Supporting Information

Title
Palladium-catalyzed Reaction of Acylzirconocene Chloride and Stereoselective Formation of Bicyclo[3.3.0]compounds

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Preparation of a solution of acylzirconocene chloride complex 1 in THF
Under Ar atmosphere, to a suspension of Cp2Zr(H)Cl (1 mmol, 1.0 equiv) in CH2Cl2 (3 mL) was added alkene or alkyne (2.0 mmol) and the mixture was stirred at ambient temperature for 0.5 h. The reaction mixture was further stirred under CO atmosphere (1 atm) for 2 h at ambient temperature. The clear solution was concentrated to dryness in vacuo by using vacuum pump (10⁻³ mmHg) to give acylzirconocene chloride powder. After the powder was further subjected to vacuum for 2 h, a solution of 1 in THF was prepared by the addition of anhydrous THF (6 mL) to the powder, and the solution was directly used as a 1 mmol solution for the next step.

Typical procedure for the formation of 4 (entry 6, Table 1)
To a solution of n-nonanoylzirconocene chloride (1 mmol) (1a) in THF (6 mL) was added successively a solution of (E)-1-phenyl-4-(2-propenyloxy)-2-buten-1-one (101 mg, 0.5 mmol) in ether (12 mL), 1M solution of Me2Zn in hexane (0.5 mmol) and Pd(OAc)2 (0.05 mmol) at 0 °C, and the mixture was stirred at ambient temperature for 3 h. The reaction mixture darkened and became turbid. After being quenched with aq. NaHCO3 under ice cooling, the mixture was extracted with ethyl acetate and dried over MgSO4. The filtered solution was concentrated to dryness, providing a crude product. Purification by silica gel column chromatography (hexanes/ethyl acetate = 10 : 1) afforded the product (143 mg, 83% yield). Yield was calculated from (E)-1-phenyl-4-(2-propenyloxy)-2-buten-1-one (101 mg, 0.5 mmol).

[(3aS*,4R*,5R*,6aS*)-5-hydroxy-5-octylhexahydro-1H-cyclopenta[c]furan-4-yl](phenyl)methanone (entry 6, Table 1)
Colorless crystals; mp 62 °C; 1H NMR (400 MHz, CDCl3): δ = 0.81 (t, J = 7.0 Hz, 3H), 1.12-1.37 (m, 12H), 1.41-1.54 (m, 3H), 2.23 (dd, J = 13.0, 7.9 Hz, 1H), 3.03-3.13 (m, 2H), 3.39 (dd, J = 9.7, 5.2 Hz, 1H), 3.56 (dd, J = 15.7, 6.7 Hz, 2H), 3.73 (d, J = 9.7 Hz, 2H), 4.48 (s, 1H), 7.47-7.98 (m, 5H); 13C NMR (100.6 MHz, CDCl3): δ = 14.0, 22.6, 24.9, 29.1, 29.4, 30.0, 31.8, 39.9, 43.1, 46.1, 50.7, 56.8, 72.0, 74.2, 87.2, 128.5, 128.7, 134.1, 137.7, 206.6; IR (neat): ν = 3400, 1670 cm⁻¹; EIMS m/z = 344 (M⁺); Anal. Calcd for C22H32O3: C, 76.70; H, 9.36. Found: C, 76.75; H, 9.28.

[(1R*,2R*,3aS*,6aS*)-2-hydroxy-2-octyloctahydro-1-pentalenyl](phenyl)methanone (entry 1, Table 1)
Colorless oil; 1H NMR (400 MHz, CDCl3): δ = 0.84 (t, J = 7.1 Hz, 3H), 1.12-1.37 (m, 14H), 1.38-1.53 (m, 4H), 1.58-1.72 (m, 3H), 2.15 (dd, J = 13.0, 8.0 Hz, 1H), 2.82-2.96 (m, 2H), 3.26 (d, J = 9.3 Hz, 1H), 4.46 (bd, J = 1.8 Hz, 1H), 7.46-7.64 (m, 3H), 7.91-7.94 (m, 2H); 13C NMR (100.6 MHz, CDCl3): δ = 14.1, 22.6, 25.0, 25.4, 29.1, 29.4, 30.1, 31.8, 31.9, 32.8, 40.4, 42.0, 46.8, 49.8, 58.0, 86.8, 128.4, 128.8, 133.7, 138.2, 207.7; IR (neat): ν = 3460, 1653 cm⁻¹; EIMS m/z = 343 (M⁺ + 1); HRMS Calcd for C22H30O2: 342.25724, Found: 342.2559.

