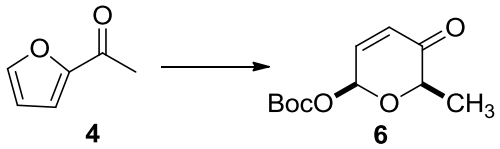
The preparation of compound 6, 7, 8, 9, 13, 14, 18, 19, 29 and their charaterization can be found in manuscript, but we include all the information in this supporting information for the readers' convenience.

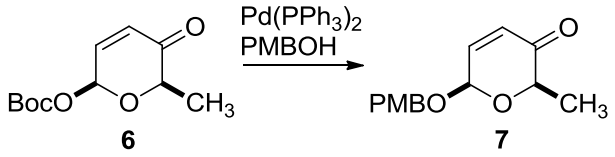
Preparation of Tert-butyl ((2*S*,6*R*)-6-methyl-5-oxo-5,6-dihydro-2*H*-pyran-2-yl) carbonate(6)



4 6

To a 1000 mL flask was added furan ketone 9 (40 g, 363.5 mmol), CH2Cl2 (240 mL), formic acid/triethylamine (5:4 (molar ratio), 480 mL) and Noyori asymmetric transfer hydrogenation catalyst (R)-Ru(η 6-mesitylene)-(R, R)-TsDPEN (222 mg, 0.1 mol%). The resulting solution was stirred at room temperature for 24 h. The reaction mixture was diluted with water (500 mL) and extracted with EtOAc (3 x 700 mL). The combined organic layers were washed with saturated NaHCO3, dried over Na2SO4, and concentrated under reduced pressure. The resulting crude furan alcohol 10 was dissolved in 603 mL of THF/H2O (3:1) and cooled to 0 oC. Solid NaHCO3 (60.9 g, 727.8 mmol), NaOAc•3H2O (49.6 g, 363.9 mmol), and NBS (64.3 g, 363.7 mmol) were added to the solution and the mixture was stirred for 1 h at 0 oC. The reaction was quenched with saturated NaHCO3 (600 mL), extracted (3 x 800 mL) with Et2O, dried (Na2SO4), concentrated under reduced pressure. The crude mixture 11 was dissolved in CH2Cl2 (500mL) and the solution was cooled to -78 oC. (Boc)2O (93 g, 400 mmol) and a catalytic amount of DMAP (1.5 g) was added to the reaction mixture. The reaction was stirred for 12 h at -78 to -30 oC, and quenched with saturated NaHCO3, extracted with Et2O, dried (Na2SO4), and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 6% EtOAc/Hexane to give 46.1 g (201.9 mmol, 60%) of Boc-protected pyranone (ent)-8: Rf (20% Et2O/Hexane) = 0.58;[α]25D = - 98 (c = 1.0, CH2Cl2); 1H NMR (600 MHz, CDCl3) δ 6.78 (dd, J = 10.2, 3.6 Hz, 1H), 6.22(d, J = 3.6 Hz, 1H), 6.09 (d, J = 10.2 Hz, 1H), 4.53 (q, J = 6.6 Hz, 1H), 1.40 (s, 9H), 1.28(d, J = 6.6 Hz, 3H); 13C NMR (150 MHz, CDCl3) δ 195.5, 151.7, 140.9, 128.2, 89.1, 83.3,72.0, 27.5, 15.1; ClHRMS: Calculated for [C11H16O5Na+]: 251.0890, Found: 251.0883.

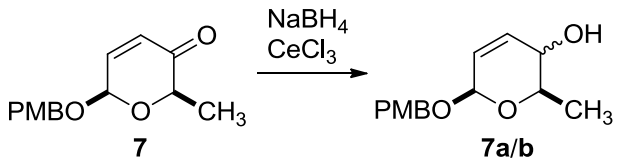
Preparation of (2*R*,6*R*)-6-((4-methoxybenzyl)oxy)-2-methyl-2*H*-pyran-3(6*H*)-one(7)



6 **7**

A CH_2Cl_2 (34 mL) solution of **6** (7.73 g, 33.9 mmol) and 4-methoxybenzyl alcohol (8.48 mL, 67.8 mmol) was cooled to 0 ℃, and a solution of $Pd_2(dba)_3$•$CHCl_3$ (351 mg, 0.339 mmol, 1 mol %) and PPh_3 (335 mg, 1.36 mmol, 4 mol %) in CH_2Cl_2 (10 mL) was added to the reaction mixture at 0 ℃. The reaction mixture was stirred at 0 ℃ for 2 h. The reaction was quenched with satd. aqueous $NaHCO_3$, extracted with ether (3 x 100 mL), dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 5% EtOAc/hexanes to give pyranone **7** (8.00 g, 32.2 mmol, 95%) as a yellow oil: R_f (10% EtOAc/hexanes) = 0.15; $[\alpha]_D^{24}$ = -24.7 (*c* = 1.1, CH_2Cl_2); ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.30 (d, *J* = 7.8 Hz, 2H), 6.90 (*J* = 7.8 Hz, 2H), 6.86 (dd, *J* = 10.2, 0.6 Hz, 1H), 6.12 (d, *J* = 10.2, 0.6 Hz, 1H), 5.37 (d, *J* = 1.2 Hz, 1H), 4.87 (d, *J* = 11.4 Hz, 1H), 4.62 (d, *J* = 11.4 Hz, 1H), 4.22 (q, *J* = 6.6 Hz, 1H), 3.81 (s, 3H), 1.52 (d, *J* = 6.6 Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 196.8, 159.6, 146.7, 129.9, 128.9, 128.1, 114.0, 94.0, 75.3, 69.8, 55.3, 17.3; CIHRMS Calcd. For $[C_{14}H_{16}O_4H]^+$: 249.1127. Found 249.1122

Preparation of (2*R*,6*R*)-6-((4-methoxybenzyl)oxy)-2-methyl-3,6-dihydro-2*H*-pyran-3-ol(7a/b)

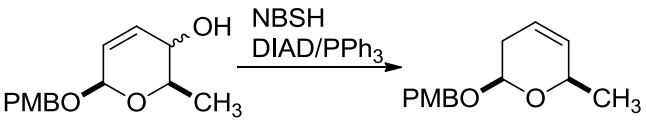


7 **7a/b**

Pyranone **7** (7.84 g, 31.6 mmol) was dissolved in CH_2Cl_2 (31.6 mL), resulting solution was cooled to -78 ℃, 0.4 M $CeCl_3$ in methanol solution (12.6 mmol, 31.6 mL) was added in a dropwise fashion, followed by adding $NaBH_4$ (1.20 g, 31.6 mmol). By TLC tracking, the reaction was done after 1.5 h. The reaction mixture was diluted with ether (6 mL), then quenched with water (6 mL), extracted with ether (3 x 60 mL), dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give allylic alcohol **7a**/**b** as a mixture of diastereomers (7.83 g, 31.3 mmol, 99%) as a colorless oil: R_f (30%

EtOAc/hexanes) = 0.45; $[\alpha]_D^{21}$ = -64.5 (*c* = 1.0, CH_2Cl_2); **7a:** ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.29 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.4 Hz, 2H), 6.13 (ddd, *J* = 10.2, 5.4, 1.8 Hz, 1H), 5.82 (d, *J* = 10.2 Hz, 1H), 5.10 (brs, 1H), 4.82 (d, *J* = 11.4 Hz, 1H), 4.58 (d, *J* = 11.4 Hz, 1H), 3.79 (s, 3H), 3.74-3.70 (m, 1H), 3.66 (brs, 1H), 2.03 (brs, 1H), 1.33 (d, *J* = 6.6 Hz, 3H); **7b:** ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.29 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.4 Hz, 2H), 5.92 (d, *J* = 10.2 Hz, 1H), 5.75 (d, *J* = 10.2 Hz, 1H), 5.15 (brs, 1H), 4.78 (d, *J* = 11.4 Hz, 1H), 4.54 (d, *J* = 11.4 Hz, 1H), 3.89 (br, 1H), 3.79 (s, 3H), 3.65-3.61 (m, 1H), 2.24 (brs, 1H), 1.37 (d, *J* = 6.6 Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) major isomer δ 159.3, 131.2, 129.7, 129.6, 113.8, 96.7, 71.5, 69.6, 68.4, 64.8, 55.3, 16.6; CIHRMS Calcd. For $[C_{14}H_{18}O_4Na]^+$: 273.1103. Found 273.1100

Preparation of (2*R*,6*R*)-2-((4-methoxybenzyl)oxy)-6-methyl-3,6-dihydro-2*H*-pyran(8)

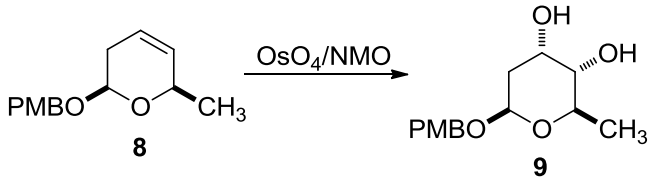


7a/b **8**

A flask charged with dry *N*-Methyl morpholine (NMM) (60 mL), triphenyl phosphine (24.0 g, 91 mmol) was cooled to -30 ℃ under argon atmosphere. Diisopropyl azodicarboxylate (16.5 mL, 83 mmol) was added and the reaction was stirred for 5 min, allylic alcohol **7a**/**b** (6.9 g, 27.6 mmol) was added to in a 1 M of NMM (27.6 mL), the resulting reaction mixture was stirred for 10 min, followed by addition of NBSH (18.0 g, 83 mmol). The reaction was stirred at -30 ℃ for 2 h and was monitored by TLC. Upon consumption of **7a**/**b**, the reaction was warmed to room temperature and stirred for another 2 h. The reaction mixture was diluted with ether (60 mL) and was quenched with satd. aqueous $NaHCO_3$, extracted with ether (3 x 150 mL), dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 5% EtOAc/hexanes to give product **8** (6.07 g, 25.9 mmol, 94%) as a colorless oil: R_f (20% EtOAc/hexanes) = 0.55; $[\alpha]_D^{24}$ = -106 (*c* = 1.0, CH_2Cl_2); ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.30 (d, *J* = 8.4 Hz, 2H), 6.88 (d, *J* = 7.8 Hz, 2H), 5.67 (dddd, *J* = 9.6, 2.4, 1.2, 1.2 Hz, 1H), 5.58 (dddd, *J* = 9.6, 5.4, 2.4, 2.4 Hz, 1H), 4.86 (d, *J* = 12.0 Hz, 1H), 4.72 (dd, *J* = 8.4, 3.0 Hz, 1H), 4.55 (d, *J* = 12.0 Hz, 1H), 4.34-4.32 (m, 1H), 3.80 (s, 3H), 2.26-2.20 (m, 1H), 2.16-2.11 (m, 1H), 1.32 (d, *J* = 6.6 Hz, 3H); ^{13}C

