Supporting Information

Nickel(0)-Mediated Sequential Addition of Carbon Dioxide and Aryl Aldehydes into Terminal Allenes

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General Information. All ^{1}H NMR and ^{13}C NMR were recorded on a JEOL EX-270 (270 MHz for ^{1}H, 67.5 MHz for ^{13}C), or JEOL AL-400 (400 MHz for ^{1}H, 100 MHz for ^{13}C) instrument in $CDCl_3$ with tetramethylsilane as an internal standard otherwise mentioned. Data are reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad signal), coupling constant (Hz), and integration. Infrared spectra (IR) were obtained on a Perkin Elmer 1605 FTIR spectrometer and absorptions are reported in reciprocal centimeters. Mass spectra were obtained on a JEOL JMS-700TZ (EI) or a JEOL JMS-FABmate (EI). Elemental Analyses were performed at the Center for Instrumental Analysis of Hokkaido University. Silica gel column chromatography was performed with Merck Silica Gel 60 (230-400 mesh ASTM).

Materials or Methods. All reactions were performed under an argon atmosphere using standard Schlenk techniques unless otherwise mentioned. THF (dehydrated, stabilizer-free) was obtained from Kanato Kagaku Co. and used without further purification. Carbon dioxide (CO_2) gas was dried by passing through a column filled with Sicapent® and used without further purification. All other solvents and reagents were purified when necessary using standard procedures. Allenes **1a**,[1] **1b**, and **1c**[2] were prepared accoring to the method reported by Mayers.[3] Allenes **1d**[4] and **1e**, and **1f** were prepared according to Crabbe's method.[5] The spectral data for all new allenes are described below.

1-Benzyloxy-4,5-hexadiene (1b). IR (neat) 3062, 3029, 2937, 2854, 1955, 1495, 1452, 1364, 1103 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.75 (tt, *J* = 7.0, 6.4 Hz, 2 H), 2.10 (tdd, *J* = 7.0, 6.4, 3.2 Hz, 2 H), 3.51 (t, *J* = 6.4 Hz, 2 H), 4.50 (s, 2 H), 4.66 (dt, *J* = 6.8, 3.2 Hz, 2 H), 5.11 (dt, *J* = 6.8, 6.4 Hz, 1 H), 7.25-7.36 (m, 5 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.00, 29.25, 69.60, 72.91, 75.00, 89.48, 127.29, 127.40, 128.13, 138.35, 207.99; LRMS (EI, *m/z*) 97 (M^+-Bn), 91; Anal Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.90; H, 8.67.

2-Penta-3,4-dienylisoindole-1,3-dione (1e). IR (nujor) 1955, 1709, 1498, 1436, 1399, 1374, 1328 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.39 (dtt, *J* = 7.2, 7.2, 2.8 Hz, 2 H), 3.78 (t, *J* = 7.2 Hz, 2 H), 4.63 (dt, *J* = 6.8, 2.8 Hz, 2 H), 5.10 (tt, *J* = 7.2, 6.8 Hz, 1 H), 7.70-7.74 (m, 2 H), 7.83-7.87 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 27.44, 37.51, 75.41, 86.23, 123.04, 131.85, 133.68, 167.94, 208.60; LRMS (EI, *m/z*) 213 (M^+), 160 ($PhthN^+$=CH_2); Anal Calcd for $C_{13}H_{11}NO_2$: C, 73.23; H, 5.20; N, 6.57. Found: C, 73.20; H, 5.30; N, 6.60

2-Hexa-4,5-dienylisoindole-1,3-dione (1f). IR (nujor) 1949, 1770, 1694, 1468, 1442, 1402, 1024 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.82 (tt, *J* = 7.6, 7.4 Hz, 2 H), 2.07 (tdt, *J* = 7.4, 6.8, 3.2 Hz, 2 H), 3.73 (t, *J* = 7.6 Hz, 2 H), 4.68 (dt, *J* = 6.8, 3.2 Hz, 2 H), 5.13 (tt, *J* = 6.8, 6.8 Hz, 1 H), 7.70-7.72 (m, 2 H), 7.83-7.85 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.34, 27.56, 37.32, 75.11, 88.53, 122.64, 131.57, 133.30, 167.70, 207.61; LRMS (EI, *m/z*) 227 (M^+), 160 ($PhthN^+=CH_2$); Anal Calcd for $C_{14}H_{13}NO_2$: C, 73.99; H, 5.77; N, 6.16. Found: C, 74.05; H, 5.78; N, 6.15.

