Supplementary Information For:

Asymmetric Transfer Hydrogenation in Water with a Supported Noyori-Ikariya Catalyst

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General:

[RuCl₂(p-cymene)]₂ and ketones were obtained from Aldrich or Lancaster. The polyethylene glycol supported TsDPEN, PTsDPEN, was prepared according to the literature¹. The asymmetric transfer hydrogenation products were analyzed by a Varian CP-3380 GC equipped with a Chrompack Chirasil-Dex CB (25 m × 0.25 mm) column and by NMR. When necessary, the products were isolated by flash chromatography (SiO₂, hexane-ethyl acetate, 8:1).

(A) General Procedure for the Preparation of Ru-Diamine Precatalyst

$[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol) were dissolved in 2 mL of water. After stirring at 40 °C for 1 h, the suspension was used for the reduction reactions.

(B) Asymmetric Transfer Hydrogenation of Acetophenone

Standard procedure at S/C = 100: After preparing the precatalyst, HCO_2Na (340 mg, 5 mmol) and acetophenone (120 mg, 1.0 mmol) were added to the solution. Following degassing three times, the solution was allowed to react at 40 °C or r.t. for a certain period of time. After cooling to room temperature, the organic phase was extracted with Et_2O (3 x 2 mL) and passed through a short silica gel column before being subjected to chiral GC analysis. For isolation, the mixture was then dried over Na_2SO_4 , concentrated, and purified by silica gel column to give the product (*R*)-1-phenylethanol⁴. Results: rt, 8 h, >99% conversion, 93% ee; 40 °C, 1 h, 99% conversion, 98% isolated yield (121 mg), 92% ee. GC (Chirasil Dex CB): carrier gas: helium, 80 psi; injection temperature: 250 °C; column temperature: 120 °C; 6.27 min (*R*); 6.90 min (*S*). ¹H NMR (CDCl_3/TMS): δ 1.50 (d, J = 6 Hz, 3 H), 2.01 (bs, 1 H), 4.90 (q, J = 6 Hz, 1 H), 7.25 – 7.40 (m, 5 H); ¹³C NMR (CDCl_3/TMS): δ 25.3, 70.9, 125.8, 127.9, 128.9, 146.2. The results for acetophenone and other ketones are summarized in the Table (page 6). GC traces for all the alcohols are given in pages 7-12.

Asymmetric transfer hydrogenation with $[\text{RuCl}_2(p\text{-cymene})]_2$ - PTsDPEN at S/C = 1000: $[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol), PTsDPEN¹ (50 mg, 0.012 mmol), acetophenone (1.2 g, 10 mmol), HCOONa (3.4 g, 50 mmol), H_2O (10 mL), 40 °C, 12 h, leading to >99% conversion and 89% ee.

(C) Asymmetric Transfer Hydrogenation of other Ketones

Asymmetric transfer hydrogenation of these ketones with $[\text{RuCl}_2(p\text{-cymene})]_2$ –PTsDPEN¹ was carried out using the same standard procedure as for acetophenone and analyzed by NMR and GC. The stereochemistry of products was assigned by comparing the GC retention time with literature data.

(*R*)-1-(2'-chlorophenyl)ethanol²: $[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol), PTsDPEN¹ (50 mg, 0.012 mmol), and 2'-chloroacetophenone (154 mg, 1 mmol), rt, 13 h, >99% conversion, 91% ee; 40 °C, 1.5 h, 100% conversion, 99% isolated yield (155 mg), 85% ee. GC (Chirasil Dex CB): carrier gas: helium, 80 psi; injection temperature: 250 °C; column temperature: 120 °C; 4.68 min (*R*); 6.33 min (*S*). ¹H NMR (CDCl_3/TMS): δ 1.48 (d, J = 6 Hz, 3 H), 2.08 (bs, 1 H), 4.68 (q, J = 6 Hz, 1 H), 7.10 – 7.30 (m, 4 H); ¹³C NMR (CDCl_3/TMS): δ 25.7, 62.6, 126.6, 127.3, 127.7, 129.0, 132.9, 143.6.

