Supporting Information

A Practical and Highly Chemoselective Hydrogenation of Aldehydes with a Copper Catalyst

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General. All hydrogenation reactions were carried out using a 100-mL stainless steel autoclave equipped with a glass inner lining and a Teflon coated stirrer bar. Use of glass inner lining is recommended because trace amount of Cu metal might come out in infrequent cases. Ethanol (dehydrated) was purchased from Kanto Kagaku. [Cu(NO3)(PPh3)2] was synthesized according to the literature. [CuH(PPh3)]6 was purchased from Sigma-Aldrich Inc. Cu(NO3)2·3H2O and NaOH was purchased from Wako Pure Chemical Industries Inc. and Nacalai Tesque Inc., respectively. 1,4-Bis(diphenylphosphino)butane was purchased from Tokyo Kasei Kogyo Co., Ltd. 3,3-Diphenylprop-2-enal, (E)-2-methylpent-2-enal and cyclohexanecarbaldehyde were purchased from Sigma-Aldrich Inc. (E)-4-Prop-1-en-2-ylcyclohexene-1-carbaldehyde ((-)perilaldehyde), (E)-2-methyl-3-phenylprop-2-enal, (E)-2-benzylidenenheptanal, (E)-3-phenylprop-2-enal, (E)-3-(furan-2-yl)prop-2-enal, (E)-2-ethylhex-2-enal, benzaldehyde, 1,3-benzoxdioxide-5-carbaldehyde, thiophene-2-carbaldehyde, 5-methylfuran-2-carbaldehyde and 3-phenylpropenal were purchased from Takasago International Corporation. (E)-3-(furan-2-yl)prop-2-enal and 1,3-benzoxdioxide-5-carbaldehyde were used as it is. Other aldehydes were distilled prior to use. Authentic compounds for GC analysis were commercially available or ambiguously synthesized. Regiochemistry of substrates and product were established according to literature or NOE analysis. E/Z ratio was determined by GC analysis. GC analyses were carried out using GL Science GC353B equipped with BC-WAX (df = 0.25 µm, 0.25 mm i.d. x 25 m (GL Science); carrier gas, helium (80 kPa), injection temp. 220 ºC, detection temp. 250 ºC. column temp. initial 50 ºC (10 min), final 230 ºC (32 min), rate 10 ºC / min) (method A), HP-1 (df = 0.25 µm, 0.32 mm i.d. x 30 m (J&W Scientific)); carrier gas, helium (103 kPa), injection temp. 220 ºC, detection temp. 250 ºC. column temp. initial 50 ºC (10 min), final 230 ºC (32 min), rate 10 ºC / min) (method B) or HP-1 (df = 0.25 µm, 0.32 mm i.d. x 30 m (J&W Scientific)); carrier gas, helium (103 kPa), injection temp. 220 ºC, detection temp. 250 ºC. column temp. initial 50 ºC (10 min), final 230 ºC (14 min), rate 5 ºC / min) (method C). NMR Spectra were obtained on Varian Mercury plus 300 or Bruker DRX 500. IR Spectra were obtained on Avatar 360 FT-IR. MS spectra were obtained on Shimadzu LCMS-IT-TOF.

