Catalytic Asymmetric Coupling of 2-Naphthols by Chiral Tridentate Oxovanadium(IV) Complexes

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SUPPORTING INFORMATION

The optimal procedures for the preparation of catalyst **8a** and for its mediated coupling of 2-naphthol, full spectroscopic characterization of **10a-g**, **11a**, and **11b**, and the linear plot are provided (7 pages).

General. ^{1}H-NMR and ^{13}C-NMR were recorded on Varian Gemini-2000 (200 MHz ^{1}H, 50 MHz ^{13}C) spectrometers in deuterochloroform with tetramethylsilane (TMS) or chloroform as an internal reference unless otherwise stated. Chemical shifts are reported in ppm (δ), coupling constants, *J*, are reported in Hz. Mass spectra were recorded on a Finnigan TCQ-700 spectrometer with ionization voltages of 70 eV. Fast atom bombardment (FAB) mass spectra were recorded on a Finnigan MAT-95S spectrometer. Data are reported in the form m/e (intensity relative to base = 100%). Analytical TLC was performed on Merck silica gel plates with QF-254 indicator. Visualization was accomplished with UV light, PMA, and $KMnO_4$. Column (flash) chromatography was performed using 32-63 μm silica gel. Solvents for extraction and chromatography were reagent grade. Analytical high-pressure liquid chromatography (HPLC) was performed on a Jasco Liquid Chromatograph equipped with PU-980 pumps, UV-975 detector, and 807-IT integrator. The columns used were Daicel Chiralpak AD, AS and Chiralcel OD columns with the detector wavelength at 254 nm. The flow rate and solvent systems were as denoted. Optical rotation were obtained on a Jasco DIP-1000 Digital Polarimeter at room temperature and reported as follows: $[\alpha]_D$, concentration (c = g/100mL), and solvent. The absolute configurations of all coupling products except **10e-g** were determined by correlation of their $[\alpha]_D$ of purified materials (or materials from their filtrates after re-crystallization) with the literature values. NMR spectroscopic assignments were made with the aid of ACD labs program. All the vanadyl complexes **1-9** were used

directly after their preparations. All the coupling products except **10g** are known compounds and are isolated as chromatographically pure materials.

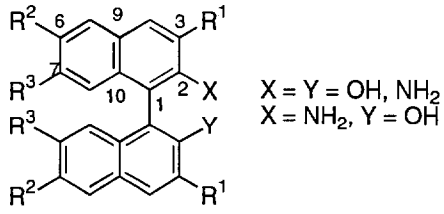
Representative procedure for complex formation

In a 50 mL, two-necked, round bottomed flask was placed α-amino acid (5 mmol) and NaOAc-$5H_2O$ (1.170 g, 10 mmol) in degassed water (10 mL). After having been stirred at 60 ℃ for 10 min to effect their complete dissolution, the reaction mixture was treated dropwise with a solution of 2-hydroxy-1-naphthaldehyde (861 mg, 5 mmol) in degassed EtOH (12.5 mL). The reaction mixture becomes homogeneous by heating at 80 °C for 15 min and was gradually cooled to ambient temperature for 2 h. To the resultant Schiff base was added a solution of vanadyl sulfate trihydrate (1.080 g, 5 mmol) in degassed water (5 mL). Dark green complex starts crashing out in 15 min. The resultant reaction mixture was stirred for 2 h and then concentrated to half of the original solvent volume. The crude vanadyl complex collected by filtration was washed sequentially with H_2O (5 × 25 mL) and cold ether (5 × 25 mL) and then dried in vacuo to provide 3.290 g of **8a** (98 %) as a dark green solid: MS (FAB) analysis for **8a** ($C_{16}H_{15}NO_4V$, 336) 1009 (M_3+H^+, 26), 992 (11), 891 (11), 673 (M_2+H^+, 100), 672 (M_2^+, 22), 627 (M_2-CO_2-H^+, 25), 556 (22), 489 (14), 455 (M+valine+$2H^+$, 10), 337 (M+H^+, 48), 291(M-CO_2-H^+, 58).

MS (FAB) analysis for **8d** ($C_{20}H_{15}NO_4V$, 384): 769 (M_2+H^+, 3), 537 (38), 385 (M+H^+, 18), 339 (M-CO_2-H^+, 25), 307 (20), 154 (100), 136 (68).