(*R*)-1-(4'-chlorophenyl)ethanol²: $[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol), PTsDPEN¹ (50 mg, 0.012 mmol), and 4'-chloroacetophenone (154 mg, 1 mmol), rt, 13 h, >99% conversion, 90% ee; 40 °C, 1.5 h, 100% conversion, 98% isolated yield (153 mg), 87% ee. GC (Chirasil Dex CB): carrier gas: helium, 80 psi; injection temperature: 250 °C; column temperature: 120 °C; 4.04 min (*R*); 5.73 min (*S*). ¹H NMR (CDCl_3/TMS): δ 1.45 (d, J = 6 Hz, 3 H), 2.04 (bs, 1 H), 4.85 (q, J = 6 Hz, 1 H), 7.26 – 7.32 (m, 4 H); ¹³C NMR (CDCl_3/TMS): δ 25.7, 70.1, 127.4, 129.0, 133.5, 144.6.

(*R*)-1-(4'-Trifluoromethylphenyl)ethanol⁶: $[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol), PTsDPEN¹ (50 mg, 0.012 mmol), and 4'-trifluoromethylacetophenone (190 mg, 1 mmol), rt, 12 h, >99% conversion, 85% ee; 40 °C, 2 h, 100% conversion, 91% isolated yield (173 mg), 82% ee. GC (Chirasil Dex CB); carrier gas: helium, 30 psi; injection temperature: 250 °C; column temperature: 95 °C; 16.70 min (*R*); 24.43 min (*S*). ¹H NMR (CDCl_3/TMS): δ 1.50 (d, J = 6 Hz, 3 H), 2.11 (bs, 1 H), 4.95 (q, J = 6 Hz, 1 H), 7.48 (d, J = 8 Hz, 2 H), 7.60 (d, J = 8 Hz, 2 H); ¹³C NMR (CDCl_3/TMS): δ 25.8, 70.2, 124.6 (q, $^1J_{\text{C-F}}$ = 271 Hz), 125.8 (q, $^3J_{\text{C-F}}$ = 4 Hz), 126.0, 130.0 (q $^2J_{\text{C-F}}$ = 32 Hz), 150.1.

(*R*)-1-(3'-methoxyphenyl)ethanol: $[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 3'-methoxyacetophenone (152 mg, 1 mmol), rt, 18 h, 98% conversion, 90% ee; 40 °C, 3 h, >99% conversion, 97% isolated yield (148 mg), 85%

ee. GC (Chirasil Dex CB): carrier gas: helium, 30 psi; injection temperature: 250 °C; column temperature: 120 °C; 10.13 min (*R*); 11.55 min (*S*). ¹H NMR (CDCl₃/TMS): δ 1.48 (d, *J* = 6 Hz, 3 H), 2.06 (bs, 1 H), 3.81 (s, 3 H), 4.86 (q, *J* = 6 Hz, 1 H), 6.81 (m, 2 H), 6.94 (m, 1 H), 7.26 (m, 1 H); ¹³C NMR (CDCl₃/TMS): δ 25.6, 55.6, 70.7, 111.3, 113.3, 118.1, 129.9, 148.0, 160.2.

(*R*)-1-(4'-Methylphenyl)ethanol^{2,7}: [RuCl₂(*p*-cymene)]₂ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 4-methylacetophenone (136 mg, 1 mmol), rt, 18 h, >99% conversion, 86% ee; 40 °C, 3 h, 100% conversion, 99% isolated yield (135 mg), 85% ee. GC (Chirasil Dex CB): carrier gas: helium, 80 psi; injection temperature: 250 °C; column temperature: 130 °C; 5.47 min (*R*); 6.07 min (*S*). ¹H NMR (CDCl₃/TMS): δ 1.47 (d, *J* = 6 Hz, 3 H), 1.91 (bs, 1 H), 2.35 (s, 3 H), 4.85 (q, *J* = 6 Hz, 1 H), 7.16 (m, 2 H), 7.26 (m, 2 H); ¹³C NMR (CDCl₃/TMS): δ 21.5, 25.5, 70.7, 125.8, 129.6, 137.6, 143.3.