[(1R*,2R*,3aS*,6aS*)-2-hydroxy-5,5-dimethyl-2-octyloctahydro-1-pentalenyl](phenyl)methanone (4a) (entry 2, Table 1)
Colorless crystals; mp 32 °C; 1H NMR (400 MHz, CDCl3): δ = 0.84 (t, J = 7.3 Hz, 3H), 0.88 (s, 3H), 1.07 (s, 3H), 1.13-1.40 (m, 14H), 1.44-1.63 (m, 4H), 1.76 (ddd, J = 12.4, 8.3, 2.0 Hz, 1H),
[(1R,2R,3aS,6aS)-2-hydroxy-5,5-dimethyl-2-(4-phenylbutyl)octahydro-1-pentalenyl][phenyl)methanone (4b) (entry 3, Table 1)

Colorless crystals; mp 81.0 - 82.0 °C. 1H NMR (400 MHz, CDCl3) δ 0.88 (s, 3H), 1.07 (s, 3H), 1.17 (dd, J = 12.2, 9.8 Hz, 1H), 1.25 - 1.46 (m, 4H), 1.48 - 1.60 (m, 5H), 1.75 (ddd, J = 12.2, 7.9, 1.8 Hz, 1H), 2.18 (dd, J = 13.0, 7.9 Hz, 1H), 2.49 - 2.54 (m, 2H), 2.90 - 3.10 (m, 2H), 3.40 (d, J = 9.5 Hz, 1H), 4.89 (d, J = 1.8 Hz, 1H), 7.07 - 7.23 (m, 5H), 7.48 - 7.92 (m, 5H); 13C NMR (100.6 MHz, CDCl3) δ 24.7, 26.8, 29.1, 32.0, 35.8, 40.5, 42.5, 44.6, 46.9, 47.9, 49.8, 49.9, 59.7, 88.9, 125.5, 128.2, 128.3, 128.4, 128.7, 133.7, 137.9, 142.6, 207.6; IR (neat) ν 3453, 1652 cm⁻¹; EIMS m/z 391 (M⁺ + 1); HRMS Calcd for C32H39O2: 372.24305, Found: 372.24532.

[(1R,2R,3aS,6aS)-2-hydroxy-2-octyl-5,5-bis([(phenylmethyl)oxy]methyl)octahydro-1-pentalenyl][phenyl)methanone (entry 4, Table 1)

1H NMR (400 MHz, CDCl3) δ 0.79 (t, J = 7.0 Hz, 3H), 1.06 - 1.45 (m, 17H), 1.72 (dd, J = 13.0, 7.7 Hz, 1H), 1.92 (dd, J = 13.0, 7.9 Hz, 1H), 2.09 (ddd, J = 13.0, 7.7, 1H), 2.79 - 2.96 (m, 2H), 3.21 (d, J = 4.8 Hz, 2H), 3.38 - 3.42 (m, 3H), 4.37 (s, 2H), 4.46 (s, 2H), 4.70 (br, J = 1.5 Hz, 1H), 7.15 - 7.87 (m, 15H); 13C NMR (100.6 MHz, CDCl3) δ 14.1, 22.6, 24.9, 29.1, 29.4, 30.1, 31.8, 37.8, 39.2, 40.7, 41.9, 47.0, 49.4, 53.3, 59.3, 72.5, 73.2, 73.3, 74.7, 76.7, 77.0, 77.3, 88.7, 127.3, 127.4, 128.2, 128.3, 128.4, 128.7, 133.6, 133.9, 138.6, 138.9, 207.4; IR (neat) ν 3453, 1651 cm⁻¹; EIMS m/z 583 (M⁺ + 1); Anal. Calcd for C32H39O2: C, 80.37; H, 8.65. Found: C, 80.19; H, 8.65.