Procedure for Nickel-Mediated Carboxylation of 1a. To a stirred suspension of $Ni(cod)_2$ (160 mg, 0.580 mmol) in degassed THF (4.5 mL) in a Schlenk-type flask under an argon atmosphere, was added DBU (0.170 mL, 1.16 mmol) at 0 °C. The flask was immersed in a liquid nitrogen bath. After the mixture was frozen, the flask was evacuated (<0.005 mmHg). A balloon filled with CO_2 was attached to the flask, and then the frozen mixture was allowed to stand at an ambient temperature until it thawed. To the resulting pale yellow suspension was slowly added a solution of **1a** (100 mg, 0.580 mmol) in degassed THF (4.5 mL) at 0 °C. After the mixture was stirred at 0 °C for 2 hr, the reaction mixture was hydrolyzed with 10% HCl aq. at 0 °C, and the aqueous layer was extracted with EtOAc. The combined organic layer was washed with brine, dried over Na_2SO_4, and concentrated. The residue was treated with diazomethane in Et_2O at 0 °C according to the standard procedures. The obtained crude material was purified by silica gel column chromatography (hexane/EtOAc=10/1) to afford ester **4a** (80.2 mg, 59%).

(2*E*)-5-Benzyloxy-2-methylpent-2-enoic acid methyl ester (4a). IR (neat) 2947, 2859, 1715, 1653, 1436, 1264, 1092 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.85 (d, *J* = 1.2 Hz, 3 H), 2.50 (dt, *J* = 7.3, 6.8 Hz, 2 H), 3.56 (t, *J* = 6.8 Hz, 2 H), 3.74 (s, 3 H), 4.53 (s, 2 H), 6.79 (tq, *J* = 7.3, 1.2 Hz, 1 H), 7.27-7.37 (m, 5 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.80, 29.58, 51.81, 68.62, 73.02, 127.42, 127.42, 128.17, 128.93, 137.91, 138.38, 168.05; LRMS (EI, *m/z*) 204 (M^+-OMe), 175, 144, 128, 91; Anal Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found: C, 71.83; H, 7.73.

Procedure for Nickel-Mediated Sequential Addition of CO_2 and 5a into 1a. To a stirred suspension of $Ni(cod)_2$ (79.0 mg, 0.290 mmol) in degassed THF (2.3 mL) in a Schlenk-type flask under an argon atmosphere, was added DBU (0.080 mL, 0.580 mmol) at 0 °C. The flask was immersed in a liquid nitrogen bath. After the mixture was frozen, the flask was evacuated (<0.005 mmHg). A balloon filled with CO_2 was attached to the flask, and then the frozen mixture was allowed to stand at an ambient temperature until it thawed. To the resulting pale yellow suspension was slowly added a solution of **1a** (50.5 mg, 0.290 mmol) in degassed THF (2.2 mL) at 0 °C. After the mixture was stirred at 0 °C for 2 hr, to this was added benzaldehyde **5a** (0.060 mL, 0.59 mmol). After 6 hr at room temperature, the reaction mixture was hydrolyzed with 10% HCl aq. at 0 °C, and the aqueous layer was extracted with EtOAc. The combined organic layer was washed with brine, dried over Na_2SO_4, and concentrated. The residue was treated with diazomethane in Et_2O at 0 °C according to the standard procedures. The obtained crude material was purified by silica gel column chromatography (hexane/EtOAc=5/1~1/1) to afford ester **6a** (46.8 mg, 47%).

