Enantioselective Synthesis of Axially Chiral Biaryls through Rhodium-Catalyzed Complete Intermolecular Cross Cyclotrimerization of Internal Alkynes

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I. General

Anhydrous CH₂Cl₂ (No. 27,099-7) was obtained from Aldrich and used as received. H8-BINAP and Segphos were obtained from Takasago International Corp. All other reagents were obtained from commercial sources and used as received. All reactions were carried out under an atmosphere of argon or nitrogen in oven-dried glassware with magnetic stirring.

II. Cross Cyclotrimerization of Diethyl Acetylenedicarboxylate and Internal Alkynes (Table 1)

General Procedure 1 (Table 1, entry 1): Under an Ar atmosphere, a CH₂Cl₂ (1.0 mL) solution of H8-BINAP (9.5 mg, 0.015 mmol) was added to a CH₂Cl₂ (1.0 mL) solution of [Rh(cod)₂](BF₄) (6.1 mg, 0.015 mmol) at rt. The solution was stirred at rt for 5 min. H₂ was introduced to the resulting solution in a Schlenk tube. After stirring at rt for 0.5 h, the resulting solution was concentrated to dryness and dissolved in CH₂Cl₂ (0.5 mL). This solution was added to a CH₂Cl₂ (0.5 mL) solution of 4-octyne (**2a**, 33.0 mg, 0.300 mmol) and washed remaining catalyst away by using CH₂Cl₂ (0.5 mL). To this solution was added a CH₂Cl₂ (0.5 mL) solution of diethyl acetylenedicarboxylate (**1a**, 102 mg, 0.600 mmol), and washed remaining substrate away by using CH₂Cl₂ (0.5 mL). The solution was stirred at rt for 16 h. The resulting solution was concentrated and purified by preparative TLC (hexane:ethyl acetate = 7:3), which furnished 5,6-dipropylphthalic acid diethyl ester (**3aa**, 102.3 mg, 0.227 mmol, 76% yield) as a colorless oil.

5,6-Dipropylbenzene-1,2,3,4-tetracarboxylic acid tetraethyl ester (3aa).

Colorless oil; IR (neat) 2920, 1720, 1190, 1100, 1015 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 4.35 (q, *J* = 7.2 Hz, 4H), 4.28 (q, *J* = 7.2 Hz, 4H), 2.63-2.69 (m, 4H), 1.50-1.62 (m, 4H), 1.36 (t, *J* = 7.2 Hz, 6H), 1.32 (t, *J* = 7.2 Hz, 6H), 1.00 (t, *J* = 7.2 Hz, 6H); ¹³C NMR

(CDCl₃, 75 MHz) δ 167.5, 166.2, 141.8, 134.9, 129.1, 62.0, 61.8, 32.5, 24.6, 14.7, 14.0, 13.9; Anal calcd for C₂₄H₃₄O₈: C, 63.98; H, 7.61. Found: C, 64.13; H, 7.84.

5-Methyl-6-pentylbenzene-1,2,3,4-tetracarboxylic acid tetraethyl ester (3ba).

Colorless oil; IR (neat) 2910, 1720, 1230, 1020 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 4.37 (q, *J* = 7.2 Hz, 2H), 4.36 (q, *J* = 7.2 Hz, 2H), 4.28 (q, *J* = 7.2 Hz, 4H), 2.63-2.70 (m, 2H), 2.36 (s, 3H), 1.46-1.58 (m, 2H), 1.30-1.38 (m, 16H), 0.90 (t, *J* = 6.8 Hz, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 167.5, 167.5, 166.1, 142.2, 137.1, 135.1, 134.6, 128.8, 128.6, 61.9, 61.8, 61.7, 32.1, 31.2, 29.6, 22.3, 16.3, 14.01, 13.98, 13.9; Anal calcd for C₂₄H₃₄O₈: C, 63.98; H, 7.61. Found: C, 64.10; H, 7.65.

6-Methylbiphenyl-2,3,4,5-tetracarboxylic acid tetraethyl ester (3ca).

