allowed to warm to room temperature. The mixture was diluted with ether (20 mL), and the organic phase was washed with water (10 mL) and saturated brine (10 mL). The organic phase was dried ($MgSO_4$), filtered, and concentrated to dryness in vacuo. The product could be further purified, if desired, by crystallization or by passage through a short pad of silica gel eluting with hexane–ethyl acetate, 5:1.

NMR Reaction of Methyllanthanum Triflate with *N,N*-Diisopropylbenzamide. A 5-mm NMR tube, sealed to a glass tube equipped with a male 14/20 joint and a stopcock inlet, was charged with 29.3 mg (0.05 mmol) of $La(OTf)_3$. The apparatus was connected to vacuum transfer manifold also connected to a Schlenk tube containing previously dried and degassed THF-d_8. A 1.0 M solution of methyllithium (prepared by reaction of *n*-butyllithium with methyl iodide in hexane followed by filtration) in THF-d_8 and a 1.0 M solution of *N,N*-diisopropylbenzamide in THF-d_8 were also separately prepared. Approximately 0.4 mL of THF-d_8 was considered onto the $La(OTf)_3$ in the NMR tube under vacuum. After refilling the apparatus with nitrogen, 50 μL of the methyllithium solution was added via syringe through the stopcock inlet to the suspension of $La(OTf)_3$ at −78 °C. The suspension was degassed by three, freeze–pump–thaw cycles, the contents of the NMR tube being mixed by warming the base of the tube during the thawing process. The apparatus was refilled with nitrogen, and 100 μL of the amide solution was added in the NMR tube at −78 °C through the stopcock. The solution was then frozen in liquid nitrogen, the apparatus was evacuated, and the NMR tube was sealed off. The tube was then quickly transferred to a NMR probe, previously equilibrated at 220 K. ^1H NMR spectra were recorded at the following temperatures: 220, 240, 260, 280, and 298 K.

Acknowledgment. We would like to thank the Natural Sciences and Engineering Research Council for generous financial support of this work.

Registry No. 1, 52093-26-2; 3 (R′ = $PhCH_2$, R″ = $PhCH_2$), 102459-18-7; 3 (R′ = Ph, R″ = OMe), 126328-28-7; 3 (R′ = (*E*)-CH_3CH = CH, R″ = OMe), 126328-29-8; 3 (R′ = Ph, R″ = Cl), 22180-78-5; 3 (R′ = Ph, R″ = Et), 1696-17-9; 3 (R′ = *m*-MePh, R″ = Et), 134-62-3; 3 (R′ = *p*-MePh, R″ = Et), 2728-05-4; 3 (R′ = *m*-ClPh, R″ = Et, 15952-65-5; 3 (R′ = *m*-MeOPh, R″ = Et), 62924-93-0; 3 (R′ = *o*-MeOPh, R″ = Et), 51674-10-3; 3 (R′ = Ph, R″ = *i*-Pr), 20383-28-2; 3 (R′ = *p*-$MeOPhCH_2$, R″ = Et), 115348-15-7; 3 (R′ = 3-pentyl, R″ = Et), 79868-38-5; 3 (R′ = 3-pyridyl, R″ = Et), 59-26-7; 3 (R′ = 4-pyridyl, R″ = Et), 530-40-5; 3 (R′ = 2-thienyl, R″ = Et), 14313-93-0; 3 (R′ = 3-thienyl, R″ = Et), 73540-75-7; 3 (R′ = 2-furyl, R″ = Et), 32488-17-8; 3 (R′ = 3-furyl, R″ = Et), 73540-76-8; 4 (R = Me, R′ = $PhCH_2$), 103-79-7; 4 (R = Me, R′ = (*E*)-CH_3CH = CH), 3102-33-8; 4 (R = Me, R′ = Ph), 98-86-2; 4 (R = Ph, R′ = Ph), 119-61-9; 4 (R = Bu, R′ = Ph), 1009-14-9; 4 (R = Me, R′ = *m*-MePh), 585-74-0; 4 (R = Me, R′ = *p*-MePh), 122-00-9; 4 (R = Me, R′ = *m*-ClPh), 99-02-5; 4 (R = Me, R′ = *m*-MeOPh), 586-37-8; 4 (R = Me, R′ = *o*-MeOPh), 579-74-8; 4 (R = Me, R′ = *p*-$MeOPhCH_2$), 122-84-9; 4 (R = Ph, R′ = 3-pentyl), 5682-46-2; 4 (R = Me, R′ = 3-pyridyl), 350-03-8; 4 (R = Me, R′ = 4-pyridyl), 1122-54-9; 4 (R = Me, R′ = 2-thienyl), 88-15-3; 4 (R = Me, R′ = 3-thienyl), 1468-83-3; 4 (R = Me, R′ = 2-furyl), 1192-62-7; 4 (R = Me, R′ = 3-furyl), 14313-09-8; 5, 126375-09-5; MeLi, 917-54-4; PhLi, 591-51-5; BuLi, 109-72-8; MeC(Ph)(OH)Me, 617-94-7; $MeOC_6H_4$-*p*-$CH_2C(Me)_2OH$, 35144-39-9; $Et_2CHC(Ph)_2OH$, 126328-30-1; $MeOC_6H_4$-*p*-$CH_2C(O)Cl$, 4693-91-8; $MeOC_6H_4$-*p*-CH_2CO_2H, 104-01-8.

