Highly Chemo- and Regioselective Intermolecular Cyclotrimerization of Alkynes Catalyzed by Cationic Rhodium(I)/Modified BINAP Complexes

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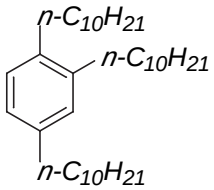
I. General

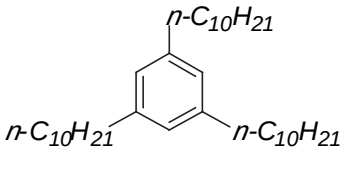
Anhydrous CH_2Cl_2 was obtained from Aldrich (No. 27,099-7) and used as received. Tol-BINAP, H8-BINAP, and DTBM-SEGPHOS were obtained from Takasago International Corp. All other reagents were obtained from commercial sources and used as received. All reactions were carried out under an atmosphere of argon in oven-dried glassware with magnetic stirring, unless otherwise indicated.

II. Cyclotrimerization of Terminal Alkynes (eq 2)

General Procedure. Under a Ar atmosphere, DTBM-SEGPHOS (59.0 mg, 0.050 mmol) and $[Rh(cod)_2]BF_4$ (20.3 mg, 0.050 mmol) were dissolved in CH_2Cl_2 (1.0 mL) and the mixture was stirred for 5 minutes. H_2 was introduced to the resulting solution in Schlenk tube. After stirring for 0.5 hour at room temperature, the resulting solution was concentrated to dryness. 1-Dodecyne (**1a**) (166 mg, 1.0 mmol) was added to the residue by using CH_2Cl_2 (2.0 mL). The mixture was stirred at room temperature for 24 hours. The resulting solution was concentrated and purified by preparative TLC (hexane), which furnished a mixture of 1,2,4-tridecylbenzene (**2a**) and 1,3,5-tridecylbenzene (**3a**) (152 mg, 0.913 mmol, 91%, **2a**:**3a** = 83:17).



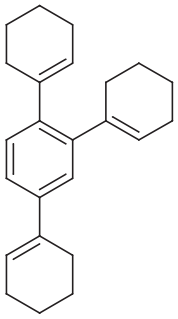
2a



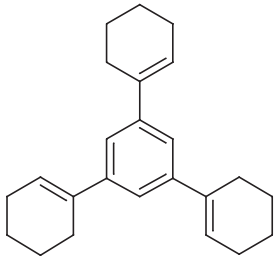
3a

1,2,4-Tridecylbenzene (2a, 83% regioselectivity).[1] Colorless oil; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.04 (d, *J* = 7.5 Hz, 1H), 6.94 (s, 1H), 6.92 (d, *J* = 7.5 Hz, 1H), 2.48-2.61 (m, 6H), 1.45-1.65

(m, 6H), 1.20-1.43 (m, 42H), 0.88 (t, J = 6.6 Hz, 9H); aryl protons of minor **3a**: δ 6.80 (s, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 142.7, 140.3, 140.2, 137.7, 129.2, 128.9, 125.8, 125.7, 36.0, 35.6, 32.8, 32.4, 31.9, 31.63, 31.62, 31.4, 29.9, 29.7, 29.65, 29.59, 29.56, 29.49, 29.38, 22.7, 14.1.



2b



3b

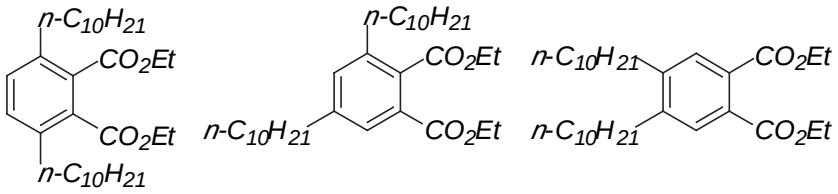
1,2,4-Tri-1-cyclohexenylbenzene (2b, 97% regioselectivity).[2] Yellow oil; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.18 (dd, J = 8.1 and 2.1 Hz, 1H), 7.13 (d, J = 2.1 Hz, 1H), 7.04 (d, J = 8.1 Hz, 1H), 6.06-6.14 (m, 1H), 5.64-5.72 (m, 2H), 2.04-2.48 (m, 12H), 1.51-1.82 (m, 12H); aryl protons of minor **3b**: δ 7.23 (s, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 142.5, 141.0, 140.6, 139.8, 139.1, 136.3, 128.4, 126.2, 125.3, 124.1, 123.4, 122.9, 29.59, 29.54, 29.48, 27.4, 25.88, 25.77, 25.76, 25.73, 23.3, 23.1, 22.2.

