Supporting Material for:

Generation of Highly Enantioselective Catalysts from the Pseudoenatiomeric Assembly of BINOL, F_8BINOL, and Ti(O*i*Pr)$_4$

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General: 2,2'-dihydroxy-5,5',6,6',7,7',8,8'-octafluoro-1,1'-binaphthyl (F_8BINOL) was prepared according to literature procedure.[1] Anhydrous toluene was obtained using the method described by Grubbs.[2] Column chromatography was carried out using 230-400 mesh silica gel.

Experimental Procedures for the Preparation of Glyoxylate-Ene Adducts (Table 1):

Ethyl (*S*)-2-hydroxy-4-phenylpent-3-enoate (3a). A mixture of (*R*)-F_8BINOL (21.6 mg, 0.05 mmol), (*S*)-BINOL (14.3 mg, 0.05 mmol), Ti(O*i*Pr)$_4$ (14.6 μL, 0.05 mmol) in toluene (1 mL) was heated at 60°C for 1 hour. The solution was cooled to –20°C. After 15 min, ethyl glyoxylate (0.75 mmol, 1.02 M solution in toluene) and α-methylstyrene (0.5 mmol) were added. Stirring was continued at –20°C for 16 hours. The reaction mixture was transferred onto a plug of silica gel and was eluted with a mixture of ether and pentane (1:4 v/v) giving the desired (*S*)-ethyl-2-hydroxy-4-phenylpent-3-enoate as colorless oil (95% yield). ^{1}H NMR (400 MHz, $CDCl_3$) : 1.22 (t, J = 7.2 Hz, 3H), 2.85 (dd, J = 14.4, 7.6 Hz, 1H), 2.87 (d, J = 6.4

Hz, 1H, OH), 3.06 (dd, J = 14.6, 4.4 Hz, 1H), 4.06 (m, 2H), 4.08 (dd, J = 7.6, 4.4 Hz, 1H), 5.21 (d, J = 1.2 Hz, 1H), 5.39 (d, J = 1.2 Hz, 1H), 7.22-7.39 (m, 3H), 7.40-7.42 (m, 2H). IR (neat, ν_{max}/cm^{-1}) : 1628, 1735, 2982, 3482. HRMS for $C_{13}H_{16}O_3$ calculated mass 220.1099; observed mass 220.1101. Enantiomeric excess determination HPLC analysis (CHIRALPAK AS column, Daicel co., Japan, 1 mL/min, Hexane : *i*-Propanol = 95 : 5, λ_{max} 250 nm) R_t = 10.06 (S)-isomer, R_t = 12.87 min (*R*)-isomer. >99% ee.

Ethyl(*S*)-2-hydroxy-4-methylpent-4-enoate (3b). In accordance with the procedure described for **3a**, the reaction of ethyl glyoxylate with 2-methylpropene afforded the desired product **3b** as colorless oil (57% yield) : ^{1}H NMR (400 MHz, $CDCl_3$) : 1.29 (t, J = 7.2 Hz, 3H), 1.78 (s, 3H), 2.36 (dd, J = 14.4, 8.4 Hz, 1H), 2.52 (dd, J = 14.4 Hz, 4 Hz, 1H), 2.75 (d, J = 6.0 Hz, 1H, OH), 4.24 (q, J = 7.2 Hz, 2H), 4.34 (dd, J = 8.2, 4.2 Hz, 1H), 4.81 (d, J = 0.8 Hz, 1H) 4.87 (d, J = 1.6 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) : 14.2, 22.5, 42.7, 61.7, 69.1, 114.0, 141.0, 174.7. IR (neat, ν_{max}/cm^{-1}): 1648, 1735, 2982, 3482. HRMS for $C_8H_{14}O_3$ calculated Mass 158.094294 and observed Mass 158.094418. Enantiomeric excess determination HPLC analysis (CHIRALPAK AS column, Daicel co., Japan, 1 mL/min, Hexane : *iso* Propanol = 95 : 5, λ_{max} 210 nm) R_t = 6.15 (S)-isomer, R_t = 7.75 min (*R*)-isomer. >99% ee.

