Ni(II)-Catalyzed Conia-Ene Reaction of β -Dicarbonyl Compounds with Alkynes

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Supporting Information

General Information:

Ni(acac)₂ and Yb(OTf)₃ were purchased from Janssen and Aldrich, respectively, and used without further purification. All reactions were performed in oven-dried flasks. Dry dioxane was purchased from Acros. THF were distilled from sodium metal-benzophenone ketyl before use. MeCN, toluene and CH₂Cl₂ were distilled from CaH₂ before use. Dichloromethane and toluene were distilled over calcium hydride. Flash column chromatography was performed on E. Merck silica gel 60 (230–400 mesh ASTM) using ethyl acetate/*n*-hexane as eluting solvents.

Nuclear magnetic resonance spectra were recorded in deuteriochloroform (CDCl₃) unless otherwise indicated, with tetramethylsilane (TMS) as an internal standard at ambient temperature on a Bruker Avance DPX 300, DPX 400 or DPX 600 Fourier Transform Spectrometer operating at 300 MHz, 400 MHz or 600 MHz for ¹H and 75.47 MHz or 100 MHz for ¹³C. Mass spectra were recorded with a Finnigan MAT 95 mass spectrometer for both low resolution and high resolution mass spectra.

Substrates **1**, **3**, **5**, **7**, **9**, **11**, **13**, **15**, **27** and **31** were prepared by alkylation of the corresponding

dicarbonyls according to the method of Malacria.¹ Substrate **17** was prepared in three steps following Toste's procedure.² Substrate **19** was prepared by a conjugate addition to the enone as reported by Malacria.^{1, 3} Substrates **21**, **23**, and **25** were prepared by intramolecular C–H insertion of the corresponding diazo compounds according to the method of Curran.⁴ Substrate **29** was prepared by exchange with D₂O in THF in the presence of K₂CO₃ (0.1 equiv).²

1 Cruciani, P.; Stammer, R.; Aubert, C.; Malacria, M. *J. Org. Chem.* **1996**, *61*, 2699.

2 Kennedy-Smith, J. J.; Staben, S. T.; Toste, F. D. *J. Am. Chem. Soc.* **2004**, *126*, 4526.

3 Renaud, J. L.; Petit, M.; Aubert, C.; Malacria, M. *Synlett* **1997**, 931.

4 Wang, C.; Gu, X.; Yu, M. S.; Curran, D. P. *Tetrahedron*. **1998**, *54*, 8355.

General Procedure for Ni(II)-Catalyzed Conia-Ene Reaction.

To a mixture of **1** (100mg, 0.55 mmol), Ni(acac)₂ (14 mg, 0.055 mmol) and Yb(OTf)₃ (23 mg, 0.037 mmol) was added dioxane (10 mL). The resulting solution was stirred and heated at 50 °C for 6 h. The cooled mixture was diluted with *n*-hexane and filtered through a 3-cm silica gel pad, followed by a wash with ether. After removal of the solvents, the crude residue was purified by flash column chromatography (EtOAc:*n*-Hexane = 1:10) give 80 mg of **2** (80%) as a colorless oil.

Compound **2**:^{1, 2} A colorless oil. ¹H NMR (300 MHz, CDCl₃) δ 5.30 (t, *J* = 2.0 Hz, 1H), 5.23 (t, *J* = 2.0 Hz, 1H), 3.75 (s, 3H), 2.48–2.36 (m, 3H), 2.22 (s, 3H), 2.24–2.15 (m, 1H), 1.76–1.64 (m, 2H). ¹³C NMR (75.5 MHz, CDCl₃) δ 203.5, 171.7, 148.7, 112.2, 70.4, 52.6, 35.0, 33.9, 26.6, 24.1.

Compound **4**:² A colorless oil. ^1H NMR (400 MHz, CDCl_3) δ 5.28 (t, J = 2.0 Hz, 1H), 5.23 (t, J = 2.0 Hz, 1H), 2.43–2.33 (m, 3H), 2.21 (s, 3H), 2.15–2.10 (m, 1H), 1.73–1.59 (m, 2H), 1.47 (s, 9H); ^{13}C NMR (100 MHz, CDCl_3) δ 203.5, 170.0, 148.8, 111.6, 81.8, 71.0, 34.9, 34.0, 27.7, 26.7, 23.9.

Compound **6**: A colorless oil. ^1H NMR (400 MHz, CDCl_3) δ 5.30 (t, J = 2.0 Hz, 1H), 5.23 (t, J = 2.0 Hz, 1H), 3.74 (s, 3H), 2.98 (heptet, J = 6.7 Hz, 1H), 2.48–2.42 (m, 2H), 2.40–2.35 (m, 1H), 2.30–2.23 (m, 1H), 1.76–1.63 (m, 2H), 1.10 (d, J = 6.6 Hz, 3H), 1.07 (d, J = 6.6 Hz, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 210.0, 171.7, 148.3, 112.3, 67.1, 52.4, 37.3, 34.6, 33.8, 23.9, 20.6; LRMS (EI, 20 eV) m/z 178 (M^+ –MeOH, 100), 153 (38); HRMS (EI) for $\text{C}_{11}\text{H}_{14}\text{O}_2$ (M^+ –MeOH): calcd 178.0994, found 178.0995.