1-([(1R,2R,3aS,6aS)-2-hydroxy-2-octyl-5,5-bis([(phenylmethyl)oxy]methyl)octahydro-1-pentalenyl][phenyl)methanone (entry 5, Table 1)

1H NMR (400 MHz, CDCl3) δ 0.88 (t, J = 7.1 Hz, 3H), 1.20 - 1.62 (m, 17H), 1.92 - 2.10 (m, 3H), 2.15 (s, 3H), 2.50 (d, J = 9.6 Hz, 1H), 2.70 - 2.91 (m, 2H), 3.33 (s, 2H), 3.46 (d, J = 5.4 Hz, 2H), 4.07 (bd, J = 1.8 Hz, 1H), 4.48 (s, 2H), 4.52 (s, 2H), 2.73 - 3.78 (m, 10H); 13C NMR (100.6 MHz, CDCl3) δ 14.1, 22.7, 24.8, 29.3, 29.5, 30.2, 31.9, 32.1, 39.0, 39.4, 40.4, 53.4, 66.0, 72.3, 73.2, 73.3, 74.7, 87.5, 127.4, 127.5, 128.3, 128.4, 139.6, 138.8, 215.0; IR (neat) ν 3472, 1691 cm⁻¹; EIMS m/z 502 (M⁺ - H2O); HRMS Calcd for C31H37O2: 520.35526, Found: 520.35413.

([(3aS,4R,5S,6aS)-5-hydroxy-5-[(E)-1-octenyl]hexahydro-1H-cyclopenta[c]furan-4-yi][phenyl)methanone (entry 7, Table 1)

Colorless crystals; mp 83-85 °C. 1H NMR (400 MHz, CDCl3) δ 0.79 (t, J = 7.2 Hz, 3H), 1.01 - 1.19 (m, 8H), 1.62 (dd, J = 13.0, 6.7 Hz, 1H), 1.78 - 1.92 (m, 2H), 2.19 (dd, J = 13.3, 8.0 Hz, 1H), 3.08 - 3.18 (m, 2H), 3.40 (d, J = 9.6, 5.4 Hz, 1H), 3.58 (ddd, J = 9.0, 6.2 Hz, 1H), 3.69 (d, J = 9.0 Hz, 1H), 3.72 - 3.78 (m, 2H), 4.50 (d, J = 1.5 Hz, 1H), 5.45 (d, J = 15.4 Hz, 1H), 5.64 (dt, J = 15.4, 6.8 Hz, 1H), 7.45 - 7.93 (m, 5H); 13C NMR (100.6 MHz, CDCl3) δ 14.0, 22.4, 28.5, 28.9, 31.5, 31.9, 43.4, 47.7, 50.0, 57.7, 72.0, 74.0, 85.9, 128.6, 128.8, 130.4, 132.3, 133.9, 137.6, 205.6; IR (neat) ν 3381, 1668 cm⁻¹; EIMS m/z 342 (M⁺); Anal. Calcd for C22H30O: C, 77.16; H, 8.2. Found: C, 77.15; H, 8.94.

([(3aS,4R,5S,6aS)-5-[(E)-4-((1,1-dimethylethyl)(diphenyl)silyl)oxy]-1-butenyl]-5-hydroxyhexahydro-1-cyclopenta[c]furan-4-yl][phenyl)methanone (entry 8, Table 1)