MS (FAB) analysis for **8g** ($C_{17}H_{17}NO_4V$, 350): 1051 (M_3+H^+, 13), 701 (M_2+H^+, 56), 700 (M_2^+, 21), 504 (M+*t*-leucine+Na^+, 76), 503 (M+ *t*-leu+Na-H^+, 62), 351 (M+H^+, 100).

Representative procedure for the coupling of 2-naphthol



In a 25-mL, two-necked, round-bottomed flask was placed catalyst **8a** (33 mg, 0.1 mmol) in anhydrous CCl_4 (5 mL). This solution was stirred under a stream of O_2 for 15 min and then treated with a solution of 2-naphthol (144 mg, 1 mmol) in CCl_4 (5 mL). The reaction mixture was stirred at ambient temperature for 6 days. The crude mixture concentrated under reduced pressure was dissolved with minimum amount of CH_2Cl_2 and purified by column chromatography (acetone/hexane, 1/5) to give (*R*)-BINOL **10a** (133 mg, 94 %). Its enantiomeric purity was determined to be 62% by HPLC on Chiralpak AD. Enantiomerically pure (*R*)-**10a** can be obtained by concentrating the filtrate after its re-crystallization from benzene: ^{1}H NMR (200 MHz, $CDCl_3$) 7.98 (d, J = 9.0, 2H, 2 × HC(4)), 7.89 (d, J = 7.6, 2H, 2 × HC(5)), 7.39 (d, J = 9.0, 2H, 2 × HC(8)), 7.42-7.25 (m, 4H, 2 × HC(6), 2 × HC(7)), 7.15 (d, J = 7.8, 2H, 2 × HC(3)), 5.05 (s, 2H, 2 × OH); ^{13}C NMR (50 MHz, $CDCl_3$) 152.86 (C(2)), 133.48 (C(10)), 131.49 (C(4)), 129.52 (C(9)), 128.47 (C(5)), 127.55 (C(7)), 124.27 (C(6)), 124.09 (C(8)), 117.81 (C(3)), 110.89 (C(1)); MS (70 eV) 286 (M^+, 100), 257 (13), 239 (12), 58 (65); TLC R_f 0.14 (hexane); $[\alpha]^{25}_D$ +36.1 (*c* 1.0, THF) for >99% ee (lit.[1] $[\alpha]^{20}_D$ –35.5 (*c* 1.0, THF) for (*S*)-**10a**); HPLC t_R 36.2 min (*R*, major), 39.5 min (*S*) (Chiralpak AD, *i*-PrOH/hexane, 8/92, 1.0 ml/min, λ = 254 nm).

Data for **10b**: ^{1}H NMR (200 MHz, $CDCl_3$) 8.05 (d, J = 2.0, 2H, 2 × HC(4)), 7.89 (d, J = 9.0, 2H, 2 × HC(5)), 7.38 (d, J = 8.0, 2H, 2 × HC(8)) 7.36 (dd, J = 9.0, 2.0, 2H, 2 × HC(7)), 6.96 (d, J = 9.0, 2H, 2 × HC(3)) 5.08 (s, 2H, 2 × OH); ^{13}C NMR (50 MHz, $CDCl_3$) 153.07 (C(2)), 131.97 (C(10)), 130.92 (C(4)), 130.74 (C(5)), 130.63 (C(9)), 130.50 (C(7)), 125.95 (C(8)),

119.04 (C(3)), 118.04 (C(6)), 110.74 (C(1)); MS (70ev) 446 ($M+2^+$, 45), 444 (M^+, 100), 442 (45), 284 (12), 256 (23), 226 (16), 142 (22), 133 (12); TLC R_f 0.22 (EtOAc/hexane, 1/5); $[\alpha]^{25}_D$ -126.4 (*c* 1.0, CH_2Cl_2) for >99% ee (lit.[2] $[\alpha]^{25}_D$ -129 (*c* 1.0, CH_2Cl_2) for (*R*)-**10b**); HPLC t_R 25.3 min (*S*), 36.7 min (*R*, major) (Chiralcel OD, *i*-PrOH/hexane, 13/87, 1.0 ml/min, λ = 254 nm).