2-{(1*R)-3-Benzyloxy-1-[(1*R**)-hydroxyphenylmethyl]propyl}acrylic acid methyl ester (6a)**. IR (neat) 3432, 3029, 2950, 2861, 1718, 1624, 1452, 1438, 1364, 1270, 1206, 1151, 1099, 1028 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.87 (dddd, *J* = 5.6,

5.6, 9.2, 14.8 Hz, 1 H), 2.06 (dddd, *J* = 4.0, 6.0, 8.0, 14.8 Hz, 1 H), 3.10-3.15 (m, 1 H), 3.30 (d, *J* = 3.5 Hz, 1 H), 3.34-3.45 (m, 2 H), 3.70 (s, 3 H), 4.40 (s, 2 H), 4.88 (dd, *J* = 5.2, 3.2 Hz, 1 H), 5.49 (s, 1 H), 6.19 (d, *J* = 1.2 Hz, 1 H), 7.21-7.34 (m, 10 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 28.42, 47.07, 52.04, 68.25, 72.79, 76.09, 126.30, 127.01, 127.06, 127.32, 127.45, 127.77, 128.08, 137.85, 140.25, 142.35, 167.61; LRMS (EI, *m/z*) 309 (M^+-OMe), 245, 234, 91; Anal Calcd for $C_{21}H_{24}O_4$: C, 74.09; H, 7.11. Found: C, 74.03; H, 7.16.

Procedure for Lactonization of 6a. To a solution of **6a** (10.0 mg, 0.0270 mmol) in THF (1.5 mL), was added NaH (60% dispersion in mineral oil, 2.0mg, 0.050 mmol) at 0 °C. The resulting mixture was stirred at 0 °C for 2 hrs followed by stirring for 20 min at room temperature, then quenched by the addition of saturated aqueous solution of NH_4Cl at 0 °C, and extracted with ether. The combined organics were dried over anhydrous Na_2SO_4, filtered, and concentrated in vacuo. The residue was purified by silica gel column chromatography (hexane/EtOAc = 4/1) to afford lactone **7a** (8.8 mg, quant.).

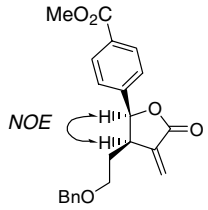
(4*R,5*S**)-4-(2-Benzyloxyethyl)-3-methylene-5-phenyldihydrofuran-2-one (7a)**. IR (neat) 3026, 2920, 2862, 1762, 1654,1496, 1456, 1265, 1101 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.31-1.45 (m, 2 H), 3.27-3.38 (m, 2 H), 3.51-3.58 (m, 1 H), 4.41 (s, 2 H), 5.52 (d, *J* = 2.4 Hz, 1 H), 5.56 (d, *J* = 7.2 Hz, 1 H), 6.32 (d, *J* = 2.4 Hz, 1 H), 7.15-7.17 (m, 2 H), 7.25-7.38 (m, 8 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 29.11, 41.23, 66.01, 73.01, 81.84, 122.29, 126.05, 127.66, 127.66, 128.23, 128.27, 128.35, 135.63, 137.73, 138.33, 170.02; LRMS (EI, *m/z*) 308 (M^+), 217, 202, 91; Anal.Calcd for $C_{20}H_{20}O_3$: C, 77.90; H, 6.54. found: C, 77.69; H, 6.70.

Typical Procedure for Lactone Synthesis from 1a using Acid-Catalyzed Lactonization. To a stirred suspension of $Ni(cod)_2$ (79.0 mg, 0.290 mmol) in degassed THF (2.3 mL) in a Schlenk-type flask under an argon atmosphere, was added DBU (0.080 mL, 0.580 mmol) at 0 °C. The flask was immersed in a liquid nitrogen bath. After the mixture was frozen, the flask was evacuated (<0.005 mmHg). A balloon filled with CO_2 was attached to the flask, and then the frozen mixture was allowed to stand at an ambient temperature until it thawed. To the resulting pale yellow suspension was slowly added a solution of **1a** (50.5 mg, 0.290 mmol) in degassed THF (2.2 mL) at 0 °C. After the mixture was stirred at 0 °C for 2 hr, to this was added benzaldehyde **5a** (0.060 mL, 0.59 mmol). After 6 hr at room temperature, the reaction mixture was hydrolyzed with 10% HCl aq. at 0 °C and the aqueous layer was extracted with EtOAc. The combined organic layer was washed with brine, dried over Na_2SO_4, and concentrated. The residue was filtered through a shot pad of silica gel (2 dia X 5 cm) using EtOAc/AcOH (100/1) as an eluent, and the solvents were evaporated in vacuo to afford a crude carboxylic acid.

