Synthesis of Highly Substituted 1,3-Dienes and 1,3,5-Trienes by the Palladium-Catalyzed Coupling of Vinylic Halides, Internal Alkynes and Organoboranes

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Supporting Information

General. The ^1H and ^{13}C NMR spectra were recorded at 300 and 75.5 MHz or 400 and 100 MHz respectively. NOESY NMR spectra were recorded at 400 MHz. All melting points are uncorrected. High resolution mass spectra were recorded on a Kratos MS50TC double focusing magnetic sector mass spectrometer using EI at 70 eV. All reagents were used directly as obtained commercially unless otherwise noted. (*E*)- β -Iodostyrene,¹ iodomethylenecyclohexane,² 1-iodo-4-phenylcyclohexene,³ bis[4-(ethoxycarbonyl)phenyl]acetylene,⁴ 3-iodocyclohex-2-en-1-ol,⁵ and 3-iodo-5,5-dimethylcyclohex-2-en-1-one⁶ were prepared according to previous literature procedures.

Alkyne Synthesis

1-(4-Nitrophenyl)-1-hexyne. To a solution of Et_3N (12 mL), $\text{PdCl}_2(\text{PPh}_3)_2$ (7.0 mg, 2 mol %), 5.0 mmol of 4-iodonitrobenzene, and 6.0 mmol of 1-hexyne (stirring for 5 min beforehand) was added CuI (10.0 mg, 1 mol %). The reaction mixture was flushed with Ar and the flask was then sealed. The mixture was stirred at 55 °C for 3 h, and the resulting solution was filtered, washed with a satd aq NaCl solution, and extracted with diethyl ether (2×30 mL). The combined ether fractions were dried over Na_2SO_4 and concentrated under vacuum to yield the crude product, which was purified by flash chromatography on silica gel using 20:1 hexane/EtOAc as the eluent to afford 862.0 mg

(85 %) of the indicated compound as a light orange oil: ^1H NMR (CDCl_3) δ 0.94-0.99 (t, $J = 7.5$ Hz, 3H), 1.47-1.52 (m, 2H), 1.59-1.64 (m, 2H), 2.43-2.48 (t, $J = 6.9$ Hz, 2H), 7.50-7.53 (d, $J = 6.9$ Hz, 2H), 8.13-8.16 (d, $J = 6.9$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 13.81, 19.48, 22.25, 30.69, 79.52, 96.98, 123.70, 132.46; IR (CHCl_3) 2926, 1519 cm^{-1} ; HRMS m/z 203.09503 (calcd $\text{C}_{12}\text{H}_{13}\text{NO}_2$, 203.09463).

General Procedure for the Palladium-Catalyzed Formation of Highly-Substituted 1,3-Dienes. Conditions A: A mixture of DMF (1.0 mL), $\text{Pd}(\text{OAc})_2$ (2.8 mg, 0.0125 mmol), LiCl (10.5 mg, 0.25 mmol), vinylic halide (0.50 mmol), internal alkyne (0.25 mmol), and tetraarylborate (0.50 mmol) was stirred in a reaction vial at room temperature for 3 min in presence of air and then the vial was capped and heated to 100 $^\circ\text{C}$ with stirring for the specified time. **Conditions B:** To a solution of vinylic halide (0.25 mmol), internal alkyne (0.50 mmol), and PdCl_2 (0.0125 mmol) in 5 mL of DMF was added 5 mL of a 2:1 DMF- H_2O solution of KF (0.50 mmol) and the boronic acid (0.50 mmol). The resulting mixture was stirred at room temperature for 3 min in presence of air, then sealed and heated to 100 $^\circ\text{C}$ with stirring for the specified time. **Conditions C:** To a solution of vinylic halide (0.25 mmol), internal alkyne (0.50 mmol), water (12.50 mmol), $n\text{-Bu}_4\text{NCl}$ (0.25 mmol), and $\text{PdCl}_2(\text{PhCN})_2$ (0.0125 mmol) in 8 mL of DMF was added KF (0.50 mmol) and the boronic acid (0.50 mmol). The resulting mixture was stirred at room temperature for 3 min in presence of air, then sealed and heated to 100 $^\circ\text{C}$ with stirring for the specified time. All reactions were monitored by TLC to establish completion. The reaction mixture was then cooled to room temperature, diluted with diethyl ether (30 mL) and washed with brine (30 mL). The aqueous layer was reextracted with diethyl ether (2×30 mL). The organic layers were combined, dried

(MgSO₄), filtered and the solvent removed under reduced pressure. The residue was purified by column chromatography on a silica gel column. The following 1,3-dienes and 1,3,5-triene have been prepared using this general procedure.

