Preparation of Ions. The protonation of arenes in HF–SbF_5 (1:1), FSO_3H–SbF_5 (4:1), and FSO_3H–SbF_5 (1:1) was analogous to the methods already described.[8] For the reactions of isopropyl or *tert*-butyl cation with the substrates, the alkyl cation (2–3 equiv) was first generated from the halide precursor in SbF_5/SO_2ClF and was then added slowly to a cold slurry (–75 °C) of the aromatic compound (1 equiv) in SO_2ClF with efficient vortex mixing.

Nuclear Magnetic Resonance Spectra and GC Analyses. ^1H NMR spectra were obtained with a Varian Model A56/60A instrument equipped with a variable-temperature probe. ^{13}C NMR spectra were recorded on a Varian FT80 equipped with a low-temperature setup using external Me_4Si as reference or a Varian XL-200 instrument using acetone-d_6 as external lock and reference. GC analyses were performed on a Varian Model 3700 gas chromatograph with a 50-m capillary column (OV101) and an on-line automatic integrator.

Acknowledgment. Support of our work by the National Institutes of Health is gratefully acknowledged. We thank Professor Melvin Newman of the Ohio State University for samples of diethyl- and dineopentyltetramethylbenzene isomers[9] as well as Professor R. Grubbs and Dr. Ken Doxsee of Cal. Tech. for a sample of hexaisopropylbenzene.[10]

Registry No. 1, 33884-69-4; **1a**–H^+, 95346-05-7; **2**, 33781-72-5; **2a**–H^+, 95346-06-8; **3**, 33962-13-9; **3a**–H^+, 95346-07-9; **3b**–H^+, 95346-11-5; **4**, 6668-20-8; **4**–H^+, 95346-08-0; **5**, 33781-73-6; **5**–H^+, 95346-09-1; **6**, 33970-83-1; **6**–H^+, 95346-10-4; **7**, 95346-02-4; **8**, 95363-48-7; **9**, 95346-03-5; **10**, 95346-04-6; **11**, 29661-23-2; $GaCl_3$, 13450-90-3; isopropyl cation, 19252-53-0; *tert*-butyl cation, 14804-25-2; hexamethylbenzene, 87-85-4; hexaethylbenzene, 604-88-6; hexaisopropylbenzene, 800-12-4.

A Short Synthesis of *dl-epi*-Pyroangolensolide and *dl*-Pyroangolensolide: Confirmation of the Structures of Pyroangolensolide and Calodendrolide

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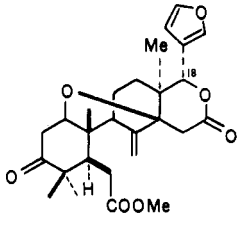
Pyroangolensolide, obtained from pyrolysis at 305 °C of methyl angolensate (**1**), has been assigned structure **2** on the basis of spectral data (IR, ^1H NMR, MS, UV, and CD).[2] The configuration about the carbon [C(18), limonoid numbering] bearing the α-oriented furan ring in structure **2** is based solely on a positive Cotton effect which is similar in profile and position to that of methyl angolensate. Pyroangolensolide has also been obtained by treatment of calodendrolide (**3**), a naturally occurring C_{15}-degraded limonoid,[4] with hydriodic acid. It should be pointed out that the structure assigned to calodendrolide is based on its conversion into pyroangolensolide. In view of the harsh conditions which were employed above for the formation of pyroangolensolide, and the fact that the configuration at C(18) in structure **2** rests solely in its optical rotatory dispersion curve, we set out to prepare both *dl*-pyroangolensolide and *dl-epi*-pyroangolensolide (cf. structure **4**). We detail below a short synthesis of racemic **2** and **4**, both crystalline, which, via single-crystal X-ray analysis, unambiguously established the structure of pyroangolensolide as **2** and confirmed the structural assignment put forth by Cassady and Lui for calodendrolide.



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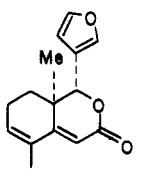

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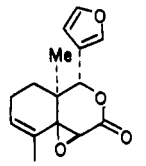

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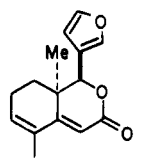
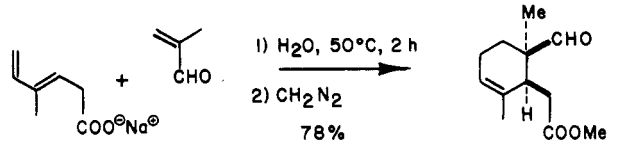


4

Tokoroyama and co-workers[8] have published an eight-step synthesis of *dl*-pyroangolensolide and *epi*-pyroangolensolide. Physical data, including a detailed ^1H NMR analysis of **2** and **4** are provided; however, in the absence of a single-crystal X-ray analysis of either **2** or **4**, the complete structural assignments for pyroangolensolide and *epi*-pyroangolensolide remain suspect.