III. Cocyclotrimerization of Diethyl Acetylenedicarboxylate and Terminal Alkynes (Table 2)

General Procedure (entry 1). Under a Ar atmosphere, H8-BINAP (5.7 mg, 0.009 mmol) and $[Rh(cod)_2]BF_4$ (3.7 mg, 0.009 mmol) were dissolved in CH_2Cl_2 (1.0 mL) and the mixture was stirred for 5 minutes. H_2 was introduced to the resulting solution in Schlenk tube. After stirring for 0.5 hour at room temperature, the resulting solution was concentrated to dryness and dissolved in CH_2Cl_2 (2.0 mL). To this solution was added dropwise over 1 minute a solution of 1-dodecyne (**1a**) (99.8 mg, 0.60 mmol) and diethyl acetylenedicarboxylate (**4**) (51.0 mg, 0.30 mmol) in CH_2Cl_2 (0.5 mL) and the solution was stirred at room temperature for 1 hour. The resulting solution was concentrated and purified by preparative TLC (hexane:ethyl acetate = 10:1), which furnished a mixture of 3,6-diphenylphthalic acid diethyl ester (**5a**), 3,5-didecylphthalic acid diethyl ester (**6a**), and 4,5-didecylphthalic acid diethyl ester (**7a**) (133 mg,

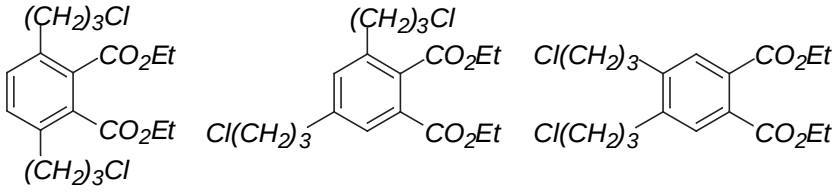
0.264 mmol, 88%, **5a**:**6a**:**7a** = 92:6:2).

This mixture could be purified by preparative TLC (hexane:ethyl acetate = 10:1), which furnished pure 3,6-diphenylphthalic acid diethyl ester (**5a**) (120 mg, 0.238 mmol, 79%).



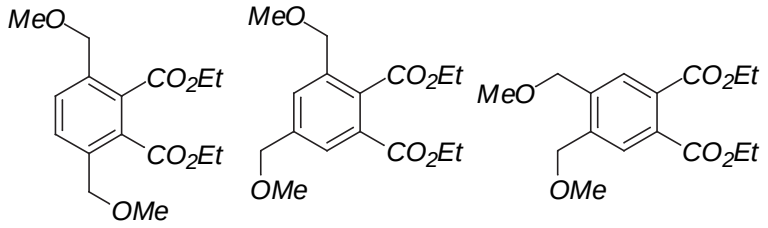
5a **6a** **7a**

3,6-Didecylphthalic acid diethyl ester (5a, entry 1). Colorless solid; Mp 44 °C (pure **5a**); IR (neat), 2750, 1670, 1230, 1160, 1060 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.20 (s, 2H), 4.32 (q, *J* = 7.2 Hz, 4H), 2.67 (t, *J* = 7.8 Hz, 4H), 1.50-1.62 (m, 4H), 1.36 (t, *J* = 7.2 Hz, 6H), 1.18-1.40 (m, 28H), 0.88 (t, *J* = 6.6 Hz, 6H); aryl protons of minor **6a**: δ 7.62 (d, *J* = 1.8 Hz, 1H), 7.20 (d, *J* = 1.8 Hz, 1H); aryl protons of minor **7a**: δ 7.48 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 168.6, 139.0, 131.8, 131.6, 61.3, 33.5, 31.9, 31.6, 29.6, 29.63, 29.60, 29.5, 29.3, 22.7, 14.12, 14.10. Anal. Calcd for $C_{32}H_{54}O_4$: C, 76.45; H, 10.83. Found: C, 76.73; H, 11.09.



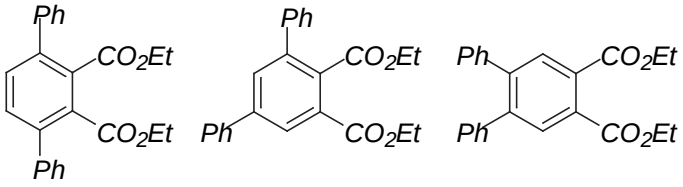
5c **6c** **7c**

3,6-Bis(3-chloropropyl)phthalic acid diethyl ester (5c, 91% regioselectivity, entry 2). Colorless oil; IR (neat) 2800, 1680, 1230, 1150, 990 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.28 (s, 2H), 4.34 (q, *J* = 7.2 Hz, 4H), 3.54 (t, *J* = 6.3 Hz, 4H), 2.86 (t, *J* = 7.5 Hz, 4H), 2.02-2.11 (m, 4H), 1.37 (t, *J* = 7.2 Hz, 6H); aryl protons of minor **6c**: δ 7.68 (d, *J* = 1.5 Hz, 1H), 7.28 (d, *J* = 1.5 Hz, 1H); aryl protons of minor **7c**: δ 7.53 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 168.1, 137.6, 132.4, 132.0, 61.7, 44.3, 34.0, 30.6, 14.1. Anal. Calcd for $C_{18}H_{24}O_4$: C, 57.61; H, 6.45. Found: C, 57.89; H, 6.51.