Synthetic Studies toward the Novel Tetracyclic Diterpene Longipenol: Construction of the ABD Tricarbocyclic Framework

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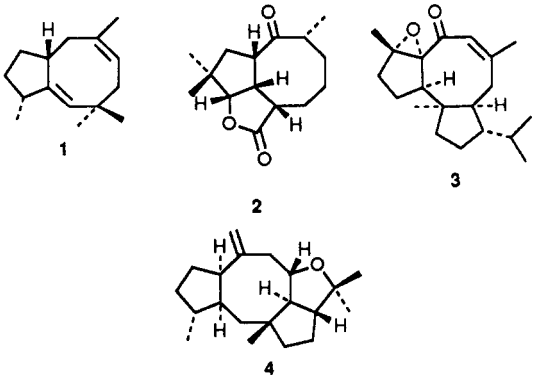
An approach (AB → ABD → ABCD) for the synthesis of tetracyclic diterpene longipenol **5** of insect origin has been conceived employing a 5-5-5 → 5-8 strategy for the construction of the highly functionalized bicyclo[6.3.0]undecanedione derivatives **18** and **19** from the readily available triquinane precursor **12**. An intramolecular Mukaiyama reaction (**22** → **23**) has been successfully effected to generate the tricyclic ABD ring system **23**.

In the past few years, several C_{15}-sesqui-, C_{20}-di-, and C_{25}-sesterterpene natural products embodying an eight-membered ring have been isolated and characterized from terrestrial plants, marine organisms, phytopathogenic fungi, and insects.[1,2] Among the more interesting carbocyclic variations present in them are the uncommon 5-8 and 5-8-5 fused ring systems represented here by precapnelladiene **1**,[3] asteriscanolide **2**,[2c] basmenone **3**,[2h] and epoxydictymene **4**.[2f] In view of the structural novelty of these cyclooctanoid terpenes, considerable synthetic activity has been witnessed in this area in the recent past.[4,5]



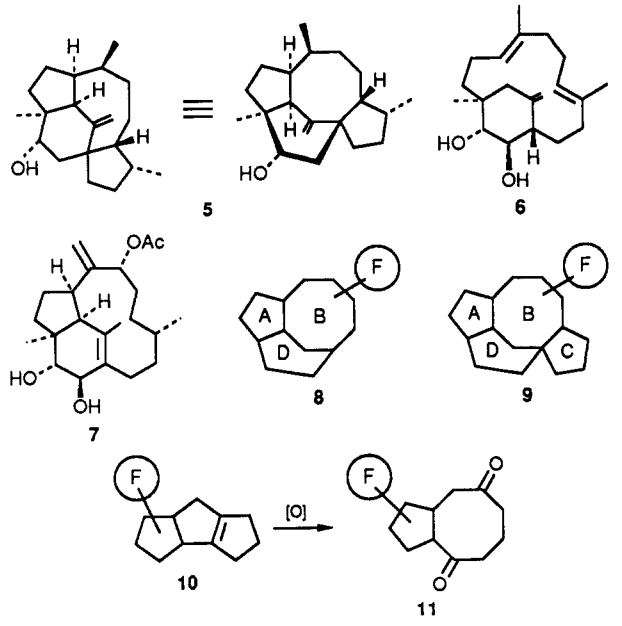
(1) (a) Devon, T. K.; Scott, A. I. *Handbook of Naturally Occuring compounds*; Academic Press: New York, 1972; Vol. II. (b) Glasby, J. S. *Enclyclopaedia of the Terpenoids*; Wiley-Interscience: New York, 1982.

(2) Some of the recently isolated cyclooctanoid natural products are (a) Crenulide: Midland S. L.; Wing, R. W.; Sims, J. J. *J. Org. Chem.* **1983**, *48*, 1906. (b) *Pachylactone*: Ishitsuka, M.; Kusumi, T.; Kakisawa, H.; Kawakami, Y.; Nagai, Y.; Sato, T. *Tetrahedron Lett.* **1983**, *24*, 5117. (c) Asteris Canolide: San Feliciano, A.; Barrero, A. F.; Medarde, M.; Miguel del Corral, J. M.; Arumbinu, A. *Ibid.* **1985**, *26*, 2369. (d) Neolamnanyl acetate: Izac, R. R.; Fenical, W.; Tagle, B.; Clardy, J. *Tetrahedron* **1981**, *37*, 2569. (e) Roseadione: Adesomoju, A. A.; Okogun, J. I.; Cava, M. P.; Carroll, P. J. *Phytochemistry* **1983**, *22*, 2535. (f) Epoxydictymene: Enoki, N.; Fusysaki, A.; Suchiro, K.; Ishida, R.; Matsumoto, T. *Tetrahedron Lett.* **1983**, *24*, 4341. (g) Anadensin: Huneck, S.; Baxter, G.; Cameron, A. F.; Connolly, J. D.; Rycroft, D. S. *Ibid.* **1983**, *24*, 3787. (h) Basmenone: Wahlberg, I.; Exlund, A. M.; Nishid, J.; Enzell, C. R.; Berg, J. E. *Ibid.* **1983**, *24*, 843. (i) Longipenol: Prestwitch, G. D.; Tempesta, M. S.; Turner, C. *Ibid.* **1984**, *25*, 1531. (j) Cystoseirol: Francisco, A. C.; Banaigs, B.; Codimier, L.; Cave, A. *Ibid.* **1985**, *26*, 4919.

(3) Ayanoglu, E.; Gebreyesus, T.; Beechan, C. M.; Djerassi, C. *Tetrahedron* **1979**, *35*, 1035.