Pale yellow oil; IR (neat) 2925, 1715, 1205, 1020 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.34-7.44 (m, 3H), 7.13-7.20 (m, 2H), 4.38 (q, *J* = 7.2 Hz, 2H), 4.33 (q, *J* = 7.2 Hz, 2H), 4.30 (q, *J* = 7.2 Hz, 2H), 3.91 (q, *J* = 7.2 Hz, 2H), 2.13 (s, 3H), 1.37 (t, *J* = 7.2 Hz, 3H), 1.35 (t, *J* = 7.2 Hz, 3H), 1.31 (t, *J* = 7.2 Hz, 3H), 0.89 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 167.4, 166.8, 166.1, 165.9, 142.8, 137.5, 137.1, 135.3, 134.9, 130.2, 128.9, 128.4, 128.2, 128.0, 62.1, 62.0, 61.9, 61.4, 17.7, 13.9, 13.8, 13.8, 13.4; Anal calcd for C₂₅H₂₈O₈: C, 65.78; H, 6.18. Found: C, 65.50; H, 6.45.

6-Methylbenzene-1,2,3,4,5-pentacarboxylic acid pentaethyl ester (3da).

Colorless oil; IR (neat) 2940, 1720, 1210, 1015 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 4.38 (q, *J* = 7.2 Hz, 4H), 4.32 (q, *J* = 7.2 Hz, 6H), 2.41 (s, 3H), 1.36 (t, *J* = 7.2 Hz, 6H), 1.34 (t, *J* = 7.2 Hz, 9H); ¹³C NMR (CDCl₃, 75 MHz) δ 166.4, 165.8, 165.2, 136.5, 135.7, 131.2, 131.2, 62.3, 62.1, 62.1, 16.5, 13.9, 13.7; Anal calcd for C₂₂H₂₈O₁₀: C, 58.40; H, 6.24. Found: C, 58.45; H, 6.41.

Biphenyl-2,3,4,5,6-pentacarboxylic acid pentaethyl ester (3ea).

Colorless solid; Mp 84.0-85.6 °C; IR (neat) 2920, 1720, 1200, 1010 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.32-7.40 (m, 3H), 7.18-7.24 (m, 2H), 4.35 (q, $J = 7.2$ Hz, 2H), 4.33 (q, $J = 7.2$ Hz, 4H), 3.95 (q, $J = 7.2$ Hz, 4H), 1.30-1.38 (m, 9H), 0.87 (t, $J = 7.2$ Hz, 6H) ^{13}C NMR (CDCl_3 , 75 MHz) δ 166.1, 165.6, 165.2, 140.2, 136.5, 136.1, 132.3, 131.6, 128.5, 128.0, 62.5, 62.3, 61.7, 13.8, 13.7, 13.3; Anal calcd for $\text{C}_{27}\text{H}_{30}\text{O}_{10}$: C, 63.03; H, 5.88. Found: C, 63.45; H, 5.97.

5,6-Bis(methoxymethyl)benzene-1,2,3,4-tetracarboxylic acid tetraethyl ester (3fa).

Colorless oil; IR (neat) 2890, 1720, 1215, 1095, 1015 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 4.63 (s, 4H), 4.35 (q, $J = 7.2$ Hz, 4H), 4.30 (q, $J = 7.0$ Hz, 4H), 3.27 (s, 6H), 1.36 (t, $J = 7.2$ Hz, 6H), 1.33 (t, $J = 7.2$ Hz, 6H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 166.9, 165.8, 138.3, 135.2, 131.0, 68.1, 62.1, 61.9, 58.1, 13.9, 13.8; Anal calcd for $\text{C}_{22}\text{H}_{30}\text{O}_{10}$: C, 58.14; H, 6.65. Found: C, 58.15; H, 6.65.

III. Synthesis of Internal Alkynes (Tables 2 and 3)

1-Methyl-2-prop-1-ynylbenzene (**2h**),¹ 1-(3-methoxyprop-1-ynyl)-2-methylbenzene (**2i**),² and 4-(1-naphthyl)-3-butyne-1-ol (**2p**)³ were prepared according to the literatures.

Acetic acid 3-*o*-tolyl-prop-2-ynyl ester (2j).

This compound was prepared from 3-*o*-tolylprop-2-yn-1-ol⁴ by treatment with $\text{Ac}_2\text{O}/\text{Et}_3\text{N}$.

