Stereospecific Synthesis of Secondary Allylic Alcohols: Selenoxide Chemistry

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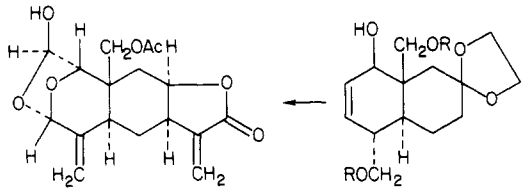
A stereospecific [2,3] sigmatropic rearrangement of secondary allylic selenoxides as a route to allylic alcohols having a defined stereochemistry is described. It has been demonstrated that secondary allylic alcohols react with aryl selenocyanates in the presence of tri-*n*-butylphosphine with inversion of configuration and that subsequent [2,3] sigmatropic rearrangement of the resulting selenoxides afforded stereospecifically generated allylic alcohol systems.

Several years ago Sharpless and Lauer[2] reported that allylic selenoxides undergo [2,3] sigmatropic rearrangements to afford allylic alcohols. In a steroid case, Salmond and co-workers[3] reported that the products derived from the 7α-and 7β-phenyl selenoxides of cholesteryl-3β-benzoate are dependent on the chirality[4] of the selenium in the selenoxide.

A facile one-step synthesis of alkyl aryl selenides by reaction of primary and secondary alcohols with (*o*-nitrophenyl) selenocyanate[5] in the presence of tri-*n*-butylphosphine has been reported by Grieco and co-workers.[6] Recently Krief and Servin[7] demonstrated that secondary alcohols react with (*o*-nitrophenyl) selenocyanate to give selenides with inversion of configuration. Clive and coworkers[8] have shown that primary allylic alcohols undergo effective contrathermodynamic isomerization when treated with aryl selenocyanate and tri-*n*-butylphosphine followed by oxidation with hydrogen peroxide.

In relation to the synthesis of *d,l*-micordilin (1),[9] a complex hemiacetal of a hydroxylated dialdehydic elemanolide, we were interested in utilizing a 1,3-transposition of a secondary allylic alcohol via an intermediate allylic selenoxide as a plausible route to the stereospecifically defined allylic alcohol system **2**. The recent report of Back



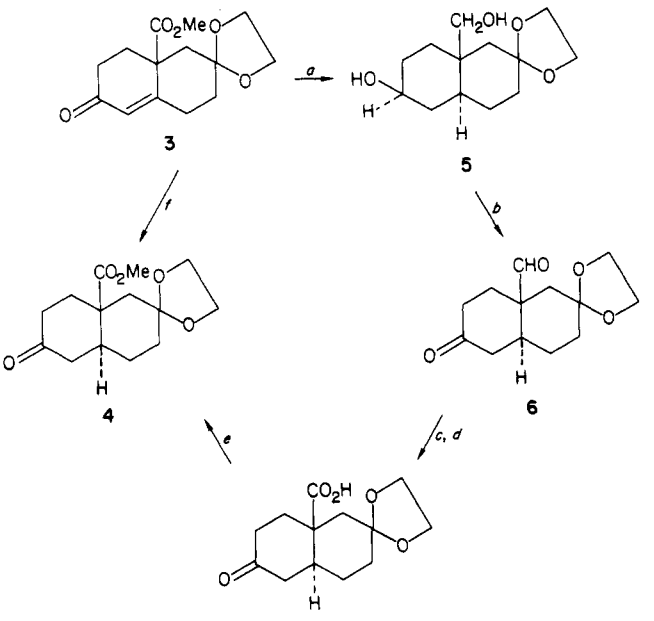
1 **2**

and McPhee[10] on the 1,3-transposition of a 3β-hydroxy-4-androstene derivative via an intermediate allylic selenoxide prompted us to communicate our results herein.

Synthesis of enone **9**, a precursor to **2**, was achieved as outlined below. Catalytic hydrogenation[11] of octalone **3**[12] gave *trans*-decalone **4** (87%). The stereochemistry depicted in **4** was verified by an alternate synthesis as shown in Scheme I. Reaction of the lithium enolate of **4** with trimethylsilyl chloride (Scheme II) afforded the silyl enol ether **10**. Subsequent oxidation of **10** with DDQ[13] gave enone **9** (36%). Alternatively **9** was obtained in a one-step transformation[14] in 40% yield by reaction of **4** with phenylselenenyl chloride in EtOAc followed by oxidation of the intermediate selenide **8** directly with H_2O_2 in the presence of pyridine.

Enone **9** is ideally suited for the construction of **2**, since the $\Delta^{1,2}$-double bond serves a dual function. First, the double bond acts as a blocking group to allow hydroxymethylation[15] at C-4, and secondly, this system provides

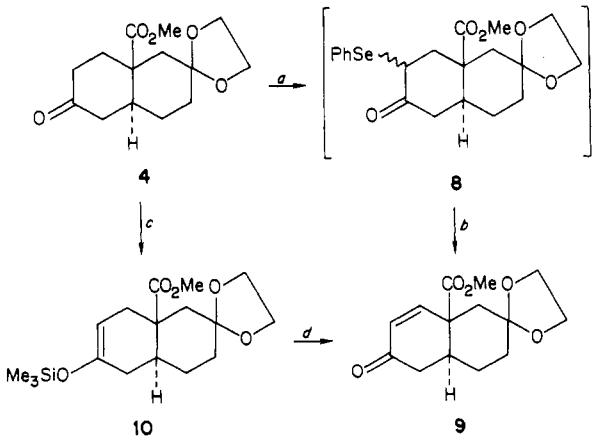
Scheme I



3 **5** **4** **6** **7**

[a] Li, NH_3, EtOH, −33 °C. [b] PDC, PTA, CH_2Cl_2, room temperature. [c] $AgNO_3$, KOH, aqueous EtOH. [d] 3.5% oxalic acid. [e] CH_2N_2, Et_2O-MeOH (5:1), 0 °C. [f] H_2, 5% Pd-C, EtOAc, room temperature.

Scheme II



4 **8** **10** **9**

[a] PhSeCl, EtOAc, room temperature. [b] 30% H_2O_2, py, CH_2Cl_2, Δ. [c] LDA, THF, −78 °C, then Me_3SiCl. [d] DDQ, PhH, 2,4,6-collidine, room temperature.

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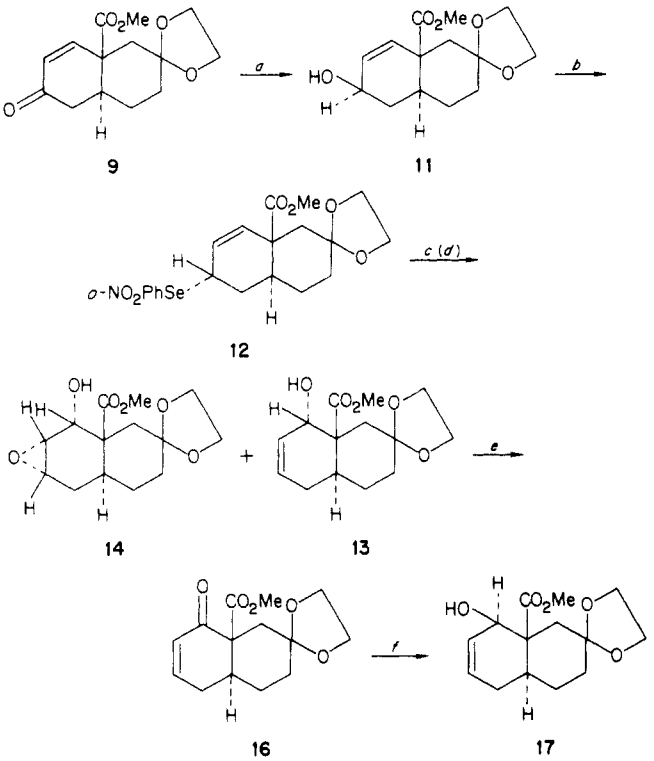
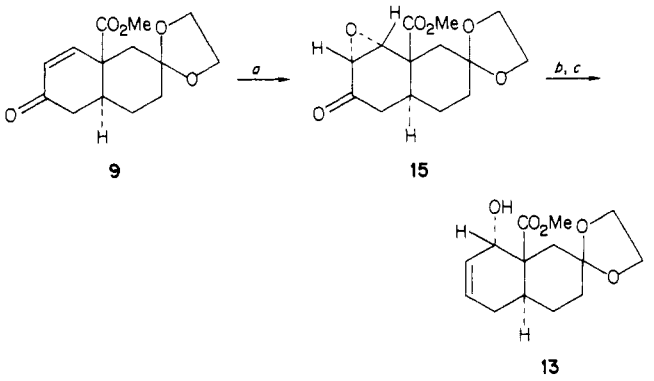
Scheme III



[a] $NaBH_4$, $CeCl_3 \cdot 7H_2O$, MeOH, 0 °C. [b] o-NO_2PhSeCN, n-Bu_3P, THF, room temperature. [c] 30% H_2O_2, THF, −30 °C. [d] 30% H_2O_2, py, THF, −20 °C; gives 13 exclusively. [e] PDC, PTA, CH_2Cl_2, room temperature. [f] a, room temperature.