Colorless crystals; mp 112.0 - 115.0 °C. 1H NMR (400 MHz, CDCl3) δ 0.98 (s, 9H), 1.60 (ddd, J = 13.1, 6.2, 1.8 Hz, 1H), 2.12 - 2.20 (m, 4H), 3.07 - 3.18 (m, 2H), 3.41 (dd, J = 9.7, 5.3 Hz, 1H), 3.45 (dd, J = 7.6, 3.2 Hz, 1H), 3.49 (dd, J = 7.6, 3.2 Hz, 1H), 3.58 (dd, J = 9.7, 5.3 Hz, 1H), 3.75
1H NMR (400 MHz, CDCl₃) δ 0.84 (t, J = 7.1 Hz, 2H), 1.13 - 1.53 (m, 24H), 2.18 - 2.27 (m, 1H), 3.00 - 3.47 (m, 6H), 3.51 (d, J = 1.89 Hz, 3H), 4.50 (bs, 1H), 7.48 - 7.96 (m, 5H); 13C NMR (75.5 MHz, CDCl₃) δ 14.1, 22.6, 24.9, 28.5, 29.1, 29.4, 30.0, 31.8, 40.5, 41.7, 46.0, 49.9, 52.0, 77.2, 79.5, 86.8, 128.5, 129.0, 134.1, 137.7, 154.9, 206.1; IR (neat) ν 3460, 1622 cm⁻¹; EIMS m/z 444 (M⁺ + 1); Anal. Calcd for C₃₉H₄₈O₄: C, 73.10; H, 9.32; N, 3.16. Found: C, 73.00; H, 9.39; N, 3.27.

[(1R*,2R*,6aR*)-2-hydroxy-5,5-dimethyl-2-octyl-1,2,4,5,6,6a-hexahydro-1-pentalenyl][phenyl]methanone (entry 10, Table 1)

1H NMR (400 MHz, CDCl₃) δ 0.85 (t, J = 7.1 Hz, 3H), 1.06 (s, 3H), 1.09 (s, 3H), 1.10 - 1.40 (m, 13H), 1.60 - 1.68 (m, 2H), 2.05 (d, J = 17.0 Hz, 1H), 2.14 (d, J = 17.0 Hz, 1H), 3.57 - 3.65 (m, 2H), 4.16 (s, 1H), 5.36 (s, 1H), 7.46 - 7.62 (m, 3H), 7.90 - 7.94 (m, 2H); 13C NMR (100.6 MHz, CDCl₃) δ 14.1, 22.6, 24.9, 29.1, 29.4, 30.0, 30.1, 30.7, 31.8, 39.9, 41.2, 58.5, 92.1, 124.0, 128.3, 128.6, 133.4, 138.1, 156.6, 204.1; IR (neat) ν 3447, 1666 cm⁻¹; EIMS m/z 368 (M⁺); Anal. Calcd for C₂₅H₂₆NO₂: C, 81.47; H, 9.85. Found: C, 81.21; H, 9.80.

[(2R*,3aS*)-2-hydroxy-5,5-dimethyl-2-oc-tyl-2,3,3a,4,5,6-hexahydro-1-pentalenyl][phenyl]methanone (entry 2, Table 1)

1H NMR (400 MHz, CDCl₃) δ 0.86 (t, J = 7.0 Hz, 3H), 0.92 (s, 3H), 1.05 (s, 3H), 1.16 (dd, J = 12.0, 11.0 Hz, 1H), 1.20 - 1.44 (m, 12H), 1.65 (dd, J = 18.5, 1.7 Hz, 1H), 1.72 - 1.85 (m, 4H), 1.89 (d, J = 18.5 Hz, 1H), 2.41 (dd, J = 12.7, 7.6 Hz, 1H), 3.18 (quint, J = 9.0 Hz, 1H), 5.11 (s, 1H), 7.42 - 7.66 (m, 5H); 13C NMR (100.6 MHz, CDCl₃) δ 14.1, 22.6, 24.9, 29.2, 29.5, 30.1, 30.3, 30.4, 31.8, 41.0, 42.2, 48.4, 91.9, 128.4, 128.7, 132.3, 133.6, 139.7, 171.4, 197.3; IR (neat) ν 3460, 1622 cm⁻¹; EIMS m/z 368 (M⁺); HRMS Calcd for C₂₅H₂₆O(M⁺ - H₂O): 349.25314, Found: 349.25311.