Pale yellow oil; IR (neat) 2900, 1740, 1215, 1025, 755 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.42 (d, $J = 7.5$ Hz, 1H), 7.09-7.27 (m, 3H), 4.94 (s, 2H), 2.43 (s, 3H), 2.14 (s, 3H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 170.3, 140.5, 132.2, 129.4, 128.7, 125.4, 121.8, 86.6, 85.3, 52.9, 20.8, 20.5; HRMS (EI) calcd for $\text{C}_{12}\text{H}_{12}\text{O}_2$ $[\text{M}]^+$ 188.0837, found 188.0812.

Propionic acid 3-*o*-tolyl-prop-2-ynyl ester (2k).

This compound was prepared from 3-*o*-tolylprop-2-yn-1-ol⁴ by treatment with $(\text{EtCO})_2\text{O}/\text{Et}_3\text{N}$.

Colorless oil; IR (neat) 2900, 1735, 1160, 755 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.41 (d, $J = 7.5$ Hz, 1H), 7.10-7.26 (m, 3H), 4.95 (s, 2H), 2.43 (s, 3H), 2.41 (q, $J = 7.5$ Hz, 2H), 1.18 (t, $J = 7.5$ Hz, 3H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 173.7, 140.5, 132.1, 129.4, 128.7, 125.4, 121.9, 86.8, 85.2, 52.8, 27.4, 20.5, 9.0; HRMS (EI) calcd for $\text{C}_{13}\text{H}_{14}\text{O}_2$ $[\text{M}]^+$ 202.0994, found 202.0950.

Acetic acid 3-(2-ethylphenyl)prop-2-ynyl ester (2l).

CH_2Cl_2 (100 mL) solution of PPh_3 (78.4 g, 0.298 mol) was added to a stirred solution of CBr_4 (49.4 g, 0.149 mol) in CH_2Cl_2 (100 mL) at 0 $^\circ\text{C}$, and the resulting mixture was stirred at 0 $^\circ\text{C}$ for 5 min. CH_2Cl_2 (100 mL) solution of 2-ethylbenzaldehyde (5.00 g, 37.3 mmol) was added at 0 $^\circ\text{C}$, and the resulting mixture was stirred at 0 $^\circ\text{C}$ for 20 min. The reaction was diluted with water, and extracted with CH_2Cl_2 . The organic layer was washed with saturated aqueous NaHCO_3 and saturated aqueous NH_4Cl , dried over Na_2SO_4 , and filtered. The filtrate was diluted with hexane and the resulting solid material was filtered. The filtrate was concentrated and the residue was purified by silica gel chromatography (hexanes: $\text{EtOAc} = 10:1$) to give 1-(2,2-dibromovinyl)-2-ethylbenzene (8.80 g, 30.4 mmol, 81% yield) as a brown oil.

^1H NMR (CDCl_3 , 300 MHz) δ 7.52 (s, 1H), 7.18-7.39 (m, 4H), 2.57 (q, $J = 7.5$ Hz, 2H), 1.20 (t, $J = 7.5$ Hz, 3H).

n-BuLi (1.51 M in hexane, 24.0 mL, 36.2 mmol) was added to a stirred solution of 1-(2,2-dibromovinyl)-2-ethylbenzene (5.00 g, 17.2 mmol) in THF (50 mL) at -70 $^\circ\text{C}$, and

the resulting mixture was stirred at $-70\text{ }^{\circ}\text{C}$ for 0.5 h. Paraformaldehyde (1.09 g, 0.362 mol) was added at rt, and the resulting mixture was stirred at rt for 2 h. The reaction was diluted with water, and extracted with Et_2O . The organic layer was washed with water and brine, dried over Na_2SO_4 , and concentrated. The residue was purified by silica gel chromatography (hexanes: EtOAc = 10:1) to give 3-(2-ethylphenyl)prop-2-yn-1-ol (2.50 g, 15.6 mmol, 90% yield) as a brown oil.

^1H NMR (CDCl_3 , 300 MHz) δ 7.41 (d, J = 7.2 Hz, 1H), 7.19-7.29 (m, 2H), 7.11-7.16 (m, 1H), 4.54 (d, J = 6.0 Hz, 2H), 2.80 (q, J = 7.5 Hz, 2H), 1.78 (t, J = 6.0 Hz, 1H), 1.23 (t, J = 7.5 Hz, 3H).

