Supporting Information for
Atom Transfer Cyclization Catalyzed by InCl₃ via Halogen Activation
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General Experimental:
Thin layer chromatography (TLC) was performed on silica gel Whatman-60F glass plates, and components were visualized by illumination with UV light or by staining with potassium permanganate solution. Chromatography was performed using silica E. Merck silica gel 60 (230-400 mesh). NMR spectra were recorded in DMSO or CDCl₃ on a Varian Inova 500 MHz, 400 MHz, or Varian Mercury 300 MHz spectrometer. ¹³C NMR was recorded using broad band proton decoupling. Chemical shifts are reported in δ relative to TMS and coupling constants in Hz. Optical rotations were recorded on a JASCO-CIP-370 instrument. Elemental analyses were performed on a Perkin Elmer Series II CHNS/O Analyzer 2400. High-resolution mass spectra (HRMS) [Positive Ion FAB (FAB⁺) or Electrospray (ES)] were in the Department of Chemistry and Molecular Biology at North Dakota State University. Melting points were determined without correction. Reactions were carried out under an inert atmosphere of nitrogen or argon. Solvents were dried using a nitrogen pressurized alumina column system from Solvtek.

Characterization Data for Substrates 1b-1e and 5:

Cis-2-(4-bromo-but-2-enyl)-2-but-2-ynyl-malonic acid diethyl ester (1b). IR (neat) cm⁻¹: 3469, 2981, 1735, 1445, 1390, 1324, 1206, 1094, 859, 735; ¹H NMR (400 MHz, CDCl₃) δ 5.84 (ddd, J = 1.6, 8.4, 19.2 Hz, 1H), 5.36 (dt, J = 8.0, 18.8 Hz, 1H), 4.18 (q, J = 7.2 Hz, 2H), 4.17 (q, J = 7.2 Hz, 2H), 4.01 (bd, J = 8.4 Hz, 2H), 2.89 (dd, J = 1.2, 8.0 Hz, 2H), 2.70 (q, J = 2.8 Hz, 2H), 1.74 (t, J = 2.4 Hz, 3H), 1.24 (t, J = 7.2 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 170.0, 129.9, 128.0, 79.4, 73.5, 56.9, 29.7, 26.8, 23.2, 14.2, 3.7; HRMS Calcd for C₁₅H₂₁BrNaO₄ (M + Na⁺): 367.0521, found 367.0519.

Cis-2-(4-bromo-but-2-enyl)-2-hept-2-ynyl-malonic acid diethyl ester (1c). IR (neat) cm⁻¹: 3471, 2959, 1736, 1465, 1367, 1205, 1094, 84.1, 74.3, 61.9, 57.0, 31.1, 29.7, 26.7, 23.2, 22.0, 18.5, 14.2, 13.7; HRMS Calcd for C₁₈H₂₇BrNaO₄ (M + Na⁺): 409.0971.

Cis-2-(4-bromo-but-2-enyl)-2-(3-phenyl-prop-2-ynyl)-malonic acid diethyl ester (1d). IR (neat) cm⁻¹: 3469, 2981, 1737, 1598, 1443, 1294, 1206, 1070, 757; ¹H NMR (400 MHz, CDCl₃) δ 7.35 (m, 2H), 7.26 (m, 3H), 5.42 (td, J = 8.0, 18.8 Hz, 1H), 4.22 (dd, J = 1.2, 8.0 Hz, 2H), 2.89 (dd, J = 2.4, 4.8, 6.8, 9.2 Hz, 2H), 1.45-1.29 m, 4H), 1.21 (t, J = 7.2 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 169.8, 131.9, 130.2, 128.3, 127.8, 123.2, 84.3, 84.0, 62.1, 57.0, 29.9, 26.7, 23.9, 14.3; HRMS Calcd for C₂₀H₂₃BrNaO₄ (M + Na⁺): 429.0677, found 429.0685.
Cis-2-(4-d-bromo-but-2-enyl)-2-prop-2-ynyl-malonic acid diethyl ester (1e). IR (neat) cm⁻¹; 2982, 2588, 1729, 1466, 1291, 1207, 1094, 857, 745; ¹H NMR (400 MHz, CDCl₃) δ 5.87 (ddd, J = 1.6, 10.0, 18.0 Hz, 1H), 5.36 (dt, J = 8.0, 16.0 Hz, 1H), 4.20 (q, J = 7.2 Hz, 2H), 4.20 (q, J = 7.2 Hz, 2H), 4.01 (bd, J = 8.4 Hz, 2H), 2.89 (dd, J = 1.6, 8.0 Hz, 2H), 2.77 (s, 2H), 1.24 (t, J = 7.2 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 169.7, 130.2, 127.6, 62.1, 56.6, 29.7, 26.6, 22.9, 14.2; HRMS Calcd for C₁₄H₁₈DBrNaO₄ (M + Na⁺): 354.0426, found 354.0418.