0022-3263/90/1955-3568$02.50/0

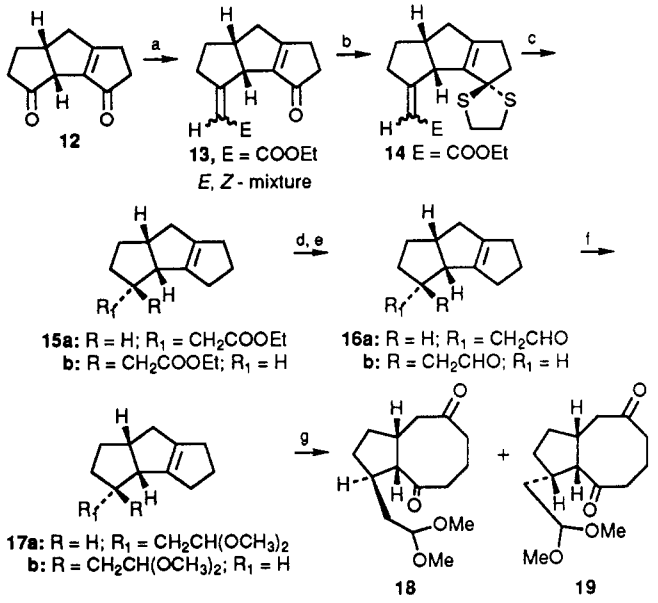
In 1984, Prestwich, Tempesta, and Turner[2i] reported the isolation of a novel tetracyclic diterpene longipenol **5** from the termite soldier *Longipeditermes longipes* from the Malaysian rain forests. Longipenol **5** cooccurs with related diterpenes **6** and **7** having the secotrinervitane and trinervitane skeleton, respectively, from which it is biogenetically derived. The tetracarbocyclic cagelike structure of **5** appealed to us as an attractive and challenging synthetic target, particularly because it incorporates 5-8-5 fused structural moiety. No synthetic efforts toward **5** have so far appeared in literature. To begin with, we essentially embarked on an exercise in carbocyclic ring construction and aimed at the generation of the functionalized ABD ring system **8** to which the ring C could be appended to give the ABCD framework **9**. Our efforts toward the successful construction of the functionalized derivative of **8** are described in this report.



Recognition of the presence of a 5-8 fused moiety in **8** and **9** led to the identification of 5-5-5 → 5-8 strategy (**10** → **11**),[4,5] in which bicyclo[3.3.0]oct-1(5)-ene functions as a masked cyclooctane-1,5-dione equivalent for the construction of the bicyclic AB portion. Suitably positioned functionality on the 5-5-5 precursor and the carbonyl functionalities in the resulting eight-membered ring (e.g. **11**) were expected to provide the necessary handle for appending the rings C and D to complete the tri- and tetracarbocyclic frameworks **8** and **9**.

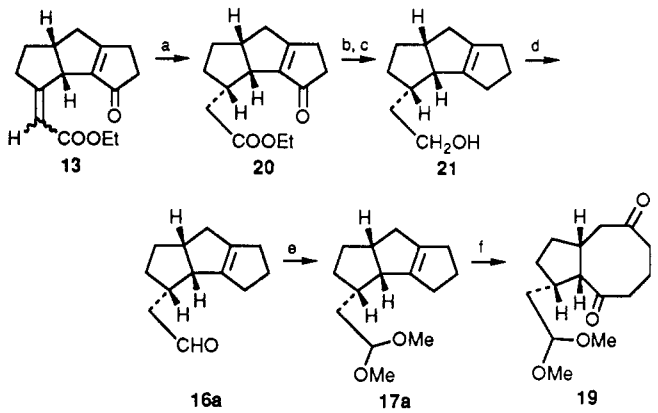
Enroute to **8**, the readily available triquinane based enedione **12**[6] was chosen as the starting material. Chemoselective Wadsworth–Emmons modification of the Wittig reaction on **12**, using triethylphosphonoacetate, furnished the unsaturated ester **13**, as a 1:5 mixture of *E*, *Z* isomers in 75% yield. Although the *E*, *Z* mixtue could be resolved for characterization purposes (vide Experimental), in practice it was not essential to separate them, and the mixture was carried on to the next step. Thioacetalization of **13** with ethanedithiol yielded **14**, which on Na–liquid NH_3 reduction[8] delivered a 1:4 distereomeric mixture of olefinic esters **15a** and **15b**, respectively, in 55% yield. The esters **15a** and **15b** defied separation, and, therefore, it was not possible to make stereochemical assignments to them. However, the major product during the Na–liquid NH_3 reduction of the α,β-unsaturated ester moiety in **14** was expected to be the thermodynamically more stable exo isomer **15b**. This was firmly established through chemical correlation described later in the sequel.

Scheme I[a]



[a] Reagents and yields: (a) $(EtO)_2P(O)CH_2COOEt$, NaH, THF, 75%; (b) ethanedithiol, PTS, benzene, 80%; (c) Na–liquid NH_3, ether, 55%; (d) LAH, ether, 90%; (e) PCC, molecular sieves, 4 Å, dichloromethane, 70%; (f) MeOH, PPTS, trimethylorthoformate, 80%; (g) RuO_2–$NaIO_4$, CCl_4–CH_3CN–H_2O, 70%.

Scheme II[a]



[a] Reagents and yields: (a) H_2–Lindlar's catalyst, ethyl acetate, 30%; (b) ethanedithiol, PTS, benzene, 75%; (c) Na–liquid NH_3, ether, 60%; (d) PCC, molecular sieves, 4 Å, dichloromethane, 80%; (e) MeOH, PPTS, trimethylorthoformate, 70%; (f) RuO_2–$NaIO_4$, CCl_4–CH_3CN–H_2O, 75%.

(4) For a compilation of earlier synthetic work on 5-8 and 5-8-5 fused systems, see ref 5. Some of the recent accomplishments in the area are (a) Feldman, K. S.; Come, J. H.; Freyer, A. J.; Kosminder, B. J.; Smith, C. M. *J. Am. Chem. Soc.* **1986**, *108*, 1327. (b) Wender, P. A.; Ihle, N. C. *Ibid.* **1986**, *108*, 4678. (c) Mehta, G.; Krishnamurthy, N. *J. Chem. Soc., Chem. Commun.* **1986**, 1319. (d) Kato, N.; Nakanishi, N.; Takeshita, H. *Bull. Chem. Soc. Jpn.* **1986**, *59*, 1109. (e) Wender, P. A.; Correia, C. R. D. *J. Am. Chem. Soc.* **1987**, *109*, 2523. (f) Rigby, J. H.; Senanayake, C. *J. org. Chem.* **1987**, *52*, 4635. (g) Paquette, L. A.; Ham, W. H. *J. Am. Chem. Soc.* **1987**, *109*, 3025. (h) Wender, P. A.; Ihle, N. C.; Correia, C. R. D. *J. Am. Chem. Soc.* **1988**, *110*, 5904. (i) Feldman, K. S.; Come, J. H.; Kosminder, B. J.; Smith, P. M.; Potella, D. P.; Wu, M.-J. *J. Org. Chem.* **1989**, *54*, 592.