Ac_2O (0.500 mL, 6.24 mmol) was added to a stirred solution of 3-(2-ethylphenyl)prop-2-yn-1-ol (0.510 g, 3.18 mmol) and pyridine (0.500 mL, 6.97 mmol) in CH_2Cl_2 (2.0 mL) at rt, and the resulting mixture was stirred at rt for 3 h. The reaction was diluted with water, and extracted with Et_2O . The organic layer was washed with brine, dried over Na_2SO_4 , and concentrated. The residue was purified by silica gel chromatography (hexanes: EtOAc = 5:1) to give acetic acid 3-(2-ethylphenyl)prop-2-ynyl ester (**2l**, 0.639 g, 3.16 mmol, 99% yield) as a pale yellow oil.

Pale yellow oil; IR (neat) 3350, 2950, 1740 1220 1020 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.41 (dd, J = 6.3 and 1.2 Hz, 1H), 7.09-7.28 (m, 3H), 4.93 (s, 2H), 2.79 (q, J = 7.5 Hz, 2H), 2.11 (s, 3H), 1.23 (t, J = 7.5 Hz, 3H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 170.2, 146.5, 132.4, 128.9, 127.8, 125.5, 121.1, 86.2, 85.0, 52.8, 27.5, 20.7, 14.7; HRMS (EI) calcd for $\text{C}_{13}\text{H}_{14}\text{O}_2$ $[\text{M}]^+$ 202.0944, found 202.1003.

Acetic acid 3-(2-chlorophenyl)prop-2-ynyl ester (**2m**).

This compound was prepared from 3-(2-chlorophenyl)prop-2-yn-1-ol⁴ by treatment with $\text{Ac}_2\text{O}/\text{Et}_3\text{N}$.

Pale yellow oil; IR (neat) 2930, 1740, 1250, 1060 750 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.48 (dd, J = 7.5 and 2.1 Hz, 1H), 7.39 (dd, J = 8.1 and 1.2 Hz, 1H), 7.17-7.29 (m, 2H), 4.95 (s, 2H), 2.13 (s, 3H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 170.1, 136.0, 133.6, 129.7, 129.2, 126.3, 122.0, 88.0, 83.0, 52.6, 20.7; HRMS (EI) calcd for $\text{C}_{11}\text{H}_9\text{ClO}_2$ $[\text{M}]^+$ 208.0291, found 208.0293.

Acetic acid 3-(2-bromophenyl)prop-2-ynyl ester (**2n**).

This compound was prepared from 3-(2-bromophenyl)prop-2-yn-1-ol⁴ by treatment with Ac₂O/Et₃N.

Pale yellow oil; IR (neat) 2940, 1730, 1260, 1020, 750 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.57 (dd, *J* = 7.8 and 1.2 Hz, 1H), 7.48 (dd, *J* = 7.5 and 1.8 Hz, 1H), 7.15-7.28 (m, 2H), 4.95 (s, 2H), 2.14 (s, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 170.2, 133.7, 132.4, 129.9, 126.9, 125.5, 124.2, 87.5, 84.7, 52.7, 20.7; HRMS (EI) calcd for C₁₁H₉BrO₂ [M]⁺ 251.9786, found 251.9734.

Acetic acid 3-naphthalen-1-yl-prop-2-ynyl ester (2o).

This compound was prepared from 3-(naphthalen-1-yl)prop-2-yn-1-ol⁴ by treatment with Ac₂O/Et₃N.

Pale yellow oil; IR (neat) 3050, 1740, 1210, 1010, 770 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 8.31 (d, *J* = 9.0 Hz, 1H), 7.80 (d, *J* = 8.1 Hz, 2H), 7.68 (dd, *J* = 7.2 and 0.9 Hz, 1H), 7.46-7.59 (m, 2H), 7.38 (dd, *J* = 8.1 and 7.2 Hz, 1H), 5.04 (s, 2H), 2.13 (s, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 170.2, 133.2, 133.0, 130.9, 129.2, 128.2, 126.8, 126.4, 125.9, 125.0, 119.6, 87.7, 84.4, 52.9, 20.7; HRMS (EI) calcd for C₁₅H₁₂O₂ [M]⁺ 224.0837, found 224.0815.

