Electronic Supplementary Material (ESI) for Green Chemistry.

Noyori-Ikariya Catalyst Supported on Tetraarylphosphonium Salt for Asymmetric Transfer Hydrogenation in Water

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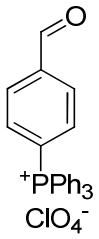
Supporting Information

1. General information

Unless otherwise specified, the chemicals were obtained commercially and used without further purification. $[RuCl_2(p\text{-cymene})]_2$ and ketones were obtained from Sigma-Aldrich and TsDPEN was prepared according to the literature.[1, 2] When indicated, the solvents were degassed using argon. The ^1H NMR and ^{13}C NMR spectra were acquired in $CDCl_3$ as solvent on a Bruker AV 300 or Bruker AV 400 spectrometer. The chemical shifts (δ) are expressed in ppm (parts per million) relative to TMS. Spin-spin coupling constants (*J*) were measured directly from the spectra and were given in Hz. Exact mass spectra (HR-MS) were performed by the Centre régional de spectroscopie de masse de l'Université de Montréal. Optical rotations were measured on Perkin-Elmer 341 polarimeter. Enantiomeric excesses were determined by SFC performed at Laboratoire d'Analyse et de Séparation Chirale par SFC de l'Université de Montréal and conversions were determined by NMR.

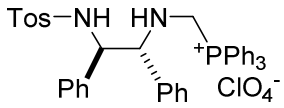
2. General procedure for preparation of TAP-TsDPEN

Synthesis of (4-(formyl)phenyl)triphenylphosphonium perchlorate



4-Bromobenzaldehyde (1.5g, 8.107 mmol), PPh_3 (2.34 g, 8.918 mmol) and $NiBr_2$ (0.88 mg, 0.4054 mmol) were weighted in a microwave tube, which was sealed and purged with argon. Then, ethyleneglycol (2.7 mL) was added *via* a syringe under Ar. The reaction was heated at 180°C and stirred for 5h. After this period, the reaction mix was left to cool to RT. Then, H_2O (30 mL), CH_2Cl_2 (30 mL) and $LiClO_4$ (1.95 g, 12.16 mmol) were added. The mixture was vigorously stirred for 2h. The two resulting phases were separated and the organic layer was washed with H_2O (2x15 mL) and $NaHCO_3$ sat. (15 mL). HCl (12 N, 10 mL) and ACN (4 mL) were sequentially added to the organic phase, which was stirred vigorously until complete deprotection of aldehyde (followed by ESI). The mixture was diluted with CH_2Cl_2 (120 mL) and washed with H_2O (2x30 mL), $NaHCO_3$ (30 mL) and brine (30 mL). The organic layer was dried over $MgSO_4$ and concentrated under vacuum. The resulting residue was dissolved in a minimum of CH_2Cl_2 and Et_2O (80 mL) was added under strong stirring. The resulting precipitate was filtered, washed with Et_2O (2x15 mL), dried under vacuum to afford the desired phosphonium salt as an off-white solid (2,839 g, 75% yield). mp: 200-205°C. ^1H NMR (300 MHz, $CDCl_3$) δ (ppm) 10.17 (s, 1H), 8.26 (dd, *J* = 8.5, 3.1 Hz, 2H), 7.95-7.85 (m, 5H), 7.83-7.74 (m, 6H), 7.72-7.61 (m, 6H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 191.1, 140.7, 140.6, 136.0, 135.9, 135.5, 135.4, 131.1, 131.0, 130.9, 130.8, 124.2, 123.1, 117.4, 116.2. HRMS(ESI) for $C_{25}H_{20}OP$ $[M]^+$, m/z calc.: 367.1246, found: 367.1258

Synthesis of TAP-TsDPEN



To a suspension of powdered molecular sieves (4 Å) in dry methanol (7 mL) was added (4-(formyl)phenyl)triphenylphosphonium perchlorate (300 mg, 0.6426 mmol), (1*R*,2*R*)-(-)-*N*-*p*-tosyl-1,2-diphenylethylenediamine (259 mg, 0,7069 mmol) and glacial acetic acid (4 drops). The reaction mixture was stirred overnight at RT. After this period, sodium borohydride (24.31 mg, 0.6426 mmol) was added and the reaction was left for 2h at RT. Then, CH_2Cl_2 (50 mL) was added, the molecular sieves were removed by filtration. The resulting solution was washed with saturated $NaHCO_3$ (2x20 mL), brine (2x20 mL), dried over $MgSO_4$, filtered and concentrated. The resulting residue was dissolved in a minimum amount of CH_2Cl_2 (2 mL) and Et_2O (20 mL) was added to induce the precipitation. The resulting off-white solid was filtered on celite pad and the pad was then washed with CH_2Cl_2 (3 x 15 mL). The filtrate solution was concentrated and dried under high vacuum to afford 420 mg of an off-white solid (80% yield). mp: 160-165°C. ^1H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.93-7.83 (m, 3H), 7.81-7.72 (m, 6H), 7.71-7.59 (m, 8H), 7.58-7.48 (m, 2H), 7.36 (d, *J* = 8.2 Hz, 2H), 7.13-7.07 (m, 3H), 7.06-7.00 (m, 2H), 6.98-6.86 (m, 5H), 6.84-6.77 (m, 2H), 4.35 (d, *J* = 8.9 Hz, 1H), 3.90 (d, *J* = 8.9 Hz, 1H), 3.82-3.65 (m, 2H), 2.48 (s br, 1H), 2.26 (s, 3H), 2.00 (s, 1H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 149.6, 149.6, 142.7, 139.1, 137.8, 137.2, 135.7, 135.7, 134.8, 134.7, 134.6, 134.5, 130.9, 130.7, 130.6, 130.4, 129.2, 128.4, 128.2, 127.9, 127.8,

127.6, 127.2, 127.1, 118.6, 117.4, 115.6, 114.4, 67.4, 64.1, 50.7, 21.5. HRMS(ESI) for $C_{46}H_{43}N_2O_2PS$ $[M]^+$, m/z calc.: 717.2699, found: 717.2706.

3. Reduction of Acetophenone with TAP-Ru-TsDPEN using different solvent and hydrogen sources

Catalysis performed in neat FA/TEA (5/2 molar ratio)

$RuCl_2$(*p*-cymene)]$_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube. HCOOH (202 µL, 5.347 mmol), Et_3N (298 µL, 2,139 mmol) and acetophenone (58.4 µL, 0.5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 40°C for 16h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis. No reaction proceeded.

Catalysis performed in CH_2Cl_2 using FA/TEA (5/2 molar ratio)

[$RuCl_2$(*p*-cymene)]$_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed CH_2Cl_2 (250 µL) was added. After stirring at 40°C for 1 h, HCOOH (101 µL, 0.267 mmol), Et_3N (149 µL, 1.069 mmol) and acetophenone (58.4 µL, 0.5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 35°C for 16h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis (24% conversion and 87.1% *ee*).

Catalysis performed in H_2O using HCOONa (5M)

[$RuCl_2$(*p*-cymene)]$_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed water (250 µL) was added. After stirring at 40°C for 1 h, HCOONa (187.9 mg, 2.79 mmol, 5M) and acetophenone (58.4 uL, 0.5 mmol) were added to the solution. Following degassing three times, the mixture was allowed to react at 40°C for 16h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis (>99% conversion and 93.8% *ee*).

Catalysis performed in neat FA/TEA (1.2/1 molar ratio)

[$RuCl_2$(*p*-cymene)]$_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube. HCOOH (124 µL, 3.287 mmol), Et_3N (376 µL, 2,705 mmol) and acetophenone (58.4 µL, 0.5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 40°C for 24h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis (83% conversion and 94.4% *ee*).

Catalysis performed in H_2O using FA/TEA (1.2/1 molar ratio) : **Scope procedure**

[$RuCl_2$(*p*-cymene)]$_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed water (250 µL) was added. After stirring at 40°C for 1 h, HCOOH (62 µL, 1.648 mmol), Et_3N (187 µL, 1.348 mmol) and acetophenone (58.4 µL, 0.5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 40°C for 16h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column eluting with Et_2O before being subjected to NMR and SFC analysis (>99% conversion and 95.7% *ee*).