(E)-2-Methyl-3-phenylprop-2-en-1-ol (Scheme 2, n = 4). To a 100-mL stainless steel autoclave was placed [Cu(NO3)(PPh3)2] (5.9 mg, 0.009 mmol) and 1,4-Bis(diphenylphosphino)butane (DPPB) (3.8 mg, 0.009 mmol). The atmosphere was replaced with nitrogen gas, followed by addition of ethanol solution (0.03 M) of NaOH (6.0 mL, 0.18 mmol) and (E)-2-methyl-3-phenylprop-2-enal2 (1.32 g; 99% yield). Hydrogen gas was initially introduced into the autoclave at a pressure of 1.0 MPa before being reduced to 0.1 MPa by carefully releasing the stop valve. After this procedure was repeated three times, hydrogen was introduced at 5.0 MPa and the solution was stirred at 50 ºC for 16 h. Silica gel chromatography (diethyl ether / hexane = 1 / 1) after removal of the solvent afforded (E)-2-methyl-3-phenylprop-2-en-1-ol3 (E / Z = 99 / 1). (1.28 g; 96% yield). GC (method A): tR = 26.0 min ((Z)-2-methyl-3-phenylprop-2-en-1-ol), 26.7 min ((E)-2-methyl-3-phenylprop-2-en-1-ol), 28.6 min ((Z)-2-methyl-3-phenylprop-2-en-1-ol). General Procedure A: (E)-2-Methyl-3-phenylprop-2-en-1-ol (Table 1, entry 1). To a 100-mL stainless steel autoclave was placed [Cu(NO3)(PPh3)2] (11.7 mg, 0.018 mmol) and 1,4-Bis(diphenylphosphino)butane (DPPB) (7.7 mg, 0.018 mmol). The atmosphere was replaced with nitrogen gas, followed by addition of ethanol solution (0.03 M) of NaOH (6.0 mL, 0.18 mmol) and (E)-2-methyl-3-phenylprop-2-enal2 (1.26 mL, 9 mmol; E / Z = 99 / 1). Hydrogen gas was initially introduced into the autoclave at a pressure of 1.0 MPa before being reduced to 0.1 MPa by carefully releasing the stop valve. After this procedure was repeated three times, hydrogen was introduced at 5.0 MPa and the solution was stirred at 50 ºC for 16 h. Silica gel chromatography (diethyl ether / hexane = 1 / 1) after removal of the solvent afforded (E)-2-methyl-3-phenylprop-2-en-1-ol (E / Z = 99 / 1) (1.32 g; 99% yield).
(E)-2-Methyl-3-phenylprop-2-en-1-ol (Table 1, entry 2). According to the general procedure A, hydrogen was introduced at 1.0 MPa (in place of 5.0 MPa) to give (E)-2-methyl-3-phenylprop-2-en-1-ol (E / Z = 99 / 1) (1.27 g, 95% yield).

(E)-2-Methyl-3-phenylprop-2-en-1-ol (Table 1, entry 3). According to the general procedure A, Cu(NO₃)₂·3H₂O (4.3 mg, 0.018 mg) was used in place of [Cu(NO₃)(PPh₃)₂] to give (E)-2-methyl-3-phenylprop-2-en-1-ol (E / Z = 98 / 2) (1.22 g, 91% yield).

(E)-2-Benzylidenehexan-1-ol (Table 1, entry 4). According to the general procedure A, (E)-2-benzylidenehexan-1-ol (1.88 mL, 9 mmol; E / Z = 95 / 5) was used as substrate to give (E)-2-benzylidenehexan-1-ol (1.81 g, 98% yield; E / Z = 95 / 5). ¹H NMR (300 MHz, CDC₁₃): (E)-isomer: δ 7.40-7.15 (m, 5H), 6.53 (s, 1H), 4.43 (s, 2H), 2.35-2.20 (m, 4H), 1.60-1.40 (m, 4H), 1.40-1.20 (m, 4H), 0.88 (t, J = 6.6 Hz, 3H); (Z)-isomer: δ 7.40-7.15 (m, 5H), 6.46 (s, 1H), 4.29 (s, 2H), 2.35-2.25 (m, 2H), 1.65-1.50 (m, 2H), 1.50-1.20 (m, 6H), 0.95-0.85 (m 3H). Regiochemistry (E or Z) was established by NOE of each isomer. ¹³C NMR (75 MHz, CDC₁₃): (E)-isomer: δ 142.39, 137.55, 128.60, 128.15, 126.42, 125.28, 67.03, 32.00, 28.71, 28.05, 22.41, 13.99.; (Z)-isomer: δ 141.58, 137.30, 128.71, 128.21, 128.18, 126.62, 60.98, 35.47, 31.69, 27.98, 22.57, 14.07. IR (NaCl): 3318, 1657 cm⁻¹. MS (EI): m/z 204, 148, 133, 130, 129, 117, 115, 105, 91. GC (method A): ³R = 21.3 min ((E)-2-benzylidenehexan-1-ol), 21.6 min ((Z)-2-benzylidenehexan-1-ol), 21.8 min ((E)-2-benzylidenehexan-1-ol), 22.0 min ((Z)-2-benzylidenehexan-1-ol).