(*E*)-1,1,2,4-Tetraphenyl-1,3-butadiene (2). The reaction mixture was chromatographed using 100:1 hexanes/EtOAc to afford 63.5 mg (71 %) of the indicated compound as a light orange solid: mp 144-145 °C (lit⁷ mp 151-152 °C); ¹H NMR (CDCl₃) δ 6.24-6.28 (d, *J* = 12.3 Hz, 1H), 6.89-6.91 (m, 2H), 7.02-7.03 (m, 3H), 7.19-7.26 (m, 11H), 7.31-7.39 (m, 5H); ¹³C NMR (CDCl₃) δ 126.47, 126.72, 126.92, 127.54, 127.56, 127.60, 128.22, 128.20, 128.77, 131.34, 131.41, 131.51, 131.74, 131.87, 138.00, 139.19, 140.73, 142.73, 143.00, 143.12; the IR spectral properties were identical to those previously reported;⁷ HRMS *m/z* 358.1728 (calcd C₂₆H₂₀S, 358.1722).

(*E,E*)-1-(2-Thienyl)-1,2,4-triphenyl-1,3-butadiene (3). The reaction mixture was chromatographed using 50:1 hexanes/EtOAc to afford 72.8 mg (80 %) of the indicated compound as a white solid: mp 145-146 °C; ¹H NMR (CDCl₃) δ 5.98-6.03 (d, *J* = 15.0 Hz, 1H), 6.33-6.35 (dd, *J* = 1.2, 3.6 Hz, 1H), 6.69-6.73 (m, 1H), 6.92-6.98 (d, *J* = 15.0 Hz, 1H), 7.05-7.18 (m, 6H), 7.33-7.36 (m, 2H), 7.42-7.48 (m, 8H); ¹³C NMR (CDCl₃) δ 126.03, 126.66, 127.38, 127.53, 127.88, 128.07, 128.47, 128.69, 129.29, 130.07, 131.08, 131.25, 131.45, 132.52, 135.92, 137.84, 138.02, 139.66, 141.76, 145.54; IR (CHCl₃) 3003, 1720 cm⁻¹; HRMS *m/z* 364.1292 (calcd C₂₆H₂₀S, 364.1286).

(*E,E*)-2-Butyl-1,4-diphenyl-1-(4-nitrophenyl)-1,3-butadiene (4). The reaction mixture was chromatographed using 10:1 hexanes/EtOAc to afford 59.3 mg (62 %) of the indicated compound as a yellow green solid: mp 139-140 °C; ¹H NMR (CDCl₃) δ 0.84-0.89 (t, *J* = 7.2 Hz, 3H), 1.28-1.36 (m, 2H), 1.54-1.61 (m, 2H), 2.40-2.46 (t, *J* = 8.1 Hz,

2H), 6.71-6.77 (d, $J = 16.2$ Hz, 1H), 6.92-6.97 (d, $J = 16.2$ Hz, 1H), 7.13-7.17 (m, 2H), 7.21-7.26 (m, 1H), 7.28-7.37 (m, 9H), 8.17-8.18 (d, $J = 4.2$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 14.12, 23.20, 30.18, 32.36, 123.69, 126.79, 127.70, 127.85, 128.33, 128.44, 128.89, 130.34, 130.74, 131.00, 137.73, 138.73, 140.31, 141.34, 146.71, 150.48; IR (CHCl_3) 2924, 1516 cm^{-1} ; HRMS m/z 383.1889 (calcd $\text{C}_{26}\text{H}_{20}\text{NO}_2$, 383.1885).