4. Reduction of Acetophenone with TAP-Ru-TsDPEN using different HCOOH/Et_3N molar ratios (Fig. 1)

[$RuCl_2$(*p*-cymene)]$_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed water (250 µL) was added. After stirring at 40°C for 1 h, HCOOH and Et_3N in different molar ratio were added. Finally, acetophenone (0.5 mmol) was added and to induce the reaction, which was stirred for 16h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis.

Table 1. Different mixtures of HCOOH/Et_3N

HCOOH/Et_3N molar ratio	n HCOOH (mmol)	V HCOOH (µL)	n Et_3N (mmol)	V Et_3N (µL)
0.25	0.42	16	1.68	234
0.5	0.79	30	1.58	220
0.75	1.11	43	1.48	207
1	1.42	53	1.42	197
1.25	1.68	63	1.34	187
1.5	1.95	72	1.29	178
2	2.36	89	1.16	161
2.5	2.70	102	1.08	148

5. Reduction of Acetophenone with TAP-Ru-TsDPEN using different conditions

Conversion and ee vs. time (Fig. 2)

$[RuCl_2(p\text{-cymene})]_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed water (250 µL) was added. After stirring at 40°C for 1h, HCOOH (62 µL, 1.648 mmol), Et_3N (187 µL, 1.348 mmol) and acetophenone (58.4 µL, 0.5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 40°C for different period of time. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis.

Reaction performed at 60°C

$[RuCl_2(p\text{-cymene})]_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed water (250 µL) was added. After stirring at 40°C for 1h, HCOOH (62 µL, 1.648 mmol), Et_3N (187 µL, 1.348 mmol) and acetophenone (58.4 µL, 0.5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 60°C for 3h. After cooling to RT, the organic phase was extracted with Et_2O (3x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis (>99% conversion and 94.3% *ee*).

Reaction performed with S/C of 1000 at 60°C

$[RuCl_2(p\text{-cymene})]_2$ (1.55 mg, 0.00241 mmol) and TAP-TsDPEN (4.9 mg, 0.06 mmol) were weighted in a MW tube and degassed water (250 µL) was added. After stirring at 40°C for 1h, HCOOH (125 µL, 3.313 mmol), Et_3N (375 µL, 2.698 mmol) and acetophenone (584.4 µL, 5 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 60°C for 48h. After cooling to RT, the organic phase was extracted with Et_2O (6x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis (55% conversion and 93.3% *ee*).

6. Catalyst recycle

Reaction performed keeping the catalyst in the reaction mixture

$[RuCl_2(p\text{-cymene})]_2$ (3.096 mg, 0.004819 mmol) and TAP-TsDPEN (9.8 mg, 0.012 mmol) were weighted in a MW tube and degassed water (500 µL) was added. After stirring at 40°C for 1 h, HCOOH (124 µL, 3.296 mmol), Et_3N (375 µL, 2.697 mmol) and acetophenone (116.7 µL, 1 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 40°C for 7h. After cooling to RT, the organic phase was extracted with Et_2O (5x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis.

A new reduction started by introducing another portion of acetophenone (116.7 µL, 1 mmol) alongside HCOOH (124 µL, 3.296 mmol), Et_3N (375 µL, 2.697 mmol). Following degassing three times, the solution was allowed to react for a certain period of time (reaction followed by TLC) and the same workup procedure was used as above. Subsequent runs were performed in the same manner as the second.

Cycles	Time (h)	Conversion (%)	*ee* (%)
1	7	>99	94.7
2	7	>99	95.0
3	7	>99	95.2
4	16	>99	94.9
5	36	75	92.1

Reaction performed with the catalyst precipitated after the reaction

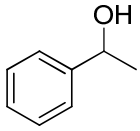
$[RuCl_2(p\text{-cymene})]_2$ (3.096 mg, 0.004819 mmol) and TAP-TsDPEN (9.8 mg, 0.012 mmol) were weighted in a MW tube and degassed water (500 µL) was added. After stirring at 40°C for 1 h, HCOOH (124 µL, 3.296 mmol), Et_3N (375 µL, 2.697 mmol) and acetophenone (116.7 µL, 1 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 60°C for 3h (reaction followed by TLC). After cooling to RT, the organic phase was extracted with Et_2O (5x2 mL), passed through a short silica gel column before being subjected to NMR and SFC analysis. Then, addition of an excess of Et_2O (6 mL) allowed to precipitate the catalyst, which was recovered by filtration through a canula. The resulting residue was dissolved in CH_2Cl_2, washed with water (2x2mL) and the organic solvent was evaporated. The catalyst was dried under vacuum and used in a second run of catalysis.

The catalyst was introduced in a MW tube and degassed water (500 µL) was added. Then, HCOOH (124 µL, 3.296 mmol), Et_3N (375 µL, 2.697 mmol) and acetophenone (116.7 µL, 1 mmol) were sequentially added. Following degassing three times, the mixture was allowed to react at 60° for 6h (reaction followed by TLC). The above workup procedure was used and the same reaction conditions were employed to perform the third catalysis.

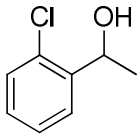
Cycles	Time (h)	Conversion (%)	*ee* (%)
1	3	>99	93.1
2	6	92	93.1
3	24	60	93.5

7. Asymmetric transfer hydrogenation of ketones

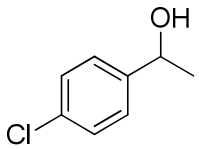
Asymmetric transfer hydrogenation of ketones with TAP-Ru-TsDPEN were analyzed by NMR and SFC. The stereochemistry of products was assigned by comparing optical rotation with previous literature results.



(*R*)-1-phenylethanol : ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.42-7.32 (m, 4H), 7.32-7.25 (m, 1H), 4.89 (q, *J* = 6.5 Hz, 1H), 2.02 (s, 1H), 1.50 (d, *J* = 6.5 Hz, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 145.9, 128.6, 127.5, 125.5, 70.5, 25.2. HRMS(ESI) for $C_8H_{10}O$ $[M+H]^+$, m/z calc.: 122.0731, found: 228.9777 (M + Ag^+). SFC analysis: Columns: OJH, Eluent: 5% IPA, Temp. 35°C, Pressure: 150 bar, (*S*)-1-phenylethanol (2.956 min), (*R*)-1-phenylethanol (3.248 min). $[\alpha]_D^{23}$ + 46.7° (*c* 1.00 in $CHCl_3$), 95.7% *ee* (*R*). lit.[3] $[\alpha]_D^{20}$ + 42.9° (*c* 1.04 in $CHCl_3$), 96% *ee* (*R*).

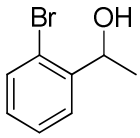


(*R*)-1-(2-chlorophenyl)ethanol : ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.53-7.50 (m, 1H), 7.26-7.09 (m, 3H), 5.22 (q, *J*= 6.5 Hz, 1H), 1.99 (s, 1H), 1.42 (d, *J*= 6.5 Hz 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 143.0, 131.6, 129.4, 128.4, 127.2, 126.4, 66.9, 23.5. HRMS(ESI) for C_8H_9ClO $[M+H]^+$, m/z calc.: 156.0341, found: 174.0685 (M + NH_4^+). SFC analysis: Columns: OJH, Eluent: 5% IPA, Temp. 35°C, Pressure: 150 bar, (*S*)-1-(2-chlorophenyl)ethanol (2.743 min), (*R*)-1-(2-chlorophenyl)ethanol (2.948 min). $[\alpha]_D^{23}$ + 61.2° (*c* 1.00 in $CHCl_3$), 89.6% *ee* (*R*). lit.[4] $[\alpha]_D^{20}$ + 61.4° (c 1.00 in $CHCl_3$), 94% *ee* (*R*).