Cis-2-(4-bromo-but-2-enyl)-2-(3,5-dimethoxy-benzyl)-malonic acid diethyl ester (5). IR (neat) cm⁻¹; 2980, 2838, 1730, 1596, 1462, 1289, 1203, 1070, 857; ¹H NMR (400 MHz, CDCl₃) δ 6.31 (t, J = 2.4 Hz, 1H), 6.20 (d, J = 2.4 Hz, 2H) 5.84 (ddd, J = 1.6, 8.4, 16.4 Hz, 1H), 5.56 (dt, J = 7.2, 14.8 Hz, 1H), 4.19 (q, J = 7.2 Hz, 4H), 3.91 (d, J = 8.4 Hz, 2H), 3.72 (s, 6H), 3.18 (s, 2H), 2.63 (dd, J = 1.6, 7.6 Hz, 2H), 1.24 (t, J = 7.2 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 170.8, 160.9, 138.0, 129.0, 128.6, 108.4, 99.0, 61.8, 58.4, 55.4, 38.7, 29.7, 26.8, 14.4, 14.3; HRMS Calcd for C₂₀H₂₇BrNaO₆ (M + Na⁺): 465.0889, found 465.0897.

Radical Cyclization to give 3:
To enyne 1a (96 mg, 0.29 mmol) in dichloromethane (10.1 mL) was added 6 equiv of Et₃B in six portions (1 equiv each) every 10 minutes along with introduction of air. The reaction was monitored by thin layer chromatography. Upon completion of the reaction (18 hr), the mixture was washed with saturated NH₄Cl. The organic layer was separated and the aqueous layer was extracted with dichloromethane (2 x 10 mL). The combined organic layers were dried over anhydrous Na₂SO₄. The solvent was removed in vacuo and the crude product was purified by flash silica gel chromatography using 40:1 hexane-ethyl acetate solution to afford 3 (51.1 mg, 53% yield) as a colorless oil.

3-Bromo-5-vinyl-cyclohex-3-ene-1,2-dicarboxylic acid diethyl ester (3). IR (neat) 3080, 2982, 1731, 1643, 1446, 1389, 1260, 1191, 922, 862 cm⁻¹; ¹H NMR (500 MHz, CDCl₃) δ 5.88 (dd, J = 2.5, 5.5 Hz, 1H), 5.60 (dddd, J = 8.5, 8.8, 16.0, 17.5 Hz, 1H), 5.13 (s, 1H), 5.11 (d, J = 5.2 Hz, 1H), 4.21 (q, J = 7.0 Hz, 4H), 3.20 (q, J = 8.5 Hz, 1H), 2.95 (dt, J = 3.0, 18.0 Hz, 1H), 2.63 (dq, J = 2.0, 7.0 Hz, 1H), 2.07 (t, J = 11.5 Hz, 1H), 1.27 (t, J = 7.0 Hz, 6H); ¹³C NMR (125 MHz, CDCl₃) δ 171.5, 171.1, 147.7, 137.6, 117.5, 101.0, 62.1, 61.9, 58.2, 48.9, 41.2, 40.4, 14.2, 14.1; HRMS Calcd for C₁₄H₁₉BrNaO₄ (M + Na⁺): 353.0364, found 353.0367.

Friedel-Crafts Cyclization of 5 to give 6:
The 3,5-dimethoxy benzyl compound 5 (40, 0.09 mmol) and dichloromethane (1.8 mL) were placed in a small screw-cap scintillation vial equipped with a magnetic stirbar. Powdered molecular sieves (4Å, 50 mg) and InCl₃ (2 mg, 0.009 mmol) were added and the reaction was allowed to stir at room temperature. Upon completion of the reaction (16 hr), the mixture was loaded on to a silica gel column directly and isolated using 10:1 hexane-ethyl acetate solution to afford 6 (28.8 mg, 88% yield) as a colorless oil.