(E)-3-Phenyldieneprop-2-en-1-ol (Table 1, entry 5). According to the general procedure A, (E)-3-phenylprop-2-en-1-ol (1.13 mL, 9 mmol; E / Z = >99 / 1) was used as substrate to give (E)-3-phenylprop-2-en-1-ol (825 mg, 68% yield, E / Z = >99 / 1). GC (method A): ³R = 27.1 min ((E)-3-phenylprop-2-en-1-ol), 29.7 min ((E)-3-phenylprop-2-en-1-ol).

(E)-3-Diphenylprop-2-en-1-ol (Table 1, entry 6). According to the general procedure A, 3,3-Diphenylprop-2-en-1-ol (937 mg, 4.5 mmol) was used as substrate. As to other conditions, [Cu(NO₃)(PPh₃)₂] (5.9 mg, 0.009 mmol), 1,4-Bis(diphenylphosphino)butane (DPPB) (3.8 mg, 0.009 mmol), ethanol solution (0.03 M) of NaOH (3.0 mL, 0.09 mmol) was used. The reaction gave 3,3-diphenyl-2-propanol (909 mg, 96% yield). GC (method A): ³R = 41.4 min ((E)-3-diphenylprop-2-en-1-ol), 49.3 min ((Z)-3-diphenylprop-2-en-1-ol).

General procedure B: (E)-3-(furan-2-yl)prop-2-en-1-ol (Table 1, entry 7). To a 100-mL stainless steel autoclave was placed [Cu(NO₃)(PPh₃)₂] (11.7 mg, 0.018 mmol), 1,4-Bis(diphenylphosphino)butane (DPPB) (7.7 mg, 0.018 mmol) and (E)-3-(furan-2-yl)prop-2-en (1.24 g, 10.2 mmol, E / Z = >99 / 1). The atmosphere was replaced with nitrogen gas, followed by addition of ethanol solution (0.03 M) of NaOH (6.0 mL, 0.18 mmol). Hydrogen gas was initially introduced into the autoclave at a pressure of 1.0 MPa before being reduced to 0.1 MPa by carefully releasing the stop valve. After this procedure was repeated three times, hydrogen was introduced at 5.0 MPa and the solution was stirred at 50 °C for 16 h. Silica gel chromatography (diethyl ether / hexane = 1 / 1) after removal of the solvent afforded (E)-3-(furan-2-yl)prop-2-en-1-ol (1.17 g, 92% yield, E / Z = >99 / 1). GC (Method A): ³R = 24.8 min ((E)-3-(furan-2-yl)prop-2-en-1-ol).

(E)-3-(Furan-2-yl)prop-2-en-1-ol (Table 1, entry 8). According to the general procedure B, [CuH(PPh₃)₉] (5.9 mg, 0.018 mmolCu) and PPh₃ (14.2 mg, 0.054 mmol) was used in place of [Cu(NO₃)(PPh₃)₂], and ethanol (6.0 mL) was used in place of ethanol solution (0.03 M) of NaOH, to give (E)-3-(furan-2-yl)prop-2-en-1-ol (1.21 g, 96% yield, E / Z = >99 / 1).

(E)-2-Methylpent-2-en-1-ol (Table 1, entry 9). According to the general procedure A, (E)-2-methylpent-2-en-1-ol (1.03 mL, 9 mmol, E / Z = 99 / 1) was used as substrate to give (E)-2-methylpent-2-en-1-ol (653 mg, 72% yield, E / Z = 96 / 4) containing ca.3% of 2-methylpent-1-ol. GC (Method A): ³R = 11.4 min (2-methylpent-2-en-1-ol), 16.1 min (2-methylpent-1-en-1-ol), 17.8 min ((Z)-2-methylpent-2-en-1-ol), 18.1 min ((E)-2-methylpent-2-en-1-ol).

(E)-2-Ethylhex-2-en-1-ol (Table 1, entry 10). According to the general procedure A, (E)-2-ethylhex-2-en-1-ol (1.34 mL, 9 mmol, E / Z = 94 / 6) was used as substrate to give (E)-2-ethylhex-2-en-1-ol which contained ca. 6% of 2-ethylhexan-1-ol (1.00 g, 87% yield, E / Z = 91 / 9). GC (method A): ³R = 15.9 min (2-ethylhex-2-en-1-ol), 19.7 min (2-ethylhexan-1-ol), 20.3 min ((Z)-2-ethylhex-2-en-1-ol), 20.7 min ((E)-2-ethylhex-2-en-1-ol).