(5) Mehta, G.; Murthy, A. N. *J. Org. Chem.* **1987**, *52*, 2875.

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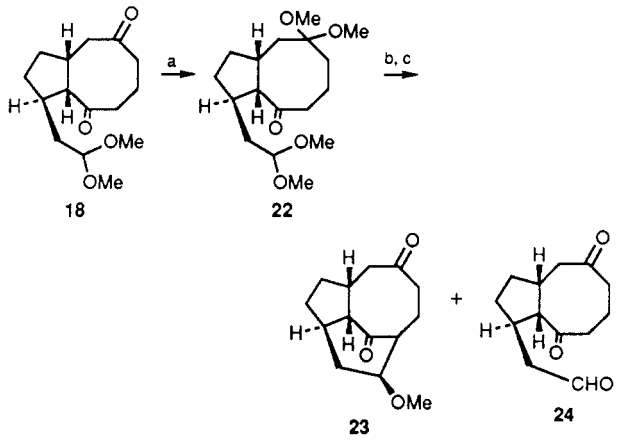
(8) Ireland, R. E.; Wrigley, T. I.; Young, W. *J. Am. Chem. Soc.* **1958**, *80*, 4604.

Scheme III[a]



[a] Reagents and yields: (a) MeOH, PPTS, trimethylorthoformate, 75%; (b) $(Me_3Si)_2NH$, *n*-BuLi, THF, TMSCl; (c) $TiCl_4$, dichloromethane, 35% for **23**, 47% for **24**.

Esters **15a,b** were converted to aldehydes **16a,b** via LAH reduction and PCC oxidation, Scheme I. The sensitive aldehyde functionality in **16a,b** was protected through conversion to dimethyl acetals **17a,b**. Catalytic RuO_2 oxidation of **17a,b** employing Sharpless reaction conditions[9] furnished a readily separable mixture of **18** and **19** (4:1), in 70% yield. The ^1H and ^{13}C NMR spectral data of **18** and **19**, summarized in the Experimental Section, were in full agreement with the assigned structures. Their stereochemistry was confirmed through an unambiguous synthesis of **19** as shown in Scheme II. Controlled catalytic hydrogenation of the ester **13** using Lindlar's catalyst gave the endo ester **20** in low yield along with other reduction products. The α,β-unsaturated ester moiety in **13** was expected to undergo hydrogenation preferably from the convex face to deliver the endo product **20**.[5,10] The ester **20** was further transformed to the endo bicyclic dione derivative **19** through the reaction sequence shown in Scheme II.

With the availability of **18** and **19** of established stereochemistry, an attempt was made to set up an intramolecular Mukaiyama reaction[11] for the construction of the ring D. First, attempt was made on the more abundant isomer **18**. In order to effect the C–C bond formation through C_3, the C_6-carbonyl group of **18** was protected as dimethyl acetal using PPTS in benzene, and **22** was readily obtained. The trimethylsilyl enol ether derived from **22**, on treatment with $TiCl_4$, furnished the tricyclic compound **23** in 35% yield along with some acetal hydrolyzed product **24**, Scheme III. The structure of the tricyclic compound **23** was revealed from its ^1H NMR resonances at δ 3.26 (3 H, s) and 3.68 (1 H, t, J = 8 Hz) due to OCH_3 and CHO-CH_3 protons, respectively, and ^{13}C NMR signals at δ 215.9, 214.8, and 81.9. With access to the tricyclic dione **23**, our initial objective of constructing the basic ABD framework was accomplished.

Experimental Section

For a general write up, see ref 12.

(2β,6β)-3-(Carbethoxymethylene)tricyclo[6.3.0.0^{2,6}]undec-1(8)-en-11-one (13). Into a 100-mL three-necked round-bottom flask fitted with dry nitrogen gas inlet, reflux condensor, pressure-equalized addition funnel, and mercury seal was taken NaH (1.50 g, 31 mmol, 50% oil dispersion), and dry THF (25 mL) was introduced. To this stirred suspension was slowly added triethyl phosphonoacetate (8 mL, 40 mmol)[6] in dry THF (20 mL). After 20 min, the enedione **12** (4.6 g, 26.1 mmol) in dry THF (20 mL) was added at once, and stirring was continued for 1 h. The reaction mixture was worked up after addition of water to the reaction mixture. The organic layer was separated, and the aqueous layer was extracted with ether (3 × 20 mL). The combined organic layers were washed with water and brine and dried over Na_2SO_4. The crude product obtained after removal of the solvent was charged on a silica gel (20 g) column. Elution with petroleum ether removed the oil impurities. Further elution with 40% ethyl acetate–petroleum ether furnished the minor isomer (800 mg, 12.5%): UV λ_{max}^{MeOH} 206 (ϵ 14470); IR (neat) ν_{max} 3050, 2950, 1710 (ester carbonyl), 1690 (enone carbonyl), 1650 (olefinic), 1200, and 1030 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 1.30 (3 H, t, J = 8 Hz, $COOCH_2CH_3$), 1.4–3.0 (10 H, m), 3.0–3.3 (1 H, m), 3.6–3.8 (1 H, m), 4.1 (2 H, q, J = 8 Hz, $COOCH_2CH_3$), and 6.2 (1 H, d, J = 2 Hz, C=C*H*COOEt); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 202.4, 185.6, 166.7, 164.9, 147.1, 114.4, 59.3, 50.5, 46.3, 40.8, 37.9, 32.6, 31.5, 25.4, and 14.1. Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.14; H, 7.37. Found: C, 72.93; H, 7.98. Continued elution with 50% ethyl acetate–petroleum ether yielded the major product (4.0 g, 62.5%): UV λ_{max}^{MeOH} 203 (ϵ 12260) and 225 (ϵ 15660); IR (neat) ν_{max} 3050, 2950, 1700 (carbonyl), 1660 (olefinic), 1630 (olefinic), 1440, 1220, and 1030 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 1.31 (3 H, t, J = 8 Hz, $COOCH_2CH_3$), 1.4–3.0 (10 H, m), 3.28 (1 H, t, J = 10 Hz), 4.23 (2 H, m, $COOCH_2CH_3$), 4.76 (1 H, br s, C_2-proton), and 5.81 (1 H, d, J = 2 Hz, C=C*H*COOEt). Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.14; H, 7.37. Found: C, 72.90; H, 6.99.