(*R*)-1-(1'-Naphthyl)ethanol^{3,5}: [RuCl₂(*p*-cymene)]₂ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 1-acetonaphthone (172 mg, 1 mmol), rt, 36 h, 85% conversion, 88% ee; 40 °C, 7 h, 99% conversion, 91% isolated yield (157 mg), 83% ee. GC (Chirasil Dex CB): carrier gas: helium, 30 psi; injection temperature: 250 °C; column temperature: 150 °C; 12.86 min (*R*); 13.75 min (*S*). ¹H NMR (CDCl₃/TMS): δ 1.64 (d, *J* = 6 Hz, 3 H), 1.95 (bs, 1 H), 5.64 (q, *J* = 6 Hz, 1 H), 7.43–8.10 (m, 7 H); ¹³C NMR (CDCl₃/TMS): δ 25.50, 70.56, 123.9, 124.1, 126.5, 126.8, 128.2, 128.9, 132.6, 134.0, 134.4, 142.8.

(*R*)-1-(2'-Naphthyl)ethanol^{4,5}: [RuCl₂(*p*-cymene)]₂ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 2-acetonaphthone (172 mg, 1 mmol), rt, 36 h, >99% conversion, 94% ee; 40 °C, 8 h, 88% conversion, 87% isolated yield (150 mg), 92% ee. GC (Chirasil Dex CB): carrier gas: helium, 30 psi; injection temperature: 250 °C; column temperature: 135 °C; 13.23 min (*R*); 14.93 min (*S*). ¹H NMR (CDCl₃/TMS): δ 1.59 (d, *J* = 6 Hz, 3 H), 1.98 (bs, 1 H), 5.07 (q, *J* = 6 Hz, 1 H), 7.25 – 7.52 (m, 7 H); ¹³C NMR (CDCl₃/TMS): δ 25.6, 71.0, 124.2, 126.2, 126.6, 128.1, 128.4, 128.7, 133.3, 133.7, 143.6.

(*R*)-1-(Furan-2-yl)ethanol^{2a,5}: [RuCl₂(*p*-cymene)]₂ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 2-acetylfuran (112 mg, 1 mmol), rt, 18 h, 98% conversion, 91% ee; 40 °C, 2.5 h, 99% conversion, 87% isolated yield (98 mg), 87% ee. GC (Chirasil Dex CB): carrier gas: helium, 30 psi; injection temperature: 250 °C; column temperature: 65 °C; 11.16 min (*R*); 11.95 min (*S*). ¹H NMR (CDCl₃/TMS): δ 1.53 (d, *J* = 8 Hz, 3 H), 2.25 (bs, 1 H), 4.87 (q, *J* = 6.5 Hz, 1 H), 6.22 (d, *J* = 3.2 Hz, 1 H), 6.32 (dd, *J* = 3.2 Hz, 1.8 Hz, 1 H), 7.37 (d, *J* = 1.8 Hz, 1 H); ¹³C NMR (CDCl₃/TMS): δ 21.7, 64.0, 105.5, 110.5, 142.3, 158.0.

(*R*)-1-Indanol^{2b,5}: [RuCl₂(*p*-cymene)]₂ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 1-indanone (134 mg, 1 mmol), rt, 18 h, >99% conversion, 93% ee; 40 °C, 3 h, 100% conversion, 97% isolated yield (131 mg), 92% ee. GC (Chirasil Dex CB): carrier gas: helium, 80 psi; injection temperature: 250 °C; column temperature: 130 °C; 11.44

min (S); 11.61 min (R). ^1H NMR (CDCl_3/TMS): δ 1.87 – 1.96 (m, 1 H), 2.12 (bs, 1 H), 2.42 – 2.50 (m, 1 H), 2.76 – 2.84 (m, 1 H), 3.00 – 3.07 (m, 1 H), 5.21 (t, J = 6 Hz, 1 H), 7.20 – 7.27 (m, 2 H), 7.38 – 7.40 (m, 2 H); ^{13}C NMR (CDCl_3/TMS): δ 30.2, 36.3, 76.8, 124.6, 125.3, 127.1, 128.7, 143.7, 145.4.