[(5R*,6aS*)-5-hydroxy-5-octyl-3,5,6a-tetrahydro-1H-cyclopenta[c]furan-4-yl][phenyl]methanone (entry 3, Table 2)

1H NMR (500 MHz, CDCl₃) δ 0.86 (t, J = 7.1 Hz, 3H), 1.14 - 1.50 (m, 12H), 1.79 - 1.92 (m, 3H), 2.40 (dd, J = 12.8, 7.3 Hz, 1H), 3.27 (dd, J = 10.4, 7.9 Hz, 1H), 3.37 (quint, J = 8.1 Hz, 1H), 3.73 (dd, J = 16.0, 1.3 Hz, 1H), 4.07 (dd, J = 16.0, 1.3 Hz, 1H), 4.17 (dd, J = 7.9, 7.9 Hz, 1H), 5.02 (s, 1H), 7.44 - 7.64 (m, 5H); 13C NMR (100.6 MHz, CDCl₃) δ 14.1, 22.6, 24.8, 29.2, 29.5, 30.0, 31.8, 40.9, 42.2, 49.1, 65.7, 128.7, 132.9, 133.8, 139.4, 165.9, 195.9; IR (neat) ν 3460, 1625 cm⁻¹; EIMS m/z 343 (M⁺ + 1); Anal. Calcd for C₂₆H₃₃O₃: C, 77.16; H, 8.83. Found: C, 76.82; H, 8.70.

((2R*,3aS*)-2-hydroxy-5,5-bis-[[((phenylmethyl)oxy)methyl]-2,3,3a,4,5,6-hexahydro-1-pentalenyl][phenyl]methanone (entry 3, Table 2)

1H NMR (500 MHz, CDCl₃) δ 0.86 (t, J = 7.1 Hz, 3H), 1.14 (dd, J = 12.8, 10.6 Hz, 1H), 1.18 - 1.40 (m, 12H), 1.71 - 1.85 (m, 4H), 2.02 - 2.09 (m, 2H), 2.14 (dd, J = 12.7, 7.7 Hz, 1H), 3.10 - 3.21 (m, 3H), 3.38 (s, 2H), 4.36 (d, J = 5.8 Hz, 2H), 5.03 (s, 1H), 7.10 - 7.68 (m, 15H); 13C NMR (125.7 MHz, CDCl₃) δ 14.1, 22.6, 24.9, 29.2, 29.5, 30.1, 31.8, 34.8, 37.9, 41.0, 45.9, 47.8, 50.9, 53.1, 73.1, 73.2, 74.2, 74.6, 92.2, 127.3, 127.4, 127.4, 127.5, 128.2, 128.3, 128.4, 128.7, 132.5, 133.6, 138.3, 138.6, 139.6, 169.6, 197.1; IR (neat) ν 3289, 1622 cm⁻¹; EIMS m/z 563 (M⁺ - H₂O); HRMS Calcd for C₃₉H₃₃O₃: 580.807720, Found: 580.807821.
1-((2R*,3aS*)-2-hydroxy-2-octyl-5,5-bis(((phenylmethyl)oxy)methyl)-2,3,3a,4,5,6-hexahydro-1-pentalenyl)-1-ethanone (entry 4, Table 2)

$^{1}$H NMR (400 MHz, CDCl$_3$) δ 0.86 (t, $J = 7.1$ Hz, 3H), 1.13 - 1.45 (m, 9H), 1.51 - 1.64 (m, 4H), 1.69 - 1.78 (m, 1H), 2.03 (dd, $J = 12.6$, 8.4 Hz, 1H), 2.25 (s, 3H), 2.29 (dd, $J = 12.6$, 8.4 Hz, 1H), 2.47 (d, $J = 19.0$ Hz, 1H), 2.60 (d, $J = 19.0$ Hz, 1H), 3.01 (quint, $J = 9.0$ Hz, 1H), 3.36 (d, $J = 8.7$ Hz, 1H), 3.43 (d, $J = 12.8$, 1H), 3.48 (s, 4H), 4.13 (s, 1H), 4.48 - 4.68 (m, 4H), 7.26 - 7.40 (m, 10H); $^{13}$C NMR (100.6 MHz, CDCl$_3$) δ 14.1, 22.7, 24.6, 29.3, 29.6, 30.1, 30.3, 31.9, 34.9, 37.3, 39.5, 44.0, 48.0, 51.8, 73.3, 73.4, 73.6, 74.7, 90.6, 127.4, 127.5, 127.6, 127.7, 128.4, 138.5, 169.3, 198.4; IR (neat) ν 3289, 1622 cm$^{-1}$; EIMS m/z 518 (M$^+$); HRMS Calcd for C$_{34}$H$_{46}$O$_4$: 518.73684, Found: 518.73429.

