OS_2$ M^+ 328.0953, found M^+ 328.0925.

***O*-2-(2-Phenyl-1(*Z*)-propenyl)-2-(2(*E*)-butenyl)-4(*Z*)-hexenyl *S*-methyl dithiocarbonate (7)**: pale yellow oil, 0.239 g (81%) from 0.224 g of the alcohol; IR (neat) 3050, 1600, 1220, 1070 cm^{-1}; 400-MHz ^1H NMR ($CDCl_3$) δ 1.65 (d, 6 H, J = 6.5 Hz), 2.16 (s, 3 H), 2.32–2.40 (m, 4 H), 2.56 (s, 3 H), 4.60 (s, 2 H), 5.20–5.60 (m, 5 H), 7.20–7.40 (m, 5 H); 100-MHz ^{13}C NMR ($CDCl_3$) δ 18.09, 18.74, 33.39, 39.48, 43.54, 77.45, 125.49, 126.15, 126.90, 128.04, 128.60, 131.00, 137.74, 145.95, 215.49; HRMS (m/z) calcd for $C_{21}H_{28}OS_2$ 360.1580, found M^+ 360.1571.

***O*-2-Ethenyl-2-(3-methyl-2-butenyl)-6-methyl-4-hexenyl *S*-methyl dithiocarbonate (8)**: pale oil yellow, 1.741 g (87%) from 1.400 g of the alcohol.

Tandem Radical Cyclization of Acyclic Homoallylic Xanthates. General Procedure: 7,8-Dimethyl-8-phenyl-5-(2-propenyl)-3-oxabicyclo[3.3.0]octane-2-thione (13). A mixture of 0.225 g (0.68 mmol) of xanthate **5**, 0.224 g (0.77 mmol) of Bu_3SnH, and 0.011 g of AIBN in 35 mL of thiophene-free, degassed dry toluene were heated at 80 °C with stirring for 1 h under argon atmosphere. The solvent was removed under reduced pressure. The pale yellow oil was purified by flash column chromatography on silica gel (benzene) to give 0.138 g of **13** in 71% yield: mp 87–88 °C; IR ($CHCl_3$) 3050, 1640, 1270, 1180, 1030 cm^{-1}; 500-MHz ^1H NMR ($CDCl_3$) δ 0.77 (d, 3 H, J = 6.7 Hz), 1.29 (s, 3 H), 1.74 (dd, 1 H, J = 12.9 and 12.9 Hz), 2.10 (dd, 1 H, J = 12.9 and 7.0 Hz), 2.39 (d, 2 H, J = 7.2 Hz), (ddq, 1 H, J = 12.9, 12.9, and 7.0 Hz), 3.58 (s, 1 H), 4.44 (d, 1 H, J = 10.0 Hz), 4.60 (d, 1 H, J = 10.0 Hz), 5.21–5.26 (m, 2 H), 5.77–5.86 (m, 1 H), 7.23–7.43 (m, 5 H); 67.80-MHz ^{13}C NMR ($CDCl_3$) INEPT δ 12.74 (CH_3), 13.99 (CH_3), 43.83 (CH_2), 45.05 (CH_2), 47.80 (CH), 50.42 (C), 53.57 (C), 78.61 (CH), 88.02 (CH_2), 120.25 (CH_2), 126.36 (CH), 126.49 (CH), 126.775 (CH), 128.00 (CH), 132.72 (C), 144.47 (C), 221.82 (C); HRMS (m/z) calcd for $C_{18}H_{22}OS$ M^+ 286.1392, found M^+ 286.1390.

7-Methylene-5-(2-propynyl)-3-oxabicyclo[3.3.0]octane-2-thione (9): oil, 0.177 g (44%) from 0.506 g of **1**.

7-Methyl-5-(2-propenyl)-3-oxabicyclo[3.3.0]octane-2-thione (10): oil, 0.684 g (76%) from 1.101 g of **2**.

7-Ethyl-5-(2(*E*)-butenyl)-3-oxabicyclo[3.3.0]octane-2-thione (11): oil, 0.555 g (67%) from 1.000 g of **3**.

7-Benzyl-5-(3-phenyl-2(*E*)-propenyl)-3-oxabicyclo[3.3.0]-octane-2-thione (12): oil, 0.425 g (53%) from 0.920 g of **4**. Spectral characterization data for thionolactones **9–12** are included in the supplementary material.