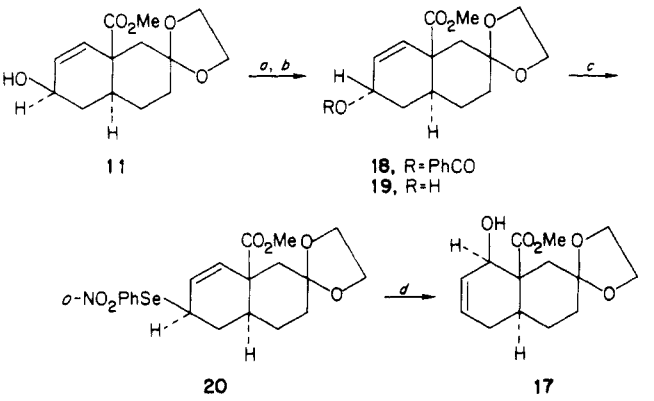
Scheme IV



[a] 30% H_2O_2, aqueous NaOH, MeOH, 0 °C. [b] 85% $NH_2NH_2 \cdot H_2O$, MeOH, 0 °C. [c] HOAc, MeOH, room temperature.

a vehicle to introduce the $\Delta^{2,3}$-double bond and the desired stereochemistry at C-1. With this in mind, the next objective was to determine a feasible route to the C-1 β-allylic alcohol functionality in **2**. Several routes toward these ends are delineated below.

Scheme V



[a] Ph_3P, $PhCO_2H$, DEAD, THF, room temperature. [b] NaOMe, MeOH, 50 °C. [c] o-NO_2PhSeCN, n-Bu_3P, THF, room temperature. [d] 30% H_2O_2, py, CH_2Cl_2, 10 °C.

Hydride reduction of enone **9** (Scheme III) in the presence of $CeCl_3$[16] afforded the 3β-alcohol **11** in 77% yield. Reaction of **11** with o-nitrophenyl selenocyanate in the presence of tri-n-butylphosphine[6] occurred with inversion of configuration to yield the 3α-selenide **12** (91%). Although allylic selenides are known [17,18] to undergo a [1,3] shift to produce the thermodynamically more stable isomer in the presence of heat, acid or light, the ease of the [1,3]

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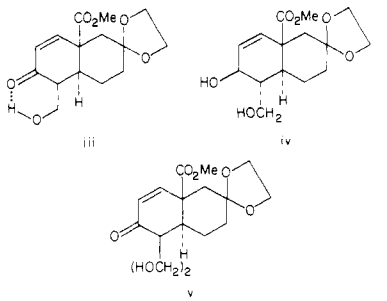
(15) Hydroxymethylation of the lithium enolate of **9** with HCHO gas at −20 °C afforded after chromatography a 40% yield of alcohol iii: ^1H NMR (250 MHz, $CDCl_3$) δ 6.66 (d, 1 H, J = 9.8 Hz), 5.97 (d, 1 H, J = 9.8 Hz), 4.24 (broadened dd, 1 H, collapses to s, on irradiation at δ 3.77), 3.77 (broadened dd, 1 H), 3.31 (m, 1 H, C-4 methine, collapses to broadened d, on irradiation at δ 3.77), on addition of D_2O the resonance signals at δ 4.24 and 3.77 sharpened to a dd (J = 3 and 11 Hz) and dd (J = 6 and 11 Hz), respectively; mass spectra (FAB), m/e 297. A trace amount of diols iv and v were also detected.



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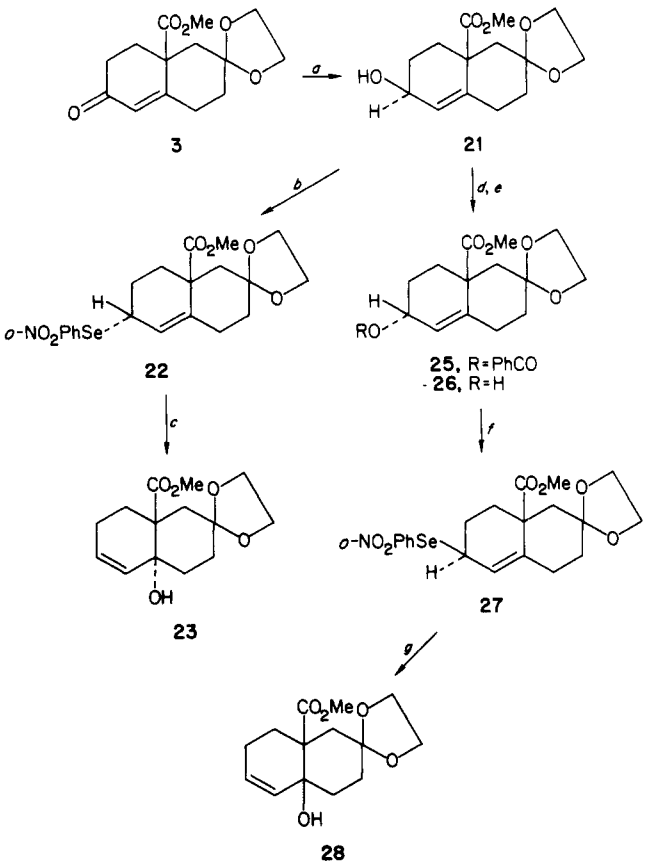
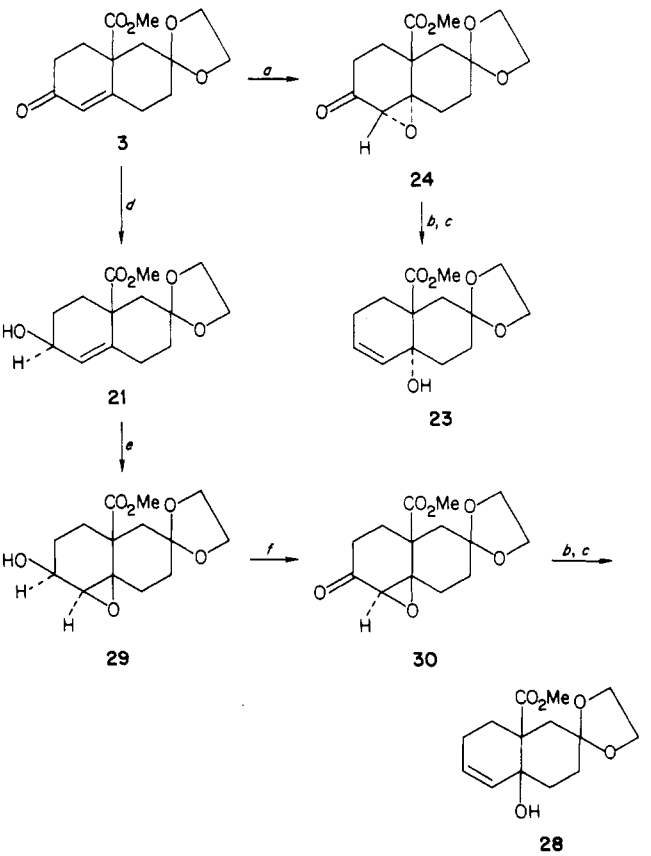
Scheme VI



[a] $NaBH_4$, $CeCl_3 \cdot 7H_2O$, MeOH, 0 °C. [b] o-NO_2PhSeCN, n-Bu_3P, THF, room temperature. [c] 30% H_2O_2, py, THF, −40 °C. [d] Ph_3P, $PhCO_2H$, DEAD, THF, room temperature. [e] NaOMe, MeOH, 50 °C. [f] o-NO_2PhSeCN, n-Bu_3P, THF, room temperature. [g] 30% H_2O_2, py, THF, −20 °C.