(2β,6β)-3-(Carbethoxymethylene)-11,11-(ethylenedithio)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene (14). A solution of the ester–enone **13** (2.0 g, 8.3 mmol), ethanedithiol (3 mL), and *p*-toluenesulfonic acid (50 mg) in dry benzene (60 mL) was refluxed with a Dean–Stark water separator for 20 min. The reaction mixture was diluted with benzene (20 mL), washed with $NaHCO_3$ solution and water, and dried. The crude residue obtained after removal of the solvent was charged on a silica gel column (20 g). Elution with 5% ethyl acetate–petroleum ether removed the ethanedithiol impurities. Further elution with 20% ethyl acetate–petroleum ether furnished the thioacetal **14** (2.1 g, 80%): UV λ_{max}^{MeOH} 209 (ϵ 19430); IR (neat) ν_{max} 2950, 1710 (carbonyl), 1660 (olefinic), 1200, and 1400 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 1.28 (3 H, t, J = 8 Hz, $COOCH_2CH_3$), 1.4–3.0 (11 H, m), 3.0–3.28 (4 H, m), 4.08 (2 H, q, J = 8 Hz, $COOCH_2CH_3$), 4.7 (1 H, br s, C_2-proton), and 5.7 (1 H, br s, C=C*H*COOEt).

(2β,6β)-3-(2-Carbethoxyethyl)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene (15a,b). Into a two-necked 500-mL round-bottom flask fitted with a guard tube was taken liquid NH_3 (200 mL). To this freshly cut sodium metal (2.4 g, 0.104 g-atom) was added piece by piece. The resulting blue solution was stirred for 5 min, and the thioacetal **18** (2.1 g, 6.2 mmol) in dry ether (50 mL) was slowly added to it. The reaction mixture was quenched with NH_4Cl solution after all ammonia had evaporated. The reaction mixture was diluted and extracted with ether (5 × 50 mL), washed, and dried. The crude material obtained after removing the solvent was loaded on a small silica gel (10 g) column. Elution with 20% ethyl acetate–petroleum ether gave a mixture of epimers **15a,b** at C_3-carbon (800 mg, 55%): IR (neat) ν_{max} 2950, 1720 (carbonyl), 1440, 1150, and 1020 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 1.0 (3 H, t, J = 8 Hz, $COOCH_2CH_3$), 1.4–2.6 (16 H, m), 2.6–3.2 (1 H, m), and 4.1 (2 H, q, J = 8 Hz, $COOCH_2CH_3$). Anal. Calcd for $C_{15}H_{22}O_2$: C, 76.88; H, 9.46. Found: C, 76.40; H, 9.52.

(2β,6β)-3-(2-Hydroxyethyl)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene (16a,b). Into a two-necked 100-mL round-bottom flask fitted with a rubber septum and mercury seal were introduced LAH (150 mg, excess) and dry ether (10 mL). To this suspension was slowly added epimeric ester mixture **15a,b** (1.0 g, 4.27 mmol) in dry ether (50 mL) through a syringe. The reaction mixture was stirred for 45 min. A few drops of ethyl acetate were added to destroy the excess hydride. The reaction mixture was diluted with water and extracted with ether (3 × 35 mL). The ethereal layer was washed and dried. Removal of solvent gave a mixture of hydroxy olefins (750 mg, 90%): IR (neat) ν_{max} 3300 (hydroxyl), 2950, 1460, 1065,

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(12) Mehta, G.; Rao, K. S. *J. Org. Chem.* **1985**, *50*, 5537.

and 1040 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.2–2.6 (16 H, m), 2.6–3.4 (2 H, m), and 3.64 (2 H, t, J = 6 Hz, CH_2CH_2OH). Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.48. Found: C, 80.93; H, 1040.

To a solution of pyridinium chlorochromate (750 mg) in dry dichloromethane (30 mL) containing activated molecular sieves (4 Å) was added the above mixture of hydroxy olefins (500 mg, 2.6 mmol). The reaction mixture was stirred for 25 min and diluted with ether (20 mL). Filtration through a small Florosil column and evaporation of solvent furnished the aldehydes **16a,b** (350 mg, 70%): IR (neat) ν_{max} 2950, 2775 (aldehyde), 1720 (carbonyl), 1450, and 1030 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.0–2.7 (16 H, m), 2.8–3.3 (1 H, m), and 9.77 (1 H, t, J = 2 Hz, C*H*O).

