Synthesis of 2-Alkylidenetetrahydrofurans by Ru-catalyzed Regio- and Stereoselective Codimerization of Dihydrofurans with α,β-Unsaturated Esters

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Materials and Methods. All manipulations were performed under an argon atmosphere by standard Schlenk techniques. All solvents were distilled under argon over appropriate drying reagents (sodium or calcium hydride). [RuCl₂(CO)₃]₂, Ru₃(CO)₁₂, Fe₃(CO)₁₂, RhCl(PPh₃)₃, IrCl(CO)(PPh₃)₂, Pd(PPh₃)₄ and Co₂(CO)₈ were obtained commercially, and used without further purification. Ru(cod)(cot),¹ Ru(cot)(dmfm)₂,² Ru(cyclooctadienyl)₂,³ RuHCl(CO)(PPh₃)₃,⁴ RuH₂(PPh₃)₄,⁵ Cp*RuCl(cod),⁶ Ru(CO)₃(PPh₃)₂,⁷ CpRuCl(PPh₃)₂,⁸ 2-phenyl- or 2-(1-naphthyl)-2,3-dihydrofuran⁹ and dimethyl fumarate-d₂¹⁰ were prepared as described in the literatures. 2,3-Dihydrofuran and ethyl acrylate were obtained commercially and distilled before use. The other reagents (2,5-dihydrofuran and acrylates) were obtained commercially and used without further purification.

Physical and Analytical Measurements. NMR spectra were recorded on a JEOL EX-400 (FT, 400MHz (¹H), 100MHz (¹³C)) instrument. Chemical shifts (δ) for ¹H and ¹³C are referenced to internal solvent resonance and reported relative to SiMe₄. IR spectra were recorded using a Nicolet Impact 410 FT-IR spectrometer. GC-MS studies were conducted on a Shimadzu GCMS-QP5000 instrument with 70-eV electron impact ionization. Elemental analyses were performed at the Microanalytical Center of Kyoto University. Analytical gas chromatography was performed on a Shimadzu GC-14B gas chromatograph with FID detection using a 3.2-mm i.d. × 3 m column with 2%
(w/w) silicone OV-17 liquid phase on a Chromosorb W(AW DMCS) support in 60/80 mesh. Naphthalene was used as an internal standard. Compounds 3b and 3c were purified on a Japan Analytical Industry Co. Ltd., Model LC-918 recycling preparative HPLC equipped with JAIGEL-1H and 2H columns (GPC) using CHCl₃ as an eluent, instead of flash column chromatography after Kugelrohr distillation.

**Ethyl 2-(5-phenyl-3,4,5-trihydro-2-furylidene)propanoate (3b).** The crude product was purified by Kugelrohr distillation (160 °C at 3 Torr) and HPLC to give 3b as a colorless liquid. GC yield 39%, isolated yield 26%; IR spectrum (neat): 1785, 1454, 1381, 1175, 1140, 1117 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 7.32-7.19 (m, 5H), 5.31 (t, J = 7.3 Hz, 1H), 4.10 (q, J = 7.3 Hz, 2H), 3.28-3.21 (m, 1H), 3.03-2.94 (m, 1H), 2.48-2.41 (m, 1H), 2.15-1.91 (m, 1H), 1.83 (s, 3H), 1.22 (t, J = 7.3 Hz, 3H); ¹³C NMR (CDCl₃, 100 MHz): δ 169.7 (C), 169.3 (C), 140.5 (C), 128.5 (2 × CH), 127.9 (CH), 125.4 (2 × CH), 98.0 (C), 83.7 (CH), 59.6 (CH₂), 33.2 (CH₂), 31.2 (CH₂), 14.6 (CH₃), 11.5 (CH₃); MS (EI) m/z 246 (M⁺). Anal. Calcd for C₁₅H₁₈O₃: C, 73.15; H, 7.37. Found: C, 73.32; H, 7.47.

**Ethyl 2-(5-(1-naphtyl)-3,4,5-trihydro-2-furylidene)propanoate (3c).** The crude product was purified by Kugelrohr distillation (200 °C at 1 Torr) and HPLC to give 3c as a colorless liquid. GC yield 79%, isolated yield 65%; IR spectrum (neat): 1700, 1639, 1553, 1490, 1414, 1302 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 7.43-7.91 (m, 7H), 6.11 (t, J = 6.8 Hz, 1H), 4.20 (q, J = 7.0 Hz, 2H), 3.22 (t, J = 7.7 Hz, 2H), 2.74-2.66 (m, 1H), 2.19-2.11 (m, 1H), 1.99 (s, 3H), 1.31 (t, J = 7.0 Hz, 3H); ¹³C NMR (CDCl₃, 100 MHz): δ 169.8 (C), 169.3 (C), 136.1 (C), 133.6 (C), 129.8 (C), 128.9 (CH), 128.2 (CH), 126.1 (CH), 125.6 (CH), 125.3 (CH), 122.8 (CH), 121.7 (CH), 98.2 (C), 81.4 (CH), 59.7 (CH₂), 32.1 (CH₂), 30.8 (CH₂), 14.6 (CH₃), 11.6 (CH₃); MS (EI) m/z 296 (M⁺). Anal. Calcd for C₁₉H₂₀O₃: C, 77.00; H, 6.80. Found: C, 77.15; H, 6.85.