Scheme VII



[a] 30% H_2O_2, aqueous NaOH, MeOH, 0 °C. [b] 85% $NH_2NH_2 \cdot H_2O$, MeOH, 0 °C. [c] HOAc, MeOH, room temperature. [d] $NaBH_4$, $CeCl_3$, MeOH, 0 °C. [e] m-CPBA, CH_2Cl_2, 0 °C. [f] PDC, PTA, CH_2Cl_2, room temperature.

shift depends to a large extent on the type of selenide employed and the reaction conditions that are utilized in the rearrangement. The regiochemical integrity of **12** is demonstrated by the high resolution NMR which shows a doublet at δ 5.78 (J = 10 Hz) and a doublet of doublets at δ 5.88 (J = 4.2, 10 Hz). Irradiation of the C-3 methine at δ 4.27 caused the doublet of doublets at δ 5.88 to collapse to a doublet, J = 10 Hz.

Subsequent treatment of **12** with H_2O_2 in the presence of pyridine at −30 °C and concomitant [2,3] sigmatropic rearrangement of the intermediate allylic selenoxide afforded stereospecifically the 1α-alcohol **13** (88%). When the above reaction was conducted in the absence of pyridine, a 4:1 mixture of **13** and epoxide **14** was obtained. Presumably epoxidation of **13** occurs with H_2O_2 in the presence of the in situ generated selenenic acid.[19] The stereochemistry at C-1 in **13** was rigorously established by an alternate synthesis as outlined in Scheme IV. The conversion of **13** to the C-1 β-alcohol **17** (Scheme III) was effected in a straightforward manner. Thus oxidation[20] of **13** and subsequent hydride reduction of the resulting enone **16** in the presence of $CeCl_3$[16] gave **17** (67%).

In order to utilize the selenoxide [2,3] sigmatropic rearrangement as a direct entry to the 1β-allylic alcohol system in **2**, a requisite 3α-allylic alcohol is required. This type of approach was realized as outlined in Scheme V by employing the Mitsunobu[21] inversion reaction in tandem with the aforementioned sigmatropic rearrangement. Reaction of the 3β-alcohol **11** with diethyl azodicarboxylate and triphenylphosphine in the presence of benzoic acid gave diester **18** in 72% yield. Transesterifcation of **18** with sodium methoxide afforded the 3α-alcohol **19** (96%). o-Nitrophenylselenenylation of **19** yielded the 3β-selenide **20** (92%) and subsequent oxidation of **20** at 10 °C[22] with H_2O_2 gave **17** (68%).

To determine the applicability of the above [2,3] sigmatropic rearrangement to stereospecifically defined tertiary allylic alcohol systems, studies involving the 3β-alcohol **21** and the 3α-alcohol **26** were undertaken as delineated in Scheme VI. As shown in the scheme, the conversion of **21** to **23**[23] and **26** to **28** follow closely the methodology for **11** and **19** (vide supra; see Experimental Section for details). The stereochemistry depicted in **23** and **28** was verified by an alternate synthesis utilizing the

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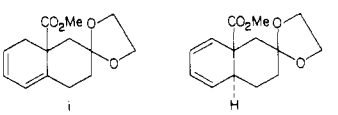
(22) Hydrogen peroxide was not effective in oxidizing **20** at −40 and −20 °C in the presence of pyridine in THF.
(23) The rearrangement at −40, −20, and 0 °C afforded approximately the same yield (60%). A less polar byproduct[24] (~20%) was isolated but not fully characterized.
(24) The byproduct i (^1H NMR (250 MHz, $CDCl_3$) δ 5.90 (m, 2 H), 5.65 (m, 1 H), 3.66 (s, 3 H)) was obtained from *syn*-elimination. Approximately 10% of ii (^1H NMR (250 MHz, $CDCl_3$) δ 5.95 (m, 1 H), 5.82 (m, 2 H), 5.56 (d, 1 H, J = 9 Hz), 3.60 (s, 3 H)) was obtained from the intermediate selenoxides of **12** and **20**.



i ii

Wharton[25] reaction as outlined in Scheme VII.

In summary, the above [2,3] sigmatropic rearrangement via secondary allylic selenoxides provides a direct stereospecific entry to allylic alcohol systems through inversion of configuration. The Mitsunobu inversion reaction in tandem with the selenoxide [2,3] sigmatropic rearrangement provides an entry to secondary allylic alcohols with retention of configuration. The ability to conduct the stereospecific reaction under mild reaction conditions and low temperatures should provide a useful synthetic method to stereo defined secondary allylic alcohols. The application of this methodology to the total synthesis of 1 is currently being investigated.

Experimental Section

Proton magnetic resonance spectra were obtained at 60 MHz with a Varian EM 360 A instrument, at 250 MHz with a Bruker WM 250 instrument, at 300 MHz with a General Electric QE-300 instrument, and at 360 MHz with a Nicolet NT-360. Chemical shifts are expressed in δ values relative to Me_4Si as an internal standard. Coupling constants (J) are given in hertz. High- and low-resolution mass spectra were obtained with a VG Micromass 70-70 F instrument by electron ionization. Infrared spectra, obtained on a Perkin-Elmer Model 727B instrument, are reported in wavenumbers (cm^{-1}). All melting points were obtained on an Electrothermal melting point apparatus and are uncorrected. All boiling points are uncorrected. Preparative chromatography was performed on Merck Silica Gel G 60 (70–230 mesh) and Merck Silica Gel G (230–400 mesh, for pressure chromatography). Thin-layer chromatography was performed with Sybron/Brinkmann Silica Gel G/UV_{254} plates, 0.25 mm (analytical). Compounds on chromatography plates were visualized by spraying with 4% phosphomolybdic acid in isopropyl alcohol followed by heating.

8a-Carbomethoxy-7,7-ethylenedioxy-1,5,6,7,8,8a-hexahydro-3(2*H*)-oxonaphthalene (3). A 60% suspension of sodium hydride–mineral oil (2.8 g, 0.07 mol) was added to dry dimethyl carbonate (18.0 g, 0.20 mol) in 40 mL of dry THF. The resulting reaction mixture was heated to reflux, and 3 mL of a solution of 4,4-ethylenedioxy-1-cyclohexanone (10.0 g, 0.064 mol) in 30 mL of dry THF was added dropwise.

A slurry of 30% KH (0.6 g) in 10 mL of dry THF was added in one portion, and then the remaining 4,4-ethylenedioxy-1-cyclohexanone solution was added dropwise over a 0.75-h period. The resulting reaction mixture was refluxed for an additional 1.5 h, cooled to an ambient temperature, and stirred overnight. the solvent was removed in vacuo; 20 mL of methanol was added to the residue, and the solvent was again removed in vacuo. The resulting enolate was then dissolved in 150 mL of methanol, placed under nitrogen, and cooled to −5 °C.

Methyl vinyl ketone (9.0 g, 0.13 mol) was added dropwise with stirring at −5 to 0 °C, and stirring was continued for 3.5 h at 0 °C and then at 5 °C (refrigerator) for 2 days. The reaction mixture was diluted with 50 mL of brine and extracted with four 100-mL portions of methylene chloride. The organic extracts were washed with two 250-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to give a semisolid. Recrystalization from methanol afforded 7.2 g (42%) of **3**: mp 122–124 °C (lit.[12] mp 124–126 °C); ^1H NMR ($CDCl_3$) δ 6.03 (d, 1 H, J = 2 Hz), 3.98 (m, 4 H), 3.79 (s, 3 H); IR (KBr) 1720 (s), 1660 (s) cm^{-1}.