(2β,6β)-3-(Formylmethyl)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene Dimethyl Acetal (17a,b). A mixture of the aldehydes **16a,b** (500 mg, 2.63), trimethyl orthoformate (1 mL), and PPTS (150 mg) in dry methanol was refluxed for 1 h. Methanol was removed under reduced pressure. The crude material was dissolved in ether (30 mL), washed with water and brine, and then dried over Na_2SO_4. The crude material obtained after removal of the solvent was bulb-to-bulb distilled at 140 °C (0.5 mm) to furnish the dimethyl acetals **17a,b** (500 mg, 80%): IR (neat) ν_{max} 2950, 1450, 1130, and 1050 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.0–2.6 (16 H, m), 2.9–3.4 (1 H, m, C_2-proton), 3.2 (6 H, s, $CH(OCH_3)_2$), and 4.2–4.4 (1 H, m, $CH(OCH_3)_2$). Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.22; H, 10.24. Found: C, 76.03; H, 10.15.

(3aβ,9aβ)-1-(Formylmethyl)decahydro-5*H*,9*H*-cyclopentacyclooctane-5,9-dione 1-(Dimethyl acetal) (18 and 19). The dimethyl acetal mixture **17a,b** (1 g, 4.23 mmol) was dissolved in a mixture of carbon tetrachloride (2 mL), acetonitrile (2 mL), and water (3 mL). To this mixture were added sodium periodate (2 g) and ruthenium dioxide (10 mg). After being stirred for 10 min, the reaction mixture was washed with water and dried. The crude material obtained after removing the solvent was loaded on a silica gel column (20 g). Careful elution with 50% ethyl acetate–petroleum ether furnished the minor endo diketone **19** (150 mg, 13%): IR (neat) ν_{max} 2950, 1700 (carbonyl), 1460, 1130, 1060, and 920 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.4–2.5 (16 H, m), 3.12 (3 H, s, OCH_3), 3.18 (3 H, s, OCH_3), and 4.1 (1 H, t, J = 8 Hz, $CH(OCH_3)_2$); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 215.8, 213.9, 104.8, 54.1, 53.8, 52.5, 46.7, 45.4, 43.6, 43.1, 40.5, 33.8, 30.0, 25.6, and 22.7. Anal. Calcd for $C_{15}H_{24}O_4$: C, 67.13; H, 9.02. Found: C, 66.80; H, 8.97. Continued elution with the same solvent system furnished the major exo diketone **18** (650 mg, 57.5%): IR (neat) ν_{max} 2950, 1700 (carbonyl), 1450, 1130, and 1050 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.0–3.0 (16 H, m), 3.08 (3 H, s, OCH_3), 3.12 (3 H, s, OCH_3), 3.0–3.2 (1 H, m, C_1-proton), and 4.12 (1 H, t, J = 8 Hz, $CH(OCH_3)_2$); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 214.5, 213.5, 103.9, 59.3, 52.5, 52.4, 44.8, 43.8, 42.8, 40.7, 38.1, 36.8, 33.1, 31.6, and 22.6. Anal. Calcd for $C_{15}H_{24}O_4$: C, 67.13; H, 9.02. Found: C, 67.01; H, 9.00.

(2β,6β)-3-(Carbethoxymethylene)tricyclo[6.3.0.0^{2,6}]undec-1(8)-en-11-one (20). The ester–enone **13** (500 mg, 2.03 mmol) was hydrogenated over Lindlar's catalyst (20 mg) in ethyl acetate (10 mL). After the consumption of the starting material, the reaction mixture was filtered and the solvent was removed. The concentrate obtained after removal of the ethyl acetate was loaded on a silica gel column (10 g). Elution with 30% ethyl acetate–hexane removed all the perhydro compounds (350 mg). Further elution with 40% ethyl acetate–hexane furnished the required endo dihydro compound **20** (150 mg, 30%): IR (neat) ν_{max} 2950, 1730 (ester carbonyl), 1700 (enone carbonyl), 1640 (olefinic), 1460, 1400, 1180, and 1040 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.14 (3 H, t, J = 8 Hz, $COOCH_2CH_3$), 1.4–3.0 (14 H, m), 3.3 (1 H, br s, C_2-proton), and 4.1 (2 H, q, J = 8 Hz, $COOCH_2CH_3$); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 203.8, 189.0, 173.5, 147.9, 59.8, 47.0, 46.9, 40.8, 40.4, 39.9, 36.8, 33.8, 30.6, 25.5, and 14.1. Anal. Calcd for $C_{15}H_{20}O_3$: C, 72.55; H, 8.12. Found: C, 72.32; H, 8.02.

(2β,6β)-3-(2-Hydroxyethyl)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene (21). To a solution of endo ester–enone **39** (70 mg, 0.28 mmol) in benzene (10 mL) were added *p*-toluenesulfonic acid (5 mg) and ethanedithiol (0.3 mL), and the mixture was refluxed with a Dean–Stark water separator for 25 min. The reaction mixture was diluted with benzene (15 mL), washed with $NaHCO_3$ solution, and dried. The crude residue obtained after removal of the solvent was charged on a silica gel column (5 g). Elution with 10% ethyl acetate–hexane removed the ethanedithiol impurities. Further elution with 20% ethyl acetate–hexane furnished the thioacetal (70 mg, 75%): IR (neat) ν_{max} 2950, 1730 (ester carbonyl), 1420, 1160, and 1040 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.2 (3 H, t, J = 8 Hz, $COOCH_2CH_3$), 1.3–2.9 (14 H, m), 3.1 (1 H, br s, C_2-proton), 3.3 [4 H, d, J = 2 Hz, $S(CH_2)_2S$], and 4.1 (2 H, q, J = 8 Hz, $COOCH_2CH_3$); ^{13}C NMR (25 MHz, $CDCl_3$) δ 174.0, 151.9, 140.5, 71.3, 59.8, 49.3, 48.7, 40.4, 39.6, 38.5, 38.4, 35.7, 33.5, 30.9, 29.9, and 14.2. Into a two-necked 50-mL round-bottom flask fitted with a guard tube and stopper was taken liquid NH_3 (15 mL). To this freshly cut sodium metal (110 mg, 4.7 mg atom) was added piece by piece. The resulting blue solution was stirred for 5 min, and the thioacetal (70 mg, 0.21 mmol) in dry ether (5 mL) was slowly added to it. After evaporating the ammonia, the reaction mixture was quenched with NH_4Cl solution. The reaction mixture was diluted and extracted with ether (3 × 10 mL), washed, and dried. The crude material remaining after the removal of the solvent was loaded on a small silica gel column. Elution with 10% ethyl acetate–petroleum ether removed all sulfur impurities. Further elution with 20% ethyl acetate–petroleum ether furnished the hydroxy olefin **21** (25 mg, 60%): IR (neat) ν_{max} 3350 (hydroxyl), 1460, 1060, and 1030 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.0–2.6 (16 H, m), 2.6–3.4 (2 H, m), and 3.64 (2 H, t, J = 7 Hz, CH_2OH). Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.48. Found: C, 80.79; H, 9.98.