IV. Enantioselective Cross Cyclotrimerization of Dialkyl Acetylenedicarboxylate and Internal Alkynes (Tables 2 and 3)

General Procedure 2 (Table 2, entry 3): Under an Ar atmosphere, a CH₂Cl₂ (1.0 mL) solution of (*S*)-H8-BINAP (9.5 mg, 0.015 mmol) was added to a CH₂Cl₂ (1.0 mL) solution of [Rh(cod)₂]BF₄ (6.1 mg, 0.015 mmol) at rt. The mixture was stirred at rt for 5 min. H₂ was introduced to the resulting solution in a Schlenk tube. After stirring at rt for 0.5 h, the resulting solution was concentrated to dryness and dissolved in CH₂Cl₂ (0.5 mL). This solution was added to a CH₂Cl₂ (0.5 mL) solution of 3-tolyl-2-propynyl acetate (**2j**, 56.4 mg, 0.300 mmol) and washed remaining catalyst away by using CH₂Cl₂ (0.5 mL). To this solution was added a CH₂Cl₂ (0.5 mL) solution of dimethyl acetylenedicarboxylate (**1b**, 85.3 mg, 0.600 mmol), and washed remaining substrate away by using CH₂Cl₂ (0.5 mL). The solution was stirred at rt for 16 h. The resulting

solution was concentrated and purified by preparative TLC (hexane:ethyl acetate = 2:1), which furnished (+)-5-acetoxymethyl-6-tolylphthalic acid tetramethyl ester [(+)-**3jb**], 114.8 mg, 0.243 mmol, 81% yield, 89% ee] as a colorless solid.

(+)-6-Acetoxymethyl-2'-methylbiphenyl-2,3,4,5-tetracarboxylic acid tetramethyl ester [(+)-3jb**].**

Colorless solid; Mp 144.0-144.5 °C; $[\alpha]_D^{25} +27.5$ (CHCl₃, *c* 0.754, 89% ee); IR (neat) 2950, 1720, 1440, 1340, 1220 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.19-7.34 (m, 3H), 7.03 (d, *J* = 7.5 Hz, 1H), 4.89 (d, *J* = 12.6 Hz, 1H), 4.83 (d, *J* = 12.6 Hz, 1H), 3.91 (s, 3H), 3.90 (s, 3H), 3.87 (s, 3H), 3.45 (s, 3H), 2.04 (s, 3H), 1.95 (s, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 169.8, 166.9, 166.5, 166.4, 165.7, 134.1, 136.5, 136.0, 135.6, 134.8, 134.4, 131.7, 130.2, 129.9, 129.2, 129.0, 125.5, 60.7, 53.2, 53.0, 52.3, 20.3, 19.9; Anal calcd for C₂₄H₂₄O₁₀: C, 61.01; H, 5.12. Found: C, 61.35; H, 5.08. CHIRALPAK AD, hexane:*i*-PrOH = 80:20, 0.8 mL/min, retention times: 9.7 min (minor isomer) and 11.1 min (major isomer).

(-)-6,2'-Dimethylbiphenyl-2,3,4,5-tetracarboxylic acid tetramethyl ester [(-)-3hb**].**

Colorless oil; $[\alpha]_D^{25} -13.2$ (CHCl₃, *c* 0.220, 21 % ee); IR (neat) 2950, 1725, 1440, 1340, 1220, 730 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.18-7.32 (m, 3H), 6.96 (d, *J* = 7.5 Hz, 1H), 3.92 (s, 3H), 3.89 (s, 3H), 3.85 (s, 3H), 3.43 (s, 3H), 2.04 (s, 3H), 2.03 (s, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 167.7, 167.0, 166.7, 166.2, 142.9, 138.4, 136.3, 136.2, 135.3, 134.7, 130.5, 129.9, 128.6, 128.5, 128.1, 125.7, 53.1, 53.0, 52.8, 52.2, 19.7, 17.3; HRMS (FAB) calcd for C₂₂H₂₂O₈ [M+H]⁺ 415.1393, found 415.1405. CHIRALPAK AD, hexane:*i*-PrOH = 90:10, 1.0 mL/min, retention times: 10.4 min (major isomer) and 11.6 min (minor isomer).