2-Cyclohexylidenemethyl-1,1,2-triphenylethene (6). The reaction mixture was chromatographed using hexane to afford 76.2 mg (87 %) of the indicated compound as a white solid: mp 133-134 °C; ^1H NMR (CDCl_3) δ 1.11-1.12 (m, 2H), 1.40-1.46 (m, 4H), 1.73-1.78 (m, 2H), 2.01-2.05 (m, 2H), 5.84 (s, 1H), 6.92-6.95 (m, 2H), 7.05-7.08 (m, 8H), 7.21-7.25 (m, 5H); ^{13}C NMR (CDCl_3) δ 26.72, 26.93, 28.41, 30.49, 37.53, 124.63, 126.31, 126.35, 126.80, 127.66, 127.71, 127.78, 130.85, 131.39, 131.76, 137.56, 140.88, 143.02, 143.26, 143.64, 144.22; IR (CHCl_3) 2922, 1442 cm^{-1} ; HRMS m/z 350.2035 (calcd $\text{C}_{27}\text{H}_{26}$, 350.2034).

(E)-2-Cyclohexylidenemethyl-1-(4-methoxyphenyl)-1,2-diphenylethene (7). The reaction mixture was chromatographed using 30:1 hexanes/EtOAc to afford 88.0 mg (93 %) of the indicated compound as a white solid: mp 80-81 °C; ^1H NMR (CDCl_3) δ 1.11-1.16 (m, 2H), 1.40-1.42 (m, 4H), 1.72-1.76 (m, 2H), 2.03-2.07 (m, 2H), 5.85 (s, 1H), 6.78-6.81 (m, 2H), 6.92-6.95 (m, 2H), 7.04-7.08 (m, 8H), 7.15-7.18 (m, 2H); ^{13}C NMR (CDCl_3) δ 26.74, 27.01, 28.51, 30.53, 37.56, 55.44, 113.02, 124.93, 126.15, 126.24, 127.66, 127.73, 130.88, 131.79, 132.59, 136.68, 136.72, 140.49, 143.08, 143.28, 143.85, 158.50; IR (CHCl_3) 2927, 1508 cm^{-1} ; HRMS m/z 380.2149 (calcd $\text{C}_{28}\text{H}_{28}\text{O}$, 380.2140).

(E)-2-Cyclohexylidenemethyl-1-(3-nitrophenyl)-1,2-diphenylethene (8). The reaction mixture was chromatographed using 30:1 hexane/EtOAc to afford 55.2 mg (56 %) of the indicated compound as a yellow solid: mp 130-131 °C; ¹H NMR (CDCl₃) δ 1.13-1.17 (m, 2H), 1.40-1.46 (m, 4H), 1.75-1.79 (m, 2H), 2.01-2.05 (m, 2H), 5.83 (s, 1H), 6.91-6.94 (m, 2H), 7.07-7.13 (m, 8H), 7.38-7.43 (dd, *J* = 10.2, 11.4 Hz, 1H), 7.51-7.55 (d, *J* = 10.2 Hz, 1H), 8.04-8.08 (d, *J* = 11.4 Hz, 1H), 8.21 (s, 1H); ¹³C NMR (CDCl₃) δ 26.37, 26.86, 28.18, 30.33, 37.21, 121.51, 123.55, 126.14, 126.78, 126.83, 127.77, 127.98, 128.47, 130.47, 131.41, 137.12, 138.23, 139.59, 141.81, 142.10, 144.85, 145.86, 147.84; IR (CHCl₃) 2919, 1529 cm⁻¹; HRMS *m/z* 395.1890 (calcd C₂₇H₂₅NO₂, 395.1885).

(E)-2-Cyclohexylidenemethyl-1-(2-methylphenyl)-1,2-diphenylethene (9).

The reaction mixture was chromatographed using 100:1 hexane/EtOAc to afford 74.6 mg (82 %) of the indicated compound as a white solid: mp 141-143 °C; ¹H NMR (CDCl₃) δ 1.15-1.17 (m, 2H), 1.40-1.43 (m, 4H), 1.67-1.71 (m, 2H), 1.93-1.95 (m, 2H), 2.19 (s, 3H), 5.64 (s, 1H), 6.84-6.88 (m, 2H), 6.98-7.01 (m, 3H), 7.09-7.18 (m, 9H); ¹³C NMR (CDCl₃) δ 20.24, 26.67, 27.33, 28.75, 30.68, 37.84, 124.24, 125.61, 126.05, 126.45, 127.04, 127.61, 127.92, 130.33, 130.91, 130.98, 131.27, 136.81, 138.26, 139.90, 142.60, 142.78, 143.33, 144.17; IR (CHCl₃) 1639 cm⁻¹; HRMS *m/z* 364.2197 (calcd C₂₈H₂₈, 364.2191).