Data for **10c**: ^{1}H NMR (200 MHz, $CDCl_3$) 7.78 (d, *J* = 8.8, 2H, 2 × HC(4)), 7.32 (d, *J* = 8.8, 2H, 2 × HC (8)), 7.21 (s, *J* = 2.2, 2H, 2 × HC(5)), 7.04-6.99 (m, 4H, 2 × HC (3,7)), 4.94 (s, 2H, 2 × OH), 3.90 (s, 6H, 2 × OCH_3); ^{13}C NMR (50 MHz, $CDCl_3$) 156.38 (C(6)), 151.03 (C(2)), 130.36 (C(10)), 129.89 (C(4)), 128.63 (C(9)), 125.82 (C(8)), 119.76 (C(7)), 118.16 (C(3)), 111.46 (C(1)), 106.86 (C(5)), 55.27 (OCH_3); MS (70ev) 346 (M^+, 100), 284 (28), 241 (30), 212 (64), 202 (20) ; TLC R_f 0.19 (EtOAc/hexane, 1/4); $[\alpha]^{25}_D$ -25.8 (*c* 1.0, $CHCl_3$) for 53% ee. (lit.[3] $[\alpha]^{25}_D$ –50.1 (*c* 1.0, $CHCl_3$) for (*S*)-**10c**); HPLC t_R 22.69 min (*S*), 38.41 min (*R*, major) (Chiralcel OD, *i*-PrOH/hexane, 13/87, 1 ml/min, λ = 254 nm).

Data for **10d**: ^{1}H NMR (200 MHz, $CDCl_3$) 7.88 (d, *J* = 9.0, 2H, 2 × HC(5)), 7.79 (d, *J* = 8.8, 2H, 2 × HC(4)), 7.22 (d, *J* = 8.8, 2H, 2 × HC(3)), 7.05 (dd, *J* = 9.0, 2.6, 2H, 2 × HC(6)), 6.49 (d, *J* = 2.6, 2H, 2 × HC(8)), 5.06 (s, 2H, 2 × OH), 3.58 (s, 6H, 2 × OCH_3); ^{13}C NMR (50 MHz, $CDCl_3$) 159.23 (C(7)), 153.44 (C(2)), 134.78 (C(9)), 131.20 (C(4)), 130.06 (C(5)), 124.85 (C(10)), 116.08 (C(6)),115.16 (C(3)), 110.09 (C(1)), 103.20 (C(8)), 55.11 (OCH_3); MS (70ev) 346 (100), 347 (18), 340 (15), 326 (15); TLC R_f 0.22 (EtOAc/hexane, 1/5); $[\alpha]^{25}_D$ -124.4 (*c* 1.0, MeOH) for >99% ee (lit.[4] $[\alpha]^{25}_D$ –126.4 (*c* 1.0, MeOH) for (*R*)-**10d**); HPLC t_R 15.8 min (*S*), 21.7 min (*R*, major) (Chiralcel OD, *i*-PrOH/hexane, 13/87, 1 ml/min, λ = 254 nm).

Data for **10e**[5]: ^{1}H NMR (200 MHz, $CDCl_3$) 7.78 (d, *J* = 8.0, 2H, 2 × HC(8)), 7.32-7.28 (m, 4H, 2 × HC (6,7)), 7.15 (m, 4H, 2 × HC (4,5)), 5.90 (s, 2H, 2 × OH), 4.10 (s, 6H, 2 × OCH_3); ^{13}C NMR (50 MHz, $CDCl_3$) 147.34 (C(2)), 143.77 (C(3)), 129.15 (C(9)), 128.37 (C(10)), 126.93 (C(6)), 124.76 (C(7)), 124.58 (C(5)), 124.13 (C(8)), 114.45 (C(1)), 106.30 (C(4)), 55.90 (OCH_3); MS (70ev) 346 (M^+, 100), 286 (30), 285 (90), 242 (38), 213 (42), 202 (43); TLC R_f 0.32 (EtOAc/hexane, 1/2); $[\alpha]^{25}_D$ -52.4 (*c* 1.0, THF) for >99% ee; HPLC t_R 37.7 min (*R*), 77.9 min (*S*,

major) (Chiralcel OD, *i*-PrOH/hexane, 20/80, 1.5 ml/min, λ = 254 nm).