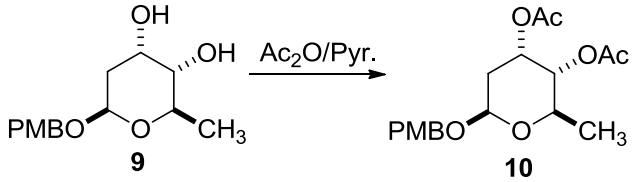
NMR (150 MHz, $CDCl_3$) δ 159.2, 130.9, 130.0, 129.6, 122.5, 113.8, 97.4, 70.6, 69.4, 55.2, 31.0, 21.2; CIHRMS Calcd. For $[C_{14}H_{18}O_3Na]^+$: 257.1154. Found 257.1148

Preparation of (2*R*,3*S*,4*S*,6*R*)-6-((4-methoxybenzyl)oxy)-2-methyltetrahydro-2*H*-pyran-3,4-diol(9)



To a *t*-butanol, acetone (8.9 mL each, 1:1) solution of pyran **8** (2.07 g, 8.85 mmol) at 0 ℃ was added a solution of (50% w/v) of *N*-methyl morpholine *N*-oxide / water (8.9 mL). Crystalline OsO_4 (22.5 mg, 0.0885 mmol) was added and the reaction was stirred for 12 h. The reaction was quenched with EtOAc and satd. aqueous $NaHCO_3$. The organic layer was separated and concentrated. The crude product was purified using silica gel flash chromatography eluting with 50% EtOAc/hexanes to give diol **9** (2.17 g, 8.09 mmol, 91%) as a colorless oil: R_f (50% EtOAc/hexanes) = 0.20; $[\alpha]_D^{21}$ = -57.8 (*c* = 1.0, CH_2Cl_2); ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.27 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.4 Hz, 2H), 4.88 (dd, *J* = 9.6, 2.4 Hz, 1H), 4.81 (d, *J* = 11.4 Hz, 1H), 4.50 (d, *J* = 11.4 Hz, 1H), 4.11 (d, *J* = 3.0 Hz, 1H), 3.80 (s, 3H), 3.74 (dq, *J* = 9.0, 6.6 Hz, 1H), 3.33 (dd, *J* = 9.6, 3.6 Hz, 1H), 2.15 (brs, 2H), 2.10 (ddd, *J* = 15.0, 2.4, 2.4 Hz, 1H), 1.77 (ddd, *J* = 14.0, 11.4, 3.0 Hz, 1H), 1.34 (d, *J* = 6.0 Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 159.3, 129.8, 129.6, 113.8, 96.7, 73.1, 70.2, 69.4, 68.0, 55.3, 37.7, 18.1; CIHRMS Calcd. For $[C_{14}H_{20}O_5Na]^+$: 291.1208. Found 291.1205.

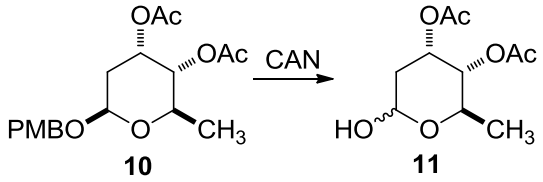
Preparation of (2*R*,3*R*,4*S*,6*R*)-6-((4-methoxybenzyl)oxy)-2-methyltetrahydro-2*H*-pyran-3,4-diyl diacetate(10)



To a solution of **9** (537 mg, 2.00 mmol) in pyridine (4.5 mL) was added Ac_2O (3.0 mL) at 0 ^{o}C. After stirring at room temperature overnight, the reactant was quenched with satd. aqueous $NaHCO_3$, extracted with EtOAc, dried over Na_2SO_4, and concentrated under

reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **10** (650 mg, 1.84 mmol, 92%) as a colorless oil: R_f (20% EtOAc/hexanes) = 0.10; $[\alpha]_D^{23}$ = -14.4 (*c* = 0.80, CH_2Cl_2); IR (thin film, cm^{-1}) 2937, 1742, 1613, 1514, 1367, 1242, 1224, 1152, 1053, 1007, 820; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.27 (d, *J* = 8.8 Hz, 2H), 6.88 (d, *J* = 8.0 Hz, 2H), 5.46 (dd, *J* = 6.8, 3.2 Hz, 1H), 4.88 (dd, *J* = 9.6, 2.8 Hz, 1H), 4.84 (d, *J* = 11.2 Hz, 1H), 4.62 (dd, *J* = 9.6, 2.8 Hz, 1H), 4.50 (d, *J* = 12.0 Hz, 1H), 3.95 (dq, *J* = 9.2, 6.4 Hz, 1H), 3.80 (s, 3H), 2.08 (s, 3H), 2.05 (ddd, *J* = 14.0, 2.8, 2.0 Hz, 1H), 2.01 (s, 3H), 1.91 (ddd, *J* = 14.4, 9.6, 3.2 Hz, 1H), 1.26 (d, *J* = 6.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.0, 169.9, 159.3, 129.6, 129.5, 113.8, 96.9, 72.5, 70.2, 68.2, 67.3, 55.2, 35.5, 21.0, 20.8, 17.9; ESI-HRMS calcd for $[C_{18}H_{24}O_7Na]^+$: 375.1414, found 375.1427.

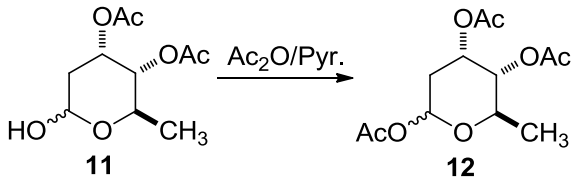
Preparation of (2*R*,3*R*,4*S*)-6-hydroxy-2-methyltetrahydro-2*H*-pyran-3,4-diyl diacetate(11)



To a solution of **10** (640 mg, 1.82 mmol) in CH_3CN/H_2O (18 mL/1.8 mL) was added CAN (2.29 g, 4.18 mmol) at room temperature. After stirring at room temperature for 1 h, the reactant was then poured into satd. aqueous $NaHCO_3$, extracted with EtOAc, dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 50% EtOAc/hexanes to give **11** (405 mg, 1.74 mmol, α:β = 3:1, 96%) as a colorless oil: R_f (50% EtOAc/hexanes) = 0.32; $[\alpha]_D^{23}$ = +65.9 (*c* = 0.90, CH_2Cl_2); IR (thin film, cm^{-1}) 3436, 2979, 2938, 1741, 1371, 1247, 1227, 1155, 1054, 947, 859; ^{1}H NMR (400 MHz, $CDCl_3$) major isomer (α): δ 5.40-5.37 (m, 1H), 5.09 (dd, *J* = 9.6, 2.4 Hz, 1H), 4.52 (dd, *J* = 10.4, 3.2 Hz, 1H), 4.30 (br, 1H), 3.94 (dq, *J* = 9.6, 6.0 Hz, 1H), 2.05 (s, 3H), 2.03 (ddd, *J* = 14.0, 3.6, 3.2 Hz, 1H), 1.95 (s, 3H), 1.78 (ddd, *J* = 14.8, 9.6, 3.2 Hz, 1H), 1.16 (d, *J* = 6.4 Hz, 3H); minor isomer (β): δ 5.40-5.37 (m, 1H), 5.16 (dd, *J* = 2.8, 2.8 Hz, 1H), 4.58 (dd, *J* = 9.6, 3.2 Hz, 1H), 4.30 (br, 1H), 4.28(dq, *J* = 8.8, 6.8 Hz, 1H), 2.08 (s, 3H), 2.07-2.03 (m, 1H), 1.95 (s, 3H), 2.00-1.90 (m, 1H), 1.15 (d, *J* = 6.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) major isomer (α): δ

170.0(2C), 92.1, 72.3, 67.9, 67.3, 36.7, 20.7, 20.6, 17.7; minor isomer (β): δ 169.9(2C), 90.4, 72.0, 66.9, 62.0, 33.7, 20.9, 20.8, 17.3; ESI-HRMS calcd for $[C_{10}H_{16}O_6Na]^+$: 255.0839, found 255.0850.