To a solution of the crude carboxylic acid in benzene (12 mL), was added pyridinium *p*-toluenensulfonate (3.6 mg, 0.0140 mmol) and the mixture was refluxed for 2 hr with azeotropic removal of water. After cooling, the resulting mixture was concentrated in vacuo and the residue was purified by silica gel column chromatography (hexane/EtOAc = 4/1) to afford lactone **7a** (53.5 mg, 60% from **1a**).

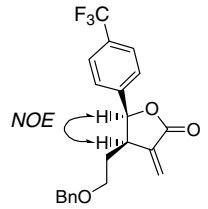
4-[(2*S,3*R**)-3-(2-Benzyloxyethyl)-4-methylene-5-oxo-tetrahydrofuran-2-yl]benzoic acid methyl ester (7b)**. IR (neat) 3030, 2951, 2859, 1771, 1723, 1613, 1436, 1281, 1109 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.29-1.35 (m, 2 H), 3.30 (ddd, *J* = 5.0, 5.6, 14.8 Hz, 1 H), 3.35 (ddd, *J* = 6.8, 9.2, 14.8 Hz, 1 H), 3.58 (m, 1 H), 3.92 (s, 3 H), 4.41 (s, 2 H), 5.54 (d, *J* = 2.0 Hz, 1 H), 5.62 (d, *J* = 7.2 Hz, 1 H), 6.34 (d, *J* = 2.0 Hz, 1 H), 7.23-7.34 (m, 7 H), 8.02 (d, *J* = 8.4 Hz, 2 H); ^{13}C NMR (100

MHz, $CDCl_3$) δ 28.96, 41.07, 52.23, 65.71, 72.98, 81.10, 122.81, 125.94, 127.61, 127.61, 128.21, 129.55, 129.94, 137.57, 137.70, 140.59, 166.07, 169.56; LRMS (EI, *m/z*) 366 (M^+), 335, 307, 275, 260, 91; Anal. Calcd for $C_{21}H_{20}O_5$: C, 72.12; H, 6.05. Found: C, 71.94; H, 6.25



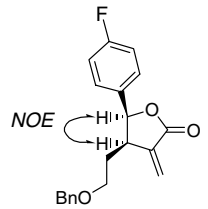
7b

(4*R,5*S**)-4-(2-Benzyloxyethyl)-3-methylene-5-(4-trifluoromethylphenyl)dihydrofuran-2-one (7c)**. IR (neat) 2930, 2863, 1772, 1326, 1166, 1123, 1067; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.38-1.44 (m, 1 H), 1.64-1.72 (m, 1 H), 3.29-3.39 (m, 2 H), 3.56-3.61 (m, 1 H), 4.42 (s, 2 H), 5.54 (d, *J* = 2.0 Hz, 1 H), 5.62 (d, *J* = 7.2 Hz, 1 H), 6.34 (d, *J* = 2.4 Hz, 1 H), 7.23-7.40 (m, 5 H), 7.36 (d, *J* = 8.4 Hz, 2 H), 7.60 (d, *J* = 8.4 Hz, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 28.97, 41.19, 65.70, 73.11, 80.95, 123.08, 123.64, 125.37, 126.36, 127.74, 127.78, 128.31, 130.39, 137.54, 137.60, 139.66, 169.53; LRMS (EI, *m/z*) 376 (M^+), 285, 270, 91; Anal Calcd for $C_{21}H_{19}F_3O_3$: C, 67.02; H, 5.09. Found C 67.16; H 5.27.