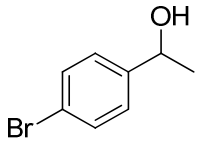


(*R*)-1-(4-chlorophenyl)ethanol : ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.32-7.29 (m, 4H), 4.87 (q, *J*= 6.4 Hz, 1H), 1.94 (s, 1H), 1.47 (d, *J*= 6.4 Hz 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 144.2, 133.1, 128.6, 126.8, 69.7, 25.3. HRMS(ESI) for C_8H_9ClO $[M+H]^+$, m/z calc.: 156.0341, found: 179.0235 (M + Na^+). SFC analysis: Columns: OJH, Eluent: 5% IPA, Temp.

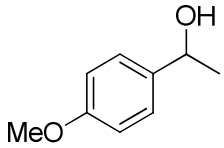
35°C, Pressure: 150 bar, (*S*)-1-(4-chlorophenyl)ethanol (3.697 min), (*R*)-1-(4-chlorophenyl)ethanol (3.899 min). $[\alpha]_D^{23}$ + 40.4° (*c* 1.00 in $CHCl_3$), 91.1% *ee* (*R*). lit.[5] $[\alpha]_D^{20}$ + 38.5° (*c* 1.06 in $CHCl_3$), 72% *ee* (*R*).



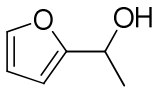
(*R*)-1-(2-bromophenyl)ethanol : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.59 (dd, *J* = 7.9, 1.7 Hz, 1H), 7.51 (dd, *J* = 7.9, 1.2 Hz, 1H), 7.34 (td, *J* = 7.5, 1.2 Hz, 1H), 7.12 (td, *J* = 7.6, 1.7 Hz, 1H), 5.24 (qd, *J* = 6.2, 2.4 Hz, 1H), 2.09 (d, *J* = 2.6 Hz, 1H), 1.48 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 144.6, 132.6, 128.7, 127.8, 126.6, 121.7, 69.1, 23.6. HRMS(ESI) for C_8H_9BrO $[M+H]^+$, m/z calc.: 199.9836, found: 222.9729 (M + Na^+). SFC analysis: Columns: ADH, Eluent: 2% IPA, Temp. 35°C, Pressure: 150 bar, (*R*)-2-bromo-phenylethanol (3.970 min), (*S*)-2-bromo-phenylethanol (4.917 min). $[\alpha]_D^{23}$ + 50.8° (*c* 1.00 in $CHCl_3$), 89.9% (*R*),. lit.[6] $[\alpha]_D^{20}$ + 50.8° (*c* 2.4 in CH_2Cl_2), 83% *ee* (*R*).



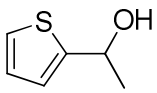
(*R*)-1-(4-bromophenyl)ethanol : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.48-7.46 (m, 2H), 7.27-7.23 (m, 2H), 4.85 (q, *J* = 6.4 Hz, 1H), 2.08 (s, 1H), 1.47 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 144.7, 131.5, 127.1, 121.1, 69.7, 25.2. HRMS(ESI) for C_8H_9BrO $[M+H]^+$, m/z calc.: 199.9836, found: 222.9729 (M + Na^+). SFC analysis: Columns: OJH, Eluent: 5% IPA, Temp. 35°C, Pressure: 150 bar, (*S*)-4-bromo-phenylethanol (4.937 min), (*R*)-4-bromo-phenylethanol (5.278 min). $[\alpha]_D^{23}$ + 32.5° (*c* 1.00 in $CHCl_3$), 91.7% *ee* (*R*). lit.[7] $[\alpha]_D^{25}$ + 30.6° (*c* 1.00 in $CHCl_3$), 78% *ee* (*R*).



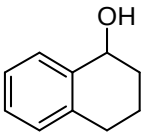
(*R*)-1-(4-methoxyphenyl)ethanol : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.23 (d, *J*=6.5, 2H), 6.82 (d, *J*=6.5, 2H), 4.81-4.77 (m, 1H), 3.74 (s, 3H), 1.66 (d, *J*= 3.3 ,1H), 1.41 (d, *J*= 3.3 Hz, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 159.0, 137.9, 126.6, 113.8, 70.0, 55.3, 25.0. HRMS(ESI) for $C_9H_{12}O_2$ $[M+H]^+$, m/z calc.: 152.0837, found: 175.0729 (M + Na^+). SFC analysis: Columns: RRWELK, Eluent: 5% IPA, Temp. 35°C, Pressure: 125 bar, (*R*)-1-(4-methoxyphenyl)ethanol (5.007 min), (*S*)-1-(4-methoxyphenyl)ethanol (5.357 min). $[\alpha]_D^{23}$ + 44.0° (*c* 1.00 in $CHCl_3$), 95.5% *ee* (*R*). lit.[8] $[\alpha]_D^{20}$ + 43.6° (*c* 1.00 in $CHCl_3$), 96% *ee* (*R*).



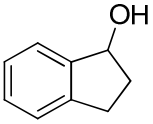
(*R*)-1-(Furan-2-yl)ethanol : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.37 (dd, *J* = 1.8, 0.8 Hz, 1H), 6.33 (dd, *J* = 3.3, 1.8 Hz, 1H), 6.23 (d, *J* = 3.2, 1H), 4.95-4.82 (m, 1H), 1.95 (d, *J* = 4.8, 1H), 1.55 (d, *J* = 6.5 Hz, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 157.7, 142.1, 110.3, 105.2, 63.8, 21.4. HRMS(ESI) for $C_6H_8O_2$ $[M+H]^+$, m/z calc.: 112.0524, found: 113.0597 (M + H^+). SFC analysis: Columns: ADH, Eluent: 2% IPA, Temp. 35°C, Pressure: 150 bar, (*S*)-1-(furan-2-yl)ethanol (3.755 min), (*R*)-1-(furan-2-yl)ethanol (3.985 min). $[\alpha]_D^{23}$+ 16.9° (*c* 1.00 in $CHCl_3$), 95.8% *ee* (*R*). lit.[4] $[\alpha]_D^{20}$ + 17.3° (*c* 0.100 in $CHCl_3$), 98% *ee* (*R*).



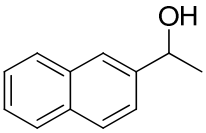
(*R*)-1-(thiophen-2-yl)ethanol : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.24 (dd, *J* = 4.5, 1.7 Hz, 1H), 7.00-6.94 (m, 2H), 5.18-5.07 (m, 1H), 2.14 (d, *J* = 4.6 Hz, 1H), 1.60 (d, *J* = 6.4, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 149.7, 126.6, 124.3, 123.1, 66.1, 25.2. HRMS(ESI) for C_6H_8OS $[M+H]^+$, m/z calc.: 128.0295, found: 151.0188 (M + Na^+). SFC analysis: Columns: OJH, Eluent: 5% IPA, Temp. 35°C, Pressure: 150 bar, (*S*)-1-(furan-2-yl)ethanol (3.575 min), (*R*)-1-(furan-2-yl)ethanol: (3.818 min). $[\alpha]_D^{23}$ + 25.8° (*c* 1.00 in $CHCl_3$), 97.2%, (*R*). lit.[9] $[\alpha]_D^{22}$ + 25.6° (*c* 0.50 in $CHCl_3$), 97% *ee* (*R*)



(*R*)-1-tetralol : : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.49-7.40 (m, 1H), 7.27-7.17 (m, 2H), 7.17-7.08 (m, 1H), 4.79 (m, 1H), 2.93-2.64 (m, 2H), 2.10-1.72 (m, 5H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 138.8, 137.1, 129.0, 128.6, 127.5, 126.1, 68.1, 32.3, 29.2, 18.8. HRMS(ESI) for $C_{10}H_{12}O$ $[M+H]^+$, m/z calc.: 148.0888, found: 171.0780 ($M + Na^+$). SFC analysis: Columns: OJH, Eluent: 5% IPA, Temp. 35°C, Pressure: 150 bar, 1-tetralone (2.055 min), (*S*)-1,2,3,4-tetrahydro-1-naphthol (4.053 min), (*R*)-1,2,3,4-tetrahydro-1-naphthol (4.275 min). $[\alpha]_D^{23}$ - 30.6° (*c* 1.00 in $CHCl_3$), 98.1% (*R*). lit.[10] $[\alpha]_D^{25}$ - 30.5° (*c* 1.00 in $CHCl_3$), 85% *ee* (*R*).