Compound **8**: A colorless oil. ^1H NMR (300 MHz, CDCl_3) δ 5.97–5.84 (m, 1H), 5.36–5.22 (m, 2H), 5.29 (t, J = 2.0 Hz, 1H), 5.24 (t, J = 2.0 Hz, 1H), 4.65 (t, J = 1.3 Hz, 1H), 4.63 (t, J = 1.3 Hz, 1H), 2.49–2.37 (m, 3H), 2.22 (s, 3H), 2.24–2.15 (m, 1H), 1.80–1.65 (m, 2H); ^{13}C NMR (75.5 MHz, CDCl_3) δ 203.2, 170.7, 148.5, 131.4, 118.6, 112.1, 70.3, 65.9, 34.9, 33.8, 26.5, 23.9;

LRMS (EI, 20 eV) m/z 182 ($M^+ - C_2H_2$, 5), 166 (67); HRMS (EI) for $C_{10}H_{14}O_3$ ($M^+ - C_2H_2$): calcd 182.0943, found 182.0942.

Compound **10**: A colorless oil. 1H NMR (300 MHz, $CDCl_3$) δ 5.82–5.73 (m, 1H), 5.29 (t, $J = 2.0$ Hz, 1H), 5.22 (t, $J = 2.0$ Hz, 1H), 5.06–4.95 (m, 2H), 3.74 (s, 3H), 2.74–2.51 (m, 2H), 2.48–2.29 (m, 5H), 2.31–2.15 (m, 1H), 1.81–1.60 (m, 2H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 204.7, 171.6, 148.5, 136.9, 115.2, 112.1, 70.2, 52.5, 38.1, 34.9, 33.8, 28.1, 23.9; LRMS (EI, 20 eV) m/z 222 (M^+ , 5), 190 (100); HRMS (EI) for $C_{13}H_{18}O_3$ (M^+): calcd 222.1256, found 222.1280.

Compound **12**:² A colorless oil. 1H NMR (300 MHz, $CDCl_3$) δ 7.84 (apparent d, $J = 7.4$ Hz, 2H), 7.52 (td, $J = 7.4$, 1.2 Hz, 1H), 7.42 (app t, $J = 7.4$ Hz, 2H), 5.36 (t, $J = 2.0$ Hz, 1H), 5.21 (t, $J = 2.0$ Hz, 1H), 4.18–4.07 (m, 2H), 2.85 (dt, $J = 13.6$, 7.0 Hz, 1H), 2.51 (tt, $J = 7.4$, 2.0 Hz, 2H), 2.18 (dt, $J = 13.6$, 7.0 Hz, 1H), 1.92–1.81 (m, 1H), 1.74–1.63 (m, 1H), 1.05 (t, $J = 7.1$ Hz, 3H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 195.3, 171.7, 149.4, 135.3, 132.5, 128.7, 128.3, 111.6, 67.4, 61.5, 36.7, 34.2, 24.2, 13.6; LRMS (EI, 20 eV) m/z 258 (M^+ , 2), 212 (35); HRMS (EI) for $C_{16}H_{18}O_3$ (M^+): calcd 258.1259, found 258.1254.

Compound **14**: A colorless oil. 1H NMR (400 MHz, $CDCl_3$) δ 7.78 (apparent d, $J = 7.9$ Hz, 2H), 7.52 (app t, $J = 8$ Hz, 1H), 7.41 (app t, $J = 6.0$ Hz, 2H), 5.41 (t, $J = 2.0$ Hz, 1H), 5.12 (t, $J = 2.0$

Hz, 1H), 2.77–2.70 (m, 1H), 2.59–2.45 (m, 2H), 2.29–2.18 (m, 1H), 2.24 (s, 3H), 1.86–1.72 (m, 2H); ^{13}C NMR (100 MHz, CDCl_3) δ 204.5, 197.9, 149.0, 135.5, 132.7, 129.3, 128.4, 113.2, 75.5, 35.8, 34.3, 27.2, 24.2; LRMS (EI, 20 eV) m/z 228 (M^+ , 5), 185 (70); HRMS (EI) for $\text{C}_{15}\text{H}_{16}\text{O}_3$ (M^+): calcd 228.1150, found 228.1152.

Compound **16**: A colorless oil. ^1H NMR (400 MHz, CDCl_3) δ 8.50 (br. s, 1H), 7.52 (apparent d, $J = 7.9$ Hz, 2H), 7.32 (app t, $J = 8$ Hz, 1H), 7.12 (app t, $J = 6.0$ Hz, 2H), 5.42 (t, $J = 2.0$ Hz, 1H), 5.32 (t, $J = 2.0$ Hz, 1H), 2.67–2.52 (m, 3H), 2.50–2.37 (m, 1H), 2.29 (s, 3H), 1.87–1.75 (m, 2H); ^{13}C NMR (100 MHz, CDCl_3) δ 205.2, 168.5, 152.3, 137.4, 128.9, 124.5, 119.8, 112.1, 72.1, 35.8, 34.0, 27.1, 24.2; LRMS (EI, 20 eV) m/z 243 (M^+ , 15), 201 (55); HRMS (EI) for $\text{C}_{15}\text{H}_{17}\text{NO}_2$ (M^+): calcd 243.1259, found 243.1261.