(E)-2-Ethyl-4(2,2,3-trimethylcyclopent-3-enyl)-but-2-en-1-ol (Table 1, entry 11). According to the general procedure A, (E)-2-ethyl-4(2,2,3-trimethylcyclopent-3-enyl)-but-2-en-1-ol (2.02 mL, 9 mmol, E / Z = 93 / 7, 94% purity) was used as substrate to give (E)-2-ethyl-4(2,2,3-trimethylcyclopent-3-enyl)-but-2-en-1-ol (E / Z = 92 / 8) which contained ca.3% of 2-ethyl-4(2,2,3-trimethylcyclopent-3-enyl)butan-1-ol (1.76 g, 94% yield, 93% purity). GC (method A): ³R = 25.6 min (2-ethyl-4(2,2,3-trimethylcyclopent-3-enyl)butan-1-ol), 27.6 min (2-ethyl-4(2,2,3-trimethylcyclopent-3-enyl)butan-1-ol), 27.9 min ((Z)-2-Ethyl-4(2,2,3-trimethylcyclopent-3-enyl)butan-1-ol), 28.2 min ((E)-2-Ethyl-4(2,2,3-trimethylcyclopent-3-enyl)butan-1-ol).

4-Prop-1-en-2-yl)cyclohexan-1-ylmethanol (Table 1, entry 12). According to General procedure A, (-)-perilaldehyde (1.40 mL, 9.0 mmol) was used as substrate to give 4-(Prop-1-en-2-yl)cyclohexan-1-ylmethanol containing ca.2% of 4-(Prop-1-en-2-yl)cyclohexylmethanol (1.26 g, 92% yield, 95% purity). GC (method A): ³R = 23.8 min ((-)perilaldehyde), 25.2 and 25.5 min (4-(Prop-1-en-2-yl)cyclohexylmethanol).
Benzylalcohol (Table 2, entry 1). According to General procedure A, benzaldehyde (914 µL, 9 mmol) was used as substrate to give benzylalcohol (890 mg, 91% yield). GC (method A): \( R = 20.2 \) min (benzaldehyde), 25.0 min (benzylalcohol).

(1,3-Benzodioxol-5-yl)methanol (Table 2, entry 2). According to General procedure B, 1,3-benzodioxole-5-carbaldehyde (1.35 g) was used as substrate to give 1,3-benzodioxol-5-methanol (1.34 g, 98% yield). GC (method A): \( R = 29.2 \) min (1,3-benzodioxole-5-carbaldehyde), 33.1 min ((1,3-benzodioxol-5-yl)methanol).

(5-Methylfuran-2-yl)methanol (Table 2, entry 3). According to General procedure A, 5-methylfuran-2-carbaldehyde (895 µL, 9 mmol) was used as substrate to give (5-methylfuran-2-yl)methanol (876 mg, 87% yield). GC (method A): \( R = 21.0 \) min (5-methylfuran-2-carbaldehyde), 23.0 min ((5-methylfuran-2-yl)methanol).

Thiophen-2-ylmethanol (Table 2, entry 4). According to General procedure A, thiophene-2-carbaldehyde (841 µL, 9 mmol) was used as substrate to give thiophene-2-ylmethanol (990 mg, 96% yield). GC (method A): \( R = 22.8 \) min (thiophene-2-carbaldehyde), 25.8 min (thiophene-2-ylmethanol).

Pyridin-3-ylmethanol (Table 2, entry 5). According to General procedure A, pyridine-3-carbaldehyde (849 µL, 9 mmol) was used as substrate to give pyridin-3-ylmethanol (832 mg, 85% yield). GC (method A): \( R = 21.0 \) min (pyridine-3-carbaldehyde), 29.0 min (pyridin-3-ylmethanol).

Cyclohexylmethanol (Table 2, entry 6). According to General procedure A, cyclohexanecarbaldehyde (1.09 mL, 9 mmol) was used as substrate to give cyclohexylmethanol (930 mg, 90% yield). GC (method A): \( R = 14.9 \) min (cyclohexanecarbaldehyde), 20.9 min (cyclohexylmethanol).