6,8-Dimethoxy-4-vinyl-3,4-dihydro-1H-naphthalene-2,2-dicarboxylic acid diethyl ester (6). IR (neat) cm⁻¹; 3078, 2359, 1729, 1607, 1491, 1390, 1198, 1101, 1049, 939, 861, 731, 668; ¹H NMR (400 MHz, CDCl₃) δ 6.30 (s, 2H), 5.78 (dd, J = 5.2, 8.4, 13.6 Hz, 1H), 4.92 (bd, J = 8.4 Hz, 1H), 4.79 (bd, J = 13.6 Hz), 4.29–4.06 (m, 4H), 3.78 (s, 3H), 3.72 (s, 3H), 3.32 (d, J =
12.4 Hz, 1H), 3.06 (d, J = 12.8 Hz, 1H), 2.53 (dd, J = 6.0, 10.8 Hz, 1H), 2.24 (dd, J = 4.8, 11.2 Hz, 1H), 1.24 (t, J = 5.6 Hz, 3H), 1.16 (t, J = 5.6 Hz, 3H); 13C NMR (100 MHz, CDCl₃) δ 171.7, 171.4, 159.2, 158.8, 141.7, 136.2, 117.8, 113.5, 104.5, 97.3, 61.5, 55.5, 55.4, 53.2, 35.7, 35.3, 34.6, 14.2, 14.1; HRMS Calcd for C₂₀H₂₆NaO₆ (M + Na⁺): 385.1627, found 385.1630.

General Procedure for Atom Transfer Cyclization of 1 to give 2/4:

To enyne 1 (50-200 mg, 1 equiv) dissolved in solvent (dichloromethane or dibromomethane, 0.1M) in a small screw-cap scintillation vial equipped with a magnetic stir bar, was added 0.2 eq of InCl₃ at room temperature and the reaction was monitored by thin layer chromatography. Upon completion of the reaction (3-4 hr) the mixture was loaded on to a silica gel column directly and isolated using 40:1 hexane-ethyl acetate solution to afford the cyclized product 2 and/or 4 as a colorless oil.

**(E)-3-Chloromethylene-4-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (2a).** IR (neat) cm⁻¹: 3466, 2982, 1736, 1446, 1247, 1188, 920, 860; ¹H NMR (400 MHz, CDCl₃) δ 5.70 (m, 2H), 5.08 (bd, J = 17.2 Hz, 1H), 5.04 (bd, J = 11.6 Hz, 1H), 4.17 (m, 4H), 2.91 (m, 2H), 2.68 (dd, J = 2.4, 4.0, 17.6 Hz, 1H), 2.40 (dd, J = 5.2, 13.2 Hz, 1H), 1.69 (dd, J = 10.0, 13.2 Hz, 1H), 1.23 (t, J = 7.2 Hz, 3H), 1.23 (t, J = 7.2 Hz, 3H); 13C NMR (100 MHz, CDCl₃) δ 170.8, 170.1, 139.8, 129.7, 126.2, 115.5, 62.0, 61.9, 54.6, 38.6, 37.2, 33.0, 14.2, 14.2; HRMS Calcd for C₁₄H₁₉ClNaO₄ (M + Na⁺): 309.0870, found 309.0855.

**(E)-3-Chloromethylene-4-d-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (2e).** IR (neat) cm⁻¹: 3446, 2981, 2360, 1734, 1447, 1298, 1188, 1095, 1021; ¹H NMR (400 MHz, CDCl₃) δ 5.67 (ddd, J = 6.8, 10.0, 17.2 Hz, 1H), 5.08 (bd, J = 17.2 Hz, 1H), 5.04 (bd, J = 10.4 Hz, 1H), 4.17 (m, 4H), 2.92 (m, 2H), 2.69 (dd, J = 4.0, 17.6 Hz, 1H), 2.40 (dd, J = 5.2, 13.2 Hz, 1H), 1.69 (dd, J = 10.0, 13.2 Hz, 1H), 1.24 (t, J = 7.2 Hz, 3H), 1.22 (t, J = 7.2 Hz, 3H); 13C NMR (100 MHz, CDCl₃) δ 170.8, 170.1, 139.7, 129.6, 115.5, 62.0, 61.9, 54.6, 38.5, 37.2, 33.0, 14.2, 14.2; HRMS Calcd for C₁₄H₁₉ClNaO₄ (M + Na⁺): 310.0931, found 310.0938.