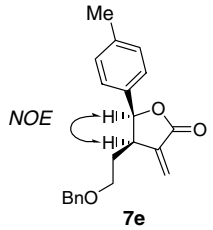
7c

(4*R, 5*S**)-4-(2-Benzyloxy-ethyl)-5-(4-fluoro-phenyl)-3-methylene-dihydro-furan-2-one (7d)** IR (neat) 3058, 3027, 2834, 2863, 1769, 1608, 1512, 1229, 1104 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.29-1.45 (m, 2 H), 3.27-3.56 (m, 2 H) 3.49-3.56 (m, 1 H), 4.42 (s, 2 H), 5.53 (d, *J* = 2.0 Hz, 1 H), 5.55 (d, *J* = 7.6 Hz, 1 H), 6.32 (d, *J* = 2.0 Hz, 1 H), 6.99-7.07 (m, 2 H), 7.11-7.16 (m, 2 H), 7.22-7.39 (m, 5 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 29.07 (CH_2), 41.22 (CH), 65.95 (CH_2), 73.00 (CH_2), 81.20 (CH), 115.39 (d, J_{CF} = 21.3 Hz, CH), 122.45 (CH_2), 127.66 (CH), 127.66 (CH), 127.83 (d, J_{CF} = 8.3 Hz, CH), 128.25 (CH), 131.48 (d, J_{CF} = 3.5 Hz, C), 137.65 (C), 138.06 (C), 162.22 (d, J_{CF} = 245.4 Hz, CF), 169.75 (C); LRMS (EI, *m/z*) 326 (M^+), 281, 235, 220, 91; Anal Calcd for $C_{20}H_{19}FO_3$: C, 73.60; H, 5.87. Found: C, 73.59; H, 5.92.



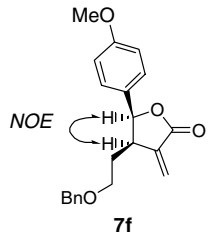
7d

(4*R,5*S**)-4-(2-Benzyloxyethyl)-3-methylene-5-*p*-tolyldihydrofuran-2-one (7e)**. IR (neat) 3029, 2922, 2862, 1767, 1662, 1454, 1267, 1116 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.32-1.48 (m, 2 H), 2.34 (s, 3 H), 3.27-3.38 (m, 2 H), 3.49-3.35 (m, 1 H), 4.41 (s, 2 H), 5.51 (d, *J* = 2.0 Hz, 1 H), 5.53 (d, *J* = 7.2 Hz, 1 H), 6.31 (d, *J* = 2.4 Hz, 1 H), 7.03 (d, *J* = 7.6 Hz, 2 H), 7.13 (d, *J* = 7.6 Hz, 2 H), 7.28-7.38 (m, 5 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 221.32, 29.10, 41.20, 66.10, 72.96, 81.86, 121.97, 126.00, 127.60, 127.60, 128.22, 128.97, 132.62, 137.74, 137.97, 138.46, 170.07; LRMS (EI, *m/z*) 322 (M^+), 231, 201, 91; Anal Calcd for $C_{21}H_{22}O_3$: C, 78.23; H, 6.88. Found: C, 78.03; H, 6.91.



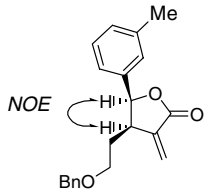
7e

(4*R,5*S**)-4-(2-Benzyloxyethyl)-5-(4-methoxyphenyl)-3-methylenedihydrofuran-2-one (7f)**. IR (neat) 3030, 2935, 2861, 1765, 1612, 1515, 1251, 1115 cm^{-1}; ^1H NMR (400 MHz, benzene-d_6) δ 1.11 (dddd, *J* = 5.2, 5.2, 8.8, 14.4 Hz, 1 H), 1.19 (dddd, *J* = 5.6, 6.0, 8.4, 14.4 Hz, 1 H) 2.92 (ddd, *J* = 5.2, 6.0, 14.8 Hz, 1 H), 2.96 (ddd, *J* = 5.2, 8.4, 14.8 Hz, 1 H), 3.06 (ddddd, *J* = 1.2, 2.4, 5.6, 7.2, 8.8 Hz, 1 H), 3.22 (s, 3 H), 4.10 (s, 2 H), 5.04 (d, *J* = 7.2 Hz, 1 H), 5.09 (d, *J* = 1.2 Hz, 1 H), 6.25 (d, *J* = 2.4 Hz, 1 H), 6.64 (d, *J* = 8.8 Hz, 2 H), 6.86 (d, *J* = 8.8 Hz, 2 H), 7.06-7.25 (m, 5 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 29.15, 41.29, 55.32, 66.15, 73.00, 81.80, 113.75, 113.93, 127.93, 127.46, 127.53, 127.65, 128.19, 128.25, 137.74, 138.52, 159.29; LRMS (EI, *m/z*) 338 (M^+), 247, 202, 91; Anal Calcd for $C_{21}H_{22}O_4$: C,74.54; H, 6.55. Found: C, 74.58; H, 6.55.