Our synthesis of *dl*-pyroangolensolide and *dl-epi*-pyroangolensolide, which was carried out via a four-step sequence, features an aqueous Diels–Alder reaction.[9] Condensation of sodium 4-methyl-3(*E*),5-hexadienoate[10]



5

with methacrolein in water (50 °C, 2 h) afforded after esterification with ethereal diazomethane a 78% isolated yield of the endo Diels–Alder adduct **5**. Less than 5% of the exo adduct **6** could be detected by ^1H NMR analysis of the crude reaction product. Addition of 3-furyllithium in tetrahydrofuran–ether (3:4) to aldehyde **5** gave rise to a mixture of lactones **7** and **8** in a ratio of 4:1. In contrast, Tokoroyama and co-workers reported that addition of 3-furyllithium to **9** gives rise directly to a mixture of *dl*-pyroangolensolide and *dl-epi*-pyroangolensolide in a ratio of 7:3. Note, the structures of **7** and **8** follows from a single-crystal X-ray analysis of our synthetic *dl-epi*-pyroangolensolide (vide infra).

(1) On leave from the University of Natal, Pietermaritzburg, South Africa.

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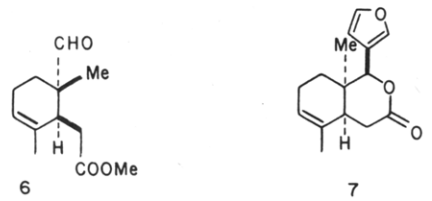

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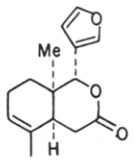

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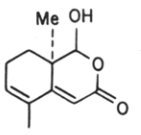

9

Subjection of lactone **7** to selenenylation[11] followed by oxidation and elimination of benzeneselenenic acid gave rise to crystalline *dl-epi*-pyroangolensolide, mp 136–137 °C (lit.[8] mp 138–140 °C), in 88% overall yield. Similar treatment of lactone **8** provide (90%) crystalline racemic pyroangolensolide, mp 135–136 °C (lit.[8] mp 145.0–145.5 °C).

The ^{1}H NMR spectra of **2** and **4** are very similar and do not allow one to make unambiguous structural assignments at C(18). This question was resolved by single-crystal X-ray analysis. Lactone **4**, mp 136–137 °C, crystallized in space group $P2_1/n$ with unit cell constants (−158 °C) of a = 8.289 (2) Å, b = 16.189 (5) Å, c = 9.204 (2) Å, β = 99.09 (1)°, and Z = 4. The structure was solved by direct methods using 1593 unique intensities collected at −158 °C. All atoms, including hydrogens, were located and refined to final residuals of R(F) = 0.0321 and R_W(F) = 0.0389. Figure 1 depicts the structure of lactone **4**. The X-ray data, along with the ^{1}H NMR spectrum of **4**, unambiguously establishes **4** as *epi*-pyroangolensolide. Furthermore, one can unequivocally state that pyroangolensolide and calodendrolide possess structures **2** and **3**, respectively.

Experimental Section

Melting points were determined on a Fisher-Johns hot-stage melting point apparatus and are uncorrected. Infrared spectra (IR) were determined on a Perkin-Elmer 298 grating infrared spectrometer, and nuclear magnetic resonance (NMR) spectra were recorded at 360 MHz (Nicolet NT-360). Chemical shifts are reported in parts per million (δ) relative to Me_4Si (δ = 0.00) as an internal standard. Element analyses were performed at the University of Natal, Pietermaritzburg, South Africa.

All solvents are reagent grade unless otherwise stated. "Dry" solvents were dried immediately before use. Tetrahydrofuran was distilled from sodium benzophenone ketyl. Thin-layer chromatography (TLC) was carried out on Analtech (Uniplate) glass plates precoated with silica gel GF (250 μm). Column chromatographic separations were performed on silica gel (Merck silica gel 60, 70–230 mesh ASTM).