(4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3(2*H*)-oxonaphthalene (4). To a solution of octalone **3** (3.0 g, 11.3 mmol) in 50 mL of ethyl acetate was added 0.45 g of 5% Pd/C, and the resulting reaction mixture was reduced with H_2 at 1 atm at room temperature. After 1 equiv of hydrogen was absorbed, the reaction mixture was filtered through Celite with suction and subsequently concentrated in vacuo to give a white solid. Trituration with an ether–hexane solution afforded 2.6 g (87%) of **4**: mp 115–116 °C; ^1H NMR (250 MHz, $CDCl_3$) δ 3.93 (m, 4 H), 3.74 (s, 3 H), 3.14 (apparent triplet, 1 H, J = 15 Hz); 2.48 (dd, J = 3, 15 Hz), 2.21 (m, 5 H), 1.67 (m, 6 H), 1.36 (d, 1H, J = 15 Hz); IR (KBr) 1720 (br) cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 4), 209 (9), 99 (100), 55 (27); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1378. Reduction of octalone **3** (20 g) gave a 75% yield of **4**.

(3α,4aβ,8aα)-1,2,3,4,4a,5,6,7,8,8a-Decahydro-7,7-ethylenedioxy-3β-hydroxy-8aβ-(hydroxymethyl)naphthalene (5). Octalone **3** (6.0 g, 0.022 mol) in 100 mL of dry THF was added dropwise to a Li–NH_3 solution[26] [Li (4.7 g, 0.68 mol); NH_3 (400 mL)] at −33 °C. The reaction mixture was stirred an additional hour at −33 °C, and then dry ethanol (60 mL) was added dropwise over a 1.0-h period. The ammonia was evaporated, and the resulting residue was dissolved in 800 mL of methylene chloride. The organic solution was washed with two 100-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Trituration with ether gave 2.1 g (40%) of **5**: mp 147–149 °C; ^1H NMR (360 MHz, $CDCl_3$) δ 3.92 (m, 5 H), 3.65 (m, 2 H), 2.13 (m, 1 H), 2.02 (dd, 1 H, J = 2.6, 13.9 Hz), 1.85 (m, 3 H), 1.15–1.74 (m), 1.16 (d, J = 13.9 Hz) [9 H], 0.95 (apparent dt, 1 H); IR (KBr) 3325 (br) cm^{-1}.

(4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-7,7-ethylenedioxy-8aβ-formyl-3(2*H*)-oxonaphthalene (6). A solution of diol **5** (2.0 g, 8.3 mmol), pyridinium dichromate (9.4 g, 25 mmol), and pyridinium trifluoroacetate (1.3 g, 6.7 mmol) in 25 mL of dry methylene chloride was stirred for 8 h at room temperature. The reaction mixture was diluted with 100 mL of methylene chloride and filtered, and the solvent was concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:6), eluting with ether–hexane solutions, afforded 900 mg (46%) of **6**: ^1H NMR ($CDCl_3$) δ 9.80 (s, br, 1 H) and 4.03 (m, 4 H). The aldehyde was not characterized further but submitted directly to oxidation.

(4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3(2*H*)-oxonaphthalene (4). $AgNO_3$[27] (764 mg, 4.50 mmol) in 3 mL of H_2O was added to aldehyde **6** (420 mg, 1.76 mmol) in 15 mL of absolute ethanol at room temperature. KOH (2.1 g, 37.5 mmol) in 35 mL of H_2O was then added dropwise at room temperature, and the resulting reaction mixture was stirred for an additional 3 h. The silver salts were filtered, and the residue was washed with 35 mL of H_2O and 5 mL of methanol. The combined filtrates were extracted with two 35-mL portions of ether. The aqueous layer was acidified (pH 4) with 3.5% oxalic acid (15 mL) and extracted with four 40-mL portions of methylene chloride. The organic extract was dried (Na_2SO_4) and concentrated in vacuo to afford 190 mg (43%) of **7**: ^1H NMR ($CDCl_3$–Me_2SO-d_6) δ 9.25 (s, br, CO_2H), 3.99 (m, OCH_2CH_2O). The carboxylic acid **7** was submitted directly to esterification.

An etheral solution of CH_2N_2 was added to acid **7** (190 mg, 0.748 mmol) in 20 mL of an ether–methanol solution (5:1) at 0 °C until a yellow color persisted. The reaction mixture was washed with two 50-mL portions of a saturated $NaHCO_3$ solution and 25 mL of brine. The aqueous washings were combined and back-extracted with two 50-mL portions of ether. The organic extracts were dried (Na_2SO_4) and concentrated in vacuo to afford an oil. Trituration with an ether-hexane solution gave 120 mg (60%) of **4**: mp 114–115.5 °C; ^1H NMR (360 MHz, $CDCl_3$) δ 3.91 (m, 4 H), 3.73 (s, 3 H), 3.14 (apparent t, J = 14.5 Hz), 2.48 (dd, J = 2.5, 13.4 Hz), 2.22 (m, 5 H), 1.81 (m, 1 H), 1.61 (m, 5 H), 1.36 (d, 1 H, J = 13 Hz); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1316.

(4aβ,8aα)-4a,5,6,7,8,8a-Hexahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3(4*H*)-oxonaphthalene (9). Phenylselenenyl chloride (2.14 g, 11.2 mmol) was added to *trans*-decalone **4** (2.5 g, 9.33 mmol) in 100 mL of dry ethyl acetate at room temperature, and the resulting reaction mixture was stirred for 3 h. Removal of the solvent in vacuo afforded an oil. The oil was dissolved in methylene chloride (100 mL) containing pyridine (2.2 g, 27.8 mmol). 30% Hydrogen peroxide (1.9 mL, 18.6 mmol) was then added over a 0.1-h period. The exothermic reaction was controlled via a water bath during the addition of H_2O_2. The reaction mixture was stirred at an ambient temperature for 0.15 h, then refluxed for 0.15 h, cooled, and diluted with 100 mL of methylene chloride. The organic layer was extracted with brine (20 mL) and saturated $NaHCO_3$ (20 mL), dried (Na_2SO_4), and concentrated

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in vacuo to give an oil. Chromatography on silica gel G (1:20), eluting with ether–hexane solutions, gave 1.0 g (40%) of **9**: mp 126–128.5 °C (ether–hexane); ^{1}H NMR (250 MHz, $CDCl_3$) δ 6.66 (d, 1 H, J = 10 Hz), 5.96 (d, 1 H, J = 10 Hz), 3.93 (m, 4 H), 3.68 (s, 3 H), 3.22 (dd, 1 H, J = 14, 17.7 Hz), 2.59 (dd, 1 H, J = 2.5, 13.2 Hz), 2.30 (m, 2 H), 2.04 (m, 1 H), 1.83 (m, 3 H), 1.53 (d, 1 H, J = 13.2 Hz); IR (KBr) 1720, 1670 cm^{-1}; mass spectrum, m/e (relative intensity) 266 (M^+, 11), 100 (36), 99 (100), 77 15), 55 (41); mass spectrum calcd for $C_{14}H_{18}O_5$ m/e 266.1153, found m/e 266.1148.

(3a,4aβ,8aα)-3,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3β-hydroxynaphthalene (11). Sodium borohydride (626 mg, 16.6 mmol) was added in small portions to a solution of enone **9** (1.0 g, 3.76 mmol) and cerium(III) chloride heptahydrate (1.5 g, 4.03 mmol) in 50 mL of methanol at 0 °C, and stirring was continued for 1 h at 0 °C. Brine (50 mL) was added and the resulting mixture extracted with three 75-mL portions of ethyl acetate. The organic extract was washed with three 20-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:12), eluting with ether–hexane solutions, gave 1.0 g of an oil. Trituration with a CCl_4–hexane solution afforded 780 mg (77%) of **11**: mp 106.5–107.5 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.74 (apparent dd, 1 H, J = 0.8, 9.8 Hz), 5.61 (apparent dd, 1 H, J = 1.7, 9.8 Hz), 4.30 (m, 1 H), 3.90 (m, 4 H), 3.66 (s, 3 H), 2.47 (dd, 1 H, J = 2.5, 13.2 Hz), 2.22 (m, 2 H), 1.98 (m, 1 H), 1.80 (m, 1 H), 1.67 (dd, 1 H, J = 4.8, 13.1 Hz), 1.23–1.62 (m), 1.35 (d, J = 13.3 Hz) [4 H]; IR (KBr) 3300, 1730 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 1), 250 (1), 99 (100), 55 (18); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1324.