7-Methylene-8-methyl-8-phenyl-5-(2-propynyl)-3-oxabicyclo[3.3.0]octane-2-thione (14): oil, 0.225 g (61%) from 0.431 g of **6**; IR ($CHCl_3$) 3300, 3050, 2975, 2910, 1655, 1600, 1310, 1170 cm^{-1}; 400-MHz ^1H NMR ($CDCl_3$) δ 1.52 (s, 3 H), 1.89 (t, 1 H, J = 2.8 Hz), 2.33 (dd, 1 H, J = 17.5 and 3.0 Hz), 2.46 (dd, 1 H, J = 17.5 and 3.0 Hz), 2.57 (d, 1 H, J = 15.5 Hz), 2.67 (ddd, 1 H, J = 15.5, 2.8 and 2.8 Hz), 3.71 (s, 1 H), 4.36 (s, 1 H, J = 10.0 Hz), 4.62 (d, 1 H, J = 10.0 Hz), 5.14 (d, 1 H, J = 2.8 Hz), 5.38 (d, 1 H, J = 2.8 Hz), 7.19–7.52 (m, 5 H); 100-MHz ^{13}C NMR ($CDCl_3$) INEPT δ 27.26 (CH_3), 27.57 (CH_2), 42.19 (CH_2), 51.63 (C), 53.46 (C), 70.87 (C), 75.92 (CH), 79.55 (CH), 83.22 (CH_2), 111.62 (CH_2), 126.22 (CH), 126.41 (CH), 128.59 (CH), 148.55 (C), 154.15 (C), 222.14 (C); high-resolution MS (m/z) found M^+ 282.1078, calcd for $C_{18}H_{18}OS$ M^+ 282.1078.

5-(2(*E*)-Butenyl)-7-ethyl-8-methyl-8-phenyl-3-oxabicyclo[3.3.0]octane-2-thione (15): oil, 0.157 g (58%) from 0.218 g of **7**; IR ($CHCl_3$) 3030, 2975, 2875, 1670, 1440, 1380, 1190, 1040, 960 cm^{-1}; 400 MHz ^1H NMR ($CDCl_3$) δ 0.75 (t, 3 H, J = 7.3 Hz), 1.12–1.19 (m, 2 H), 1.29 (s, 3 H), 1.63–1.68 (m, 2 H), 1.73 (dd, 2 H, J = 6.5 and 1.2 Hz), 2.18 (dd, 1 H, J = 13.2 and 7.2 Hz), 2.30 (d, 2 H, J = 7.2 Hz), 2.40–2.48 (m, 1 H), 3.54 (s, 1 H), 4.41 (d, 1 H, J = 9.9 Hz), 5.57 (d, 1 H, J = 9.9 Hz), 5.42–5.48 (m, 1 H), 5.60–5.69 (m, 1 H), 7.18–7.43 (m, 5 H); 67.80-MHz ^{13}C NMR ($CDCl_3$) INEPT δ 13.06 (CH_3), 14.45 (CH_3), 18.07 (CH_3), 21.75 (CH_2), 41.62 (CH_2), 43.88 (CH_2), 50.45 (C), 530.47 (C), 55.43 (CH), 79.09 (CH), 88.22 (CH_2), 125.25 (CH), 126.37 (CH), 126.40 (CH), 128.19 (CH), 130.95 (CH), 144.85 (C), 221.99 (C); HRMS (m/z) calcd for M^+ 314.1702, found M^+ 314.1694.

7-Isopropyl-5-(3-methyl-2-butenyl)-3-oxabicyclo[3.3.0]octane-2-thione (16): oil, 0.119 g (78%) from 0.184 g of **7**. Complete spectral data for **16** are provided in the supplementary material.

Oxidation of the Thionolactones to γ-Lactones. General Procedure: 7-Methyl-5-(2-propenyl)-3-oxabicyclo[3.3.0]octan-2-one (18). To a solution of 0.082 g (0.48 mmol) of thionolactone **10** in 1 mL of dry CH_2Cl_2 was added a solid of 0.108 g (1.3 equiv) with stirring at room temperature. The resulting mixture was stirred for 1.5 h. At this time, saturated $NaHCO_3$ solution was added, and the organic layer was separated, washed (brine) and dried ($MgSO_4$). The solvent was removed by rotatory evaporator. The residue was purified by flash column chromatography on silica gel (benzene) to give 0.069 g (80%) of **18**: IR (neat) 2950, 2850, 1770, 1635, 1450, 1150, 1015, 920 cm^{-1}; 500-MHz ^1H NMR ($CDCl_3$) δ 1.03 (d, 3 H, J = 6.3 Hz), 1.26–1.35 (m, 1 H), 1.52–1.59 (m, 1 H), 1.83 (dd, 0.3 H, J = 6.1 and 1.4 Hz), 1.96–2.05 (m, 1 H), 2.16–2.34 (m, 4 H), 2.67 (dd, 1 H, J = 9.6 and 6.1 Hz), 3.97 (d, 0.3 H, J = 9.4 Hz), 4.07 (d, 1 H, J = 9.1 Hz), 4.13 (d, 1 H, J = 9.1 Hz), 4.21 (dd, 0.3 H, J = 9.4 and 0.8 Hz), 5.12–5.17 (m, 2 H), 5.68–5.77 (m, 1 H); 67.80-MHz ^{13}C NMR ($CDCl_3$) INEPT δ (major) 19.67 (CH_3), 34.87 (CH), 37.09 (CH_2), 41.54 (CH_2), 45.54 (CH_2), 49.76 (CH), 51.08 (C), 76.32 (CH_2), 119.12 (CH_2), 133.04 (CH), 180.55 (C); (minor) 18.60 (CH_3), 33.92 (CH), 38.96 (CH_2), 44.01 (CH_2), 47.93 (CH_2), 49.44 (CH), 49.93 (C), 78.21 (CH_2) 119.12 (CH_2), 133.07 (CH), 180.63 (C); HRMS (m/z) calcd for $C_{11}H_{16}O_2$ M^+ 180.1149, found M^+ 180.1176.