Ethyl (*S*)-4-ethyl-2-hydroxyhex-4-enoate (3c). In accordance with the procedure described for **3a**, the reaction of ethyl glyoxylate with 2-methylpropene afforded the desired product **3c** as colorless oil (71% yield). ^{1}H NMR (400 MHz, $CDCl_3$) : 0.97 (t, J = 7.6 Hz, 3H), 1.28 (t, J = 7.2 Hz, 3H), 1.60 (d, J = 6.8 Hz, 3H), 2.07 (m, 2H), 2.27 (dd, J = 14.4, 8.4 Hz, 1H), 2.53 (dd, J = 14.4, 9.2 Hz 1H), 2.66 (d, J = 6.0 Hz, 1H, OH), 4.21 (q, J = 7.2 Hz, 3H), 4.23 (m, 1H), 5.30 (q, J = 6.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) : 12.6, 13.1, 14.2, 22.6, 41.6,

61.4, 69.4, 122.5, 136.9, 174.8. IR (neat, ν_{max}/cm^{-1}): 1735, 2936, 2966, 3482. HRMS for $C_{10}H_{18}O_3$ calculated Mass 186.125595 and observed Mass 186.125074. Enantiomeric excess determination HPLC analysis (CHIRALPAK AS column, Daicel co., Japan, 1 mL/min, Hexane : *iso* Propanol = 95 : 5, λ_{max} 210 nm) R_t = 5.78 (S)-isomer, R_t = 6.42 min (*R*)-isomer. >99% ee.

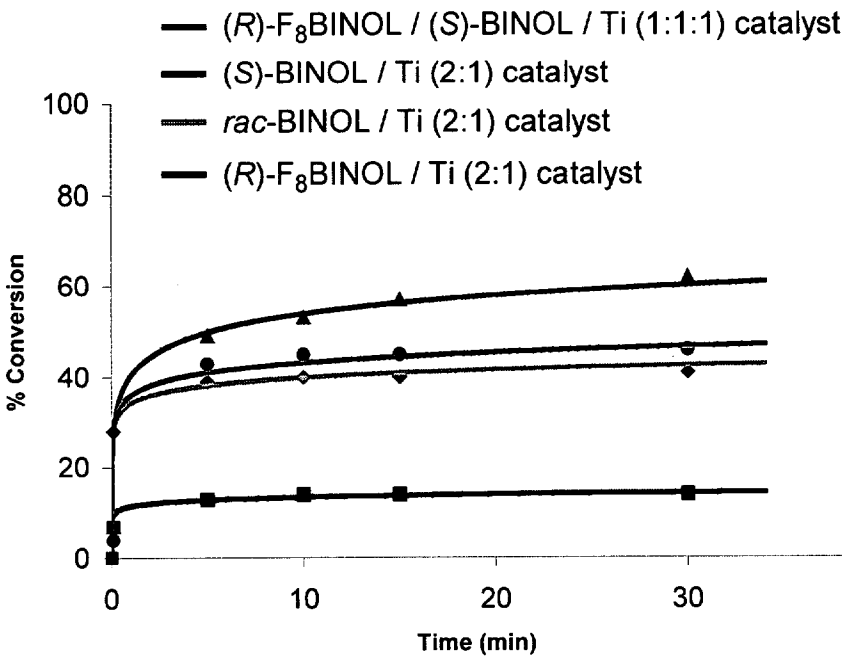
Ethyl (*S*)-3-(1'-cyclohexenyl)-2-hydroxypropionate (3d). In accordance with the procedure described for **3a**, the reaction of ethyl glyoxylate with methylenecyclohexane afforded the desired product **3d** as colorless oil (47% yield). ^1H NMR (400 MHz, $CDCl_3$) : 1.28 (t, J = 7.2 Hz, 3H), 1.48-1.64 (m, 4H), 1.84-2.04 (m, 4H), 2.28 (dd, J = 14.0, 8.0 Hz, 1H), 2.43 (dd, J = 14.0, 3.6 Hz, 1H), 2.67 (d, J = 6.4 Hz, 1H, OH), 4.22 (q, J = 7.2 Hz, 2H), 4.27 (m, 1H), 5.84 (br s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) : 14.2, 22.2, 22.8, 25.3, 28.4, 43.3, 65.5, 69.2, 125.3, 133.0, 174.9. IR (neat, ν_{max}/cm^{-1}) :1735, 2837, 2935, 3528. HRMS for $C_{11}H_{18}O_3$ calculated Mass 198.125595 and observed Mass 198.126074. Enantiomeric excess determination HPLC analysis (CHIRALPAK AS column, Daicel co., Japan, 1 mL/min, Hexane : *iso* Propanol = 95 : 5, λ_{max} 210 nm) R_t = 6.76 (S)-isomer, R_t = 7.58 min (*R*)-isomer. >99% ee.