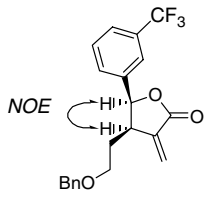
7f

(4*R,5*S**)-4-(2-Benzyloxyethyl)-3-methylene-5-(3-methylphenyl)dihydrofuran-2-one (7g)**. IR (neat) 3030, 2921, 2862, 1769, 1267, 1104 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.32-1.44 (m, 2 H), 2.32 (s, 3 H), 3.27-3.37 (m, 2 H), 3.48-3.55 (m, 1 H), 4.41 (s, 2 H), 5.51 (d, *J* = 2.4 Hz, 1 H), 5.52 (d, *J* = 7.2 Hz, 1 H), 6.31 (d, *J* = 2.4 Hz, 1 H), 6.94-6.96 (m, 2 H), 7.10-7.37 (m, 7 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.60, 29.07, 41.13, 66.04, 72.93, 81.84, 122.11, 123.09, 126.57, 127.59, 127.59, 128.16, 128.21, 128.91, 135.51, 137.70, 137.98, 138.37, 170.02; LRMS (EI, *m/z*) 322 (M^+), 276, 231, 91; Anal Calcd for $C_{21}H_{22}O_3$: C, 78.23; H, 6.88. Found: C, 78.39; H, 6.82.



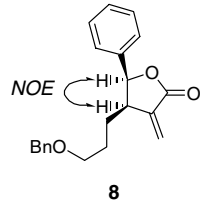
7g

(4*R,5*S**)-4-(2-Benzyloxyethyl)-3-methylene-5-(3-trifluoromethylphenyl)dihydrofuran-2-one (7h)**. IR (neat) 3031, 2925, 2863, 1773, 1454, 1331, 1125 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.24-1.38 (m, 2 H), 3.29-3.39 (m, 2 H) 3.56-3.62 (m, 1 H), 4.42 (s, 2 H), 5.55 (d, *J* = 2.0 Hz, 1 H), 5.62 (d, *J* = 7.2 Hz, 1 H), 6.35 (d, *J* = 2.4 Hz, 1 H), 7.29-7.39 (m, 6 H), 7.47-7.60 (m, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 28.99 (CH_2), 41.18 (CH), 65.74 (CH_2), 73.09 (CH_2), 80.98 (CH), 122.94 (q, J_{CF} = 3.5 Hz, CH), 123.05 (CH_2), 123.60 (q, J_{CF} = 269.7 Hz, CF_3), 125.07 (q, J_{CF} = 3.6 Hz, CH), 127.70 (CH), 127.72 (CH), 128.29 (CH), 128.93 (CH), 129.28 (CH), 130.81 (q, J_{CF} = 32.7 Hz, C), 136.80 (C), 137.56 (C), 137.62 (C), 169.47 (C); LRMS (EI, *m/z*) 376 (M^+), 285, 299, 91; Anal Calcd for $C_{21}H_{19}F_3O_3$: C, 67.02; H, 5.09. Found: C, 67.21; H, 5.09.