7-Methylene-5-(2-propynyl)-3-oxabicyclo[3.3.0]octan-2-one (17): oil, 0.138 g (85%) from 0.177 g of **9**. Spectral characterization data for **17** are included in the supplementary material.

5-(2(*E*)-Butenyl)-7-ethyl-3-oxabicyclo[3.3.0]octan-2-one (19): oil, 0.421 g (81%) from 0.550 g of **11**: 400-MHz ^1H NMR ($CDCl_3$) δ 0.88 (t, 3 H, J = 7.5 Hz), 0.90 (t, 0.6 H, J = 7.0 Hz), 1.21–1.42 (m, 3 H), 1.50–1.80 (m, 4 H), 1.95–2.09 (m, 1 H), 2.10–2.35 (m, 3 H), 2.64 (dd, 1 H, J = 10.0 and 5.5 Hz), 3.95 (d, 0.2 H, J = 10.0 Hz), 4.05 (d, 1 H, J = 10.0 Hz), 4.12 (d, 1 H, J = 10.0 Hz),

4.20 (d, 0.2 H, J = 10.0 Hz), 5.30–5.40 (m, 1 H), 5.50–5.60 (m, 1 H); 67.80-MHz ^{13}C NMR ($CDCl_3$) INEPT δ (major) 12.83 (CH_3), 17.97 (CH_3), 28.20 (CH_2), 34.83 (CH_2), 40.01 (CH_2), 42.04 (CH), 42.14 (CH_2), 49.21 (CH), 76.18 (CH_2), 125.54 (CH), 129.74 (CH), 180.78 (C); (minor) 13.00 (CH_3), 17.97 (CH_3), 27.43 (CH_2), 36.83 (CH_2), 41.15 (CH), 43.25 (CH_2), 45.81 (CH_2), 49.36 (CH), 51.05 (C), 78.28 (CH), 127.80 (CH), 180.78 (C); HRMS (m/z) calcd for $C_{13}H_{20}O_2$ M^+ 208.1463, found M^+ 208.1489.

7,8-Dimethyl-8-phenyl-5-(2-propenyl)-3-oxabicyclo-[3.3.0]octan-2-one (20): oil, 0.0184 g (85%) from 0.022 g of **13**; IR ($CHCl_3$) 3025, 2975, 2850, 1760, 1600, 1190, 1020, 920 cm^{-1}; 500-MHz ^1H NMR ($CDCl_3$) δ 0.92 (d, 3 H, J = 6.8 Hz), 1.30 (s, 3 H), 1.74 (t, 1 H, J = 13.1 Hz), 2.13 (dd, 1 H, J = 13.1 and 6.9 Hz), 2.31 (dd, 1 H, J = 13.7 and 7.1 Hz), 2.35 (dd, 1 H, J found M^+ 13.7 and 7.1 Hz), 2.68–2.76 (m, 1 H), 2.98 (s, 1 H), 4.12 (d, 1 H, J = 9.5 Hz), 4.25 (d, 1 H, J = 9.5 Hz), 5.16 (dd, 1 H, J = 13.0 and 1.4 Hz), 5.20 (d, 1 H, J = 8.5 Hz), 5.73–5.81 (m, 1 H), 7.20–7.51 (m, 5 H); 67.8-MHz ^{13}C NMR ($CDCl_3$) INEPT δ 13.50 (CH_3), 16.79 (CH_3), 29.66 (CH_2), 44.75 (CH_2), 45.04 (CH), 48.29 (C), 51.39 (C), 63.42 (CH), 79.28 (CH_2), 120.02 (CH), 126.08 (CH), 126.33 (CH), 128.40 (CH), 132.69 (CH), 146.34 (C), 176.90 (C); HRMS (m/z) calcd for $C_{18}H_{22}O$ M^+ 270.1619, found M^+ 270.1619.