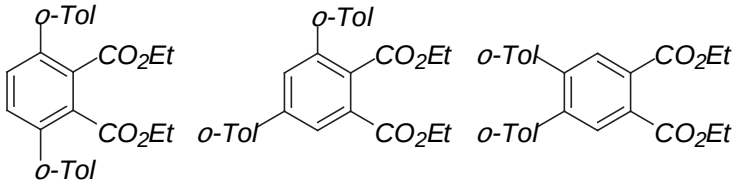
5d **6d** **7d**

3,6-Bis(methoxymethyl)phthalic acid diethyl ester (5d, 86% regioselectivity, entry 3). Colorless oil; IR (neat) 2750, 1660, 1220, 1070, 990 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.54 (s, 2H), 4.59 (s, 4H), 4.33 (q, *J* = 7.2 Hz, 4H), 3.35 (s, 6H), 1.36 (t, *J* = 7.2 Hz, 6H); aryl protons of minor **6d**: δ 7.85-7.87 (m, 1H), 7.61-7.63 (m, 1H); aryl protons of minor **7d**: δ 7.77 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 167.5, 136.6, 131.2, 129.8, 71.8, 61.5, 58.5, 13.9. Anal. Calcd for $C_{16}H_{22}O_4$: C, 61.92; H, 7.15. Found C, 61.60; H, 6.95.



5e **6e** **7e**

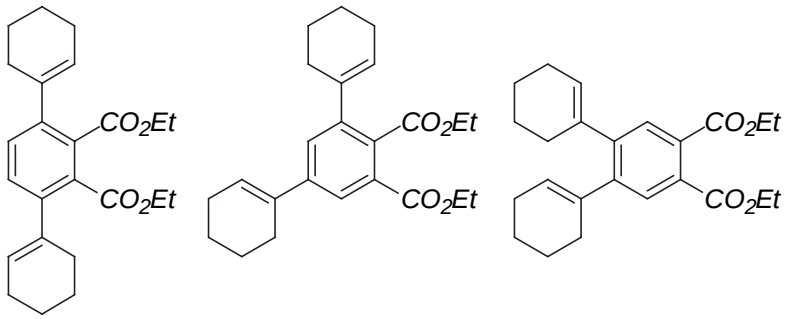
3,6-Diphenylphthalic acid diethyl ester (5e, 89% regioselectivity, entry 4). Colorless solid; Mp 99-105 °C; IR (neat) 1680, 1200, 1110, 1040, 740, 670 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.47 (s, 2H), 7.32-7.66 (m, 10H), 4.07 (q, *J* = 7.2 Hz, 4H), 0.97 (t, *J* = 6.9 Hz, 6H); aryl protons of minor **6e**: δ 8.21 (d, *J* = 2.1 Hz, 1H), 7.74 (d, *J* = 2.1 Hz, 1H); aryl protons of minor **7e**: δ 7.79 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 168.3, 139.9, 132.3, 131.5, 129.0, 128.4, 128.3, 127.7, 61.5, 13.5. Anal. Calcd for $C_{24}H_{22}O_4$: C, 76.99; H, 5.92. Found: C, 76.82; H, 6.01.



5f **6f** **7f**

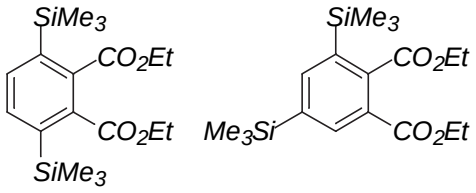
3,6-Di-*o*-tolylphthalic acid diethyl ester (5f, 89% regioselectivity, entry 5). Colorless solid; Mp 103-108 °C; IR (neat) 2800, 1680, 1380, 1200, 1100, 730 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.33 (s, 2H), 7.07-7.29 (m, 8H), 3.98 (q, *J* = 7.2 Hz, 1.6H), 3.97 (q, *J* = 7.2 Hz, 2.4H), 2.21 (s, 3.5H), 2.17 (s, 2.5H), 0.88 (t, *J* = 7.2 Hz, 2.5H), 0.87 (t, *J* = 7.2 Hz, 3.5H); aryl protons of minor

6f: δ 7.99 (d, *J* = 2.1 Hz, 1H), 7.38 (d, *J* = 2.1 Hz, 1H); aryl protons of minor **7f**: δ 7.69 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 167.9, 139.9, 139.8, 139.5, 136.2, 135.9, 132.6, 129.3, 127.9, 125.2, 61.2, 20.4, 13.4. Anal. Calcd for $C_{26}H_{26}O_4$: C, 77.59; H, 6.51. Found C, 77.41; H, 6.47.