Data for **10f**: ^{1}H NMR (200 MHz, $CDCl_3$) 7.76 (d, J = 7.2, 2H, 2 × HC(8)), 7.54-7.25 (m, 14H, 2 × HC(6,7), 2 × C_6H_5), 7.16 (d, J = 4.0, 4H, 2 × HC(4,5)), 6.01 (s, 2H, 2 × OH), 5.33 (s, 4H, 2 × OCH_2); ^{13}C NMR (50 MHz, $CDCl_3$) 146.49 (C(2)), 143.83 (C(3)), 136.07 (C(2')), 134.01 (C(9)), 128.83 (C(10,3',7')), 127.98 (C(4',5',6')), 126.99 (C(6)), 124.82 (C(7)), 124.69 (C(5)), 124.09 (C(8)), 114.45 (C(1)),107.59 (C(4)), 71.08 (C(1')); MS (70ev) 498 (M^+, 38), 91 (100); TLC R_f 0.33 (EtOAc/hexane, 1/4); $[\alpha]^{25}_D$ -35.0 (*c* 1.0, CH_2Cl_2) for 68% ee (lit.[6] $[\alpha]^{25}_D$ –8.2 (*c* 0.8, THF) for 24% ee of (*S*)-**10f**);; HPLC t_R 18.4 min (*S*, major), 25.0 min (*R*) (Chiralpak AS, *i*-PrOH/hexane, 20/80, 1.5ml/min,λ= 254nm).

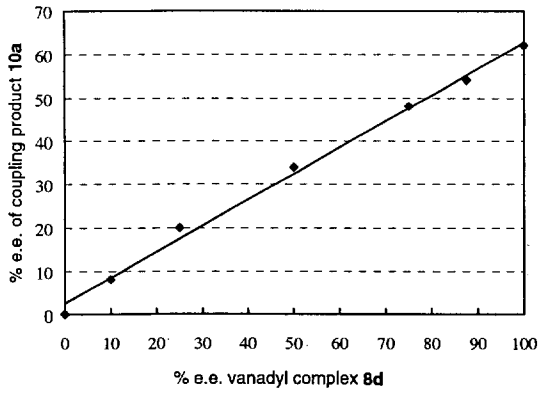
Data for **10g**: ^{1}HNMR (200 MHz, $CDCl_3$) 7.64-7.59 (m, 2H, 2 × HC(8)), 7.33-7.25 (m, 24H, 2 × HC(6,7), 4 × C_6H_5)), 7.13-7.07 (m, 4H, 2 × HC(4,5)), 6.61 (s, 2H, 2 × OH), 4.68 (s, 2H, 2 × Ph_2COH); ^{13}CNMR (50 MHz, $CDCl_3$) 151.21 (C(1',1")), 145.58 (C(2)), 145.24 (C(3)), 133.88 (C(4)), 133.17 (C(10)), 130.98 (C(5)),128.92 (C(6)); C(Ar): 128.12, 128.04, 127.89, 127.63, 124.25; 124.25 (C(7)), 124.11 (C(8)), 114.14 (C(1)), 82.98 (C(11)); MS (70ev) 614 (M^+-2H_2O, 62), 539 (38), 537(60), 230(100); TLC R_f 0.38 (EtOAc/hexane, 1/8); $[\alpha]^{25}_D$ -23.3 (*c* 1.0, CH_2Cl_2) for 35% ee; HPLC t_R 19.4 min (*S*), 32.1 min (*R*, major) (Chiralpak AD, *i*-PrOH/hexane, 8/92, 1.0 ml/min,λ= 254nm); Anal. Calcd. For $C_{46}H_{34}O_4$ (650.73): C, 84.90; H, 5.27. Found: C, 84.69; H, 5.27.