(3β,4aβ,8aα)-3,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3α-((*o*-nitrophenyl)seleno)-naphthalene (12). Tri-*n*-butylphosphine (389 μL, 1.56 mmol) was added via a syringe to a solution of the 3β-alcohol **11** (280 mg, 1.04 mmol) and *o*-nitrophenyl selenocyanate (354 mg, 1.56 mmol) in 6 mL of dry THF over a 10-min period at room temperature under nitrogen. The reaction mixture was stirred for 6 h and then concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:20), eluting with ether–hexane solutions, gave a solid. Trituration with ether–hexanes afforded 427 mg (91%) of **12**: mp 154–156 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 8.30 (dd, 1 H, J = 1.0, 8.3 Hz), 7.57 (m, 2 H), 7.35 (m, 1 H), 5.88 (dd, 1 H, J = 4, 10 Hz, collapses to d, J = 10 Hz, on irradiation at δ 4.27), 5.78 (d, 1 H, J = 10 Hz), 4.27 (m, 1 H), 3.94 (m, 4 H) 3.66 (s, 3 H), 3.01 (dq, 1 H, J = 4.6, 13 Hz), 2.49 (apparent dd, 1 H, J = 2.2, 13.2 Hz), 2.19 (dq, 1 H, J = 4.6, 13 Hz), 1.42–1.85 (m), 1.45 (d, J = 13.2 Hz) [6 H]; IR (KBr) 1725 cm^{-1}; mass spectrum, m/e (relative intensity) 453 (M^+, 0.4), 251 (57), 191 (74), 147 (58), 99 (100), 91 (47), 55 (39); mass spectrum calcd for $C_{20}H_{23}NO_6Se$ (M – 202 = loss of NO_2PhSe) m/e 251.1283, found m/e 251.1282.

(1β,4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1α-hydroxynaphthalene (13). An 85% hydrazine hydrate solution (75 μL, 2.03 mmol) was added dropwise via a syringe to a solution of the α-epoxide **15** (120 mg, 0.43 mmol) in 15 mL of dry methanol at 0 °C, and stirring was continued at 0 °C for 0.5 h. The reaction mixture bath (0 °C) was replaced by a water bath (20 °C), and then glacial acetic acid (4.0 μL) was added via a syringe. The reaction mixture was stirred for an additional 1 h and then diluted with 100 mL of methylene chloride. The organic solution was washed with brine (20 mL), dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:20), eluting with ether–hexane solutions, gave 60 mg (52%) of **13**: ^{1}H NMR (360 MHz, $CDCl_3$) δ 5.94 (m, 1 H), 5.85 (m, 1 H, collapses to a broadened d, J = 11 Hz, on irradiation at δ 4.09), 4.09 (broadened s, 1 H), 3.91 (m, 4 H), 3.63 (s, 3 H), 2.52 (m, 1 H), 2.03–2.21 (m, 3 H), 1.94 (d, 1 H, J = 13.6 Hz), 1.39–1.90 (m, 6 H); IR (CCl_4) 3420, 1730 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 4), 198 (27), 167 (20), 147 (12), 99 (100), 77 (11), 55 (21); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1357.

(1β,4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1α-hydroxynaphthalene (13) and (1β,2β,3β,4aβ,8aα)-1,2,3,4,4a,5,6,7,8,8a-Decahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1α-hydroxy-2α,3α-epoxynaphthalene (14). A 30% hydrogen peroxide solution (1.98 mL, 19.4 mmol) was added via a syringe to a solution of the 3α-selenide **12** (390 mg, 0.86 mmol) in 10 mL of dry THF at −30 °C over a 0.2-h period. The reaction mixture was stirred at −30 °C for 2 h, allowed to warm to room temperature, and then diluted with ethyl acetate (80 mL). The organic solution was washed with 5% $NaHCO_3$ (10 mL) and brine (10 mL), dried (Na_2SO_4), and concentrated in vacuo to give an oil. Chromatography on silica gel G, eluting with ether–hexane solution, gave 180 mg of a 4:1 mixture of **13**:**14** as determined by 360-MHz NMR analysis. Rechromatography of the oil (180 mg) on silica gel G (1:50), eluting with ether–hexane solutions, afforded 36 mg (15%) of epoxide **14**: mp 125–128 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 4.14 (dd, 1 H, J = 5.6, 9.7 Hz), 3.88 (m, 4 H), 3.68 (s, 3 H), 3.40 (m, 2 H), 2.43 (m, 2 H), 2.13 (dd, 1 H, J = 2.7, 13.9 Hz), 2.00 (m, 2 H), 1.89 (d, 1 H, J = 13.9 Hz), 1.73 (m, 1 H), 1.51 (m, 3 H); IR (KBr) 3480, 1730 cm^{-1}; mass spectrum, m/e (relative intensity) 284 (M^+, 2), 255 (2), 127 (40), 99 (100), 55 (18); mass spectrum calcd for $C_{14}O_{20}O_6$ m/e 284.1259, found m/e 284.1259. It also afforded 120 mg (52%) of **13**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.94 (m, 1 H), 5.85 (m, 1 H), 4.09 (broadened s, 1 H), 3.91 (m, 4 H), 3.63 (s, 3 H), 2.52 (m, 1 H), 2.02–2.22 (m, 3 H), 1.51–1.91 (m, 6 H), 1.94 (d, 1 H, J = 13.6 Hz); IR (CCl_4) 3420, 1730 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 5), 198 (36), 167 (23), 147 (14), 99 (100), 77 (11), 55 (20); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1324. When the reaction was carried out in the presence of pyridine, an 88% yield of **13** was obtained.

(1β,2β,4aβ,8aα)-1,2,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1α,2α-epoxy-3(4*H*)-oxonaphthalene (15). A 10% sodium hydroxide solution (250 μL) was added via a syringe to a solution of enone **9** (300 mg, 1.13 mmol) in 7 mL of methanol containing 30% hydrogen peroxide (640 μL, 6.26 mmol) at 0 °C, and stirring was continued for 1 h at 0 °C. The reaction mixture was diluted with 100 mL of methylene chloride. The organic solution was washed with 10 mL of brine and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:10), eluting with ether–hexane solutions, gave 230 mg (72%) of **15** as an oil. Trituration with ether–hexanes afforded 184 mg (58%) of **15**: mp 117–118.5 °C; ^{1}H NMR ($CDCl_3$) δ 3.93 (m, 4 H), 3.72 (s, 3 H), 3.57 (d, 1 H, J = 4 Hz), 3.29 (d, 1 H, J = 4 Hz), 2.06 (m, 9 H); IR (KBr) 1740, 1720 cm^{-1}; mass spectrum, m/e (relative intensity) 282 (M^+, 1), 223 (7), 99 (100), 55 (10); calcd for $C_{14}H_{18}O_6$ m/e 282.1103, found m/e 282.1104.

(3β,4aβ,8aα)-3,4,4a,5,6,7,8,8a-Octahydro-3α-(benzoyloxy)-8aβ-carbomethoxy-7,7-ethylenedioxynaphthalene (18). Diethyl azodicarboxylate (1.2 g, 6.89 mmol) in dry THF (5 mL) was added dropwise over a 0.3-h period to a solution of alcohol **11** (1.2 g, 4.48 mmol), triphenylphosphine (1.8 g, 6.86 mmol), and benzoic acid (820 mg, 6.71 mmol) in 25 mL of dry THF at room temperature under nitrogen. The reaction mixture was stirred for an additional 2.5 h and then diluted with 125 mL of ethyl acetate. The organic solution was washed with two 25-mL portions of a saturated $NaHCO_3$ solution and two 25 mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:10), eluting with ether–hexane solutions, gave an oil. Trituration with ether yielded 1.2 g (72%) of **18**: mp 141–143 °C; ^{1}H NMR ($CDCl_3$) δ 8.12 (m, 2 H), 7.50 (m, 3 H), 5.93 (broadened s, 2 H), 5.52 (m, 1 H), 3.93 (m, 4 H), 3.69 (s, 3 H), 1.32–2.84 (m, 9 H); IR (KBr) 1690 (br) cm^{-1}; mass spectrum, m/e (relative intensity) 372 (M^+, 10), 313 (11), 267 (41), 250 (14), 191 (30), 105 (48), 99 (100), 77 (19); mass spectrum calcd for $C_{21}H_{24}O_6$ m/e 372.1572, found m/e 372.1572.