7h

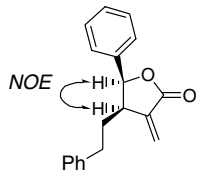
(4*R,5*S**)-4-(3-Benzyloxypropyl)-3-methylene-5-phenyldihydrofuran-2-one (8)**. IR (neat) 3060, 3031, 2942, 2859, 1767, 1453, 1265, 1100 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.01-1.15 (m, 1 H), 1.24-1.34 (m, 1 H), 1.39-1.50 (m, 1 H), 1.52-1.62 (m, 1 H), 3.25-3.30 (m, 3 H), 4.38 (S, 2 H), 5.59 (d, J = 7.2 Hz, 1 H), 5.63 (d, *J* = 2.0 Hz, 1 H), 6.34 (d, *J* = 2.4 Hz, 1 H), 7.20-7.38(m, 10 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.91, 26.58, 44.35, 69.53, 72.70, 81.95, 122.02, 126.00, 127.23, 127.30, 128.08, 128.18, 128.25, 135.56, 137.96, 138.69, 170.08; LRMS (EI, *m/z*) 231 (M^+-Bn), 216, 91; Anal Calcd for $C_{21}H_{22}O_3$: C, 78.23; H, 6.88. Found: C, 78.21; H, 6.96.



8

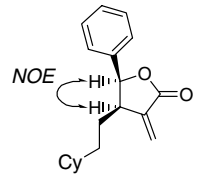
(4*R,5*S**)-3-Methylene-4-phenethyl-5-phenyldihydrofuran-2-one (9)**. IR (nujor) 1763, 1654, 1455, 1243 cm^{-1} ; ^1H NMR (400 MHz, $CDCl_3$) δ 1.37 (dddd, *J* = 13.6, 10.0, 8.6, 6.4 Hz, 1 H), 1.58 (dddd, *J* = 13.6, 10.0, 7.6, 6.0 Hz, 1 H), 2.42 (ddd, *J* = 14.0, 10.0, 6.4 Hz, 1 H), 2.51 (ddd, *J* = 14.0, 10.0, 6.0 Hz, 1 H), 3.27 (ddddd, *J* = 10.0, 8.6, 7.2, 2.4, 2.4 Hz, 1 H), 5.60 (d, *J* = 7.2 Hz, 1 H), 5.63(d, *J* = 2.4 Hz, 1 H), 6.37 (d, *J* = 2.4 Hz, 1 H), 6.91-7.40 (m, 10 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 30.95, 32.51, 43.82, 81.95, 121.96, 125.91, 126.17, 127.95, 128.24, 128.24, 128.37, 128.41, 135.51, 138.70,

140.43, 170.02; LRMS (EI, *m/z*) 278 (M+), 172, 44; Anal Calcd for $C_{19}H_{18}O_2$: C, 81.99; H, 6.52. Found: C, 81.86; H, 6.67.



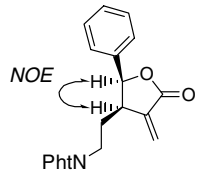
9

(4*R,5*S**)-4-(2-Cyclohexylethyl)-3-methylene-5-phenyldihydrofuran-2-one (10)**. IR (neat) 3033, 2922, 2850, 176, 1663, 1497, 1453, 12661146, 1109; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.64-0.74 (m, 2 H), 0.97-1.28 (m, 8 H), 1.40-1.62 (m, 5 H), 3.47-3.22 (m, 1 H), 5.59-5.60 (m, 1 H), 5.60 (d, J = 2.0 Hz, 1 H), 6.34 (d, J = 2.4 Hz, 1 H), 7.20-7.22 (m, 2 H), 7.30-7.40 (m, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 26.34, 26.35, 26.44, 26.64, 33.16, 33.24, 34.16, 37.52, 44.88, 82.20, 121.69, 126.13, 126.15, 128.21, 135.69, 138.94, 170.32; LRMS (EI, *m/z*) 284 (M+), 178, 82; Anal. Calcd for $C_{19}H_{24}O_2$: C, 80.24; H, 8.51. Found: C, 80.15; H, 8.54.