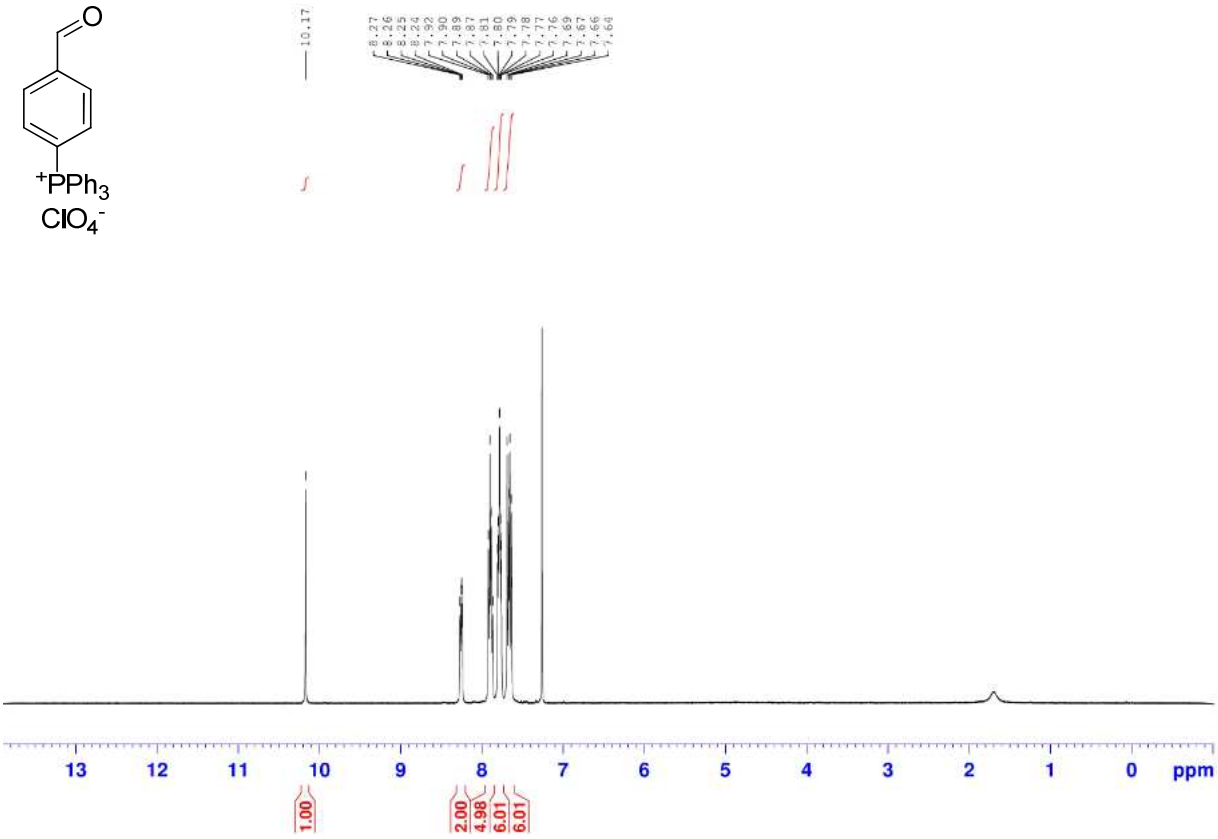
(*R*)-1-Indanol : ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.46-7.39 (m, 1H), 7.31-7.21 (m, 3H), 5.30-5.22 (m, 1H), 3.14-3.01 (m, 1H), 2.90-2.76 (m, 1H), 2.57-2.43 (m, 1H), 2.03-1.89 (m, 1H), 1.73 (s, 1H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 145.0, 143.3, 128.3, 126.7, 124.9, 124.2, 46.0, 35.9, 29.8, 11.3. HRMS(ESI) for $C_9H_{10}O$ $[M+H]^+$, m/z calc.: 134.0731, found: 157.0623 ($M + Na^+$). SFC analysis: Columns: OJH, Eluent: 2% IPA, Temp. 35°C, Pressure: 150 bar, (*R*)-1-indanol (5.546 min), (*S*)-1-indanol (5.963 min). $[\alpha]_D^{23}$ - 32.9° (*c* 1.00 in $CHCl_3$), 96.8%, (*R*). lit.[4] $[\alpha]_D^{20}$ - 32.1° (*c* 0.90 in $CHCl_3$), 98% *ee* (*R*).

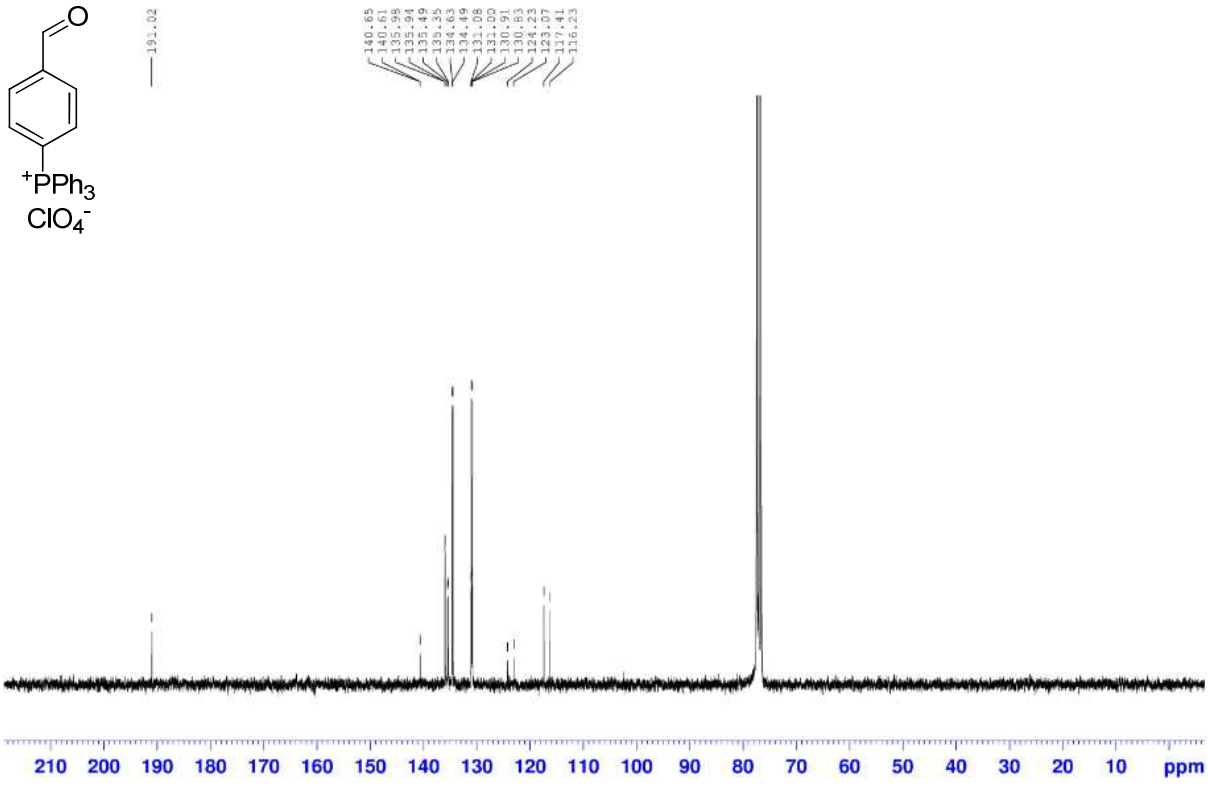


(*R*)-1-(2-naphtyl)ethanol: ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 7.86-7.83 (m, 4H), 7.54-7.47 (m, 3H), 5.08 (q, *J* = 6.4 Hz, 1H), 2.05 (s, 1H), 1.59 (d, *J* = 6.4 Hz, 3H). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm) 143.2, 133.3, 132.9, 128.3, 127.9, 127.6, 126.1, 125.7, 123.8, 123.8, 70.5, 25.1. HRMS(ESI) for $C_{12}H_{12}O$ $[M+H]^+$, m/z calc.: 172.0888, found: 195.0780 ($M + Na^+$). SFC analysis: Columns: OJH, Eluent: 8% IPA, Temp. 35°C, Pressure: 150 bar, (*S*)-1-(2-naphtyl)ethanol (8.770 min), (*R*)-1-(2-naphtyl)ethanol (11.990 min). $[\alpha]_D^{23}$ + 59.8° (*c* 1.00 in $CHCl_3$), 93.7% (*R*). lit.[8] $[\alpha]_D^{20}$ + 60.4° (*c* 1.00 in $CHCl_3$), 97% *ee* (*R*).