Ethyl (*S*)-3-(1'-cyclopentenyl)-2-hydroxypropionate (3e). In accordance with the procedure described for **3a**, the reaction of ethyl glyoxylate with methylenecyclopentane afforded the desired product **3e** as colorless oil (59 % yield). ^1H NMR (400 MHz, $CDCl_3$) : 1.28 (t, J = 7.2 Hz, 3H), 1.86 (quint, J = 7.6 Hz, 2H), 2.19-2.28 (m, 4H), 2.48 (dd, J = 14.4, 7.6 Hz, 1H), 2.59 (dd, J = 15.2, 2.8 Hz, 1H), 2.78 (d, J = 6 Hz, OH, 1H), 4.22 (dq, J = 1.6, 7.2 Hz, 2H), 4.32 (dd, J = 7.6, 4.2 Hz, 1H), 5.50 (br s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) : 14.2, 23.5, 32.5, 35.2, 36.2, 61.6, 69.4, 127.8, 139.3, 174.8. IR (neat, ν_{max}/cm^{-1}) : 1735, 2847, 2949, 3482. HRMS for $C_{10}H_{16}O_3$ calculated Mass 184.109945 and observed Mass 184.109046.

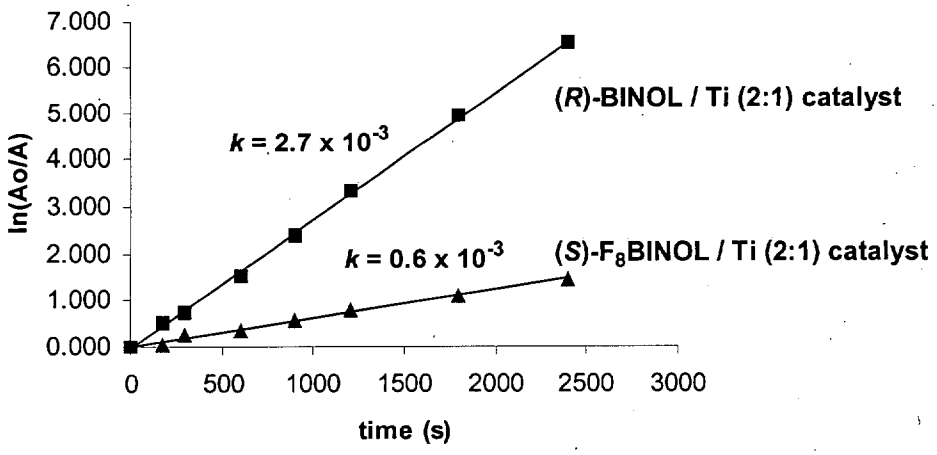
Enantiomeric excess determination HPLC analysis (CHIRALPAK AS column, Daicel co., Japan, 1 mL/min, Hexane : *iso*-Propanol = 95 : 5, λ_{max} 210 nm) R_t = 6.72 (S)-isomer, R_t = 7.74 min (*R*)-isomer. >99% ee.

Preparation of (*R*)-F_8BINOL/Ti/(*S*)-BINOL complex (4): A solution mixture of (*R*)-F_8BINOL (21.6 mg, 0.05 mmol), (*S*)-BINOL (14.3 mg, 0.05 mmol) and Ti(O*i*Pr)$_4$ (14.6 μL, 0.05 mmol) in toluene (1 mL) was stirred at 60°C for 1 hour and allowed to stand at ambient temperature. After 7 – 10 days, the Ti(IV)/(*R*)-F_8BINOL/(*S*)-BINOL complex (**4,** 3.4 mg, 7.9% yield) was isolated as X-ray quality dark red crystals. ^{19}F NMR (400 MHz, CD_2Cl_2, $CFCl_3$ ref): -140.18, -143.78, -144.38, -145.65, -148.17, -149.88, -151.44, -153.01, -158.04, -159.75, -160.14, -163.14, -163.85.

Conversion/time characteristics of the Ti(IV)-based catalysts for the glyoxylate-ene reaction between ethyl glyoxylate and α-methylstyrene



Initial rates of the BINOL- and F_8BINOL- derived catalysts in glyoxylate-ene reaction between ethyl glyoxylate and α-methylstyrene (concentration of ethyl glyoxylate: 0.877M, T: -30°C)



References

1. Yudin, A. K.; Martyn, L. J. P.; Pandiaraju, S.; Zheng, J.; Lough, A. *Organic Lett.* **2000**, *2*, 41.

2. Pangborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, *15*, 1518.