10

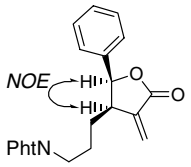
2-{2-[(2*S,3*R**)-4-Methylene-5-oxo-2-phenyltetrahydrofuran-3-yl]ethyl}isoindole-1,3-dione (11)**. IR (nujor) 2923, 2854, 1760, 1709, 1458, 1376, 1269, 1155, 1114 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.29 (dddd, *J* = 13.8, 6.7, 6.7, 6.7 Hz, 1 H), 1.72 (dddd, *J* = 13.8, 6.7, 6.7, 6.7 Hz, 1 H), 3.28-3.33 (m, 1 H), 3.55-3.60 (m, 2 H), 5.72 (d, *J* = 7.6 Hz, 1 H), 5.85 (d, *J* = 2.6 Hz, 1 H), 6.42 (d, *J* = 2.6 Hz, 1 H), 7.25-7.27 (m, 2 H), 7.34-7.39 (m, 3 H), 7.71-7.73 (m, 2 H), 7.82-7.84 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 28.12, 35.08, 41.64, 81.65, 122.54, 123.13, 126.31, 128.51, 128.60, 131.59, 133.91, 135.33, 137.82, 167.88, 169.73; LRMS (EI, *m/z*) 347 (M^+), 241, 213; Anal Calcd for $C_{21}H_{17}NO_4$: C, 72.61; H, 4.93; N, 4.03. Found: C, 72.59; H, 4.96; N, 4.02.



11

2-{3-[(2*S,3*R**)-4-Methylene-5-oxo-2-phenyltetrahydrofuran-3-yl]propyl}isoindole-1,3-dione (12)**. IR (neat) 3063, 3033, 2941, 2867, 1770, 1715, 1397, 1266, 1149, 1113 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.96-1.05 8m, 1 H), 1.29-1.37 (m, 1 H), 1.47-1.58 (m, 1 H), 1.58-1.69 (m, 1 H), 3.29-3.35 (m, 1 H), 3.50 (ddd, *J* = 14.0, 6.8, 5.0 Hz, 2 H), 5.60 (d, *J* = 7.2

Hz, 1 H), 5.66 (d, *J* = 2.0 Hz, 1 H), 6.36 (d, *J* = 2.4 Hz, 1 H), 7.10-7.28 (m, 5 H), 7.70-7.74 (m, 2 H), 7.77-7.81 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.44, 26.32, 37.13, 43.65, 81.72, 122.32, 122.93, 125.88, 128.11, 128.17, 131.65, 133.66, 135.21, 138.19, 167.71, 169.89; LRMS (EI, *m/z*) 361 (M^+), 211, 173, 160; Anal Calcd for $C_{22}H_{19}NO_4$: C, 73.12; H, 5.30; N, 3.88. Found: C, 72.95; H, 5.47; N, 3.75.



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Registrry Number: 203677-52-0 (**1a**); 40339-21-7 (**1c**); 260554-38-9 (**1d**).

References

1. Oh, C. H.; Yoo, H. S.; Jung, S. H. *Chem. Lett.* **2001**, *31*, 1288.

2. Ohno, H.; Miyamura, K.; Tanaka, T.; Oishi, H.; Toda, A.; Takemoto, Y.; Fuji, N.; Ibuka, T. *J. Org. Chem.***2002**, *67*, 1359.

3. (a) Myers, A. G.; Zheng, Bin. *J. Am. Chem. Soc.* **1996**, *118*, 4492. (b) Myers, A. G.; Zheng, B.; Movassaghi, M. *J. Org. Chem*. **1997**, *62*, 7507.

4. Ahmed, M. Arnauld, T.; Barrett, A. G.; Braddock, D. C.; Flack, K.; Procopiou, P. A. *Org. Lett.* **2000**, *2*, 551.

5. (a) Crabbé, P.; Fillion, H.; André, D.; Luche, J.-L. *J. Chem. Soc., Chem. Commun.* **1979**, 859. (b) Searles, S.; Li, Y.; Nassim, B.; Lopes, M.-T. R.; Tran, P. T.; Crabbé, P. *J. Chem. Soc., Perkin Trans I* **1984**, 747. (c) Crabbé, P; Nassim, B.; Lopes, M.-T. R. *Organic Synthesis*; Wiley: New York, 1990; Collect. Vol. VII, p 276.