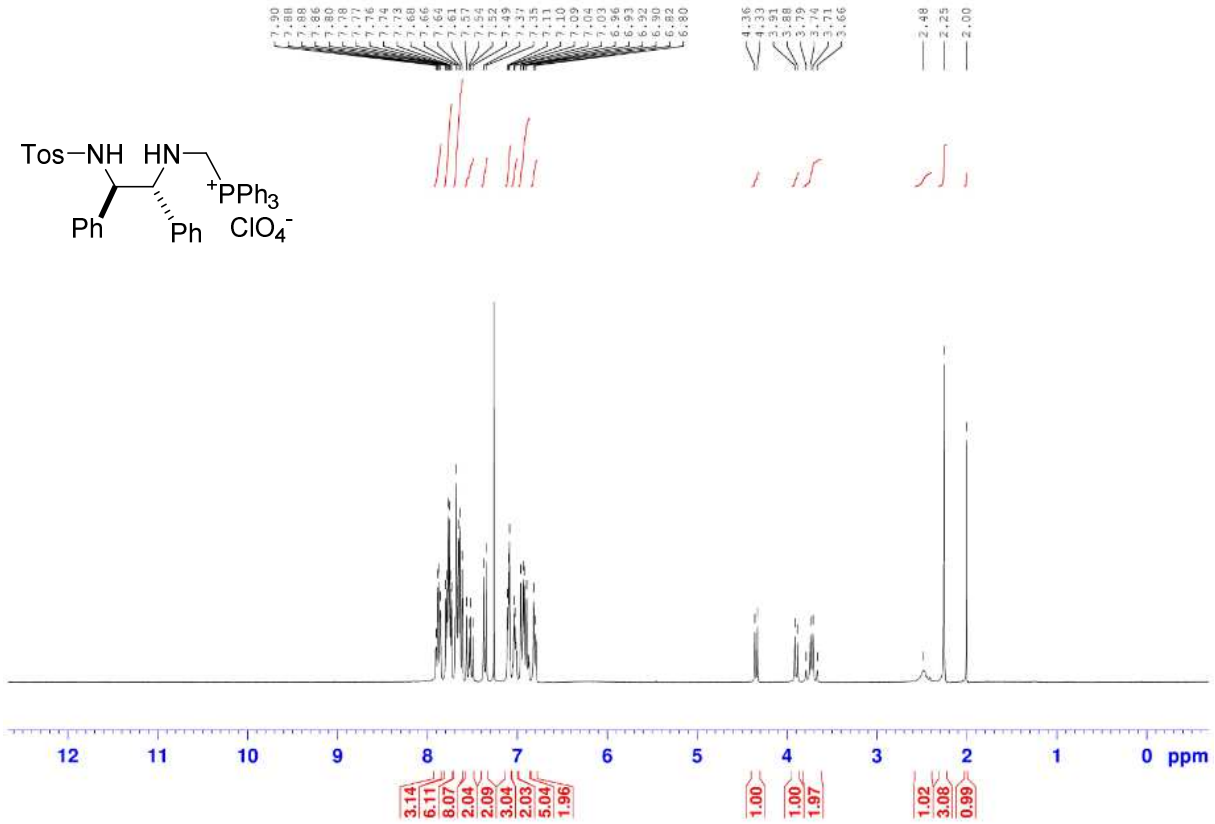
8. Analytic data for the synthesis of TAP-TsDPEN and the reduction of ketones

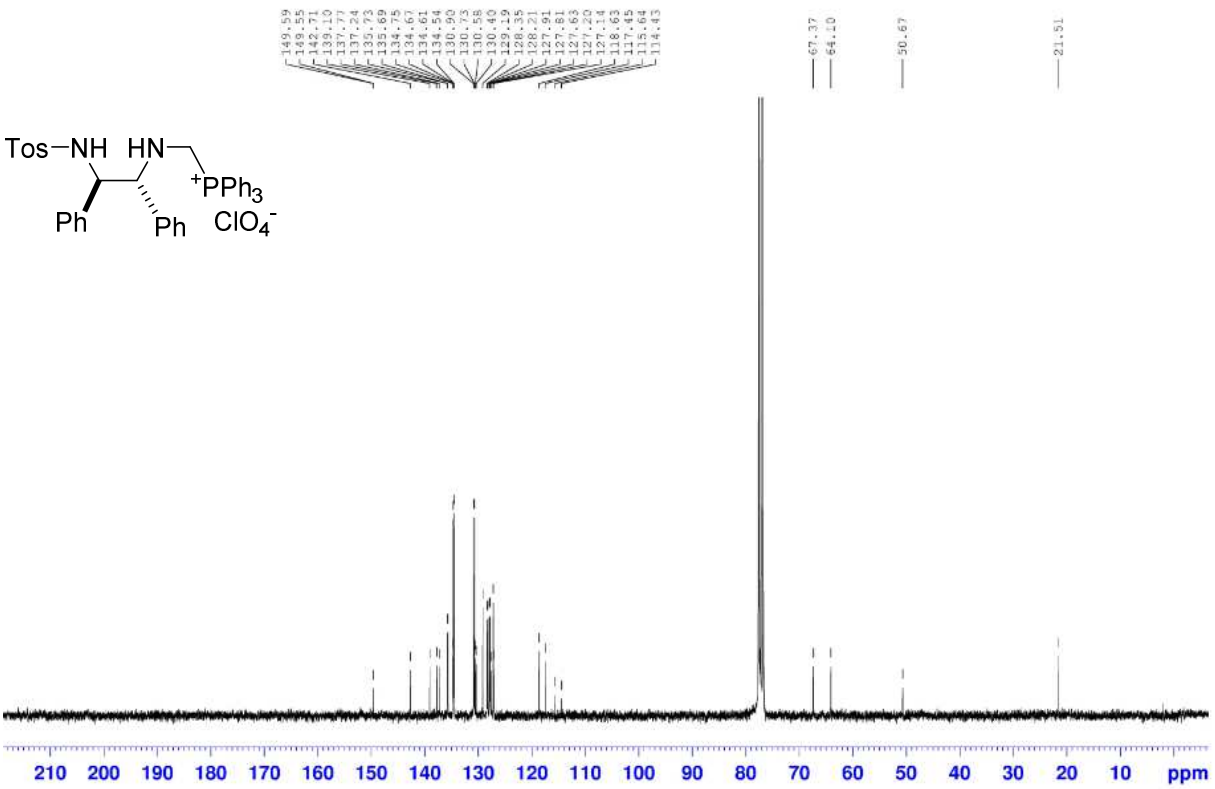
(4-(formyl)phenyl)triphenylphosphonium perchlorate