(2β,6β)-3β-(Formylmethyl)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene (16a). The hydroxy olefin **21** (25 mg, 0.13 mmol) in dichloromethane (5 mL) was added to a solution of pyridinium chlorochromate (35 mg) in dry dichloromethane (3 mL) containing activated molecular sieves (4 Å). The reaction mixture was stirred for 25 min and diluted with ether (5 mL). Filtration through a small Florosil column and evaporation of the solvent furnished the aldehyde **16a** (20 mg, 80%): IR (neat) ν_{max} 2950, 2475 (aldehyde), 1730 (carbonyl), 1450, and 1020 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 0.9–2.7 (16 H, m), 2.7–3.3 (1 H, m), and 9.77 (1 H, t, J = 2 Hz, C*H*O).

(2β,6β)-3β-(Formylmethyl)tricyclo[6.3.0.0^{2,6}]undec-1(8)-ene Dimethyl Acetal (17a). To a solution of the aldehyde **16a** (20 mg, 0.10 mmol) in dry methanol (5 mL) were added trimethyl orthoformate (0.2 mL) and PPTS (5 mg). The reaction mixture was refluxed for 1 h, and the methanol was removed under reduced pressure. The crude material was dissolved in ether (10 mL), washed with water and brine, and dried over Na_2SO_4. After evaporating the solvent, the concentrate was filtered through a small silica gel column to furnish dimethyl acetal **17a** (18 mg, 70%): IR (neat) ν_{max} 2950, 1460, and 1020 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.2–2.6 (16 H, m), 2.6–3.0 (1 H, m), 3.3 [6 H, s, $CH(OCH_3)_2$], and 4.4 (1 H, t, J = 7 Hz, $CH(OCH_3)_2$).

(3aβ,9aβ)-1β-(Formylmethyl)decahydro-5*H*,9*H*-cyclopentacyclooctane-5,9-dione 1-(Dimethyl acetal) (19). The olefinic acetal **17a** (18 mg, 0.076 mmol) was dissolved in a mixture of carbon tetrachloride (0.5 mL), acetonitrile (0.5 mL), and water (0.8 mL). To this mixture sodium periodate (80 mg) and ruthenium dioxide (2 mg) were added. After being stirred for 10 min the reaction mixture was diluted and extracted with dichloromethane (5 mL). The organic layer was washed with water and dried. The crude material obtained after removal of the solvent was passed through a small silica gel column, and the resulting diketo acetal **19** (12 mg, 75%) was found to be identical (IR, ^{1}H NMR) with the minor endo diketo acetal **19** obtained from the mixture of olefinic acetals **17a,b**.

(3aβ,9aβ)-1α-(Formylmethyl)decahydro-5,5-dimethyoxy-9*H*-cyclopentacyclooctan-9-one (22). The major exo diketo acetal **18** (250 mg, 0.932 mmol), trimethyl orthoformate (0.5 mL), and PPTS (80 mg) were refluxed in dry methanol (25 mL) for 1 h. Methanol was removed under reduced pressure, and the resulting crude material was dissolved in ether (50 mL). The ethereal layer washed with water and brine and dried over Na_2SO_4. The crude material obtained after removing the solvent was filtered through a small silica gel column to get bis-acetal **22** (220 mg, 75%): IR (neat) ν_{max} 2950, 1700 (carbonyl), 1460, 1130, and 1060 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.0–2.6 (17 H, m), 3.0 (3 H, s, OCH_3), 3.04 (3 H, s, OCH_3), 3.12 (3 H, s, OCH_3), 3.16 (3 H, s, OCH_3), and 4.1 [1 H, dd, J_1 = 8 Hz, $CH(OCH_3)_2$]; ^{13}C NMR (25 MHz, $CDCl_3$) δ 216.0, 104.4, 102.5, 58.7, 51.9, 47.5, 47.0, 40.4, 38.4, 38.1, 35.0, 34.8, 33.0, 31.9, and 18.3.