**tert-Butyl 2-(3,4,5-trihydro-2-furylidene)propanoate (3d).** The crude product was purified by
flash column chromatography (ethyl acetate/hexane = 1/1) and Kugelrohr distillation (120 °C at 10 Torr) to give 3d as a colorless liquid. GC yield 72%, isolated yield 55%; IR spectrum (neat): 1693, 1639, 1455, 1366 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 4.18 (t, J = 6.8 Hz, 2H), 3.01 (t, J = 7.0 Hz, 2H), 2.09-2.02 (m, 2H), 1.78 (s, 3H), 1.48 (s, 9H); ¹³C NMR (CDCl₃, 100 MHz): δ 169.0 (C), 168.7 (C), 99.1 (C), 79.0 (C), 71.0 (CH₂), 30.9 (CH₂), 28.5 (3 × CH₃), 24.7 (CH₂), 11.7 (CH₃); MS (EI) m/z 198 (M⁺). Anal. Calcd for C₁₁H₁₈O₃: C, 66.64; H, 9.15. Found: C, 66.85; H, 9.06.

**Methyl 3-phenyl-2-(3,4,5-trihydro-2-furylidene)propanoate (3e).** The crude product was purified by flash column chromatography (ethyl acetate/hexane = 1/3) and Kugelrohr distillation (150 °C at 5 Torr) to give 3e as a colorless liquid. GC yield 44%, isolated yield 19%; IR spectrum (neat): 1698, 1633, 1494, 1436 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 7.26-7.21 (m, 5H), 4.25 (t, J = 7.1 Hz, 2H), 3.67 (s, 2H), 3.66 (s, 3H), 3.12 (t, J = 7.8 Hz, 2H), 2.14-2.07 (m, 2H); ¹³C NMR (CDCl₃, 100 MHz): δ 171.7 (C), 169.2 (C), 141.7 (C), 128.3 (2 × CH), 127.9 (2 × CH), 125.4 (CH), 101.7 (C), 71.6 (CH₂), 51.0 (CH₃), 31.8 (CH₂), 31.2 (CH₂), 24.4 (CH₂); MS (EI) m/z 232 (M⁺). Anal. Calcd for C₁₄H₁₆O₃: C, 72.39; H, 6.94. Found: C, 72.46; H, 6.96.

**Methyl 2-(3,4,5-trihydro-2-furylidene)butanoate (3f).** The crude product was purified by flash column chromatography (ethyl acetate/hexane = 1/3) and Kugelrohr distillation (110 °C at 10 Torr) to give 3f as a colorless liquid. Isolated yield 11%; IR spectrum (neat): 1740, 1632, 1434, 1374 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 4.14 (t, J = 7.0 Hz, 2H), 3.70 (s, 3H), 3.06 (t, J = 7.8 Hz, 2H), 2.32 (q, J = 7.3 Hz, 2H), 2.11-2.03 (m, 2H), 0.99 (t, J = 7.3 Hz, 3H); ¹³C NMR (CDCl₃, 100 MHz): δ 170.4 (C), 169.5 (C), 104.1 (C), 71.3 (CH₂), 50.8 (CH₃), 31.0 (CH₂), 24.4 (CH₂), 19.5 (CH₂), 13.9 (CH₃); MS (EI) m/z 170 (M⁺). Anal. Calcd for C₉H₁₆O₃: C, 63.51; H, 8.29. Found: C, 63.25; H, 8.28.

**Dimethyl 2-(3,4,5-trihydro-2-furylidene)butane-1,4-dioate (3g).** The crude product was purified by flash column chromatography (ethyl acetate/hexane = 1/1) and Kugelrohr distillation (130 °C at 10
Torr) to give 3g as a colorless liquid. GC yield 64%, isolated yield 55%; IR spectrum (neat): 1747, 1714, 1643, 1376 cm⁻¹; ¹H NMR (CDCl₃, 400 MHz): δ 4.25 (t, J = 7.1 Hz, 2H), 3.69 (s, 3H), 3.68 (s, 3H), 3.37 (s, 2H), 3.15 (t, J = 7.8 Hz, 2H), 2.15-2.09 (m, 2H); ¹³C NMR (CDCl₃, 100 MHz): δ 173.0 (C), 172.5 (C), 168.4 (C), 95.8 (C), 72.0 (CH₂), 51.7 (CH₃), 51.1 (CH₃), 31.6 (CH₂), 31.1 (CH₂), 24.3 (CH₂); MS (EI) m/z 214 (M⁺). Anal. Calcd for C₁₀H₁₄O₅: C, 56.07; H, 6.59. Found: C, 56.36; H, 6.61.

References