(Z)-4-Cyclohexylidenemethyl-5-phenyl-4-octene (10). The reaction mixture was chromatographed using hexane to afford 60.0 mg (85 %) of the indicated compound as a colorless oil: ¹H NMR (CDCl₃) δ 0.87-0.95 (m, 8H), 1.23-1.30 (m, 6H), 1.37-1.44 (m, 2H), 1.65-1.69 (m, 2H), 1.86 (m, 2H), 2.13-2.18 (dd, *J* = 7.8, 9.6 Hz, 2H), 2.39-2.44 (t, *J* = 14.1 Hz, 2H), 5.41 (s, 1H), 7.09-7.22 (m, 5H); ¹³C NMR (CDCl₃) δ 14.19, 14.48,

21.86, 22.06, 26.77, 26.82, 28.23, 30.12, 35.65, 35.70, 36.83, 123.36, 125.58, 127.41, 129.76, 134.53, 137.46, 139.54, 144.42; IR (CHCl₃) 2955, 1445 cm⁻¹; HRMS *m/z* 282.2350 (calcd C₂₁H₃₀, 282.2347).

(Z)-2-[(4-Phenylcyclohexylidene)methyl]-1-phenyl-1,2-di[4-(ethoxycarbonyl)phenyl]ethene (12). The reaction mixture was chromatographed using 10:1 hexane/EtOAc to afford 48.0 mg (68 %) of the indicated compound as a light yellow green solid: mp 137-138 °C; ¹H NMR (CDCl₃) δ 0.88-0.92 (m, 1H), 1.33-1.39 (m, 6H), 1.40-1.62 (m, 3H), 1.88-1.93 (m, 1H), 2.15-2.17 (m, 1H), 2.29-2.34 (m, 2H), 2.49-2.53 (m, 1H), 4.29-4.37 (m, 4H), 5.92 (s, 1H), 6.98-7.02 (d, *J* = 10.5 Hz, 1H), 7.08-7.11 (m, 2H), 7.14-7.19 (m, 3H), 7.23-7.33 (m, 7H), 7.73-7.82 (m, 4H); ¹³C NMR (CDCl₃) δ 14.55, 30.41, 33.83, 35.55, 37.34, 44.35, 61.12, 124.59, 126.23, 127.03, 127.58, 128.02, 128.53, 128.68, 129.22, 129.37, 130.73, 131.41, 131.64, 137.88, 141.64, 143.02, 143.26, 146.85, 147.45, 147.90, 166.68, 166.71; IR (CHCl₃) 2918, 1715 cm⁻¹; HRMS *m/z* 570.2770 (calcd C₃₉H₃₈O₄, 570.2781).

(2Z)-2-(4-Phenylcyclohexylidene)methyl-3-[(E)-2-phenylethenyl]but-2-ene-1,4-diol (13). The reaction mixture was chromatographed using 1:2 hexane/EtOAc to afford 28.0 mg (57 %) of the indicated compound as a light yellow oil: ¹H NMR (CDCl₃) δ 1.44-1.47 (m, 1H), 1.59-1.64 (m, 1H), 1.82-1.86 (m, 2H), 2.05-2.11 (m, 3H), 2.38-2.90 (m, 1H), 2.50-2.54 (m, 2H), 2.68-2.70 (m, 1H), 4.37 (s, 2H), 4.59 (s, 2H), 5.87 (s, 1H), 6.80-6.86 (d, *J* = 16.8 Hz, 1H), 7.04-7.13 (m, 3H), 7.16-7.19 (m, 1H), 7.24-7.28 (m, 3H), 7.32-7.37 (m, 2H), 7.44-7.47 (m, 2H); ¹³C NMR (CDCl₃) δ 30.36, 34.47, 36.55, 37.17, 44.56, 58.58, 63.41, 76.83, 77.25, 77.68, 120.92, 126.27, 126.68, 127.04, 127.81, 128.34,

128.96, 129.03, 136.64, 137.88, 140.43, 145.60, 146.73; IR (CHCl₃) 3370, 2926 cm⁻¹; HRMS *m/z* 360.2096 (calcd C₂₆H₃₂, 360.2089).