**(E)-3-Bromomethylene-4-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (4a).** IR (neat) cm⁻¹: 3030, 2984, 2940, 1728, 1447, 1248, 910, 733; ¹H NMR (400 MHz, CDCl₃) δ 5.96 (bs, 1H), 5.71 (dd, J = 5.6, 8.0, 13.6 Hz, 1H), 5.10 (bd, J = 13.6 Hz, 1H), 5.06 (bd, J = 8.0 Hz, 1H), 4.18 (m, J = 7.2 Hz, 4H), 3.00 (bd, J = 13.6 Hz, 1H), 2.95 (m, 1H), 2.82 (bddd, J = 2.0, 3.4, 17.2 Hz, 1H), 2.46 (dd, J = 4.0, 10.8 Hz, 1H), 1.75 (dd, J = 8.4, 10.8 Hz, 1H), 1.28 (t, J = 7.2 Hz, 3H), 1.27 (t, J = 7.2 Hz, 3H); 13C NMR (100 MHz, CDCl₃) δ 170.7, 170.1, 139.6, 130.5, 119.3, 115.6, 62.1, 62.0, 39.8, 39.4, 32.8, 14.3, 14.2; HRMS Calcd for C₁₄H₁₉BrO₄ (M⁺): 330.0467, found 330.0459.

**(E)-3-(1-Bromoethylidene)-4-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (4b).** IR (neat) cm⁻¹: 3045, 2984, 1728, 1638, 1263, 910, 733; ¹H NMR (400 MHz, CDCl₃) δ 5.62 (ddd, J = 7.6, 10.0, 17.6 Hz, 1H), 5.00 (bddd, J = 1.2, 14.8 Hz, 1H), 4.97 (dd, J = 1.2, 14.8 Hz, 1H), 4.16 (m, J = 7.2 Hz, 4H), 3.35 (q, J = 7.6 Hz, 1H), 3.03 (ddq, J = 2.4, 14.0, 2.4 Hz, 1H), 3.02 (ddq, J = 1.6, 13.2, 1.6 Hz, 1H), 2.70 (ddd, J = 1.2, 8.4, 13.2 Hz, 1H), 2.16 (bs, 3H), 1.22 (t, J = 7.2 Hz, 3H), 1.22 (t, J = 7.2 Hz, 3H); 13C NMR (100 MHz, CDCl₃) δ 171.5, 171.2, 139.3, 138.9, 116.4, 115.4, 61.8, 61.8, 58.8, 46.3, 43.5, 41.8, 39.5, 25.7, 14.2; HRMS Calcd for C₁₅H₂₁BrO₄ (M⁺): 344.0623, found 344.0624.
\( (E)-3-(1\text{-Bromopentylidene})-4\text{-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (4c). IR (neat) cm}^{-1} 3060, 2959, 2932, 1734, 1464, 1258, 914, 735; ^1H\ NMR (400 MHz, CDCl\textsubscript{3}) \delta 5.66 (dd, \( J = 8.0, 10.0, 17.2 \text{ Hz, 1H}), 5.02 (bddd, \( J = 1.2, 17.6 \text{ Hz, 1H}), 4.99 (bddd, \( J = 1.2, 10.8 \text{ Hz, 1H}), 4.15 (m, \text{ 4H}), 3.37 (q, \( J = 7.2 \text{ Hz, 1H}), 3.10-2.90 (m, \text{ 2H}), 2.67 (dd, \( J = 8.4, 13.2 \text{ Hz, 1H}), 2.36 (t, \( J = 7.6 \text{ Hz, 2H}), 2.14 (dd, \( J = 6.8, 13.2 \text{ Hz, 1H}), 1.51-1.42 (m, \text{ 3H}); ^13C\ NMR (100 MHz, CDCl\textsubscript{3}) \delta 171.5, 171.2, 139.5, 139.1, 138.1, 123.7, 115.3, 115.2, 61.8, 61.8, 58.7, 48.6, 46.4, 41.8, 39.4, 39.1, 38.8, 37.3, 30.7, 30.5, 22.0, 21.9, 14.2, 14.1; \text{ HRMS Calcd for C}_{18}H_{27}BrO_4 (M^+) : 386.1090, found 386.1093.}