Intramolecular Aldol reaction

1-[3-hydroxy-3-methyl-2-(phenylcarbonyl)cyclopentyl]-1-nonanone (7a and b) (Scheme 5)

A reaction of 1-phenyl-2-hepten-1,6-dione (101.1 mg, 0.5 mmol) and 1a (1.0 mmol) was carried out as described in typical reaction procedure to give a mixture of 7a, b (112 mg, 65%). The mixture was separated by silica gel column chromatography (hexanes/ethyl acetate = 10 : 1) to give 1S*-isomer as a first effluent and 1R*-isomer as a second effluent.

1-[(1S*,2R*,3S*)-3-hydroxy-3-methyl-2-(phenylcarbonyl)cyclopentyl]-1-nonanone

$^{1}$H NMR (400 MHz, CDCl$_3$) δ 0.86 (t, $J = 7.2$ Hz, 3H), 1.10 - 1.32 (m, 10H), 1.29 (s, 3H), 1.39 - 1.50 (m, 2H), 1.68 - 1.82 (m, 2H), 1.90 - 1.99 (m, 1H), 2.24 (dt, $J = 16.9$, 7.6 Hz, 1H), 2.34 - 2.47 (m, 2H), 3.59 - 3.67 (m, 1H), 3.80 (s, 1H), 4.16 (d, $J = 9.7$ Hz, 1H), 7.25 - 7.59 (m, 3H), 7.98 - 8.01 (m, 2H); $^{13}$C NMR (100.6 MHz, CDCl$_3$) δ 14.1, 22.6, 23.5, 26.6, 27.2, 29.0, 29.1, 31.8, 40.7, 42.5, 128.7, 128.8, 133.8, 137.7, 205.1, 211.9; IR (neat) ν 3465, 1706, 1671 cm$^{-1}$; EIMS m/z 345 (M$^+$ + 1); HRMS Calcd for C$_{22}$H$_{32}$O$_3$: 344.23514, Found: 344.23217.

1-[(1R*,2R*,3S*)-3-hydroxy-3-methyl-2-(phenylcarbonyl)cyclopentyl]-1-nonanone

$^{1}$H NMR (400 MHz, CDCl$_3$) δ 0.86 (t, $J = 7.2$ Hz, 3H), 1.13 (s, 3H), 1.17 - 1.30 (m, 10H), 1.50 - 1.59 (m, 2H), 1.86 - 1.95 (m, 3H), 2.12 - 2.20 (m, 1H), 2.41 (dt, $J = 17.0$, 7.2 Hz, 1H), 2.47 (s, 1H), 2.52 (dt, $J = 17.0$, 7.2 Hz, 1H), 3.62 - 3.69 (m, 1H), 4.25 (d, $J = 6.7$ Hz, 1H), 7.45 - 7.60 (m, 3H), 8.05 - 8.08 (m, 2H); $^{13}$C NMR (100.6 MHz, CDCl$_3$) δ 14.1, 22.6, 23.6, 25.2, 26.9, 29.1, 29.2, 29.3, 31.8, 42.0, 42.1, 128.7, 129.0, 133.4, 137.7, 200.9, 213.0; IR (neat) ν 3483, 1705, 1671 cm$^{-1}$; EIMS m/z 344 (M$^+$); HRMS Calcd for C$_{22}$H$_{32}$O$_3$: 344.23514, Found: 344.23560.