(1β,4α,12β)-2-Methoxytricyclo[5.4.2.0^{4,12}]tridecane-10,13-dione (23). Into a three-necked round-bottom flask fitted with dry nitrogen gas inlet, rubber septum, and mercury seal was introduced *n*-BuLi (0.15 mL) in hexane. It was cooled to −78 °C, and hexamethyldisilazane (0.1 mL) was added. The mixture was stirred for 20 min, and then THF (1 mL) was added to dissolve the solid material formed. After 10 min the bis-acetal **22** (30 mg, 0.095 mmol) in THF (2 mL) was slowly added, and the mixture was stirred for 20 min. Then freshly distilled trimethylsilyl chloride (0.1 mL) was added to quench the enolate. After 20 min $NaHCO_3$ solution was added to the reaction mixture, and it was extracted with ether (3 × 5 mL). The organic layer was washed and dried. The silyl enol ether obtained after removing the solvent was dissolved in dry dichloromethane (5 mL) and was taken into another three-necked round-bottom flask fitted with dry nitrogen set up. The reaction mixture was cooled to −78 °C, and $TiCl_4$ (0.1 mL) in dry dichloromethane (1 mL) was introduced. After being stirred for 30 min at −78 °C and for 1 h at 0 °C, the reaction mixture was quenched with $NaHCO_3$ solution. The organic layer was diluted and extracted with dichloromethane (3 × 5 mL). The crude material obtained after removing the solvent was charged on a small silica gel column. Careful elution with 60% ethyl acetate–petroleum ether furnished the cyclized diketone **23** (8 mg, 35.5%): IR (neat) ν_{max} 2950, 1700 (carbonyl), 1460, 1280, and 1100 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.0–2.9 (16 H, m), 3.26 (3 H, s, OCH_3), and 3.68 (1 H, t, J = 8 Hz, $CHOCH_3$); ^{13}C NMR spectrum (25.0 MHz, $CDCl_3$), δ 215.9, 214.8, 81.9, 58.6, 56.3, 54.4, 45.8, 43.2, 36.7, 35.9, 33.1, 29.6(2C) and 27.8. Anal. Calcd for $C_{14}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 71.42; H, 8.40.

Further elution with 70% ethyl acetate–petroleum ether yielded the diketo aldehyde **24** (10 mg, 47%): IR (neat) ν_{max} 2950, 2775 (aldehyde), 1700 (carbonyl), 1460, and 1280 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 1.8–3.6 (16 H, m), 3.6–3.9 (1 H, m), and 9.49 (1 H, d, J = 2 Hz, CHO); ^{13}C NMR (25.0, MHz, $CDCl_3$) δ 214.2, 213.1, 201.8, 58.7, 49.2, 44.7, 43.7, 42.7, 40.3, 34.1, 32.5, 30.5, and 22.8.

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Registry No. **5**, 90955-44-5; (±)-**12**, 126543-04-2; (±)-(*E*)-**13**, 126543-05-3; (±)-(*Z*)-**13**, 126543-14-4; (±)-**14**, 126543-06-4; (±)-**15a**, 126543-07-5; (±)-**15b**, 126640-54-8; (±)-**16a**, 126543-08-6; (±)-**16b**, 126640-55-9; (±)-**16b** (R = $(CH_2)_2OH$), 126640-53-7; (±)-**17a**, 126543-09-7; (±)-**17b**, 126640-56-0; (±)-**18**, 126543-10-0; (±)-**19**, 126640-57-1; (±)-**20**, 126543-11-1; (±)-**20** (ethylene dithioacetal), 126543-03-1; (±)-**21**, 126543-02-0; (±)-**22**, 126543-12-2; (±)-**22** (TMS enol ether), 126578-19-6; **23**, 126543-13-3; (±)-**24**, 126543-15-5; $HS(CH_2)_2SH$, 540-63-6.

Evidence for Ketene Intermediates in the Reactions of 2-Oxobutanedioic Acid Diesters with Alcohols and Water

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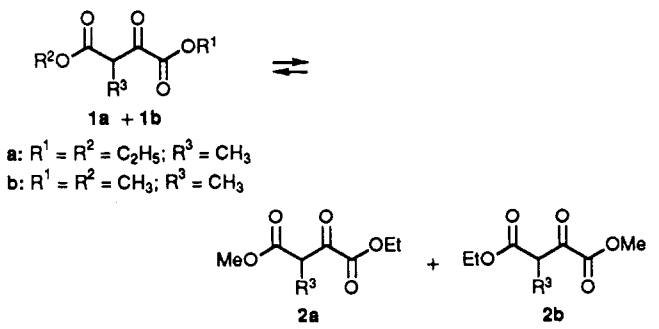
The reactions of the diethyl ester (**1a**) and dimethyl ester (**1b**) of 3-methyl-2-oxobutanedioic acid with excess ethanol, methanol, or water in a sealed tube at approximately 125 °C were studied. With methanol, **1a** yielded mainly 3-methyl-2-oxobutanedioic acid 1-ethyl 4-methyl diester, **2a**; with ethanol, **1b** yielded mainly the 4-ethyl 1-methyl diester, **2b**, while reaction of **1a** with water yielded carbon dioxide, 2-oxobutanoic acid ethyl ester, **6**, and 2-methyl-3-oxopropanoic acid ethyl ester, **7**. These results suggested that the ketene intermediates 3-methyl-2,4-dioxo-3-butenoic acid ethyl or methyl ester, **4a** and **4b**, respectively, are implicated. The similarity of these reactions to those exhibited by ethyl acetoacetate, such as alkoxy group exchange, and formation of dehydroacetic acid, now thought to proceed by way of acetylketene, was demonstrated.

The decarbonylation of α-oxobutanedioic acid diesters,[1] **1**, at temperatures on the order of 175 °C, has long been the subject of mechanism studies[2] and has synthetic utility.[3] It has been established that decarbonylation is a first-order reaction,[2,4] that an enolizable hydrogen on the β-carbon atom is required,[5] and that the carbon atom lost as carbon monoxide is the ester carbonyl adjacent to the α-keto group.[2]

More recently a lower temperature reaction was observed which leads to alkoxy group scrambling without loss of carbon monoxide. Mixtures of the diethyl and dimethyl esters of 3-methyl-2-oxobutanedioic acid, **1a** and **1b**, heated to 120 °C, were reported to yield the mixed diesters, **2a** and **2b**[6] (Scheme I). The results were attributed to cyclic intermediates such as those shown in Scheme II.

Scheme I



Not mentioned in that study[6] is the close resemblance of the alkoxy exchange reaction to ones occurring when ethyl acetoacetate or diethyl malonates and alcohols other

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