Formation of Diels–Alder Adduct 5. To a suspension of 2.52 g (0.02 mol) of 4-methyl-3(*E*),5-hexadienoic acid in 10 mL of water was added 1.6 g (0.019 mol) of sodium bicarbonate. After 30 min, 280 mg (0.004 mol) of freshly distilled methacrolein was added to the homogeneous solution and the reaction was warmed to 50 °C and vigorously stirred for 2 h (a trace of hydroquinone was found to suppress polymerization of the methacrolein). The reaction was quenched by the addition of 10 mL of a 1.0 N solution of hydrochloric acid. The product was isolated by extraction with ether. The combined ether extracts were dried over anhydrous magnesium sulfate and concentrated in vacuo. The crude acid was treated with ethereal diazomethane. Workup provided 2.76 g of a residue which was purified on 130 g of silica gel. Elution with hexane/ether, 4:1, afforded 652 mg (78%) of ester **5** as a colorless oil: IR ($CHCl_3$) 1719, 1670 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.14 (s, 3 H, CH_3), 1.43 (dd, 1 H, J = 6.8 Hz, 13.3 Hz), 1.69 (d, 3 H, J = 1.5 Hz, olefinic methyl), 1.70 (m, 1 H), 2.05 (m, 2 H, allylic methylene), 2.31 (m, 2 H, CH_2COOCH_3), 2.55 (t, 1 H, J = 5.9 Hz, —CH), 3.66 (s, 3 H, $COOCH_3$), 5.40 (br s, 1 H, =CH), 9.55 (s, 1 H, CHO). Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.62. Found: C, 68.30; H, 8.69.

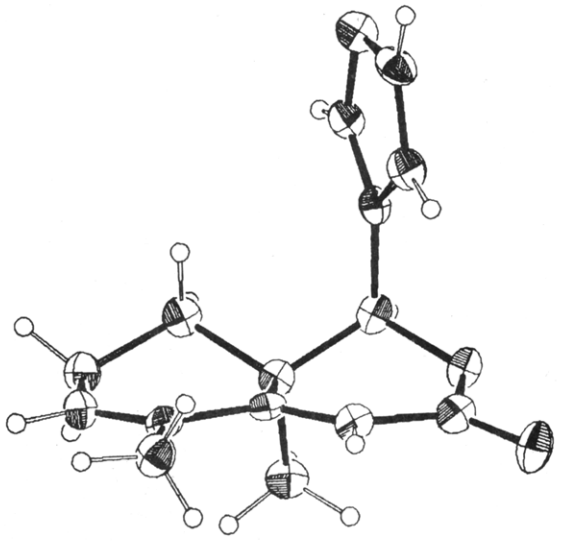

Figure 1. ORTEP view of *dl-epi*-pyroangolensolide.

***cis*-1β-(3-Furyl)-1,4,4a,7,8,8a-hexahydro-5,8aα-dimethyl-3*H*-2-benzopyran-3-one (7) and *cis*-1α-(3-Furyl)-1,4,4a,7,8,8a-hexahydro-5,8aα-dimethyl-3*H*-2-benzopyran-3-one (8).** A solution of 147 mg (1.0 mmol) of freshly distilled 3-bromofuran in 4.0 mL of dry ether cooled to −78 °C under argon was treated with 0.625 mL (1.0 mmol) of a 1.6 M solution of *n*-butyllithium in hexane. After 30 min at −78 °C, 210 mg (1.0 mmol) of Diels–Alder adduct **5** in 3.0 mL of tetrahydrofuran was added dropwise to the ethereal solution of furyllithium cooled to −85 °C. The reaction was quenched after 75 min by the addition of 5.0 mL of 1.0 N hydrochloric acid. The combined ether extracts were dried over anhydrous magnesium sulfate and were concentrated under reduced pressure, leaving 277 mg of a residue which was chromatographed on 70 g of silica gel. Elution with hexane/ether, 2:1, provided, in order of elution, 60 mg of starting material **5** (R_f 0.46, hexane/ether, 2:1), 30 mg (17%) of lactone **8** which readily crystallized as white needles from ethanol [mp 122 °C; R_f 0.24; IR ($CHCl_3$) 1735 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.86 (s, 3 H, CH_3), 1.42 (m, 1 H), 1.62 (m, 1 H), 1.72 (s, 3 H, olefinic methyl), 2.03 (m, 2 H, allylic CH_2), 2.39 (dd, 1 H, J = 11.2, 15.8 Hz), 2.85 (dd, 1 H, J = 5.4, 15.8 Hz), 5.04 (s, 1 H, —CHO), 5.58 (br s, 1 H, =CH), 6.43 (s, 1 H), 7.26 (br s, 1 H). Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.14; H, 7.36. Found: C, 73.15; H, 7.43.], and 125 mg (71%) of lactone **7** [mp 114 °C; R_f 0.18; IR ($CHCl_3$) 1722 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.88 (s, 3 H, CH_3), 1.32 (m, 1 H), 1.52 (m, 1 H), 1.69 (d, 3 H, J = 1.4 Hz, olefinic methyl), 1.9–2.1 (m, 2 H), 2.11 (m, 2 H), 2.50 (dd, 1 H, J = 6.5, 18.0 Hz), 2.97 (dd, 1 H, J = 10.0, 18.0 Hz), 5.11 (s, 1 H, —CHO), 5.41 (s, 1 H, =CH), 6.41 (s, 1 H), 7.41 (br s, 1 H), 7.45 (s, 1 H). Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.14; H, 7.36. Found: C, 73.43; H, 7.34.].