\( (E)-3-(Bromophenylmethylene)-4\text{-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (4d). IR (neat) cm}^{-1} 3084, 2986, 2940, 1726, 1445, 1263, 909, 729; ^1H\ NMR (400 MHz, CDCl\textsubscript{3}) \delta 7.33-7.20 (m, \text{ 5H}), 5.34 (ddd, \( J = 7.2, 10.0, 17.2 \text{ Hz, 1H}), 4.64 (bdt, \( J = 1.2, 10.0 \text{ Hz, 1H}), 4.60 (d, \( J = 1.2, 17.2 \text{ Hz, 1H}), 4.19 (m, \text{ 4H}), 3.44 (q, \( J = 6.8 \text{ Hz, 1H}), 3.28 (dd, \( J = 1.2, 18.0 \text{ Hz, 1H}), 2.64 (ddd, \( J = 1.2, 8.0, 13.2 \text{ Hz, 1H}), 1.26 (m, \text{ 6H}); ^13C\ NMR (100 MHz, CDCl\textsubscript{3}) \delta 171.6, 171.3, 142.9, 140.2, 138.1, 129.2, 129.0, 128.4, 128.3, 128.2, 117.4, 115.4, 62.0, 62.0, 58.5, 47.0, 44.0, 14.3, 14.2; \text{ HRMS Calcd for C}_{20}H_{23}BrO_4 (M^+) : 406.0779.}

\( (E)-3\text{-Bromomethylene-4-d-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester (4e). IR (neat) cm}^{-1} 2981, 2937, 1737, 1643, 1367, 1298, 1095; ^1H\ NMR (400 MHz, CDCl\textsubscript{3}) \delta 5.66 (ddd, \( J = 6.8, 10.0, 16.8 \text{ Hz, 1H}), 5.08 (bd, \( J = 16.4 \text{ Hz, 1H}), 5.04 (bd, \( J = 10.0 \text{ Hz, 1H}), 4.18 (m, \text{ 4H}), 3.09 (bdt, \( J = 1.6, 17.6 \text{ Hz, 1H}), 2.90 (m, \text{ 1H}), 2.82 (dd, \( J = 3.6, 17.2 \text{ Hz, 1H}), 2.44 (dd, \( J = 5.6, 13.6 \text{ Hz, 1H}), 1.71 (dd, \( J = 10.4, 13.6 \text{ Hz, 1H}), 1.23 (t, \( J = 6.0 \text{ Hz, 3H}), 1.22 (J = 6.0 \text{ Hz, 3H}); ^13C\ NMR (100 MHz, CDCl\textsubscript{3}) \delta 170.6, 170.0, 139.5, 119.1, 115.5, 62.0, 61.9, 55.1, 39.6, 39.3, 32.8, 14.2, 14.2; \text{ HRMS Calcd for C}_{14}H_{18}BrDNaO_4 (M + Na^+) : 354.0426, found 354.0446.}

\( (E)-3\text{-Iodomethylene-4-vinylcyclopentane-1,1-dicarboxylic acid diethyl ester. IR (neat) cm}^{-1} 3466, 2982, 1736, 1446, 1247, 1188, 920, 860; ^1H\ NMR (400 MHz, CDCl\textsubscript{3}) \delta 6.21 (bs, 1H), 5.65 (ddd, \( J = 6.8, 10.0, 17.2 \text{ Hz, 1H}), 5.09 (bd, \( J = 15.6 \text{ Hz, 1H}), 5.04 (bd, \( J = 12.4 \text{ Hz, 1H}), 4.18 (m, \text{ 4H}), 3.20 (bd, \( J = 17.6 \text{ Hz, 1H}), 2.92 (m, \text{ 1H}), 2.80 (dd, \( J = 2.4, 3.6, 17.6 \text{ Hz, 1H}), 2.48 (dd, \( J = 5.6, 13.6 \text{ Hz, 1H}), 1.75 (dd, \( J = 10.0, 13.6 \text{ Hz, 1H}), 1.24 (t, \( J = 7.2 \text{ Hz, 3H}), 1.22 (t, \( J = 7.2 \text{ Hz, 3H}); ^13C\ NMR (100 MHz, CDCl\textsubscript{3}) \delta 170.5, 170.1, 139.5, 138.8, 115.5, 92.6, 62.0, 61.9, 55.7, 43.3, 41.2, 32.4, 14.2, 14.2; \text{ HRMS Calcd for C}_{14}H_{19}InNaO_4 (M + Na^+) : 401.0226, found 401.0226.}
EtO₂C⁻⁻⁻⁻EtO₂C⁻⁻⁻⁻Br

Pulse Sequence: 42p21
Solvent: CDCl₃
Temp: 25.0 °C
Sample: 25.0 Hz/300.1 MHz
Resolution: 4006.4802 MHz
Repeattion: 250 repetitions
Power: 10 Hz

Data Processing:
Total 5 min, 14 sec