(3β,4aβ,8aα)-3,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3α-hydroxynaphthalene (19). Sodium methoxide (202 mg, 3.74 mmol) was added to a soluiton of diester **18** (1.16 g, 3.12 mmol) in 20 mL of dry methanol, and the reaction mixture was heated to 50 °C for 3 h under nitrogen. The reaction mixture was cooled, diluted with ethyl acetate (150 mL), washed with two 20-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:10), eluting with ether–hexane solutions, gave 800 mg (96%) of **19**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.83 (dd, 1 H, J = 4, 9.7 Hz), 5.73 (d, 1 H, J = 9.7 Hz); 4.22 (m, 2 H, C-3H and OH), 3.91 (m, 4 H), 3.63 (s, 3 H), 2.59 (dd, 1 H, J = 5, 14 Hz), 2.47 (m, 1 H), 1.32–2.34 (m), 1.44 (d, J = 13 Hz) [7 H]; IR (CCl_4) 3370, 1740 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 8), 209 (22), 149 (20), 99 (100), 86 (26), 71 (11), 57 (16); mass spectrum calcd for

$C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1322.

(3α,4αβ,8aα)-3,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3β-((o-nitrophenyl)seleno)naphthalene (20). Tri-*n*-butylphosphine (814 μL, 3.27 mmol) was added via a syringe to a solution of the 3α-alcohol **19** (730 mg, 2.72 mmol) and *o*-nitrophenyl selenocyanate (742 mg, 3.27 mmol) in 8 mL of dry THF over a 5-min period at room temperature under nitrogen. The reaction mixture was stirred for 3 h and then concentrated in vacuo to afford a solid. Trituration with ether–hexanes (1:1) gave 1.1 g (92%) of **20**: (44), mp 220–223 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.25 (broadened d, 1 H, J = 8.0 Hz), 7.60 (d, 1 H, J = 8.0 Hz), 7.47 (m, 1 H), 7.29 (m, 1 H), 5.88 (dd, 1 H, J = 1.8, 9.7 Hz), 5.65 (dd, 1 H, J = 1.8, 9.7 Hz), 4.13 (m, 1 H, C-3H), 4.92 (m, 4 H), 3.66 (s, 3 H), 2.54 (m, 2 H), 2.15 (m, 2 H), 1.57 (m, 4 H), 1.39 (d, 1 H, J = 13.2 Hz); IR (KBr) 1720 cm^{-1}; mass spectrum, m/e (relative intensity) 453 (M^+), 404 (6), 251 (44), 191 (54), 147 (45), 99 (100), 78 (35); mass spectrum calcd for $C_{20}H_{23}NO_6Se$ (M − 202 = loss of NO_2PhSe) m/e 251.1283, found m/e 251.1280.

(1α,4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1β-hydroxynaphthalene (17). A 30% hydrogen peroxide solution (1.60 mL, 15.7 mmol) was added dropwise via a syringe to a solution of the 3β-selenide **20** (200 mg, 0.44 mmol) and pyridine (2 mL) in 50 mL of dry methylene chloride at 10 °C over a 5-min period. The reaction mixture was stirred at 10 °C for 10 h and then quenched with 5 mL of a saturated NH_4Cl solution. Methylene chloride (100 mL) was added to the reaction mixture, and the resulting organic solution was washed with 15 mL of brine, dried (Na_2SO_4), and concentrated in vacuo to afford a residue. Chromatography on silica gel G (1:30), eluting with ether–hexane solutions, afforded 80 mg (68%) of **17**: ^{1}H NMR (250 MHz), $CDCl_3$) δ 5.62 (m, 2 H), 3.93 (m, 6 H), 3.70 (s, 3 H), 2.71 (dd, 1 H, J = 2.6, 13.8 Hz), 2.31 (m, 1 H), 2.08 (m, 2 H), 1.71 (m, 4 H), 1.48 (d, 1 H, J = 13.8 Hz); IR (CCl_4) 3470, 1700 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 3), 250 (6), 236 (5), 198 (21), 99 (100), 55 (16); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1329.

(1α,4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1β-hydroxynaphthalene (17). Sodium borohydride (18 mg, 0.476 mmol) was added in small portions to a solution of enone **16** (30 mg, 0.113 mmol) and cerium(III) chloride heptahydrate (44 mg, 0.118 mmol) in 2 mL of methanol at room temperature. The reaction mixture was stirred at room temperature for 3 h and then diluted with ethyl acetate (50 mL). The organic solution was washed with two 5-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to give an oil. Chromatography on a silica gel G Sep-Pak, eluting with 10 mL of methylene chloride, afforded 20 mg (67%) of **17**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.62 (m, 2 H), 3.93 (m, 6 H), 3.70 (s, 3 H), 2.71 (dd, 1 H, J = 2.6, 13.8 Hz), 2.31 (m, 1 H), 2.08 (m, 2 H), 1.71 (m, 4 H), 1.48 (d, 1 H, J = 13.8 Hz); IR (CCl_4) 3470, 1700 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 1), 250 (3), 236 (3), 198 (26), 99 (100), 55 (21); mass spectrum calcd for $C_{14}H_{20}O_4$ m/e 268.1310, found m/e 268.1327.

(4aβ,8aα)-4a,5,6,7,8,8a-Hexahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-1(4*H*)-oxonaphthlene (16). A solution of alcohol **13** (35 mg, 0.131 mmol), pyridinium dichromate (147 mg, 0.391 mmol), and pyridinium trifluoroacetate (20 mg, 0.104 mmol) in 2 mL of dry methylene chloride was stirred overnight at room temperature. The reaction mixture was filtered and the residue washed with additional methylene chloride. The organic solvent was concentrated in vacuo to afford an oil. Chromatography on a silica gel G Sep-Pak, eluting with 10 mL of ether–hexane (1:1) solution, gave 30 mg (86%) of **16**: mp 137–140 °C; ^{1}H NMR ($CDCl_3$) δ 7.10 (ddd, 1 H, J = 2, 5, 11 Hz), 6.0 (broadened d, J = 11 Hz), 3.96 (m, 4 H), 3.70 (s, 3 H), 1.20–3.16 (m, 9 H); mass spectrum, m/e (relative intensity), 266 (M^+, 8), 198 (19), 149 (27), 99 (100), 68 (35), 57 (39); mass spectrum calcd for $C_{14}H_{18}O_5$ m/e 266.1153, found m/e 266.1161.

(3α,8aα)-1,2,3,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3β-hydroxynaphthalene (21). Sodium borohydride (750 mg, 19.8 mmol) was added in small portions to a solution of enone **4** (1.20 g, 4.51 mmol) and cerium(III) chloride heptahydrate (1.85 g, 4.97 mmol) in 100 mL of methanol at 0 °C. The reaction mixture was stirred at 0 °C for 1 h and then quenched with 25 mL of acetone. The solvent was reduced in vacuo, brine (70 mL) was added, and the resulting mixture was extracted with four 40-mL portions of ethyl acetate. The organic extract was washed with three 20-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to give an oil. Chromatography on silica gel G (1:15), eluting with ether–hexanes solutions, afforded 930 mg (77%) of **21**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.64 (broadened s, 1 H), 4.23 (broadened m, 1 H), 3.93 (m, 4 H), 3.71 (s, 3 H), 2.68 (m, 1 H), 2.50 (dd, 1 H, J = 2.9, 13.5 Hz), 2.26 (m, 1 H), 2.12 (m, 1 H), 1.96 (m, 1 H), 1.26–1.81 (m), 1.35 (d, J = 13.5 Hz) [7 H]; IR (CCl_4) 3450, 1740 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 3), 250 (48), 191 (50), 165 (12), 147 (19), 123 (19), 99 (28), 87 (100), 77 (22), 55 (26); mass spectrum calcd for $C_{14}H_{20}O_6$ m/e 268.1310, found m/e 268.1306.