Supplementary Material Available: IR, ^1H NMR, ^{13}C NMR, and high-resolution mass spectral data for compounds **1–4**, **8–12**, **16**, and **17**; NOESY spectrum of **13**; and ^1H NMR and ^{13}C NMR spectra for compounds **1–16** and **18–20** (62 pages). Ordering information is given on any current masthead page.

A Systematic Study of Benzyl Cation Initiated Cyclization Reactions

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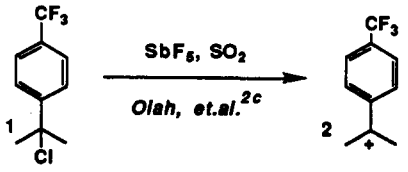
A systematic investigation of benzyl cation initiated cyclization reactions to form six-membered carbocycles is presented. The generation of benzyl cations from benzylic bromides, ethers, and alcohols followed by intramolecular capture provided good yields of cyclized products by use of several different cyclization terminators (e.g., phenyl, alkene, β-keto ester). A study on the effect of changing the electronic nature of substituents para to the benzyl cation showed that even electron-withdrawing substituents such as quaternary ammonium afford high yields of cyclization products. The formation of five- and seven-membered carbocycles was briefly investigated and found to be less general than the formation of the corresponding six-membered carbocycles.

Introduction

The stability of benzyl cations is well-documented and has been the subject of considerable theoretical and experimental study.[1,2] Olah and co-workers have studied these intermediates in super acid media using a variety of spectroscopic techniques and found that even benzyl carbenium ions with electron-withdrawing substituents on the phenyl ring, such as p-trifluoromethyl cation **2**, can be formed (eq 1).[2] The ready availability of benzyl cations has not resulted in their general use as synthesis intermediates, presumably due to the stringent conditions required to generate them.



(1)

The major role of aromatic rings in cyclization has been that of a terminator (internal nucleophile).[3] The use of an aromatic ring to initiate a cyclization has received less attention, but has been utilized in synthesis.[4-8] For ex-

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(5) For current examples and leading references for cyclization reactions with the generation of benzyl cations via loss of a benzylic leaving group, see: (a) Ziegler, F. E.; Schwartz, J. A. *J. Org. Chem.* **1978**, *43*, 985. (b) Kuhn, von M.; von Wartburg, A. *Helv. Chim. Acta*, **1967**, *50*, 1546. (c) Brown, E.; Loriot, M.; Robin, J.-P. *Tetrahedron Lett.* **1979**, *20*, 1389. (d) Ganeshpure, P. A.; Stevenson, R. *J. Chem. Soc., Perkin Trans. 1* **1981**, 1681. (e) Bradley, J. P.; Jarvis, T. C.; Johnson, C. D.; McDonnell, P. D.; Weatherstone, T. A. P. *Tetrahedron Lett.* **1983**, *24*, 2851. (f) Berney, D.; Schuh, K. *Helv. Chim. Acta* **1980**, *63*, 1785. (g) Nichols, D. E.; Boyles, D. A. *J. Org. Chem.* **1988**, *53*, 5128. (h) Lednicer, D.; Emmert, D. E.; Duncan, G. W.; Lyster, S. C. *J. Med. Chem.* **1967**, *10*, 1051. (i) Lednicer, D.; Emmert, D. E.; Lyster, S. C.; Duncan, G. W. *J. Med. Chem.* **1969**, *12*, 881. (j) Boissin, P.; Dhal, R.; Brown, E. *Tetrahedron Lett.* **1989**, *30*, 4371. (k) Ipaktschi, J.; Lauterbach, G. *Angew. Chem., Intl. Ed. Engl.* **1986**, *25*, 354. (l) Marcuzzi, F.; Melloni, G.; Modena, G. *J. Org. Chem.* **1979**, *44*, 3022. (m) Marcuzzi, F.; Melloni, G. *J. Chem. Res., Synop.* **1979**, 184. (n) Marcuzzi, F.; Melloni, G. *Tetrahedron Lett.* **1975**, *16*, 2771. (o) Mayr, H.; Bäuml, E. *Tetrahedron Lett.* **1984**, *25*, 1127. (p) Mayr, H.; Pock, R. *Chem. Ber.* **1986**, *119*, 2473. (q) Murphy, W. S.; Wattanasin, S. *J. Chem. Soc., Perkin Trans. 1* **1980**, 1567. (r) Murphy, W. S.; Wattanasin, S. *Tetrahedron Lett.* **1980**, *21*, 1887. (s) Murphy, W. S.; Wattanasin, S. *J. Chem. Soc., Perkin Trans. 1* **1981**, 2920. (t) Murphy, W. S.; Wattanasin, S. *J. Chem. Soc., Perkin Trans. 1* **1982**, 271.

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