5b **6b** **7b**

3,6-Di-1-cyclohexenylphthalic acid diethyl ester (5b, 91% regioselectivity, entry 6). Colorless oil; IR (neat) 3200, 2750 1660, 1180, 770 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.18 (s, 2H), 5.57-5.62 (m, 2H), 4.26 (q, *J* = 7.2 Hz, 4H), 2.03-2.33 (m, 8H), 1.55-1.80 (m, 8H), 1.33 (t, *J* = 7.2 Hz, 6H); aryl protons of minor **6b**: δ 7.83 (d, *J* = 1.8 Hz, 1H), 7.33 (d, *J* = 1.8 Hz, 1H); aryl protons of minor **7b**: δ 7.46 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 168.7, 141.7, 137.3, 131.3, 129.5, 126.7, 61.4, 29.8, 25.5, 23.1, 21.9, 14.1. Anal. Calcd for $C_{24}H_{30}O_4$: C, 75.36; H, 7.91. Found C, 74.87; H, 7.97.

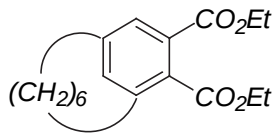


5g **6g**

3,6-Bis(trimethylsilyl)phthalic acid diethyl ester (5g, 99% regioselectivity, entry 7). Mp 65-68 °C; IR (neat) 2770, 1660, 1200, 1130, 1070, 790 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.65 (s, 2H), 4.32 (q, *J* = 7.2 Hz, 4H), 1.37 (t, *J* = 7.2 Hz, 6H), 0.30 (s, 18H); aryl protons of minor **6g**: δ 8.00 (d, *J* = 1.2 Hz, 1H), 7.87 (d, *J* = 1.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 170.3, 140.4, 137.7, 135.8, 61.9, 14.3, 0.3. Anal. Calad for $C_{18}H_{30}Si_2O_4$: C, 58.97; H, 8.25. Found C, 59.10; H, 8.36.

IV. Synthesis of Metacyclophane

Under a Ar atmosphere, H8-BINAP (2.5 mg, 0.00625 mmol) and $[Rh(cod)_2]BF_4$ (3.9 mg, 0.00625 mmol) were dissolved in CH_2Cl_2 (1.0 mL) and the mixture was stirred for 5 minutes. H_2 was introduced to the resulting solution in Schlenk tube. After stirring for 0.5 hour at room temperature, the resulting solution was concentrated to dryness and dissolved in CH_2Cl_2 (20 mL). To this solution was added dropwise over 1 minute a solution of 1,9-decadiyne (**8**) (16.8 mg, 0.125 mmol) and diethyl acetylenedicarboxylate (**4**) (21.3 mg, 0.125 mmol) in CH_2Cl_2 (2.0 mL) and the solution was stirred at room temperature for 1 hour. The resulting solution was concentrated and purified by preparative TLC (hexane:ethyl acetate = 3:1), which furnished a metacyclophane **9** (19.0 mg, 0.0623 mmol, 50%).



9

[6]Metacyclophane-8,9-dicarboxylic acid diethyl ester (9). Colorless oil; IR (neat) 2800, 1670, 1420, 1230, 750 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.50 (d, *J* = 1.2 Hz, 1H), 7.45 (d, *J* = 1.2 Hz, 1H), 4.29-4.43 (m, 4H), 2.54-2.84 (m, 4H), 1.72-1.91 (m, 2H), 1.16-1.48 (m, 4H), 1.36 (t, *J* = 7.2 Hz, 6H), 0.20-0.65 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 168.9, 166.7, 144.2, 141.1, 139.3, 130.6, 129.5, 125.6, 61.3, 61.2, 34.3, 32.6, 32.4, 32.3, 27.8, 27.5, 14.13, 14.11. HRMS (FAB). Calad for $C_{18}H_{24}O_4$: 304.1753. Found 304.1779. Anal. Calad for $C_{18}H_{24}O_4$: C, 71.03; H, 7.95. Found C, 71.29; H, 7.96.

V. References

(1) Yong, L.; Butenschön, H. *Chem. Commun.* **2002**, *23*, 2852-2853.

(2) Dérien, S.; Clinet, J.–C.; Duñach, E.; Périchon, J. *J. Organamet. Chem.* **1992**, *424*, 213-224.