(3β,8aα)-1,2,3,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3α-((o-nitrophenyl)seleno)naphthalene (22). Tri-*n*-butylphosphine (1.40 mL, 5.52 mmol) was added dropwise via a syringe to a solution of the 3β-alcohol **21** (1.0 g, 3.73 mmol) and *o*-nitrophenyl selenocyanate (1.27 g, 5.60 mmol) in 25 mL of dry THF under nitrogen. The reaction mixture was stirred for 4 h and then concentrated in vacuo to afford a solid. Chromatography on silica gel G (1:10), eluting with ether–hexane solutions, afforded 1.6 g of an oil which solidified on standing. Trituration with an ether–hexane solution gave 1.4 g (82%) of **22**: mp 144–147 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 8.27 (m, 1 H), 7.51 (m, 2 H), 7.31 (m, 1 H), 5.80 (d, 1 H, J = 4.1 Hz, collapses to s, on irradiation at δ 4.26), 4.26 (m, 1 H), 3.96 (m, 4 H), 3.71 (s, 3 H), 2.72 (m, 1 H), 2.57 (dd, 1 H, J = 2.6, 13.5 Hz), 2.33 (m, 1 H), 1.57–2.08 (m), 1.44 (d, J = 13.5 Hz) [7 H]; IR (KBr) 1715 cm^{-1}; mass spectrum, m/e (relative intensity) 453 (M^+), 404 (0.8), 251 (100), 191 (53), 147 (53), 105 (22); mass spectrum calcd for $C_{20}H_{23}NO_6Se$ (M − 202 = loss of NO_2PhSe) m/e 251.1283, found m/e 251.1283.

(4aβ,8aα)-1,2,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-4aα-hydroxynaphthalene (23). An 85% hydrazine hydrate solution (75 μL, 2.03 mmol) was added dropwise via a syringe to a solution of the α-epoxide **24** (120 mg, 0.43 mmol) in 15 mL of dry methanol at 0 °C, and stirring was continued at 0 °C for 2 h. The reaction mixture bath (0 °C) was replaced by a water bath (20 °C), and then glacial acetic acid (4 μL) was added via a syringe. The reaction was stirred for 3 h and then diluted with 100 mL of ethyl acetate. The organic solution was washed with brine (10 mL), dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:20), eluting with ether–hexane solutions, gave 80 mg (70%) of **23** as an oil. Trituration with an ether–hexane solution yielded 26 mg (23%) of **23**: mp 139–141 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 5.91 (d, 1 H, J = 9.9 Hz), 5.70 (m, 1 H), 3.90 (m, 4 H), 3.65 (s, 3 H), 2.57 (dt, 1 H, J = 5, 14 Hz), 1.56–2.12 (m, 10 H); IR (KBr) 3470, 1730 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 0.4), 250 (2), 236 (8),209 (3) 99 (100), 86 (34), 55 (12); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1316.

(4aβ,8aα)-1,2,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-4aα-hydroxynaphthalene (23). A 30% hydrogen peroxide solution (1.0 mL, 9.79 mmol) was added via a syringe to a solution of the 3α-selenide **22** (200 mg, 0.44 mmol) in 8 mL of dry THF–pyridine (3:1) at −40 °C. The reaction mixture was stirred at −40 °C for 3 h. Saturated NH_4Cl (10 mL) was added at −40 °C, and the reaction mixture was diluted with 100 mL of ethyl acetate. The organic layer was washed with saturated $NaHCO_3$ (15 mL) and brine (15 mL), dried (Na_2SO_4), and concentrated in vacuo to give an oil. Chromatography on silica gel G (1:25), eluting with ether–hexane solutions, gave a solid. Trituration with an ether–hexane solution gave 75 mg (64%) of **23**: mp 140.5–141.5 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 5.91 (d, 1 H, J = 9.9 Hz), 5.70 (m, 1 H), 3.90 (m, 4 H), 3.65 (s, 3 H), 2.57 (dt, 1 H, J = 5, 14 Hz), 1.57–2.12 (m, 10 H); IR (KBr) 3460, 1730 cm^{-1}; mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1324.

(4β,4aβ,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-4α,4aα-epoxy-3(2*H*)-oxonaphthalene (24). A 10% sodium hydroxide solution (600 μL) was added via a syringe to a solution of octalone **3** (300 mg, 1.13 mol) in 10 mL of methanol containing 30% hydrogen peroxide (1.28 mL, 12.5 mmol) at 0 °C, and stirring was continued for 6 h at 0 °C. The reaction mixture was diluted with 100 mL of ethyl acetate, washed with two 20-mL portions of brine, dried (Na_2SO_4), and concen-

trated in vacuo to give 250 mg of an oil. Trituration with an ethyl acetate–hexane solution afforded 161 mg (51%) of **24**: mp 156–159 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 3.98 (m, 4 H), 3.72 (s, 3 H), 3.34 (s, 1 H), 2.67 (dt, 1 H, J = 5.1, 14.2 Hz) 2.53 (dd, 1 H, J = 2.8, 13.6 Hz), 2.35 (m, 1 H), 2.02 (m, 3 H), 1.76 (m), 1.70 (d, J = 13.6 Hz) [4 H], 1.37 (m, 1 H); IR (KBr) 1720 cm^{-1}; mass spectrum, m/e (relative intensity), 282 (M^+, 43), 253 (29), 223 (79), 195 (12), 167 (12), 149 (16), 99 (100), 86 (42), 55 (17); mass spectrum calcd for $C_{14}H_{18}O_6$ m/e 282.1102, found m/e 282.1103.

(3β,8aα)-1,2,3,5,6,7,8,8a-Octahydro-3α-(benzoyloxy)-8aβ-carbomethoxy-7,7-ethylenedioxynaphthalene (25). Diethyl azodicarboxylate (439 mg, 2.52 mmol) in 5 mL of dry THF was added dropwise over a 0.25-h period to a solution of alcohol **21** (450 mg, 1.68 mmol), triphenylphosphine (661 mg, 2.52 mmol), and benzoic acid (307 mg, 2.51 mmol) in 10 mL of dry THF at room temperature under nitrogen. The reaction mixture was stirred for an additional 4 h and then diluted with 80 mL of ethyl acetate. The organic solution was washed with two 15-mL portions of saturated $NaHCO_3$ solution, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:15), eluting with ether–hexane solutions, gave 600 mg (96%) of **25**: ^{1}H NMR ($CDCl_3$) δ 8.10 (m, 2 H), 7.53 (m, 3 H), 5.83 (apparent dd, 1 H, J = 2, 5 Hz), 5.41 (m, 1 H), 3.94 (m, 4 H), 3.70 (s, 3 H), 1.12–2.77 (m, 10 H); IR (CCl_4) 1720 (br) cm^{-1}; mass spectrum, m/e (relative intensity) 372 (M^+), 250 (38), 191 (32), 147 (27), 122 (58), 105 (100), 77 (72); mass spectrum calcd for $C_{21}H_{24}O_6$ m/e 372.1572, found m/e 372.1572.

(3β,8aα)-1,2,3,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3α-hydroxynaphthalene (26). Sodium methoxide (105 mg, 1.94 mmol) was added to a solution of diester **25** (600 mg, 1.61 mmol) in 10 mL of dry methanol, and the reaction mixture was heated to 50 °C under nitrogen for 3.5 h. The reaction mixture was cooled, diluted with ethyl acetate (100 mL), washed with three 15-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:10), eluting with ether–hexane solutions, gave 310 mg (72%) of **26**: ^{1}H NMR (360 MHz, $CDCl_3$) δ 5.77 (apparent d, 1 H, J = 3.6 Hz), 4.19 (broadened s, 1 H), 3.96 (m, 4 H), 3.69 (s, 3 H), 2.72 (m), 2.54 (m), 2.31 (m), 1.95 (m) [4 H], 1.21–1.82 (m, 7 H); IR (CCl_4) 3420, 1730 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 2), 250 (34), 191 (35), 147 (33), 129 (30), 117 (19), 105 (49), 87 (100), 84 (72), 77 (21); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1322.