Compound **18**:² A colorless oil. ^1H NMR (300 MHz, CDCl_3) δ 5.67 (t, $J = 2.2$ Hz, 1H), 5.17 (br. s, 1H), 4.30–4.20 (m, 2H), 2.84–2.77 (m, 1H), 2.67 (ddd, $J = 9.2, 11.7, 15.7$ Hz, 1H), 2.55–2.41 (m, 3H), 2.27 (ddd, $J = 2.0, 6.0, 15.6$ Hz, 1H), 2.10 (dd, $J = 2.2, 11.6$ Hz, 1H), 1.93–1.87 (m, 2H), 1.27 (t, $J = 7.1$ Hz, 3H); ^{13}C NMR (75.5 MHz, CDCl_3) δ 204.8, 169.3, 145.9, 111.0, 68.1, 61.0, 42.0, 38.3, 35.0, 31.9, 31.7, 14.1; LRMS (EI, 20 eV) m/z 208 (M^+ , 20), 164 (100); HRMS (EI) for $\text{C}_{12}\text{H}_{16}\text{O}_3$ (M^+): calcd 208.1099, found 208.1093.

Compound **20**.^{2,3} A colorless oil. ¹H NMR (400 MHz, CDCl₃) δ 5.22 (t, *J* = 2.4 Hz, 1H), 4.98 (t, *J* = 2.4 Hz, 1H), 4.28–4.18 (m, 2H), 3.04 (apparent quintet, *J* = 7.2 Hz, 1H), 2.51–2.46 (m, 2H), 2.43–2.36 (m, 2H), 1.97–1.84 (m, 3H), 1.71–1.64 (m, 1H), 1.58–1.50 (m, 2H), 1.26 (t, *J* = 7.0 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 206.0, 170.6, 148.0, 111.7, 71.7, 61.5, 47.7, 39.5, 29.8, 28.0, 25.8, 23.8, 14.0; LRMS (EI, 20 eV) *m/z* 222 (*M*⁺, 18), 176 (100); HRMS (EI) for C₁₃H₁₈O₃ (*M*⁺): calcd 222.1256, found 222.1247.

Compound **22**.^{2,3} A colorless oil. ¹H NMR (400 MHz, CDCl₃) δ 5.36 (t, *J* = 2.4 Hz, 1H), 5.21 (t, *J* = 2.0 Hz, 1H), 3.71 (s, 3H), 3.25–3.18 (m, 1H), 2.52–2.48 (m, 2H), 2.45–2.40 (m, 2H), 2.19–2.10 (m, 1H), 2.06–1.97 (m, 1H), 1.67–1.56 (m, 2H); ¹³C NMR (100 MHz, CDCl₃) δ 211.1, 170.3, 146.6, 112.2, 69.6, 52.7, 48.7, 37.5, 32.4, 29.5, 24.4; LRMS (EI, 20 eV) *m/z* 194 (*M*⁺, 55), 162 (90); HRMS (EI) for C₁₁H₁₄O₃ (*M*⁺): calcd 194.0943, found 194.0943.

Compound **24**.² A colorless oil. ¹H NMR (400 MHz, CDCl₃) δ 5.58 (t, *J* = 2.0 Hz, 1H), 5.33 (t, *J* = 1.9 Hz, 1H), 4.37 (dd, *J* = 9.3, 7.9 Hz, 1H), 3.98 (dd, *J* = 9.3, 4.9 Hz, 1H), 3.53–3.49 (m, 1H), 2.54–2.47 (m, 2H), 2.44 (s, 3H), 2.20–2.11 (m, 1H), 1.67–1.58 (m, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 200.0, 173.6, 146.9, 112.4, 70.6, 70.2, 44.5, 33.6, 29.2, 25.7; LRMS (EI, 20 eV) *m/z*

180 (M^+ , 3), 138 (100); HRMS (EI) for $C_{10}H_{12}O_3$ (M^+): calcd 180.0786, found 180.0785.

Compound **26**: A colorless oil. 1H NMR (300 MHz, $CDCl_3$) δ 5.53 (t, J = 2.2 Hz, 1H), 5.21 (t, J = 2.2 Hz, 1H), 3.53 (dd, J = 8.3, 10.6 Hz, 1H), 3.14–3.05 (m, 2H), 2.44–2.31 (m, 2H), 2.37 (s, 3H), 2.12–2.01 (m, 1H), 1.50–1.39 (m, 1H), 1.37 (s, 9H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 204.3, 170.6, 148.3, 110.6, 73.3, 54.2, 47.9, 39.8, 34.1, 30.5, 27.3, 26.5; LRMS (EI, 20 eV) m/z 235 (M^+ , 18), 193 (55); HRMS (EI) for $C_{14}H_{21}NO_2$ (M^+): calcd 235.1573, found 235.1573.