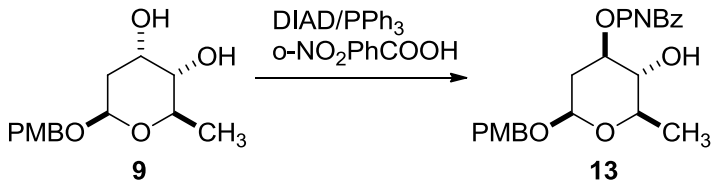
Preparation of (4*S*,5*R*,6*R*)-6-methyltetrahydro-2*H*-pyran-2,4,5-triyl triacetate(12)



11 12

To a solution of **11** (395 mg, 1.70 mmol) in pyridine (3.8 mL) was added DMAP (cat.) and Ac_2O (2.5 mL) at 0 ^oC. After stirring at room temperature overnight, the reactant was quenched with satd. aqueous $NaHCO_3$, extracted with EtOAc, dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **12** (427 mg, 1.56 mmol, α:β = 1:4, 92%) as a colorless oil: R_f (20% EtOAc/hexanes) = 0.17; $[\alpha]_D^{20}$ = +55.9 (*c* = 1.3, CH_2Cl_2); IR (thin film, cm^{-1}) 2982, 2940, 1741, 1434, 1368, 1216, 1145, 1053, 1023, 981; ^1H NMR (400 MHz, $CDCl_3$) δ major isomer (β): δ 6.04 (dd, *J* = 9.6, 2.0 Hz, 1H), 5.49 (dd, *J* = 7.2, 2.8 Hz, 1H), 4.63 (dd, *J* = 9.6, 2.8 Hz, 1H), 4.09 (dq, *J* = 8.8, 6.0 Hz, 1H), 2.10 (s, 6H), 2.06-2.04 (m, 1H), 2.02 (s, 3H), 1.99-1.93 (m, 1H), 1.23 (d, *J* = 5.6 Hz, 3H); minor isomer (α): δ 6.08 (d, *J* = 3.6 Hz, 1H), 5.32 (dd, *J* = 6.4, 3.2 Hz), 4.67 (dd, *J* = 10.4, 3.2 Hz, 1H), 4.30 (dq, *J* = 9.6, 6.0 Hz, 1H), 2.10 (s, 3H), 2.09 (s, 3H), 2.08-2.06 (m, 1H), 2.04 (s, 3H), 2.00-1.93 (m, 1H), 1.20 (d, *J* = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) major isomer (β): δ 170.0(2C), 169.2, 90.5, 71.9, 69.4, 66.6, 34.0, 21.1, 20.9, 20.7, 17.9; minor isomer (α): δ 169.8(2C), 169.4, 90.1, 71.8, 65.8, 64.1, 32.2, 21.1, 21.0, 20.7, 17.4; ESI-HRMS calcd for $[C_{12}H_{18}O_7Na]^+$: 297.0945, found 297.0961.

Preparation of (2*R*,3*R*,4*R*,6*R*)-3-hydroxy-6-((4-methoxybenzyl)oxy)-2-methyltetrahydro-2*H*-pyran-4-yl 4-nitrobenzoate(13)

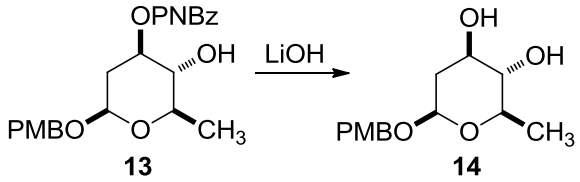


9 13

To a THF (45 mL) solution of diol **9** (2.17 g, 8.09 mmol) at 0 ℃ was added PPh_3 (3.18 g, 12.2 mmol) and *p*-nitrobenzoic acid (2.68 g, 16.2 mmol), DIAD (2.6 mL, 13.0 mmol)

was added dropwise and the reaction mixture was warmed up to room temperature and stirred for 24 hours. The reaction mixture was diluted with EtOAc (100 mL), quenched with satd. aqueous $NaHCO_3$, extracted with ether (3 x 100 mL), dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 15% EtOAc/hexanes to give nitrobenzoate **13** (2.30 g, 5.51 mmol, 68%) as a white solid: R_f (30% EtOAc/hexanes) = 0.40; $[\alpha]_D^{24}$ = -38.2 (*c* = 0.5, CH_2Cl_2); ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.27 (d, *J* = 9.0 Hz, 2H), 8.19 (d, *J* = 9.0 Hz, 2H), 7.27 (d, *J* = 8.4 Hz, 2H), 6.88 (d, *J* = 8.4 Hz, 2H), 5.06 (ddd, *J* = 11.4, 8.4, 4.8 Hz, 1H), 4.83 (d, *J* = 11.4 Hz, 1H), 4.65 (dd, *J* = 9.6, 1.8 Hz, 1H), 4.56 (d, *J* = 11.4 Hz, 1H), 3.80 (s, 3H), 3.47 (dd, *J* = 9.6, 8.4 Hz, 1H), 3.41 (dq, *J* = 9.0, 6.0 Hz, 1H), 2.39 (ddd, *J* = 12.6, 5.4, 1.8 Hz, 1H), 1.85 (ddd, *J* = 12.0, 12.0, 9.6 Hz, 1H), 1.43 (d, *J* = 6.0 Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 164.8, 159.4, 150.7, 135.0, 130.8, 129.7, 129.2, 123.5, 113.9, 97.4, 75.7, 74.9, 72.0, 70.2, 55.3, 36.4, 17.8; CIHRMS Calcd. For $[C_{21}H_{23}NO_8Na]^+$: 440.1321. Found 440.1317

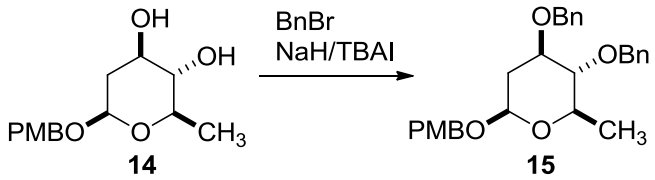
Preparation of (2*R*,3*S*,4*R*,6*R*)-6-((4-methoxybenzyl)oxy)-2-methyltetrahydro-2*H*-pyran-3,4-diol(14)



To a solution of **13** (1.25 g, 3.00 mmol) in THF/H_2O (35 mL/7 mL) was added LiOH (144 mg, 6.00 mmol) and the reaction mixture was stirred for 1 h at room temperature. The reaction mixture was quenched with satd. aqueous $NaHCO_3$, extracted with CH_2Cl_2, dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 50% EtOAc/hexanes to give **14** (710 mg, 2.65 mmol, 88%) as a white solid: R_f (50% EtOAc/hexanes) = 0.10; mp: 68–70 ℃; $[\alpha]_D^{20}$ = -60.6 (*c* = 1.9, CH_2Cl_2); IR (thin film, cm^{-1}) 3393, 2933, 1613, 1514, 1453, 1249, 1067, 821; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26 (d, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.8 Hz, 2H), 4.80 (d, *J* = 11.6 Hz, 1H), 4.50 (d, *J* = 10.8 Hz, 2H), 3.79 (s, 3H), 3.51 (ddd, *J* = 11.6, 8.0, 4.4 Hz, 1H), 3.29 (br, 2H), 3.22 (dq, *J* = 8.8, 6.0 Hz, 1H), 3.06 (dd, *J* = 9.2, 8.8 Hz, 1H), 2.15 (ddd, *J* = 12.4, 4.8, 1.6 Hz, 1H), 1.63 (ddd, *J* = 12.4, 11.6, 9.6 Hz,

1H), 1.33 (d, *J* = 6.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.3, 129.7, 129.3, 113.8, 98.0, 77.4, 71.6, 71.5, 70.1, 55.2, 38.9, 17.7; EI-HRMS calcd for $[C_{14}H_{20}O_5]^+$: 268.1305, found 268.1308.

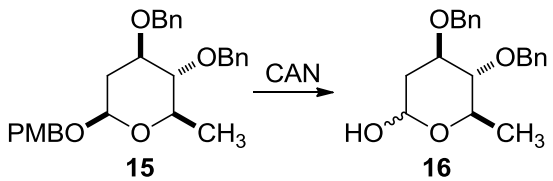
Preparation of (2*R*,3*R*,4*R*,6*R*)-3,4-bis(benzyloxy)-6-((4-methoxybenzyl)oxy)-2-methyltetrahydro-2*H*-pyran(15)



14 **15**

To a solution of **14** (623 mg, 2.32 mmol) in dry DMF (12 mL) was added NaH (460 mg, *ca.* 60% in oil, 11.6 mmol). After stirring at room tempetature for 10 min, BnBr (1.0 mL, 5.80 mmol) and TBAI (85 mg, 0.232 mmol) were then added at 0 ^{o}C and the mixture was stirred at room temperature for 1 h. The reactant was then poured into satd. aqueous NH_4Cl and extracted with EtOAc, dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 10% EtOAc/hexanes to give **15** (936 mg, 2.09 mmol, 90%) as a colorless oil: R_f (EtOAc/hexanes = 10/1) = 0.21; $[\alpha]_D^{22}$ = -59.3 (*c* = 1.5, CH_2Cl_2); IR (thin film, cm^{-1}) 2933, 1612, 1513, 1454, 1247, 1092, 1070, 750, 698; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35-7.27 (m, 12H), 6.89 (d, *J* = 8.8 Hz, 2H), 4.96 (d, *J* = 10.8 Hz, 1H), 4.83 (d, *J* = 11.6 Hz, 1H), 4.67 (d, *J* = 11.2 Hz, 2H), 4.56 (d, *J* = 11.2 Hz, 1H), 4.51 (d, *J* = 11.6 Hz, 1H), 4.48 (ddd, *J* = 11.2, 8.4, 2.8 Hz, 1H), 3.81 (s, 3H), 3.62 (ddd, *J* = 14.0, 8.8, 5.2 Hz, 1H), 3.35 (dq, *J* = 9.6, 6.4 Hz, 1H), 3.17 (dd, *J* = 8.8, 8.8 Hz, 1H), 2.35 (ddd, *J* = 12.4, 5.2, 2.0 Hz, 1H), 1.65 (ddd, *J* = 12.4, 11.6, 9.6 Hz, 1H), 1.38 (d, *J* = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.3, 138.5, 138.3, 129.7, 129.5, 128.4(2C), 128.3, 128.0, 127.7, 127.6(2C), 113.8, 98.0, 83.7, 79.3, 75.2, 71.3, 70.0, 55.2, 36.9, 18.2; ESI-HRMS calcd for $[C_{28}H_{32}O_5Na]^+$: 471.2142, found 471.2151.