2-Phenylpropan-1-ol (Table 2, entry 7). According to General procedure A, 2-phenylpropanal (1.21 mL, 9 mmol) was used as substrate to give 2-phenylpropan-1-ol (932 mg, 76% yield). GC (method A): \( R = 22.0 \) min (2-phenylpropanal), 25.7 min (2-phenylpropan-1-ol).

3-Phenylpropan-1-ol (Table 2, entry 8). According to General procedure A, 3-phenylpropanal (1.18 mL, 9 mmol) was used as substrate to give 3-phenylpropan-1-ol (120 mg, 10% yield, 96% purity) and 2-benzyl-5-phenylpent-2-en-1-ol (919 mg, 63%, E/Z mixture (92/8)). GC (method A): \( R = 24.0 \) min (3-phenylpropanal), 27.0 min (3-phenylpropan-1-ol). 2-Benzyl-5-phenylpent-2-en-1-ol: \( ^{1}H \) NMR (CDCl$_3$) \( \delta \) 7.30-7.00 (m, 10H), 5.58 (t, \( J = 7.2 \) Hz, 1H), 3.88 (s, 2H), 3.35 (s, 2H), 2.66 (t, \( J = 7.2 \) Hz, 2H), 2.44 (tt, \( J = 7.2, 7.2 \) Hz, 2H). \( ^{13}C \) NMR (CDCl$_3$) \( \delta \) 141.74, 139.48, 138.17, 128.48, 128.47, 128.45, 128.37, 127.20, 126.05, 125.93, 66.71, 35.88, 33.78, 29.82. IR (KBr): 3383, 1665 cm$^{-1}$. MS (EI): 324, 306, 235, 221, 197, 194, 183, 180, 179, 165, 155, 152, 151, 138, 124, 123, 109, 97, 95, 83, 81, 71, 57.

Undecanol (Table 2, entry 9). According to General procedure A, undecanal (1.86 mL, 9 mmol) was used as substrate to give undecan-1-ol (145 mg, 9% yield, 95% purity) and 2-nonyltridec-2-en-1-ol (919 mg, 63%, E/Z mixture (92/8)). GC (method A): \( R = 21.4 \) min (undecanal), 24.6 min (undecan-1-ol), 41.3 min (2-nonyltridec-2-en-1-ol). 2-nonyltridec-2-en-1-ol: \( ^{1}H \) NMR (CDCl$_3$) \( \delta \) 5.40 (t, \( J = 7.5 \) Hz, 1H), 4.03 (s, 2H), 2.10-1.95 (m, 4H), 1.70-1.60 (m, 30H), 1.50-1.40 (m, 6H), selected peaks for minor isomer: 5.30 (t, \( J = 7.2 \) Hz, 1H), 4.13 (s, 2H). \( ^{13}C \) NMR (CDCl$_3$), some peaks overlapped: 139.12, 127.15, 31.91, 31.90, 29.80, 29.78, 29.64, 29.59, 29.56, 29.55, 29.41, 29.35, 29.33, 28.65, 38.05, 27.47, 22.68, 14.10. (NaCl): 3310, 1667 cm$^{-1}$. MS (EI): 324, 306, 235, 221, 197, 194, 183, 180, 179, 165, 155, 152, 151, 138, 124, 123, 109, 97, 95, 83, 81, 71, 57.

(4) (E)- and (Z)-isomer was identified by NOE analysis of each isomers and E / Z ratio was determined by GC (method B): \( R = 21.3 \) min (E), 21.6 min (Z).
(7) (E) and (Z)-isomers: Chan, K. C.; Jewell, R. A.; Nutting, W. H.; Rapoport, H. J. Org. Chem. 1968, 33, 3382. E / Z ratio was determined by \( ^{1}H \) NMR.
(8) The substrate contained ca. 3% of 2-ethylheptan-1-ol; (E)- and (Z)-isomer was identified by NOE analysis of each isomers. E / Z ratio was determined by GC (method B): \( R = 5.5 \) min (E), 5.9 min (Z).
(10) E / Z ratio was determined by GC (method C): \( R = 26.3 \) min (E), 26.5 min (Z).