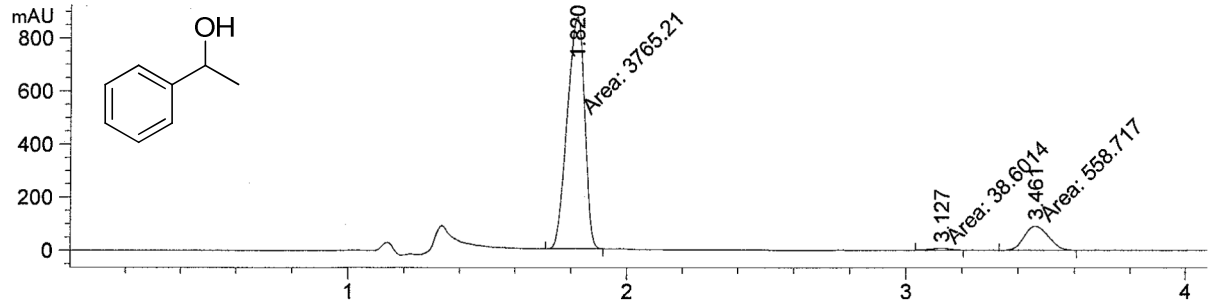
TAP-TsDPEN


Tos—NH HN
+PPh3
Ph
Ph
ClO4-
12 11 10 9 8 7 6 5 4 3 2 1 0 ppm

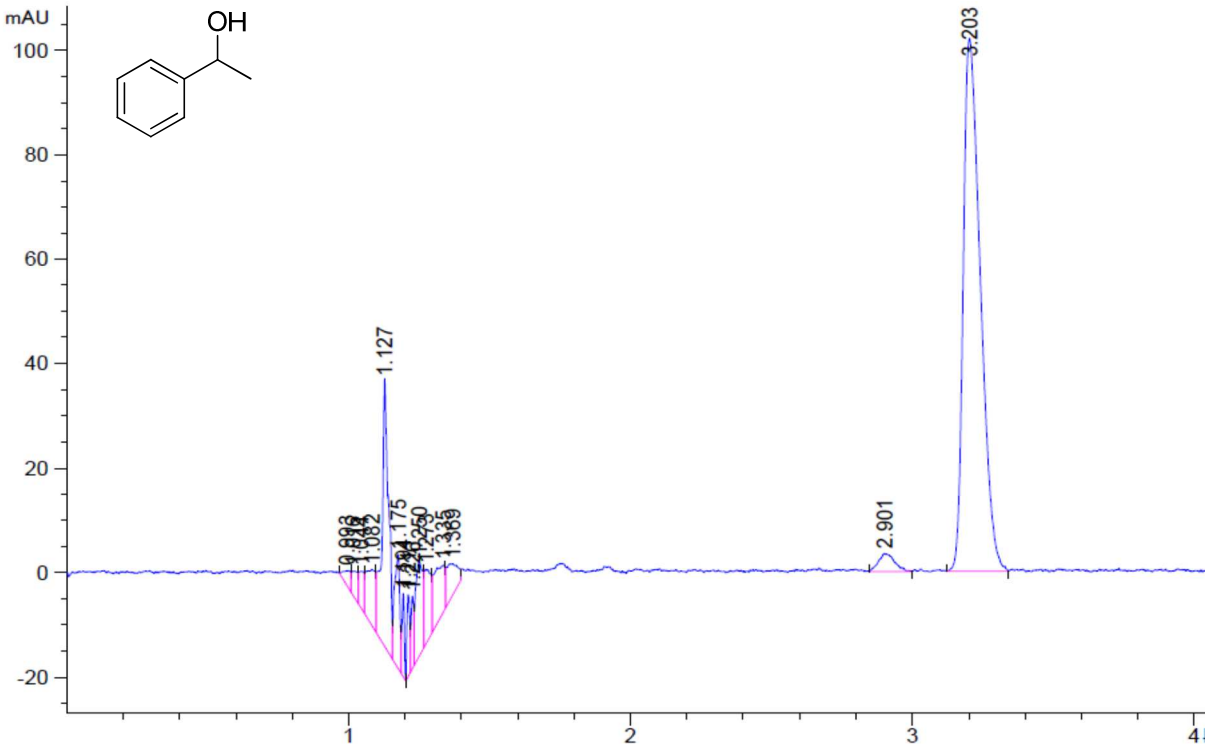

Tos—NH HN
+PPh3
Ph
Ph
ClO4-
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 ppm

Optimization of the reaction conditions

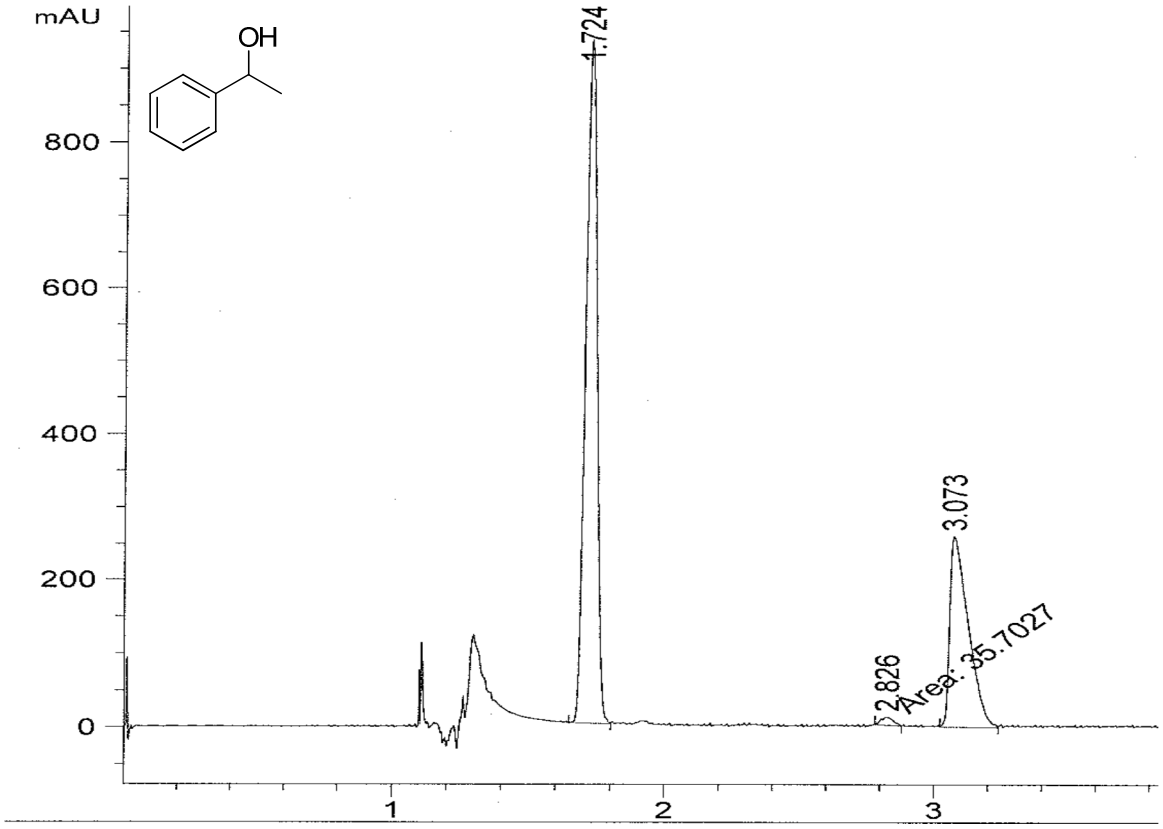
Reduction of Acetophenone in CH_2Cl_2 using FA/TEA (5/2 molar ratio)