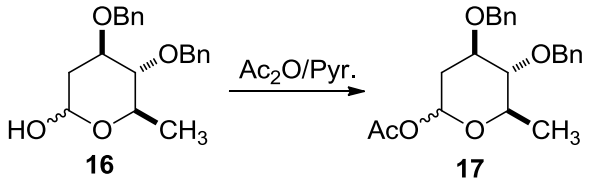
Preparation of (4*R*,5*R*,6*R*)-4,5-bis(benzyloxy)-6-methyltetrahydro-2*H*-pyran-2-ol(16)



15 **16**

To a solution of **15** (647 mg, 1.44 mmol) in CH_3CN/H_2O (14.4 mL/1.44 mL) was added CAN (1.82 g, 3.32 mmol) at room temperature. After stirring at room tempetature for 1 h, the reactant was then poured into satd. aqueous $NaHCO_3$ and extracted with EtOAc, dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **16** (397 mg, 1.21 mmol, α:β = 1.6:1, 84%) as a white solid: R_f (20% EtOAc/hexanes) = 0.17; mp: 93–95 ℃; $[\alpha]_D^{23}$ = +25.4 (*c* = 1.0, CH_2Cl_2); IR (thin film, cm^{-1}) 3354, 2985, 1497, 1397, 1306, 1090, 1029, 997, 750, 694; ^{1}H NMR (400 MHz, $CDCl_3$) major isomer (α): *δ* 7.37-7.28 (m, 10H), 5.33 (d, *J* = 2.8 Hz, 1H), 4.96 (d, *J* = 10.4 Hz, 1H), 4.69-4.64 (m, 3H), 4.05-3.96 (m, 2H), 3.15 (dd, *J* = 9.6, 8.8 Hz, 1H), 2.77 (br, 1H), 2.32 (dd, *J* = 13.2, 5.6 Hz, 1H), 1.68 (ddd, *J* = 14.4, 13.2, 3.6 Hz, 1H), 1.28 (d, *J* = 6.8 Hz, 3H); minor isomer (β): *δ* 7.37-7.28 (m, 10H), 4.96 (d, *J* = 10.8 Hz, 1H), 4.75 (dd, *J* = 9.6, 1.2 Hz, 1H), 4.71-4.60 (m, 3H), 3.64 (ddd, *J* = 13.2, 8.8, 5.2 Hz, 1H), 3.44 (br, 1H), 3.40 (dq, *J* = 9.6, 6.0 Hz, 1H), 3.15 (dd, *J* = 8.8, 8.8 Hz, 1H), 2.41 (ddd, *J* = 12.8, 5.2, 1.6 Hz, 1H), 1.56 (ddd, *J* = 12.8, 11.6, 9.6 Hz, 1H), 1.33 (d, *J* = 5.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) major isomer (α): *δ* 138.6, 138.5, 128.4, 128.3, 128.0(2C), 127.6(2C), 91.9, 84.2, 76.8, 75.2, 71.8, 67.4, 35.7, 18.2; minor isomer (β): *δ* 138.3, 138.2, 128.4, 128.3, 128.0(2C), 127.7, 127.6, 93.8, 83.3, 78.9, 75.2, 71.5, 71.4, 38.3, 18.2; ESI-HRMS calcd for $[C_{20}H_{24}O_4Na]^+$: 351.1567, found 351.1580.

Preparation of (4*R*,5*R*,6*R*)-4,5-bis(benzyloxy)-6-methyltetrahydro-2*H*-pyran-2-ol(17)

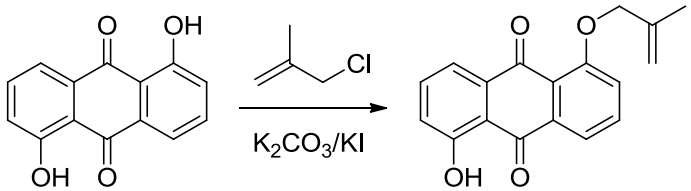


16 **17**

To a solution of **16** (460 mg, 1.40 mmol) in pyridine (3.2 mL) was added Ac_2O (2.1 mL) at 0 ^{o}C. After stirring at room tempetature overnight, the reactant was quenched with satd. aqueous $NaHCO_3$, extracted with EtOAc, dried over Na_2SO_4, and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 10% EtOAc/hexanes to give **17** (515 mg, 1.39 mmol, α:β = 2.8:1, 99%) as a colorless oil: R_f (EtOAc/hexanes = 10/1) = 0.32; $[\alpha]_D^{22}$ = +48.0 (*c* = 0.9, CH_2Cl_2); IR (thin film, cm^{-1}) 2932, 1750, 1454, 1366, 1275, 1260, 1100, 1028, 971, 750, 698; ^{1}H NMR

(400 MHz, $CDCl_3$) major isomer (α): δ 7.37-7.30 (m, 10H), 6.18 (d, J = 2.4 Hz, 1H), 4.99 (d, J = 10.0 Hz, 1H), 4.71-4.68 (m, 3H), 3.95 (ddd, J = 13.2, 8.8, 4.8 Hz, 1H), 3.84 (dq, J = 10.0, 6.8 Hz, 1H), 3.21 (dd, J = 9.6, 8.8 Hz, 1H), 2.30 (ddd, J = 14.0, 5.2, 1.6 Hz, 1H), 2.07 (s, 3H), 1.81 (ddd, J = 14.4, 13.2, 3.2 Hz, 1H), 1.32 (d, J = 5.6 Hz, 3H); minor isomer (β): δ 7.37-7.30 (m, 10H), 5.69 (dd, J = 10.0, 1.6 Hz, 1H), 4.97 (d, J = 11.2 Hz, 1H), 4.72-4.62 (m, 3H), 3.71 (ddd, J = 14.0, 8.8, 5.6 Hz, 1H), 3.50 (dq, J = 9.2, 5.6 Hz, 1H), 3.18 (dd, J = 8.8, 8.8 Hz, 1H), 2.39 (ddd, J = 12.4, 4.8, 2.0 Hz, 1H), 2.12 (s, 3H), 1.77 (ddd, J = 12.8, 12.0, 10.0 Hz, 1H), 1.36 (d, J = 5.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) major isomer (α): δ 169.4, 138.3, 138.2, 128.4(2C), 128.0(2C), 127.6, 127.6, 91.7, 83.5, 76.6, 75.3, 71.7, 69.7, 34.4, 21.0, 18.2; minor isomer (β): δ 169.1, 138.2, 138.0, 128.4(2C), 128.0(2C), 127.7, 127.6, 91.8, 83.0, 78.7, 75.2, 72.3, 71.6, 35.6, 21.0, 18.0; ESI-HRMS calcd for $[C_{22}H_{26}O_5Na]^+$: 393.1672, found 393.1688.

Preparation of 1-hydroxy-5-((2-methylallyl)oxy)anthracene-9,10-dione(5a)

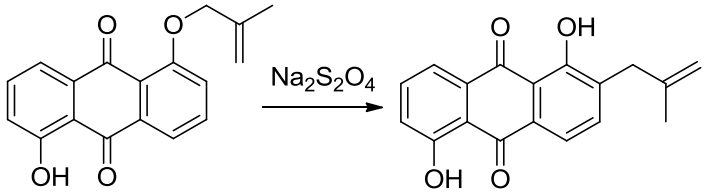


5 **5a**

A mixture of 1,5-dihydroxyanthracene-9,10-dione (7.20 g, 30.0 mmol), methallyl chloride (4.40 mL, 40.5 mmol), anhydrous potassium carbonate (22.9 g, 166 mmol), and potassium iodide (1.76 g, 10.5 mmol) in DMF (400 mL) was stirred at 75 ^{o}C for 7 h under argon. The mixture was filtered and the purple solid was washed with acetone. The solvent removed under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 10% EtOAc/hexanes to give ether **5a** (3.70 g, 12.6 mmol, 42%) as an orange solid: R_f (20% EtOAc/hexanes) = 0.50; ^{1}H NMR (600 MHz, $CDCl_3$) δ 12.45 (s, 1H), 7.94 (dd, J = 7.8, 1.2 Hz, 1H), 7.76 (dd, J = 7.8, 1.2 Hz, 1H), 7.68-7.62 (m, 2H), 7.31 (d, J = 8.4 Hz, 1H), 7.22 (dd, J = 8.4, 1.2 Hz, 1H), 5.35 (s, 1H), 5.09 (s, 1H), 4.63 (s, 2H), 1.92 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 188.6, 181.3, 161.9, 159.5, 139.6, 136.8, 135.3, 135.0, 134.8, 122.8, 121.7, 119.8, 119.5, 119.3, 115.6, 113.3, 72.8, 19.3 CIHRMS Calcd. For $[C_{14}H_{16}O_4H]^+$: 249.1127. Found 249.1122

Ref.: Beauregard, D. A.; Cambie, R. C.; Higgs, K. C.; Rutledge, P. S.; Woodgate, P. D. *Aust. J. Chem.* **1994**, *47*, 1321-1333.