***dl-epi*-Pyroangolensolide (4).** To a solution of 0.40 mmol of lithium diisopropylamide (prepared from 55.9 μL of diisopropylamine and 250 μL of a 1.6 M solution of *n*-butyllithium in hexane) in dry tetrahydrofuran (1.0 mL) under argon was added at −78 °C 50 mg (0.20 mmol) of lactone **7** in 1.0 mL of tetrahydrofuran. After 45 min, 81 mg (0.41 mmol) of benzeneselenenyl chloride in 1.5 mL of tetrahydrofuran containing 69.5 μL of hexamethylphosphoramide was added dropwise at −78 °C. The reaction was quenched after 2.5 h with 5.0 mL of 1.0 N hydrochloric acid. The product was isolated by extraction with ether. The combined organic extracts were dried over anhydrous magnesium sulfate, filtered, and concentrated in vacuo. The crude product (129 mg) was chromatographed on 25 g of silica gel. Elution with hexane/ether, 2:1, provided 75 mg (92%) of a mixture of selenides, which were employed directly in the next reaction.

(11) Cf. Grieco, P. A.; Miyashita, M. *J. Org. Chem.* **1974**, *39*, 120.

The above mixture of selenides (55 mg) was dissolved in 1.0 mL of tetrahydrofuran, cooled to 0 °C, and treated with 20.4 μL of acetic acid and 96.2 μL of 30% hydrogen peroxide. After 40 min the reaction was quenched by the careful addition of aqueous sodium bicarbonate. The product was isolated by extraction with ether. The combined organic extracts were dried over anhydrous magnesium sulfate. The solvent was removed under reduced pressure. The crude product was filtered through 3.0 g of silica gel. Elution with ether gave 28 mg (84%) of pure *dl-epi*-pyroangolensolide (**4**): mp 136–137 °C; IR ($CHCl_3$) 1690 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.2–1.5 (m, 2 H, CH_2), 1.37 (s, 3 H, CH_3), 1.90 (d, 3 H, J = 0.7 Hz, olefinic CH_3), 2.2–2.4 (m, 2 H, allylic CH_2), 5.10 (s, 1 H, —CHO), 5.90 (s, 1 H), 6.12 (d, 1 H, J = 5.4 Hz), 6.26 (br s, 1 H), 7.32 (br s, 1 H), 7.38 (br s, 1 H). Anal. Calcd for $C_{15}H_{16}O_3$: C, 73.75; H, 6.60. Found: C, 74.10; H, 6.50.

***dl*-Pyroangolensolide (2).** To a solution of lithium diisopropylamide (0.24 mmol) in 1.0 mL of dry tetrahydrofuran (prepared from 33.5 μL of diisopropyl amine and 150 μL of a 1.6 M solution of *n*-butyllithium in hexane) cooled to −78 °C under argon was added 30 mg (0.12 mmol) of lactone **8** in 0.75 mL of tetrahydrofuran. After 40 min, 49 mg (0.26 mmol) of benzeneselenenyl chloride in 0.8 mL of tetrahydrofuran containing 41.7 μL of hexamethylphosphoramide was added at −78 °C. The reaction was quenched after 5 h with 5.0 mL of 1 N hydrochloric acid. The product was isolated by extraction with ether. Standard workup left 72 mg of a residue which was chromatographed on 22 g of silica gel. Elution with hexane/ether, 2:1, afforded 39 mg of a mixture of selenides which were used directly in the next reaction.