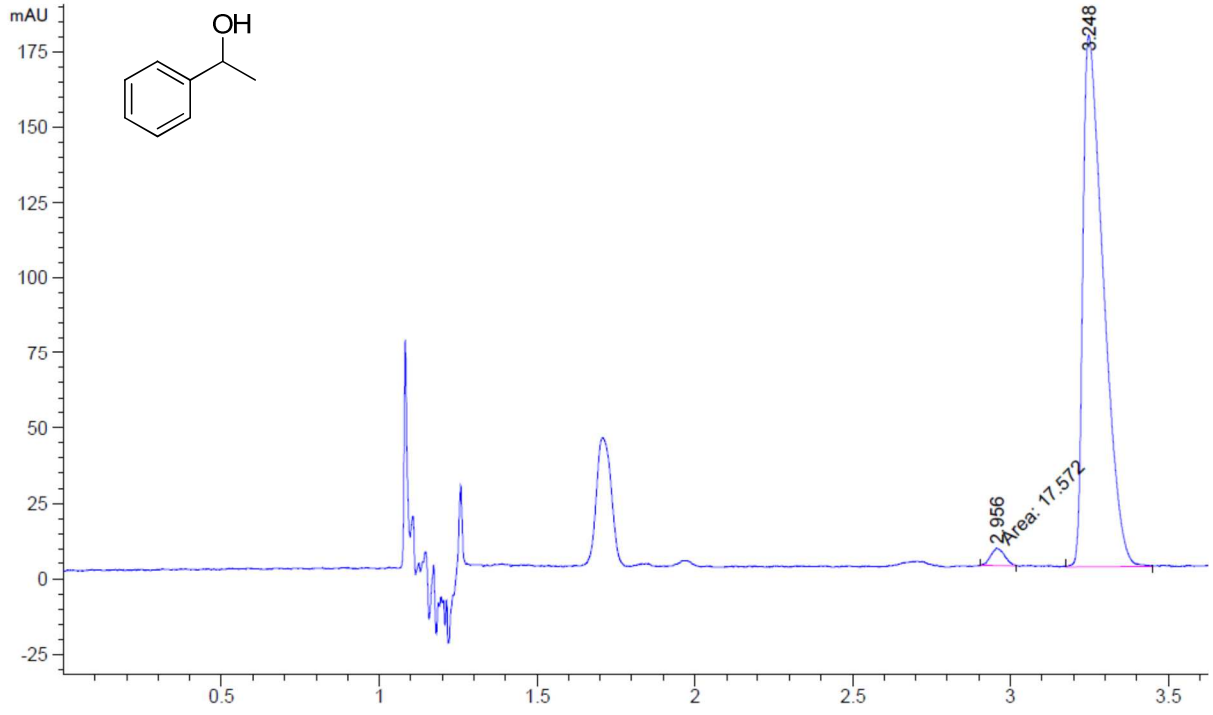
Reduction of Acetophenone in H_2O using HCOONa (5M)



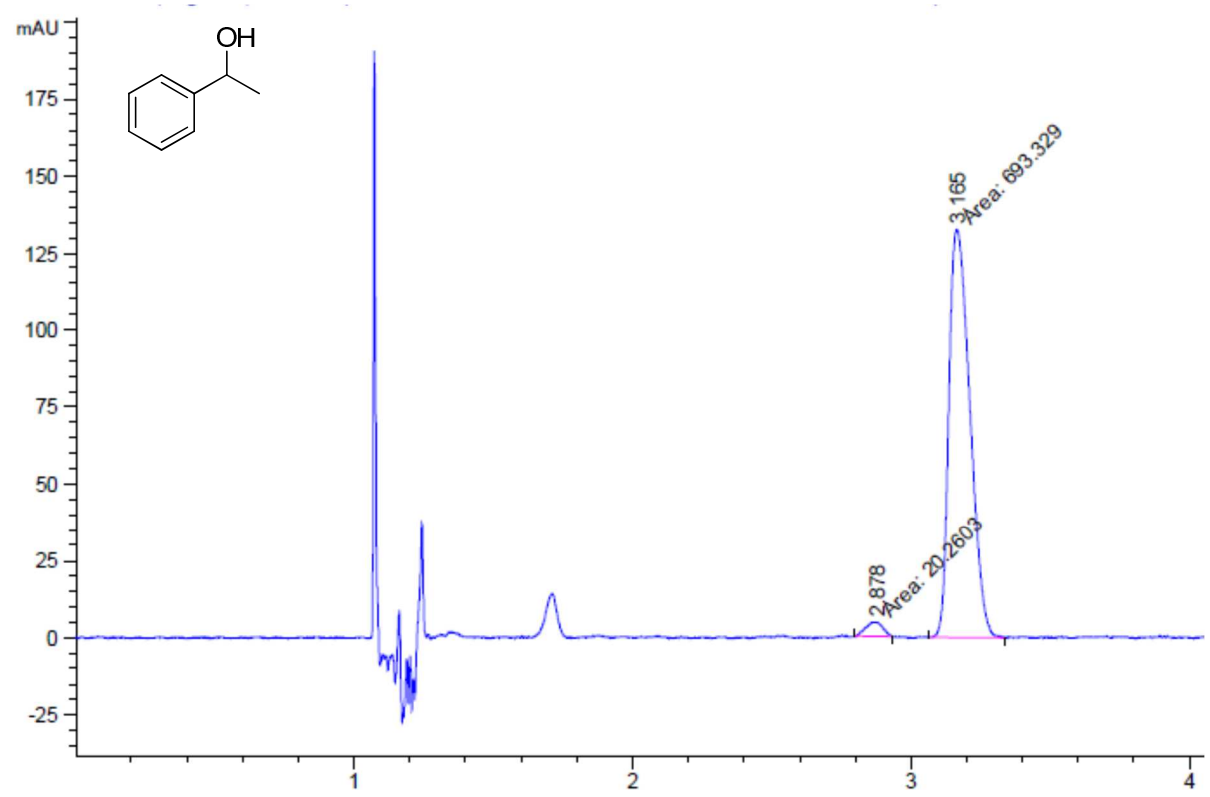
Reduction of Acetophenone in neat FA/TEA (5/2 molar ratio)



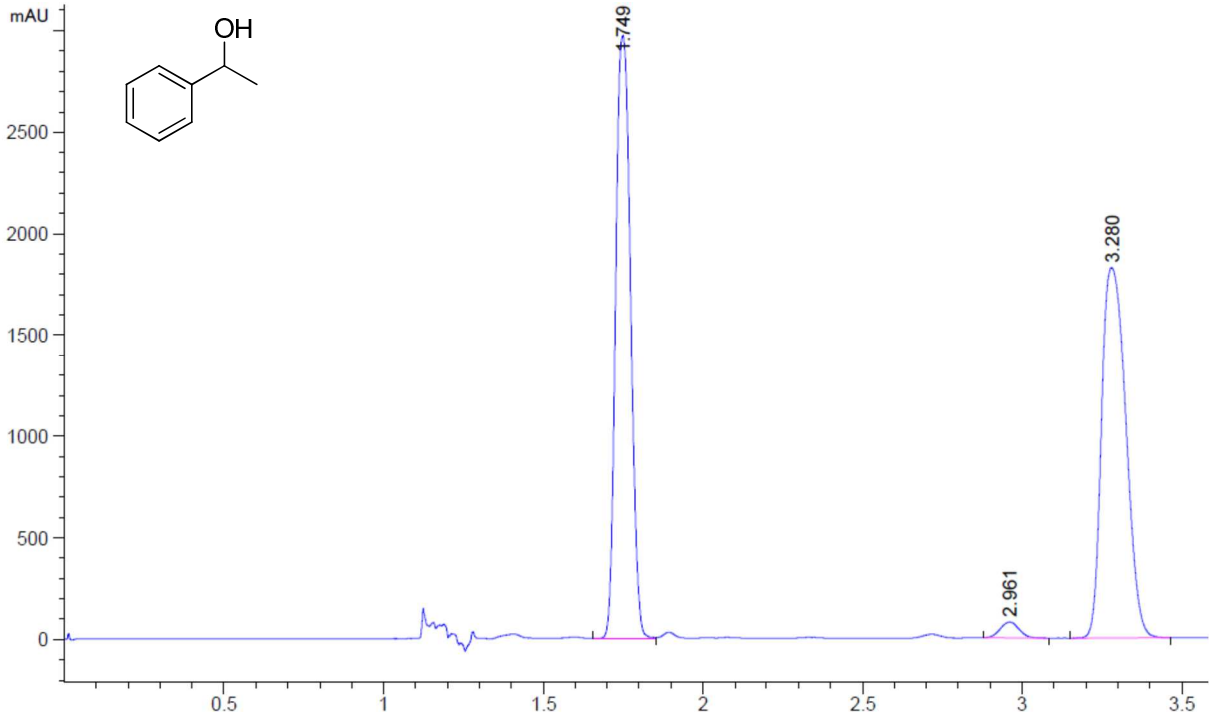
Reduction of Acetophenone in H_2O using FA/TEA (1.2/1 molar ratio)