Preparation of 1,5-dihydroxy-2-(2-methylallyl)anthracene-9,10-dione(5b)

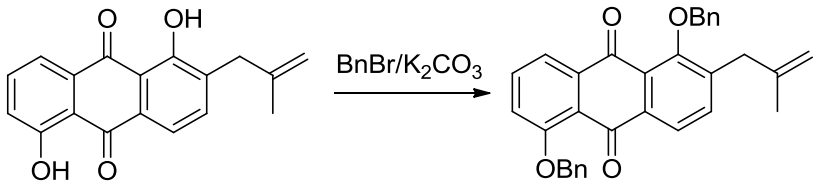


5a **5b**

A solution of the ether **5a** (883 mg, 3.00 mmol) in DMF (100 mL) was added to a heated (90 ^{o}C) solution of sodium dithionite (1.04 g, 6.00 mmol) in water (200 mL) and DMF (100 mL) under argon, and the mixture was heated under reflux for 3 h. Sodium hydroxide (0.30 g, 7.50 mmol) was added and the refluxing continued for a further 0.75 h. The mixture was cooled to room temperature, and then it was extracted with EtOAc (200 mL) for three times. The combined organic layers were washed with water for five times, dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 10% EtOAc/hexanes to give diphenol **5b** (790 mg, 2.68 mmol, 89%) as an orange solid: R_f (10% EtOAc/hexanes) = 0.35; ^{1}H NMR (600 MHz, $CDCl_3$) δ 13.05 (s, 1H), 12.70 (s, 1H), 7.85 (dd, J = 7.8, 1.2 Hz, 1H), 7.81 (d, J = 7.2 Hz, 1H), 7.68 (dd, J = 7.8, 7.8 Hz, 1H), 7.57 (d, J = 7.8 Hz, 1H), 7.32 (dd, J = 8.4, 0.6 Hz, 1H), 4.90 (s, 1H), 4.74 (s, 1H), 3.49 (s, 2H), 1.78 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 188.2, 187.8, 162.7, 161.2, 143.0, 137.0, 136.5, 133.3, 131.4, 124.8, 119.3, 119.2, 119.0, 116.1, 115.5, 112.9, 37.4, 22.5.

Ref.: Bercich, M. D.; Cambie, R. C.; Howe, T. A.; Rutledge, P. S.; Thomson, S. D.; Woodgate, P. D. *Aust. J. Chem.* **1995**, *48*, 531-549.

Preparation of 1,5-bis(benzyloxy)-2-(2-methylallyl)anthracene-9,10-dione(5c)

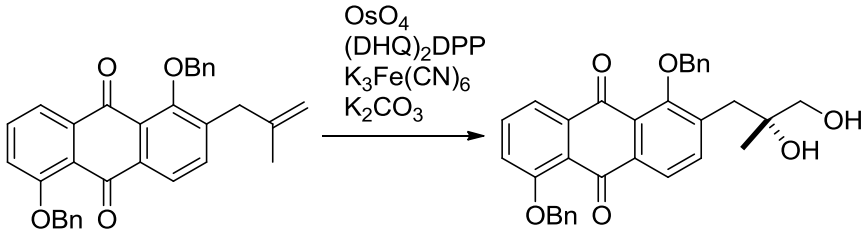


5b **5c**

Benzyl bromide (1.07 mL, 9.00 mmol) and potassium carbonate (4.15 g, 30.0 mmol) were added to a solution of diphenol **5b** (883 mg, 3.00 mmol) in acetone (150 mL), and

the mixture was heated at reflux overnight. The mixture was filtered and concentrated. The crude product was purified using silica gel flash chromatography eluting with 50% CH_2Cl_2/hexanes to give ether **5c** (1.26 g, 2.66 mmol, 89%) as a yellow solid: R_f (20% EtOAc/hexanes) = 0.52; mp: 109–110 ℃; IR (thin film, cm^{-1}) 1669, 1584, 1573, 1452, 1261, 1022, 697; ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.10 (d, J = 7.8 Hz, 1H), 7.94 (dd, J = 7.8, 0.6 Hz, 1H), 7.66-7.60 (m, 6H), 7.44-7.30 (m, 7H), 5.34 (s, 2H), 5.04 (s, 2H), 4.88 (s, 1H), 4.65 (s, 1H), 3.44 (s, 2H), 1.70 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 182.9, 182.2, 158.7, 156.9, 143.8, 141.0, 137.3, 137.2, 136.3, 136.1, 135.9, 134.7, 128.7, 128.5, 128.4, 128.1, 127.9, 126.8, 125.4, 123.4, 121.6, 120.1, 119.0, 113.1, 76.2, 71.0, 37.8, 22.6; ESI-HRMS calcd for $[C_{32}H_{26}O_4Na]^+$: 497.1723, found 497.1727.

Preparation of (*R*)-1,5-bis(benzyloxy)-2-(2,3-dihydroxy-2-methylpropyl)anthracene-9,10-dione(5d)

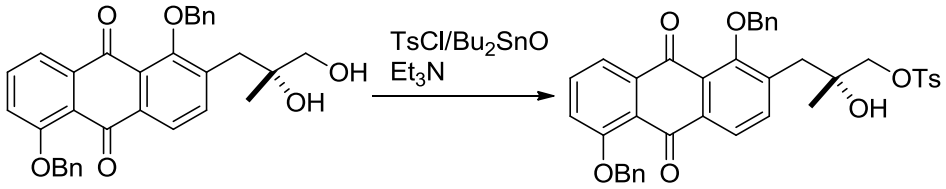


5c **5d**

A round-bottom flask was charged with *t*-BuOH (37 mL), water (37 mL), $K_3Fe(CN)_6$ (3.65 g, 11.1 mmol), K_2CO_3 (1.53 g, 11.1 mmol), $(DHQ)_2DPP$ (688 mg, 0.738 mmol), and OsO_4 (37.0 mg, 0.148 mmol). After the mixture was stirred at room temperature for 5 min, the mixture was cooled to 0 ^{o}C. Unsaturated ether **5c** (1.75 g, 3.69 mmol) was added at once, and the heterogeneous slurry was stirred vigorously for 6 h at 0 ^{o}C and then at room temprature overnight. Na_2SO_3 (2.00 g) was added, and the mixture was stirred for 1 h. EtOAc (20 mL) was added, and the aqueous layer was extracted with EtOAc for three times. The combined organic layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 50% EtOAc/hexanes to give diol **5d** (1.84 g, 3.62 mmol, 98%) as a yellow solid: R_f (50% EtOAc/hexanes) = 0.24; mp: 129–130 °C; $[\alpha]_D^{26}$ = +6.9 (c = 0.83, CH_2Cl_2, 88% ee); IR (thin film, cm^{-1}) 3453, 1669, 1585, 1570, 1264, 1015, 697; ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.12 (d, J = 7.8 Hz, 1H), 7.94 (dd, J = 7.8, 1.2 Hz, 1H), 7.68-7.60 (m,

6H), 7.46-7.32 (m, 7H), 5.34 (s, 2H), 5.08 (d, *J* = 10.2 Hz, 1H), 5.05 (d, *J* = 10.2 Hz, 1H), 3.29 (d, *J* = 10.8 Hz, 1H), 3.24 (d, *J* = 11.4 Hz, 1H), 2.97 (d, *J* = 13.2 Hz, 1H), 2.83 (d, *J* = 13.2 Hz, 1H), 2.27 (br, 2H), 1.07 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 182.6, 181.9, 158.7, 156.6, 138.7, 138.2, 137.1, 136.4, 136.2, 136.1, 134.9, 128.9, 128.8(2C), 128.7, 127.9, 126.8, 125.2, 123.7, 121.4, 120.2, 119.1, 76.9, 73.6, 71.0, 69.0, 39.2, 23.5; ESI-HRMS calcd for $[C_{32}H_{28}O_6Na]^+$: 531.1778, found 531.1778. The ee value was determined by the use of Mosher's reagent.

Preparation of (*R*)-3-(1,5-bis(benzyloxy)-9,10-dioxo-9,10-dihydroanthracen-2-yl)-2-hydroxy-2-methylpropyl 4-methylbenzenesulfonate(5e)

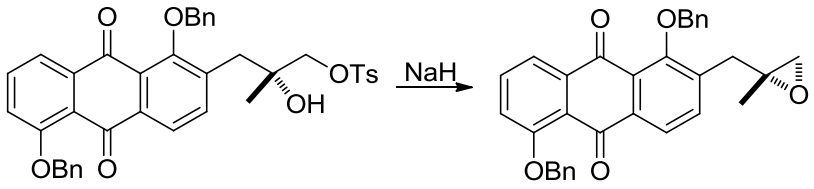


5d **5e**

To a solution of diol **5d** (1.83 g, 3.60 mmol) in dry CH_2Cl_2 (36.0 mL) were added dibutyltin oxide (~1 mg), *p*-toluenesulfonyl chloride (1.03 g, 5.40 mmol), triethylamine (0.75 mL, 5.40 mmol) at 0 ^{o}C. The reaction mixture was stirred at room temperature overnight. After completion of reaction the mixture was quenched with water. The layers were separated, and the water layer was extracted with CH_2Cl_2 for 3 times. The combined organic layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 3% EtOAc/CH_2Cl_2 to give **5e** (2.18 g, 3.29 mmol, 91%) as a yellow solid: R_f (20% EtOAc/hexanes) = 0.14; mp: 174–175 °C; $[\alpha]_D^{22}$ = +13.6 (*c* = 0.95, CH_2Cl_2); IR (thin film, cm^{-1}) 3492, 2930, 1670, 1586, 1265, 1176, 984, 843; ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.04 (d, *J* = 8.4 Hz, 1H), 7.93 (dd, *J* = 7.8, 1.2 Hz, 1H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.66 (dd, *J* = 8.4, 7.8 Hz, 1H), 7.62-7.54 (m, 5H), 7.44-7.30 (m, 9H), 5.35 (s, 2H), 5.07 (d, *J* = 10.8 Hz, 1H), 5.03 (d, *J* = 10.8 Hz, 1H), 3.76 (d, *J* = 9.6 Hz, 1H), 3.69 (d, *J* = 9.6 Hz, 1H), 3.19 (br, 1H), 2.99 (d, *J* = 13.8 Hz, 1H), 2.99 (d, *J* = 13.8 Hz, 1H), 2.76 (d, *J* = 13.8 Hz, 1H), 2.42 (s, 3H), 1.06 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 182.6, 181.8, 158.8, 156.7, 145.0, 138.0, 137.4, 137.2, 136.7, 136.3, 136.2, 134.9, 132.5, 129.9, 128.9, 128.8, 128.7, 128.6,

128.0, 127.9, 126.8, 125.2, 123.7, 121.5, 120.2, 119.1, 76.9, 75.5, 72.0, 71.1, 39.1, 24.2, 21.6; ESI-HRMS calcd for $[C_{39}H_{34}O_8SNa]^+$: 685.1867, found 685.1872.