(3α,8aα)-1,2,3,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3β-((o-nitrophenyl)seleno)naphthalene (27). Tri-*n*-butylphosphine (349 μL, 1.40 mmol) was added via a syringe to a solution of the 3α-alcohol **26** (250 mg, 0.93 mmol) and *o*-nitrophenyl selenocyante (300 mg, 1.32 mmol) in 8 mL of dry THF over a 5 min period under nitrogen at room temperature with stirring. Stirring was continued for 2.5 h and the solvent concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:10), eluting with ether–hexane solutions, gave 320 mg (76%) of solid **27**. Trituration with an ether–hexane solution gave 175 mg (42%) of **27**: mp 166–168 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.26 (dd, 1 H, J = 3.0, 9.0 Hz), 7.69 (d, J = 9.0 Hz), 7.52 (m, 1 H), 7.31 (m, 1 H), 5.81 (broadened s, 1 H), 4.07 (m), 3.96 (m) [5 H], 3.71 (s, 3 H), 2.74 (m, 1 H), 2.53 (apparent dd, 1 H), 2.25 (m, 2 H), 2.13 (m, 1 H), 1.51–1.82 (m, 4 H), 1.43 (d, 1 H, J = 12 Hz); IR (KBr) 1720 cm^{-1}; mass spectrum, m/e (relative intensity) 453 (M^+), 404 (1), 251 (100), 192 (68), 105 (48), 99 (21), 87 (71); mass spectrum calcd for $C_{20}H_{23}NO_6Se$ (M − 202 = loss of NO_2PhSe) m/e 251.1283, found m/e 251.1283.

(4aα,8aα)-1,2,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-4aβ-hydroxynaphthalene (28). An 85% hydrazine hydrate solution (75 μL, 2.03 mmol) was added dropwise via a syringe to a solution of the β-epoxide **30** (120 mg, 0.43 mmol) in 15 mL of dry methanol at 0 °C, and stirring was continued at 0 °C for 2 h. The reaction mixture bath (0 °C) was replaced by a water bath (20 °C), and acetic acid (10 μL) was added via a syringe. The reaction mixture was stirred for 1 h and then diluted with 100 mL of ethyl acetate. The organic solution was washed with two 10-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:20), eluting with ether–hexane solutions, gave 50 mg (44%) of **28**: ^{1}H NMR (360 MHz), $CDCl_3$) δ 5.78 (m, 1 H), 5.56 (d, 1 H, J = 10 Hz), 4.61 (s, 1 H), 3.89 (m, 4 H), 3.72 (s, 3 H), 1.48–2.30 (m, 10 H); IR (CCl_4) 3500, 1725 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 1), 250 (4), 154 (19), 99 (100), 55 (18); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1322.

(3α,4aα,4aα,8aα)-1,2,3,4,4a,5,6,7,8,8a-Decahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-3β-hyroxy-4β,4aβ-epoxynaphthalene (29). An 80% *m*-chloroperoxybenzoic acid solution (410 mg, 1.90 mmol) in 6 mL of dry methylene chloride was added to a solution of the 3β-alcohol **21** (340 mg, 1.27 mmol) in 4 mL of dry methylene chloride at 0 °C under nitrogen. The reaction mixture was stirred at 0 °C for 4 h and then diluted with 100 mL of ethyl acetate. The organic solution was washed with two 10-mL portions of 10% NaOH, dried (Na_2SO_4), and concentrated in vacuo to give 300 mg (83%) of **29**: ^{1}H NMR ($CDCl_3$) δ 3.82–4.29 (m), 3.78 (s) [9 H], 3.18 (d, 1 H, J = 5 Hz); mass spectrum, m/e (relative intensity) 284 (M^+, 0.2), 255 (8), 225 (20), 99 (100), 84 (2), 55 (30); mass spectrum calcd for $C_{14}H_{20}O_6$ m/e 284.1259, found m/e 284.1271.

(4aα,8aα)-1,2,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-4aβ-hydroxynaphthalene (28). A 30% hydrogen peroxide solution (220 μL, 2.15 mmol) was added via a syringe to a solution of the 3β-selenide **27** (164 mg, 0.362 mmol) in 12 mL of THF–pyridine (3:1) at −20 °C. The reaction mixture was stirred at −20 °C for 4 h and then diluted with 100 mL of ethyl acetate. The organic solution was washed with two 10-mL portions of brine, dried (Na_2SO_4), and concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:20), eluting with ether–hexane solutions, afforded 50 mg (52%) of **28**: ^{1}H NMR (360 MHz, $CDCl_3$) δ 5.77 (m, 1 H), 5.56 (d, 1 H, J = 10 Hz), 4.61 (s, 1 H), 3.91 (m, 4 H), 3.72 (s, 3 H), 1.49–2.33 (m, 10 H); IR (CCl_4) 3500 and 1725 cm^{-1}; mass spectrum, m/e (relative intensity) 268 (M^+, 2), 250 (16), 154 (21), 99 (100), 55 (16); mass spectrum calcd for $C_{14}H_{20}O_5$ m/e 268.1310, found m/e 268.1324.

(4α,4aα,8aα)-1,4,4a,5,6,7,8,8a-Octahydro-8aβ-carbomethoxy-7,7-ethylenedioxy-4β,4aβ-epoxy-3(2*H*)-oxonaphthalene (30). A solution of the β-epoxyalcohol **29** (300 mg, 1.06 mmol), pyridinium dichromate (1.2 g, 3.19 mmol), and pyridinium trifluoroacetate (164 mg, 0.85 mmol) in 8 mL of dry methylene chloride was stirred at room temperature overnight. The reaction mixture was filtered and the residue washed with additional methylene chloride. The organic solvent was concentrated in vacuo to afford an oil. Chromatography on silica gel G (1:10), eluting with an ether–hexane solution (1:1), gave 230 mg (77%) of **30** as an oil. Trituration with an ether–hexane solution afforded 160 mg (54%) of **30**: mp 136–138 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 3.98 (m, 4 H), 3.79 (s, 3 H), 3.00 (s, 1 H), 2.82 (dt, 1 H, J = 4.9, 13.6 Hz), 2.46 (m, 2 H), 2.20 (m, 2 H), 1.84 (m), 1.74 (d, J = 13.5 Hz) [4 H], 1.29 (m, 1 H); IR (KBr) 1690 (br) cm^{-1}; mass spectrum, m/e (relative intensity) 282 (M^+, 3), 223 (23), 99 (100), 55 (32); mass spectrum calcd for $C_{14}H_{18}O_6$ m/e 282.1102, found m/e 282.1102.

Registry No. **3**, 96792-15-3; **4**, 96792-16-4; **5**, 96792-17-5; **6**, 96792-18-6; **7**, 96792-19-7; **9**, 96792-20-0; **9** (lithium enolate), 96792-37-9; **11**, 96792-21-1; **12**, 96792-22-2; **13**, 96792-23-3; **14**, 96792-25-5; **15**, 96792-24-4; **16**, 96792-27-7; **17**, 96844-58-5; **18**, 96792-26-6; **19**, 96844-56-3; **20**, 96844-57-4; **21**, 96792-28-8; **22**, 96792-29-9; **23**, 96792-30-2; **24**, 96792-31-3; **25**, 96792-32-4; **26**, 96792-33-5; **27**, 96792-34-6; **28**, 96792-35-7; **29**, 96792-36-8; **30**, 96844-59-6; **i**, 96792-41-5; **ii**, 96792-42-6; **iii**, 96792-38-0; **iv**, 96792-39-1; **v**, 96792-40-4; dimethyl carbonate, 616-38-6; 4,4-ethylenedioxy-1-cyclohexanone, 4746-97-8; methyl vinyl ketone, 78-94-4; phenylselenenyl chloride, 5707-04-0; *o*-nitrophenyl selenocyanate, 51694-22-5.