(+)-6-Acetoxymethyl-2'-methylbiphenyl-2,3,4,5-tetracarboxylic acid tetraethyl ester [(+)-3ja**].**

(*R*)-H8-BINAP was used as ligand. Colorless solid; Mp 79.5-80.9 °C; $[\alpha]_D^{25} +29.2^\circ$ (CHCl₃, *c* 1.01, 93% ee); IR (neat) 2940, 1716, 1420, 1365, 1215(br), 1020, 730 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.17-7.32 (m, 3H), 7.04 (d, *J* = 7.2 Hz, 1H), 4.90 (d, *J* = 12.0 Hz, 1H), 4.82 (d, *J* = 12.0 Hz, 1H), 4.24-4.39 (m, 6H), 3.91 (q, *J* = 7.2 Hz, 2H), 2.06 (s, 3H), 1.93 (s, 3H), 1.37 (t, *J* = 7.2 Hz, 3H), 1.36 (t, *J* = 7.2 Hz, 3H), 1.32 (t, *J* = 7.2 Hz, 3H), 0.89 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 169.8, 166.5, 166.2, 166.0, 165.4, 142.8, 136.7, 135.9, 135.0, 134.7, 131.9, 130.7, 129.8, 129.4, 128.9, 125.4, 62.3, 62.2, 61.5, 60.7, 20.3, 20.0, 13.8, 13.7, 13.3; HRMS (FAB) calcd for C₂₈H₃₃O₁₀ [M+H]⁺ 529.2074, found 529.2077. CHIRALPAK OD-H, hexane:*i*-PrOH = 95:5, 1.0 mL/min, retention times: 12.3 min (major isomer) and 14.0 min (minor isomer).

(+)-2'-Methyl-6-propionyloxymethylbiphenyl-2,3,4,5-tetracarboxylic acid tetramethyl ester [(+)-3kb].

Colorless solid; Mp 89.6-90.8 °C; $[\alpha]_D^{25} +27.6^\circ$ (CHCl₃, *c* 0.984, 91% ee); IR (neat) 2940, 1725, 1215, 730 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.17-7.33 (m, 3H), 7.03 (dd, *J* = 7.2 and 0.9 Hz, 1H), 4.90 (d, *J* = 12.3 Hz, 1H), 4.83 (d, *J* = 12.3 Hz, 1H), 3.91 (s, 3H), 3.89 (s, 3H), 3.86 (s, 3H), 3.44 (s, 3H), 2.21 (q, *J* = 7.5 Hz, 2H), 2.17 (s, 3H), 2.04 (s, 3H), 1.05 (t, *J* = 7.5 Hz, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 173.2, 166.9, 166.5, 166.4, 165.7, 143.1, 136.5, 135.9, 135.8, 134.8, 134.5, 131.7, 130.2, 129.9, 129.2, 129.0, 125.4, 60.5, 53.1, 52.9, 52.3, 27.0, 19.9, 8.8; Anal calcd for C₂₅H₂₆O₁₀: C, 61.72; H, 5.39. Found: C, 61.55; H, 5.43. CHIRALPAK AD, hexane:*i*-PrOH = 92:8, 1.0 mL/min, retention times: 20.5 min (minor isomer) and 24.8 min (major isomer).

(+)-6-Acetoxymethyl-2'-ethylbiphenyl-2,3,4,5-tetracarboxylic acid tetramethyl ester [(+)-3lb].

Colorless solid; Mp 46.0-48.2 °C; $[\alpha]_D^{25} +15.1^\circ$ (CHCl_3 , c 1.05, 92% ee); IR (neat) 2925, 1730, 1240, 1080, 1020 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.29-7.39 (m, 2H), 7.20 (dt, $J = 7.5$ and 1.5 Hz, 1H), 7.02 (d, $J = 6.6$ Hz, 1H), 4.89 (d, $J = 12.6$ Hz, 1H), 4.83 (d, $J = 12.6$ Hz, 1H), 3.91 (s, 3H), 3.89 (s, 3H), 3.86 (s, 3H), 3.44 (s, 3H), 2.24-2.38 (m, 2H), 1.94 (s, 3H), 1.10 (t, $J = 7.5$ Hz, 3H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 169.7, 166.9, 166.5, 166.4, 165.8, 143.0, 142.1, 136.0, 135.8, 134.7, 133.8, 131.7, 130.3, 129.4, 129.2, 127.8, 125.3, 60.8, 53.4, 53.2, 53.0, 52.3, 25.8, 20.4, 13.9; HRMS (FAB) calcd for $\text{C}_{25}\text{H}_{26}\text{O}_{10}$ $[\text{M}+\text{H}]^+$ 487.1604, found 487.1612. CHIRALPAK AD, Hexane:*i*-PrOH = 80:20, 0.8 mL/min, retention times: 8.9 min (minor isomer) and 10.4 min (major isomer).