(*R*)-1-Tetralol⁵: $[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol), 1-tetralone (148 mg, 1 mmol), rt, 18 h, >99% conversion, 94% ee; 40 °C, 3 h, 98% conversion, 97% isolated yield (145 mg), 92% ee. GC (Chirasil Dex CB); carrier gas: helium, 30 psi; injection temperature: 250 °C; column temperature: 120 °C; 13.31 min (S); 13.75 min (R). ^1H NMR (CDCl_3/TMS): δ 1.72 – 1.81 (m, 2 H), 1.85 – 2.00 (m, 3 H), 2.67 – 2.85 (m, 2 H), 4.76 (t, J = 4 Hz, 1 H), 7.07 – 7.42 (m, 4 H); ^{13}C NMR (CDCl_3/TMS): δ 19.2, 29.7, 32.7, 68.5, 126.6, 128.0, 129.1, 129.4, 137.5, 139.2.

(D) Catalyst recycle

$[\text{RuCl}_2(p\text{-cymene})]_2$ (3.1 mg, 0.005 mmol) and PTsDPEN¹ (50 mg, 0.012 mmol) were dissolved in 2 mL of water. After stirring at 40 °C for 1 h, HCO_2Na (680 mg, 10 mmol) and acetophenone (120 mg, 1.0 mmol) were added to the solution. Following degassing three times, the solution was allowed to react at 40 °C for a certain period of time. After cooling to room temperature, the organic phase were extracted with Et_2O (2 x 3 mL) by using a syringe. The conversion and enantioselectivity were determined by GC analysis (Chrompack Chirasil-Dex CB (25 m x 0.25 mm) column).

A new reduction started by introducing another portion of acetophenone (120 mg) alongside 1 equiv. HCOOH (0.1 mL, 10 M). Following degassing three times, the solution was allowed to react and the same workup procedure was used as above. Subsequent runs were performed in the same manner as the second. There was no significant decrease in the reaction rates in the first 11 runs; but the 14th run gave a 87% conversion in 48 h.

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Ketones	S/C	Tempt. (°C)	Time(h)	conv.(%)	e.e.(%)	config
100	22 40	8 1	>99 99	93 92	<i>R</i>
100	22 40	13 1.5	>99 100	91 85	<i>R</i>
100	22 40	13 1.5	>99 100	90 87	<i>R</i>
100	22 40	12 2	>99 100	85 82	<i>R</i>
100	22 40	18 3	98 >99	90 85	<i>R</i>
100	22 40	18 3	>99 100	86 85	<i>R</i>
100	22 40	36 7	85 99	88 83	<i>R</i>
100	22 40	36 8	>99 88	94 92	<i>R</i>
100	22 40	18 2.5	98 99	91 87	<i>R</i>
100	22 40	18 3	>99 100	93 92	<i>R</i>
100	22 40	18 3	>99 98	94 92	<i>R</i>

(*R*) – 1 - Phenylethanol

(*R*) – 1- (2'- Chlorophenyl)ethanol

(*R*) – 1 – (4' - Chlorophenyl)ethanol

(*R*) – 1 - (4' - Trifluoromethylphenyl)ethanol

(*R*) – 1- (3' – Methoxyphenyl)ethanol

(*R*)- 1 – (4' – Methylphenyl)ethanol

(*R*) – 1- (1' – Naphthyl)ethanol

(*R*) – 1 – (2' - Naphthyl)ethanol

(*R*) -1- (Furan-2-yl)ethanol

(*R*) - 1 - Indanol

(R) – 1- Tetralol