1,1,2-Triphenyl-2-(4-phenylcyclohex-1-enyl)ethene (15). The reaction mixture was chromatographed using 100:1 hexane/EtOAc to afford 80.3 mg (78 %) of the indicated compound as a white solid: mp 121-122 °C; ¹H NMR δ (CDCl₃) 1.62-1.71 (m, 1H), 1.83-1.99 (m, 1H), 2.03-2.08 (m, 3H), 2.20-2.26 (m, 1H), 2.60-2.75 (m, 1H), 5.58 (s, 1H), 6.94-6.96 (m, 2H), 7.05-7.08 (m, 3H), 7.12-7.20 (m, 6H), 7.21-7.30 (m, 9H); ¹³C NMR (CDCl₃) δ 29.64, 30.25, 33.91, 39.61, 126.15, 126.33, 126.55, 126.64, 127.08, 127.71, 128.51, 129.74, 130.27, 130.62, 131.58, 139.40, 139.82, 142.21, 143.62, 143.73, 144.90, 147.18 (one sp² carbon was missing due to overlap); IR (CHCl₃) 2920, 1491 cm⁻¹; HRMS *m/z* 412.2196 (calcd C₃₂H₂₈, 412.2191).

(Z)-4-Phenyl-5-(4-phenylcyclohex-1-enyl)-4-octene (16). The reaction mixture was chromatographed using hexane to afford 54.3 mg (63 %) of the indicated compound as a colorless oil: ¹H NMR (CDCl₃) δ 0.87-0.92 (t, *J* = 7.5 Hz, 3H), 0.97-1.02 (t, *J* = 7.5 Hz, 3H), 1.29-1.34 (m, 2H), 1.47-1.54 (m, 3H), 1.71-1.80 (m, 1H), 1.93-1.94 (m, 3H), 2.01-2.18 (m, 1H), 2.26-2.31 (dd, *J* = 6.0, 7.8 Hz, 2H), 2.39-2.44 (dd, *J* = 6.0, 9.3 Hz, 2H), 2.45-3.60 (m, 1H), 5.25 (s, 1H), 7.11-7.30 (m, 10H); ¹³C NMR (CDCl₃) δ 14.22, 14.40, 21.86, 21.92, 29.81, 30.25, 33.64, 34.29, 36.12, 39.74, 125.76, 125.86, 126.02, 127.08, 127.57, 128.46, 129.24, 136.31, 138.98, 140.52, 144.72, 147.54; IR (CHCl₃) 2957, 1599 cm⁻¹; HRMS *m/z* 344.2512 (calcd C₂₆H₃₂, 344.2504).

5,5-Dimethyl-3-phenylcyclohex-2-enone (18). The reaction mixture was chromatographed using 10:1 hexane/EtOAc to afford 45.0 mg (90 %) of the indicated

compound as a colorless oil. The spectral properties were identical to those previously reported.⁸

3-(Triphenylethenyl)cyclohex-2-enol (20). The reaction mixture was chromatographed using 4:1 hexane/EtOAc to afford 36.0 mg (41 %) of the indicated compound as a white solid: mp 131-132 °C; ¹H NMR (CDCl₃) δ 1.47-1.51 (m, 2H), 1.61-1.72 (m, 3H), 1.88-1.92 (m, 2H), 4.03 (s, 1H), 5.49-5.50 (t, *J* = 1.8 Hz, 1H), 6.95-6.98 (m, 2H), 7.06-7.15 (m, 8H), 7.18-7.30 (m, 5H); ¹³C NMR (CDCl₃) δ 19.03, 29.42, 31.46, 65.83, 126.66, 126.88, 126.93, 127.82, 127.96, 128.07, 130.19, 130.45, 131.41, 131.47, 140.19, 140.92, 142.84, 143.16, 143.65, 144.83; IR (CHCl₃) 3408, 1645 cm⁻¹; HRMS *m/z* 352.1833 (calcd C₂₆H₂₄O, 352.1827).

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Current Data Parameters
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PROCNO    1

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RG          90.5
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TE          300.0 K
G0          0.00000300 sec
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F2 - Processing parameters
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