(+)-6-Acetoxymethyl-2'-chlorobiphenyl-2,3,4,5-tetracarboxylic acid tetramethyl ester [(+)-3mb].

Colorless solid; Mp 107.1-109.2 °C; $[\alpha]_D^{25} +2.58^\circ$ (CHCl_3 , c 1.91, 84% ee); IR (neat) 2910, 1720, 1440, 1220 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.47 (dd, $J = 7.8$ and 1.5 Hz, 1H), 7.30-7.41 (m, 2H), 7.23 (dd, $J = 7.2$ and 2.1 Hz, 1H), 4.96 (d, $J = 12.6$ Hz, 1H), 4.84 (d, $J = 12.6$ Hz, 1H), 3.91 (s, 6H), 3.87 (s, 3H), 3.50 (s, 3H), 1.93 (s, 3H); ^{13}C NMR (CDCl_3 , 75 MHz) δ 169.8, 166.7, 166.2, 166.1, 165.6, 140.7, 136.0, 135.5, 134.9, 134.0, 133.6, 132.2, 131.1, 130.8, 130.4, 129.3, 126.4, 60.6, 53.2, 53.0, 52.5, 20.3; HRMS (ESI) calcd for $\text{C}_{23}\text{H}_{21}\text{ClO}_{10}$ $[\text{M}+\text{Na}]^+$ 515.0721, found 515.0711. CHIRALPAK AD, hexane:*i*-PrOH 80:20, 0.8 mL/min, retention times: 14.3 min (minor isomer) and 16.2 min (major isomer).

(R)-(-)-6-Acetoxymethyl-2'-bromobiphenyl-2,3,4,5-tetracarboxylic acid tetramethyl ester [(R)-(-)-3nb].

Colorless solid; Mp 115.0-117.0 °C; $[\alpha]_D^{25} -6.09^\circ$ (CHCl_3 , c 1.61, 91% ee); IR (neat) 2930, 1720, 1430, 1210, 1020 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.64 (d, $J = 7.8$ Hz, 1H), 7.22-7.41 (m, 3H), 4.97 (d, $J = 12.6$ Hz, 1H), 4.82 (d, $J = 12.6$ Hz, 1H), 3.91 (s, 6H), 3.87 (s, 3H), 3.50 (s, 3H), 1.94 (s, 3H) ^{13}C NMR (CDCl_3 , 75 MHz) δ 169.8, 166.7, 166.3, 166.0, 165.7, 142.3, 136.1, 135.8, 135.3, 134.9, 132.5, 132.2, 131.2, 130.8, 130.4, 126.9, 123.6, 60.7, 53.2, 53.0, 52.5, 20.4; HRMS (ESI) calcd for $\text{C}_{23}\text{H}_{21}\text{BrO}_{10}$ $[\text{M}+\text{Na}]^+$ 559.0216, found 559.0223. CHIRALPAK AD, hexane:*i*-PrOH = 70:30, 0.8 mL/min, retention times: 9.6 min (minor isomer) and 11.2 min (major isomer).

(+)-5-Acetoxymethyl-6-naphthalen-1-yl-benzene-1,2,3,4-tetracarboxylic acid tetramethyl ester [(+)-3ob].

Pale yellow oil; $[\alpha]_D^{25} +9.30^\circ$ (CHCl_3 , c 1.93, 95% ee); IR (neat) 2925, 1720, 1440, 1240 cm^{-1} ; ^1H NMR (CDCl_3 , 300 MHz) δ 7.89 (t, $J = 8.4$ Hz, 2H), 7.38-7.53 (m, 3H), 7.26-7.32 (m, 2H), 4.80 (d, $J = 12.3$ Hz, 1H), 4.76 (d, $J = 12.3$ Hz, 1H), 3.93 (s, 3H), 3.90 (s, 3H), 3.86 (s, 3H), 3.21 (s, 3H), 1.76 (s, 3H); ^{13}C NMR (CDCl_3 , 100 MHz) δ 169.6, 166.9, 166.4, 166.8, 142.1, 136.6, 135.0, 133.1, 132.4, 131.9, 131.8, 130.7, 129.3, 128.2, 127.5, 126.6, 126.2, 125.6, 124.8, 60.8, 53.2, 53.2, 53.0, 52.2, 20.1; HRMS (FAB) calcd for $\text{C}_{27}\text{H}_{24}\text{O}_{10}$ $[\text{M}]^+$ 508.1370, found 508.1366. CHIRALPAK AD, hexane:*i*-PrOH = 80:20, 0.8 mL/min, retention times: 16.3 min (major isomer) and 19.3 min (minor isomer).