Data for **11a**: ^{1}H NMR (200 MHz, $CDCl_3$) 7.95-7.8 (m, 4H, HC (4,4',5,5')), 7.40-7.13 (m, 8H, HC(3,3',6-8,6'-8')), 5.12 (s, 1H, OH), 3.73 (s, 2H, NH_2); ^{13}C NMR (50 MHz, $CDCl_3$) 151.92 (C(2')), 143.76 (C(2)), 134.18 (C(10')), 133.26 (C(10)), 130.65 (C(4')), 130.41 (C(5')), 129.57 (C(9')), 128.43 (C(9)), 128.36 (C(5)), 128.28 (C(4)), 127.36 (C(7)), 126.99 (C(7')), 124.58 (C(6')), 123.78 (C(6)), 123.69 (C(8)), 122.81 (C(8')), 118.21 (C(3')), 117.75 (C(3)), 114.31 (C(1)), 108.60 (C(1')); MS (70ev) 286 (28), 285 (M^+,100), 284 (10), 268 (M-H_2O^+,20), 267 (11.3), 256 (13), 239 (12.2), 144 (12.2); TLC R_f 0.31 (EtOAc/hexane, 1/4); $[\alpha]^{25}_D$ -19.6 (*c* 1.0,

THF) for 20% ee (lit.[7] $[\alpha]^{25}_D$ –97 (*c* 1.0, THF) for (*S*)-**11a**); HPLC t_R 18.42 min (*S*, major), 34.54 min (*R*) (Chiralpak AD, *i*-PrOH/hexane, 8/92, 1.0 ml/min, λ = 254 nm).

Data for **11b**: ^{1}H NMR (200 MHz, $CDCl_3$) 7.81 (d, *J* = 8.6, 4H, 2 × HC(5,8)), 7.26-7.06 (m, 8H, 2 × HC(3,4,6,7)), 3.53 (bs, 4H, 2 × NH_2); ^{13}C NMR (50 MHz, $CDCl_3$) 142.70 (C(2)), 133.74 (C(10)), 129.53 (C(5)), 128.54 (C(9)), 128.18 (C(7)), 126.87 (C(4)), 123.99 (C(6)), 122.47 (C(8)), 118.40 (C(3)), 112.70 (C(1)); MS (70ev) 284 (M^+, 100), 266 (63), 239 (23), 132 (20); TLC R_f 0.27 (EtOAc/hexane, 1/4); $[\alpha]^{25}_D$ -17.6 (*c* 1.0, pyridine) for 12% ee (lit.[7] $[\alpha]^{25}_D$ +158 (*c* 2.0, pyridine) for (*R*)-**11b**); HPLC t_R 12.74 min (*S*, major), 38.41 min (*R*) (Chiralpak AD, *i*-PrOH/hexane, 15/85, 1.2 ml/min, λ = 254 nm).

Crystal data for **8d'**: $C_{18}H_{22}NO_6V$, M_r = 399.31, orthorhombic, space group $P2_12_12$, *a* = 10.2532(3) Å, *b* = 28.55740(10) Å, *c* = 6.6141(2) Å, *V* = 1936.64(8) Å^3, *Z* = 4, ρ_{calcd} = 1.370 Mgm^{-3}, *T* = 295(2) K, Siemens SMART CCD diffractometer, $Mo_{k\alpha}$ radiation (λ = 0.71073), μ = 0.544 mm^{-1}. The structure was solved by the Patterson method (SHELXS-86). All non-hydrogen atoms were refined anisotropically (SHEL**XL**-93). Final block-diagonal matrix least-square refinement on F^2 with all 3841 reflections and 248 variables converged to *R*1 ($I > 2\sigma(I)$) = 0.0672, *wR2* (all data) = 0.0976, and GOF = 1.039. Crystallographic data (excluding structure factors) for the structure reported in the paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-148685 (**8d'**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).



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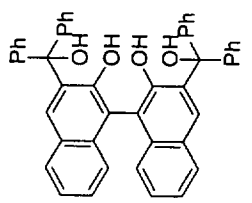

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6	7.287	1.5
7	7.272	1.7
8	7.260	20.0
9	7.251	2.0
10	7.244	1.6
11	7.140	2.7
12	7.121	1.1
13	7.095	0.6
14	7.074	0.6
15	6.536	0.9
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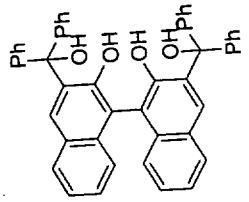

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7	128.919	0.2
8	128.115	0.5
9	128.039	0.5
10	127.887	0.5
11	127.629	0.7
12	127.447	0.2
13	124.266	0.2
14	124.109	0.2
15	114.141	0.1
16	82.978	0.1
17	77.637	1.4
18	77.000	1.4
19	76.363	1.4