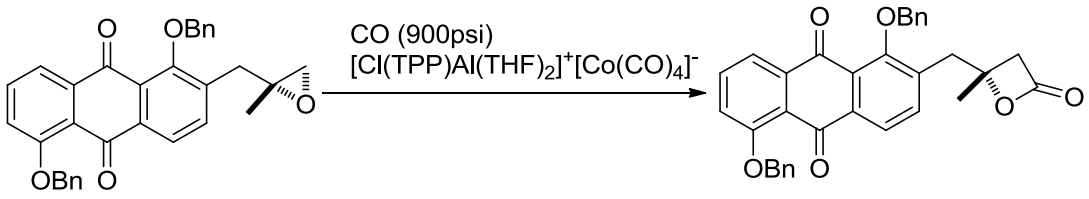
Preparation (*R*)-1,5-bis(benzyloxy)-2-((2-methyloxiran-2-yl)methyl)anthracene-9,10-dione(18)



5e **18**

To a solution of **5e** (331 mg, 0.50 mmol) in dry THF (50 mL) was added NaH (100 mg, *ca.* 60% in oil, 2.50 mmol) at 0 ^oC. The reaction mixture was stirred at room temperature overnight. After completion of reaction the mixture was quenched with water. The layers were separated, and the water layer was extracted with CH_2Cl_2 for three times. The combined organic layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give epoxide **18** (227 mg, 0.463 mmol, 92%) as a yellow solid: R_f (20% EtOAc/hexanes) = 0.26; mp: 114–115 °C; $[\alpha]_D^{21}$ = -27.9 (*c* = 0.26, CH_2Cl_2); IR (thin film, cm^{-1}) 2932, 1670, 1585, 1452, 1262, 1022, 699; ^1H NMR (600 MHz, $CDCl_3$) δ 8.09 (d, *J* = 8.4 Hz, 1H), 7.93 (dd, *J* = 7.8, 1.2 Hz, 1H), 7.72 (d, *J* = 7.8 Hz, 1H), 7.64 (dd, *J* = 8.4, 7.8 Hz, 1H), 7.61-7.58 (m, 4H), 7.44-7.31 (m, 7H), 5.34 (s, 2H), 5.09 (d, *J* = 10.8 Hz, 1H), 5.00 (d, *J* = 10.2 Hz, 1H), 3.00 (d, *J* = 14.4 Hz, 1H), 2.96 (d, *J* = 14.4 Hz, 1H), 2.55 (d, *J* = 4.8 Hz, 1H), 2.54 (d, *J* = 4.8 Hz, 1H), 1.25 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 182.8, 182.0, 158.7, 157.0, 138.3, 137.2, 137.0, 136.9, 136.3, 136.2, 134.8, 128.7, 128.6, 128.5, 128.2, 127.9, 126.8, 125.2, 123.3, 121.5, 120.1, 119.0, 76.5, 71.0, 56.6, 53.2, 36.2, 21.3; ESI-HRMS calcd for $[C_{32}H_{26}O_5Na]^+$: 513.1672, found 513.1681.

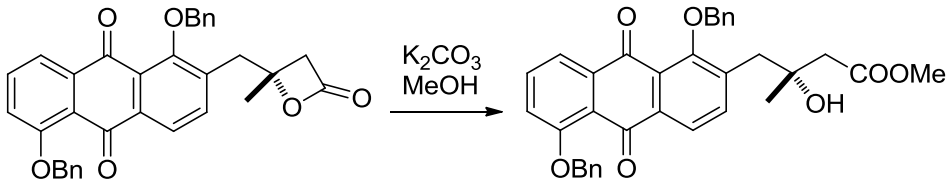
Preparation of (*R*)-1,5-bis(benzyloxy)-2-((2-methyl-4-oxooxetan-2-yl)methyl)anthracene-9,10-dione(19)



18 **19**

A six-chamber stainless-steel high-pressure reactor was dried overnight under vacuum at 100 ℃. In a glove box, 8 mL vials equipped with Teflon-coated magnetic stir bars were charged with 20.0 mg (0.0408 mmol) of epoxide **18** and 2.0 mL of a 0.0020 M stocksolution of $[Cl(TPP)Al(THF)_2]^+[Co(CO)_4]^-$ (4.4 mg, 0.0040 mmol, 10 mol %) in THF. The vials were then placed in a custom-made 6-well high-pressure reactor. The reactor was sealed taken out of the glove box and pressured with carbon monoxide to 900 psi. The reactor was then sealed again and the reaction mixtures were stirred for 20 h at 40 ℃. The reactor was then cooled to ambient temperature and carefully vented in a well-ventilated hood. The crude reaction mixtures were concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give β-lactone **19** as a yellow solid (14.8 mg, 0.0285 mmol, 70%). Residual amounts of ethylacetate and hexanes were removed by suspending the powder in methanol and subsequently removing all volatiles under vacuum at 22 ℃. R_f (20% EtOAc/hexanes) = 0.11; mp: 134–135 °C; $[\alpha]_D^{24}$ = -10.2 (*c* = 1.0, CH_2Cl_2); IR (thin film, cm^{-1}) 2926, 1818, 1669, 1585, 1261, 734, 696; ^1H NMR (400 MHz, $CDCl_3$) δ 8.11 (d, *J* = 8.0 Hz, 1H), 7.92 (d, *J* = 6.8 Hz, 1H), 7.70 (d, *J* = 8.0 Hz, 1H), 7.66 (dd, *J* = 8.4, 8.0 Hz, 1H), 7.61-7.59 (m, 2H), 7.52 (dd, *J* = 8.0, 1.6 Hz, 2H), 7.44-7.32 (m, 7H), 5.34 (s, 2H), 5.08 (d, *J* = 10.8 Hz, 1H), 5.04 (d, *J* = 11.2 Hz, 1H), 3.30 (d, *J* = 16.4 Hz, 1H), 3.18 (d, *J* = 14.0 Hz, 1H), 3.10 (d, *J* = 14.4 Hz, 1H), 3.04 (d, *J* = 16.8 Hz, 1H), 1.50 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.7, 181.7, 167.2, 158.7, 157.0, 137.5, 137.0, 136.9, 136.7, 136.1(2C), 134.9, 128.7(2C), 128.5, 128.4, 127.9, 126.7, 125.2, 123.5, 121.3, 120.0, 119.0, 77.8, 76.9, 70.9, 47.3, 38.5, 24.8; ESI-HRMS calcd for $[C_{33}H_{26}O_6Na]^+$: 541.1622, found 541.1625.

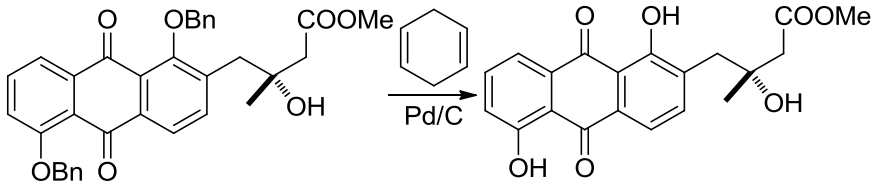
Preparation of (*R*)-methyl 4-(1,5-bis(benzyloxy)-9,10-dioxo-9,10-dihydroanthracen-2-yl)-3-hydroxy-3-methylbutanoate(20)



19 **20**

To a solution of **19** (52 mg, 0.10 mmol) in methanol (1 mL) was added K_2CO_3 (18 mg, 0.13 mmol), and the reaction was stirred at room temperature for 1 h. The mixture was quenched with water (5 mL) and extracted with CH_2Cl_2 for three times. The combined organic layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give ester **20** (53 mg, 0.096 mmol, 96%) as a yellow solid: R_f (20% EtOAc/hexanes) = 0.10; mp: 34–36 ℃; $[\alpha]_D^{22}$ = +0.30 (*c* = 1.1, CH_2Cl_2); IR (thin film, cm^{-1}) 3499, 2927, 1731, 1670, 1585, 1452, 1262, 1015; ^1H NMR (400 MHz, $CDCl_3$) δ 8.10 (d, *J* = 8.0 Hz, 1H), 7.92 (d, *J* = 6.8 Hz, 1H), 7.76 (d, *J* = 8.0 Hz, 1H), 7.66-7.57 (m, 5H), 7.44-7.30 (m, 7H), 5.34 (s, 2H), 5.03 (s, 2H), 3.85 (br, 1H), 3.60 (s, 3H), 2.97 (d, *J* = 13.2 Hz, 1H), 2.93 (d, *J* = 13.2 Hz, 1H), 2.45 (d, *J* = 16.4 Hz, 1H), 2.41 (d, *J* = 16.0 Hz, 1H), 1.20 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.7, 182.0, 173.1, 158.6, 157.0, 138.6, 138.4, 137.2, 136.8, 136.4, 136.2, 134.8, 128.7, 128.6, 128.4, 128.3, 127.9, 126.7, 125.1, 123.2, 121.4, 120.1, 119.0, 76.6, 71.7, 71.0, 51.5, 44.4, 41.3, 27.3; ESI-HRMS calcd for $[C_{34}H_{31}O_7]^+$: 551.2070, found 551.2072.