(+)-5-(2-Acetoxyethyl)-6-naphthalen-1-yl-benzene-1,2,3,4-tetracarboxylic acid tetraethyl ester [(+)-3pa]. Under an Ar atmosphere, a CH_2Cl_2 (1.0 mL) solution of (*S*)-H8-BINAP (9.5 mg, 0.015 mmol) was added to a CH_2Cl_2 (1.0 mL) solution of $[\text{Rh}(\text{cod})_2]\text{BF}_4$ (6.1 mg, 0.015 mmol) at rt. The mixture was stirred at rt for 5 min. H_2 was introduced to the resulting solution in a Schlenk tube. After stirring at rt for 0.5 h, the resulting solution was concentrated to dryness and dissolved in CH_2Cl_2 (0.5 mL). This solution was added to a CH_2Cl_2 (0.5 mL) solution of 4-(1-naphthyl)-3-butyn-1-ol (59.5 mg, 0.300 mmol) and washed remaining catalyst away by using CH_2Cl_2 (0.5 mL). To this solution was added a CH_2Cl_2 (0.5 mL) solution of diethyl acetylenedicarboxylate

(102 mg, 0.600 mmol), and washed remaining substrate away by using CH₂Cl₂ (0.5 mL). The solution was stirred at rt for 16 h. The resulting solution was diluted with CH₂Cl₂ (5.0 mL). To this solution, Ac₂O (0.28 ml, 3.0 mmol) and Et₃N (0.42 ml, 3.0 mmol) was added at rt and the solution was stirring at rt for 3 h. The resulting solution was concentrated and purified by preparative TLC (hexane:ethyl acetate = 2:1), which furnished (+)-5-(2-acetoxyethyl)-6-naphthalen-1-yl-benzene-1,2,3,4-tetracarboxylic acid tetraethyl ester [(+)-**3pa**, 130.1 mg, 0.225 mmol, 75% yield, 96% ee] as a pale yellow solid.

Pale yellow solid; Mp 43.2-44.8 °C; $[\alpha]_D^{25} +10.7$ (CHCl₃, *c* 0.754, 96 % ee); IR (neat) 2950, 1720, 1220, 1020 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz) δ 7.90 (t, *J* = 8.4 Hz, 2H), 7.26-7.55 (m, 5H), 4.27-4.44 (m, 6H), 3.94-4.02 (m, 1H), 3.83-3.91 (m, 1H), 3.63 (q, *J* = 6.9 Hz, 2H), 2.83-2.93 (m, 1H), 2.55-2.64 (m, 1H), 1.84 (s, 3H), 1.39 (t, *J* = 7.2 Hz, 3H), 1.38 (t, *J* = 7.2 Hz, 3H), 1.31 (t, *J* = 7.2 Hz, 3H), 0.42 (t, *J* = 7.2 Hz, 3H); ¹³C NMR (CDCl₃, 75 MHz) δ 170.3, 167.0, 166.3, 166.2, 165.7, 141.7, 138.2, 136.7, 135.4, 133.4, 133.2, 131.9, 131.8, 129.6, 129.1, 128.2, 127.9, 126.7, 126.2, 125.7, 124.8, 63.4, 62.33, 62.30, 62.26, 61.2, 30.4, 20.7, 13.88, 13.86, 13.8, 12.9; HRMS (FAB) calcd for C₃₂H₃₄O₁₀ [M]⁺ 578.2152, found 578.2137. CHIRALPAK AD, hexane:*i*-PrOH = 80:20, 0.8 mL/min, retention times: 10.4 min (minor isomer) and 15.6 min (major isomer).

V. References

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