The above mixture of selenides (32 mg) was dissolved in 1.6 mL of tetrahydrofuran and was treated at 10 °C with 11.0 μL of acetic acid and 52.4 μL of 30% hydrogen peroxide. After 40 min, the temperature was raised to 20 °C. The reaction was quenched after 60 min with a saturated solution of sodium bicarbonate. The product was isolated by extraction with ether. The combined organic extracts were dried over anhydrous magnesium sulfate. The solvent was removed in vacuo. The residue was chromatographed on 10 g of silica gel. Elution with hexane/ether, 2:1, provided 20 mg of pure *dl*-pyroangolensolide: mp 135–136 °C; IR 1710 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.03 (s, 3 H, CH_3), 1.4–1.5 (m, 2 H, CH_2), 1.89 (d, 3 H, J = 1.4 Hz, olefinic CH_3), 2.26 (br s, 2 H, allylic CH_2), 5.12 (s, 1 H, —CHO), 5.84 (br s, 1 H), 6.14 (br t, 1 H, J = 3.97 Hz), 6.45 (br s, 1 H), 7.42 (br s, 1 H), 7.48 (br s, 1 H).

Acknowledgment. This investigation was supported by a Public Health Service Research Grant (GM 33605) from the National Institute of General Medical Sciences. We are indebted to Dr. Kiyoshi Yoshida for bringing this problem to our attention and numerous helpful discussions. We thank Miss S. Kohler for carrying out the C, H analyses and the C.S.I.R. for awarding a postdoctoral bursary to S. E. Drewes.

Registry No. *dl*-**2**, 52730-12-8; **3**, 35986-56-2; *dl*-**4**, 52730-11-7; *dl*-**5**, 95421-96-8; *dl*-**7**, 95421-99-1; *dl*-**8**, 95421-97-9; (*E*)-CH_2=$CHC(CH_3)$=$CHCH_2CO_2H$, 95421-98-0; methacrolein, 78-85-3; 3-bromofuran, 22037-28-1; 3-furyllithium, 53101-93-2.

Polystyryldiphenylphosphine as a Deoxygenation Reagent for Sulfoxides

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Sulfur-containing compounds have played an increasingly important role in organic synthesis due to the ease of incorporation of the element into complex structures, the ability to modify the valency of the atom, the variety of chemical characteristics exhibited by those varied oxidation states, and the ease of removal of sulfur as needed for the synthesis.[1] The interconversion of oxidation states is a crucial aspect of the successful use of sulfur in synthetic applications, and one transformation which has received extensive investigation has been the sulfoxide to sulfide reduction reaction.[2]

The use of trivalent phosphorus compounds for the sulfoxide–sulfide conversion has been recognized for some time and a comparison of reactivity of a variety of such compounds with Me_2SO is available.[3] More specifically, the use of triphenylphosphine as a reductant for Me_2SO was first recognized in 1962[4] and has been exploited in the reduction of a variety of sulfoxides since that time by using as coreactants CCl_4,[5] acids,[6] and I_2/NaI.[7] These methods all show good chemoselectivity and proceed under generally mild conditions. They do suffer, however, from some potential separation difficulties due to the requisite formation of triphenylphosphine oxide and to the use of any excess triphenylphosphine. To avoid these purification requirements, we chose to investigate the use of polystyryldiphenylphosphine as a reducing agent for sulfoxides.[8]

All three coreactants mentioned above were utilized in combination with the polymeric reagent. Dibenzyl sulfoxide (**6**) was reduced to the sulfide in 85% yield by using a catalytic amount of HCl combined with the polymeric reagent with a 6-h reflux in THF solvent. It was concluded that lengthy contact with acid would significantly effect the generality of the procedure and this method was pursued no further. The I_2/NaI combination with polystyryldiphenylphosphine gave effective reduction of sulfoxide **5** but did require larger excesses of phosphine (1.5 equiv) and longer reflux times (1.5 h) than those reported for the solution-phase reaction.[7] Acetonitrile is a very poor swelling solvent for a lightly cross-linked (2%) polystyrene bead, leaving a number of phosphine sites inaccessible for reaction. Use of the better swelling solvent THF gave poor reduction yields both in the solution phase and with the polymeric reagent, demonstrating the need for the polar acetonitrile solvent reported by Olah.[7] In addition to the solvent restrictions, the use of I_2/NaI does require additional purification steps since the excess reagents must be removed by aqueous washes. As described below, the selection of CCl_4 as the coreactant provides mild reaction conditions along with ease of workup and was the method chosen for the remainder of our work.

As can be observed in Table I, the procedure is successful in reducing diaryl, arylalkyl, and dialkyl sulfoxides to their corresponding sulfides in excellent yields with substrates possessing alkyl substituents affording slightly lower yields than their aryl counterparts. The process is compatible with a variety of functional groups, particularly

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