Preparation of (*R*)-methyl 4-(1,5-dihydroxy-9,10-dioxo-9,10-dihydroanthracen-2-yl)-3-hydroxy-3-methylbutanoate(3)

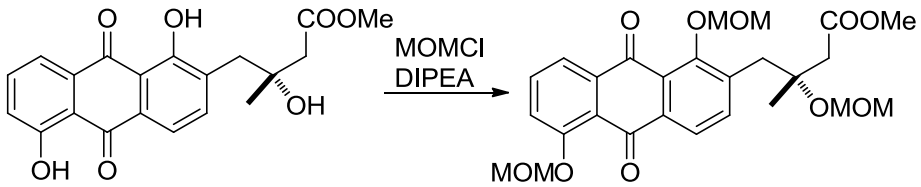


20 **3**

To a solution of ester **20** (33 mg, 0.0599 mmol) in ethanol (0.4 mL) were added 1,4-cyclohexadiene (0.1 mL) and 10% Pd-C (10 mg), and the mixture was stirred at reflux for 2 h. The reactant was filtered on a short pad of silica. After concentration under reduced pressure, the crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **3** (19 mg, 0.0513 mmol, 86%) as a yellow solid: R_f

(20% EtOAc/hexanes) = 0.33; mp: 107–109 ℃; $[\alpha]_D^{22}$ = -11.8 (*c* = 1.0, $CHCl_3$); IR (thin film, cm^{-1}) 3490, 2924, 1726, 1627, 1432, 1372, 1315, 1259, 792; ^1H NMR (400 MHz, $CDCl_3$) δ 13.17 (s, 1H), 12.65 (s, 1H), 7.82 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.79 (d, *J* = 8.0 Hz, 1H), 7.69 (d, *J* = 7.6 Hz, 1H), 7.66 (dd, *J* = 8.0, 8.0 Hz, 1H), 7.31 (dd, *J* = 8.4, 1.2 Hz, 1H), 3.90 (br, 1H), 3.71 (s, 3H), 3.10 (d, *J* = 13.6 Hz, 1H), 3.03 (d, *J* = 13.2 Hz, 1H), 2.59 (d, *J* = 16.0 Hz, 1H), 2.54 (d, *J* = 16.0 Hz, 1H), 1.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.3, 187.7, 173.3, 162.7, 161.3, 139.7, 136.6, 134.6, 133.1, 131.7, 125.0, 119.3, 118.8, 116.1, 115.5, 71.8, 51.8, 44.3, 40.4, 27.2. ESI-HRMS calcd for $[C_{20}H_{19}O_7]^+$: 371.1125, found 371.1137.

Preparation of (*R*)-methyl 4-(1,5-bis(methoxymethoxy)-9,10-dioxo-9,10-dihydroanthracen-2-yl)-3-(methoxymethoxy)-3-methylbutanoate(21)

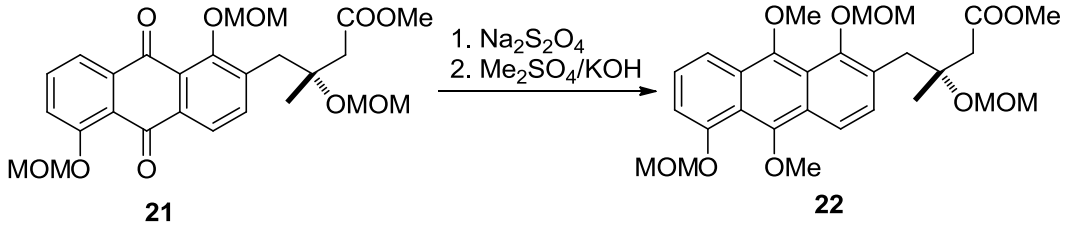


3 **21**

To a solution of **3** (111 mg, 0.300 mmol) in CH_2Cl_2 (3.0 mL) were added DIPEA (0.522 mL, 3.00 mmol) and MOMCl (0.139 mL, 1.80 mmol), and the mixture was stirred at room temperature for 2 days. The reactant was quenched with satd. $NaHCO_3$ and extracted with CH_2Cl_2. The organic layer was then washed with 1N aqueous HCl and dried over Na_2SO_4. After concentration under reduced pressure, the crude product was purified using silica gel flash chromatography eluting with 30% EtOAc/hexanes to give **21** (143 mg, 0.284 mmol, 95%) as a yellow oil: R_f (20% EtOAc/hexanes) = 0.09; $[\alpha]_D^{22}$ = -31.8 (*c* = 0.73, CH_2Cl_2); IR (thin film, cm^{-1}) 2984, 1735, 1670, 1586, 1439, 1264, 1154, 734; ^1H NMR (400 MHz, $CDCl_3$) δ 7.98 (d, *J* = 8.4 Hz, 1H), 7.90 (d, *J* = 7.2 Hz, 1H), 7.79 (d, *J* = 8.0 Hz, 1H), 7.65 (dd, *J* = 8.4, 8.0 Hz, 1H), 7.50 (d, *J* = 8.4 Hz, 1H), 5.35 (s, 2H), 5.16 (d, *J* = 6.8 Hz, 1H), 5.08 (d, *J* = 6.8 Hz, 1H), 4.76 (d, *J* = 8.0 Hz, 1H), 4.74 (d, *J* = 8.0 Hz, 1H), 3.66 (s, 3H), 3.61 (s, 3H), 3.54 (s, 3H), 3.34 (d, *J* = 13.6 Hz, 1H), 3.28 (s, 3H), 3.20 (d, *J* = 13.2 Hz, 1H), 2.63 (d, *J* = 14.0 Hz, 1H), 2.56 (d, *J* = 13.6 Hz, 1H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.7, 182.2, 171.0, 157.1, 156.5, 138.7, 138.3, 136.9, 135.9, 134.7, 124.1, 122.8, 121.8, 121.5, 121.0, 102.2, 95.1, 91.1, 77.6, 57.8, 56.5,

55.4, 51.5, 44.2, 39.5, 23.1. ESI-HRMS calcd for $[C_{26}H_{30}O_{10}Na]^+$: 525.1731, found 525.1744.

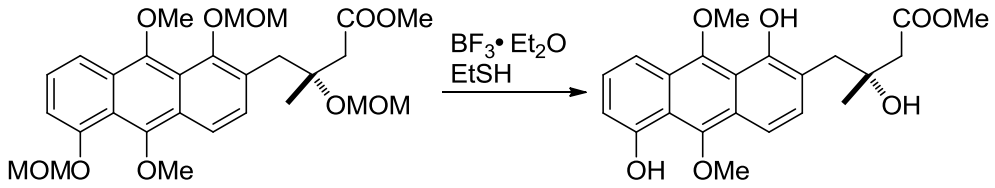
Preparation of (*R*)-methyl 4-(9,10-dimethoxy-1,5-bis(methoxymethoxy)anthracen-2-yl)-3-(methoxymethoxy)-3-methylbutanoate(22)



21 **22**

A solution of $Na_2S_2O_4$ (2.24 g, 12.9 mmol) in degassed water (49 mL) was added to a suspension of anthraquinone **24** (650 mg, 1.29 mmol) and nBu$_4$NBr (103 mg, 0.32 mmol) in degassed THF (22 mL). After stirring at room temperature for 2 h, 50% degassed aqueous KOH (1.94 mL) was added to the mixture, which was stirred for 10 min. After adding Me_2SO_4 (0.33 mL, 3.23 mmol) and stirring for 30 min, the reaction was stopped by adding water at 0 ^oC and the mixture was extracted with CH_2Cl_2. The combined organic extracts were washed with brine, dried over Na_2SO_4 and concentrated under reduced pressure. The crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **22** (433 mg, 0.813 mmol, 63%) as a brown oil: R_f (20% EtOAc/hexanes) = 0.18; $[\alpha]_D^{23}$ = -10.8 (c = 0.40, CH_2Cl_2); IR (thin film, cm^{-1}) 2929, 1736, 1449, 1359, 1294, 1152, 1033, 972, 924, 810, 765; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09 (d, J = 8.8 Hz, 1H), 8.05 (d, J = 8.8 Hz, 1H), 7.43 (d, J = 8.8 Hz, 1H), 7.35 (dd, J = 8.8, 8.0 Hz, 1H), 7.09 (d, J = 6.4 Hz, 1H), 5.40 (s, 2H), 5.12 (d, J = 6.8 Hz, 1H), 5.09 (d, J = 6.4 Hz, 1H), 4.90 (d, J = 7.2 Hz, 1H), 4.83 (d, J = 8.0 Hz, 1H), 4.01 (s, 3H), 3.90 (s, 3H), 3.70 (s, 3H), 3.63 (s, 3H), 3.61 (s, 3H), 3.43-3.30 (m, 2H), 3.35 (s, 3H), 2.77 (d, J = 14.8 Hz, 1H), 2.63 (d, J = 14.8 Hz, 1H), 1.49 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.4, 153.1, 150.1, 148.6, 146.9, 129.6, 128.4, 127.9, 127.3, 125.2, 119.3, 118.6, 118.4, 116.8, 110.0, 101.2, 96.0, 91.2, 78.5, 63.3, 62.7, 58.0, 56.5, 55.3, 51.4, 44.1, 40.0, 23.3. ESI-HRMS calcd for $[C_{28}H_{37}O_{10}]^+$: 533.2381, found 533.2391.

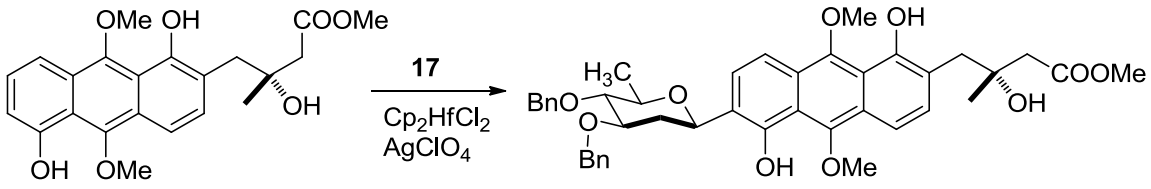
Preparation of (*R*)-methyl 4-(1,5-dihydroxy-9,10-dimethoxyanthracen-2-yl)-3-hydroxy-3-methylbutanoate(23)



22 **23**

To a solution of **25** (74 mg, 0.139 mmol) and EtSH (0.21 mL) in CH_2Cl_2 (1.7 mL) was added BF_3•Et_2O (0.17 mL, 1.39 mmol) at -78 ^oC. The mixture was stirred at -78 ^oC for 30 min. Then the temperature was gradually warmed to -30 ^oC during 30 min. The reactant was quenched with satd. $NaHCO_3$, extracted with EtOAc and dried over Na_2SO_4. After concentration under reduced pressure, the crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **23** (50 mg, 0.125 mmol, 90%) as a yellow oil: R_f (20% EtOAc/hexanes) = 0.20; $[\alpha]_D^{21}$ = -6.8 (*c* = 0.70, $CHCl_3$); IR (thin film, cm^{-1}) 3334, 2987, 1730, 1361, 1276, 1261, 1020,764; ^1H NMR (400 MHz, $(CD_3)_2CO$) δ 10.14 (s, 1H), 9.75 (s, 1H), 7.71 (d, *J* = 8.4 Hz, 1H), 7.67 (d, *J* = 9.2 Hz, 1H), 7.46 (d, *J* = 9.2 Hz, 1H), 7.39 (dd, *J* = 8.8, 7.6 Hz, 1H), 6.82 (d, *J* = 7.2 Hz, 1H), 4.20 (brs, 1H), 4.12 (s, 3H), 4.11 (s, 3H), 3.64 (s, 3H), 3.13 (d, *J* = 13.6 Hz, 1H), 3.09 (d, *J* = 14.0 Hz, 1H), 2.61 (d, *J* = 15.2 Hz, 1H), 2.55 (d, *J* = 15.6 Hz, 1H), 1.34 (s, 3H); ^{13}C NMR (100 MHz, $(CD_3)_2CO$) δ 173.1, 154.5, 151.5, 148.9, 148.6, 132.3, 127.5, 126.3, 125.4, 118.4, 117.2, 116.9, 113.2, 112.4, 109.0, 73.1, 64.6, 64.5, 51.4, 45.5, 41.7, 27.4; ESI-HRMS calcd for $[C_{22}H_{25}O_7]^+$: 401.1595, found 401.1598.

Preparation of (*R*)-methyl 4-(6-((2*R*,4*R*,5*R*,6*R*)-4,5-bis(benzyloxy)-6-methyltetrahydro-2*H*-pyran-2-yl)-1,5-dihydroxy-9,10-dimethoxyanthracen-2-yl)-3-hydroxy-3-methylbutanoate(2)

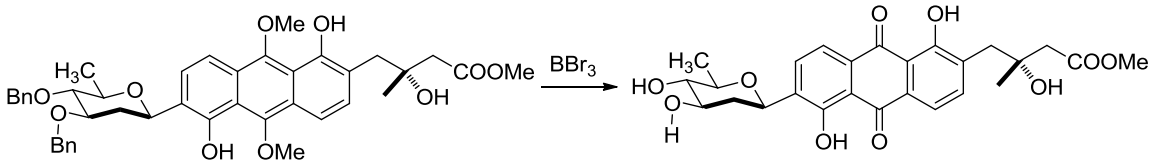


23 **24**

To a stirred mixture of Cp_2HfCl_2 (208 mg, 0.548 mmol), $AgClO_4$ (226 mg, 1.09 mmol) and powdered molecular sieves 4Å (1.60 g) in CH_2Cl_2 (2.0 mL) was added **22** (73 mg,

0.182 mmol) in CH_2Cl_2 (2.0 mL) and **17** (135 mg, 0.364 mmol) in CH_2Cl_2 (3.0 mL) at -78 ^oC. The temperature was then gradually raised to 0 ^oC during 1 h. The reactant was then quenched with satd. aqueous $NaHCO_3$. The mixture was filtered through Celite, extracted with CH_2Cl_2, and dried over Na_2SO_4. After concentration under reduced pressure, the crude product was purified using silica gel flash chromatography eluting with 20% EtOAc/hexanes to give **23** (62 mg, 0.0872 mmol, 48%) as a yellow oil: R_f (20% EtOAc/hexanes) = 0.13; $[\alpha]_D^{20}$ = +40.4 (*c* = 1.2, CH_2Cl_2); IR (thin film, cm^{-1}) 3320, 2926, 1732, 1533, 1453, 1417, 1362, 1259, 1112, 1004, 749; ^1H NMR (400 MHz, $CDCl_3$) δ 10.18 (s, 1H, OH), 10.13 (s, 1H, OH), 7.70 (d, *J* = 8.8 Hz, 1H), 7.63 (d, *J* = 8.8 Hz, 1H), 7.62 (d, *J* = 9.6 Hz, 1H), 7.41-7.27 (m, 11H), 5.12 (dd, *J* = 12.0, 2.4 Hz, 1H), 5.05 (d, *J* = 11.2 Hz, 1H), 4.76 (d, *J* = 10.4 Hz, 2H), 4.68 (d, *J* = 12.0 Hz, 1H), 4.10 (s, 3H), 4.07 (s, 3H), 3.92 (ddd, *J* = 14.0, 8.8, 5.2 Hz, 1H), 3.70 (s, 1H, OH), 3.69 (s, 3H), 3.65 (dq, *J* = 9.6, 6.0 Hz, 1H), 3.30 (dd, *J* = 8.8, 8.8 Hz, 1H), 3.18 (d, *J* = 14.0 Hz, 1H), 3.10 (d, *J* = 14.0 Hz, 1H), 2.66 (d, *J* = 11.6 Hz, 1H), 2.59 (d, *J* = 11.6 Hz, 1H), 2.56 (ddd, *J* = 12.4, 5.2, 2.0 Hz, 1H), 1.78 (ddd, *J* = 12.4, 11.6, 10.0 Hz, 1H), 1.43 (d, *J* = 5.6 Hz, 3H), 1.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 150.8, 148.8, 148.3, 147.8, 138.6, 138.6, 131.4, 128.4(2C), 128.1, 127.7, 127.6(2C), 127.5, 125.0, 124.7, 120.7, 117.1, 116.2, 115.9, 112.8, 112.0, 84.2, 81.2, 75.8, 75.3, 72.7, 71.3, 70.8, 64.1, 64.0, 51.5, 44.4, 41.1, 37.5, 27.4, 18.7; ESI-HRMS calcd for $[C_{42}H_{47}O_{10}]^+$: 711.3164, found 711.3169.

Preparation of Vineomycinone B_2 methyl ester(1)



23 **1**

To a solution of **23** (29 mg, 0.0408 mmol) in CH_2Cl_2 (5.5 mL) was added BBr_3 (275 mg, 1.10 mmol) in CH_2Cl_2 (0.9 mL) at -78 ^oC. After stirring at -78 ^oC for 25 min, the reactant was then quenched with satd. aqueous $NaHCO_3$. After stirring for 5 min, the mixture was acidified with 1N aqueous HCl, extracted with CH_2Cl_2 and dried over Na_2SO_4. After concentration under reduced pressure, the crude product was purified using silica gel flash chromatography eluting with EtOAc to give vineomycinone B_2 methyl ester **1** (18 mg, 0.0360 mmol, 88%). Recrystallization from $CHCl_3$-hexanes gave **1** as orange needles:

R_f (EtOAc) = 0.52; $[\alpha]_D^{20}$ = +109 (*c* = 0.27, dioxane); IR (thin film, cm^{-1}) 3392, 2923, 1726, 1626, 1581, 1476, 1432, 1374, 1260, 1070, 1020, 792; ^{1}H NMR (400 MHz, $CDCl_3$) δ 13.22 (s, 1H), 13.10 (s, 1H), 7.92 (d, *J* = 8.4 Hz, 1H), 7.86 (d, *J* = 8.0 Hz, 1H), 7.81 (d, *J* = 8.0 Hz, 1H), 7.69 (d, *J* = 7.2 Hz, 1H), 4.94 (dd, *J* = 11.6, 1.6 Hz, 1H), 3.93 (s, 1H, OH), 3.86 (ddd, *J* = 12.0, 8.0, 5.2 Hz, 1H), 3.72 (s, 3H), 3.53 (dq, *J* = 8.8, 6.0 Hz, 1H), 3.22 (dd, *J* = 9.2, 8.8 Hz, 1H), 3.11 (d, *J* = 13.2 Hz, 1H), 3.02 (d, *J* = 13.2 Hz, 1H), 2.60 (d, *J* = 16.4 Hz, 1H), 2.54 (d, *J* = 16.4 Hz, 1H), 2.52 (ddd, *J* = 12.4, 5.2, 2.0 Hz, 1H), 2.34 (br, 1H, OH), 2.26 (br, 1H, OH), 1.48 (ddd, *J* = 12.4, 11.6, 11.6 Hz, 1H), 1.42 (d, *J* = 6.0 Hz, 3H), 1.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 188.2, 188.1, 173.3, 161.3, 158.9, 139.6, 138.2, 134.6, 133.3, 131.8, 131.7, 119.4, 118.9, 115.6, 115.4, 78.1, 76.0, 73.1, 71.8, 71.2, 51.8, 44.3, 40.4, 39.4, 27.2, 18.1; ESI-HRMS calcd for $[C_{26}H_{29}O_{10}]^+$: 501.1755, found 501.1768.