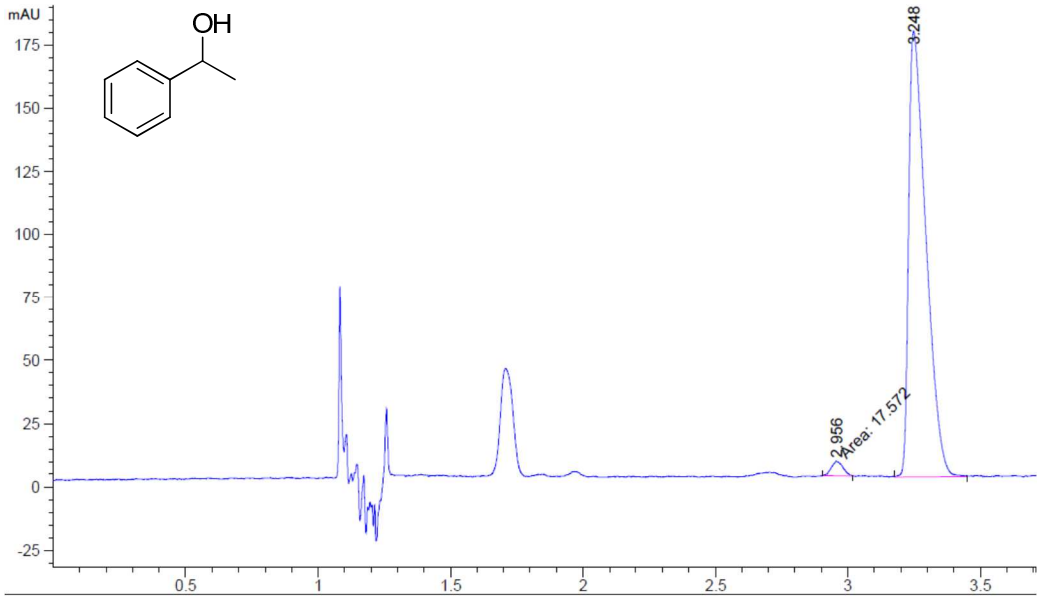
Reduction of Acetophenone using TAP-Ru-TsDPEN in aqueous FA/TEA (1.2/1 molar ratio) at 60°C



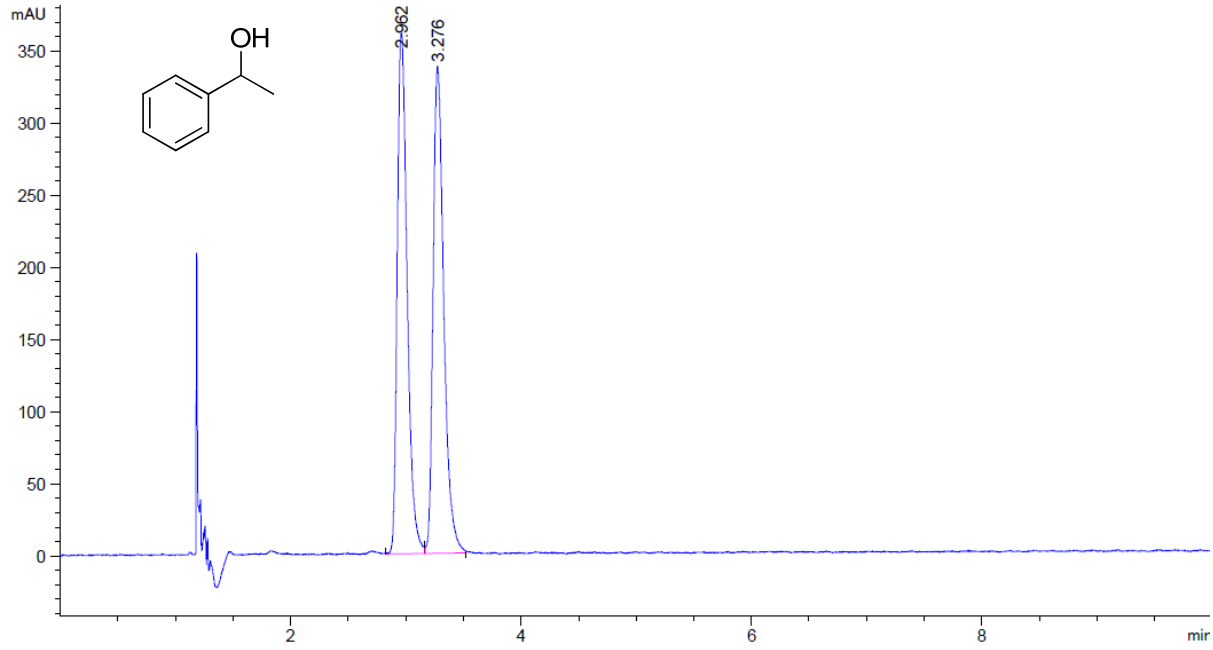
Reduction of Acetophenone using TAP-Ru-TsDPEN in aqueous FA/TEA (1.2/1 molar ratio) at 60° with SC = 1000C

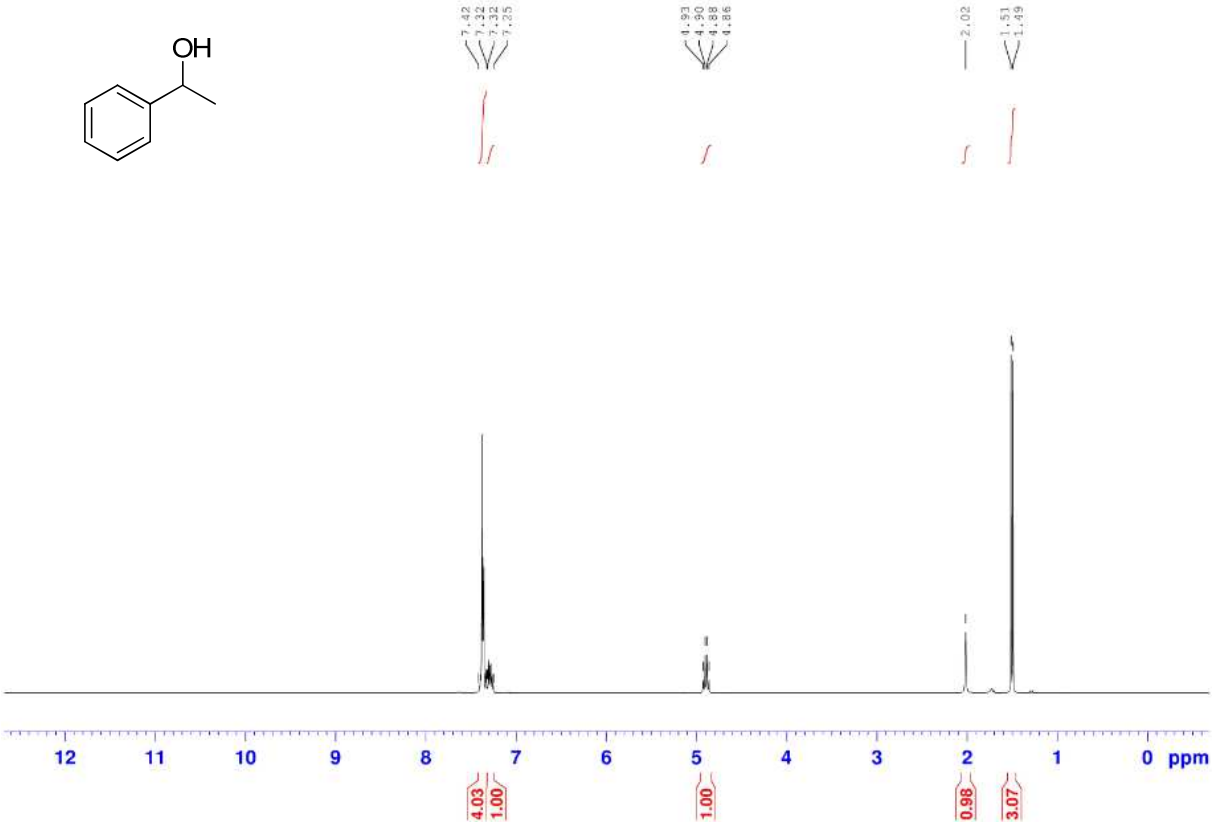


Reduction of Acetophenone using TAP-Ru-TsDPEN in aqueous FA/TEA (1.2/1 molar ratio) at 40°C (>99% conversion and 95.7% ee) : ***scope conditions****.*

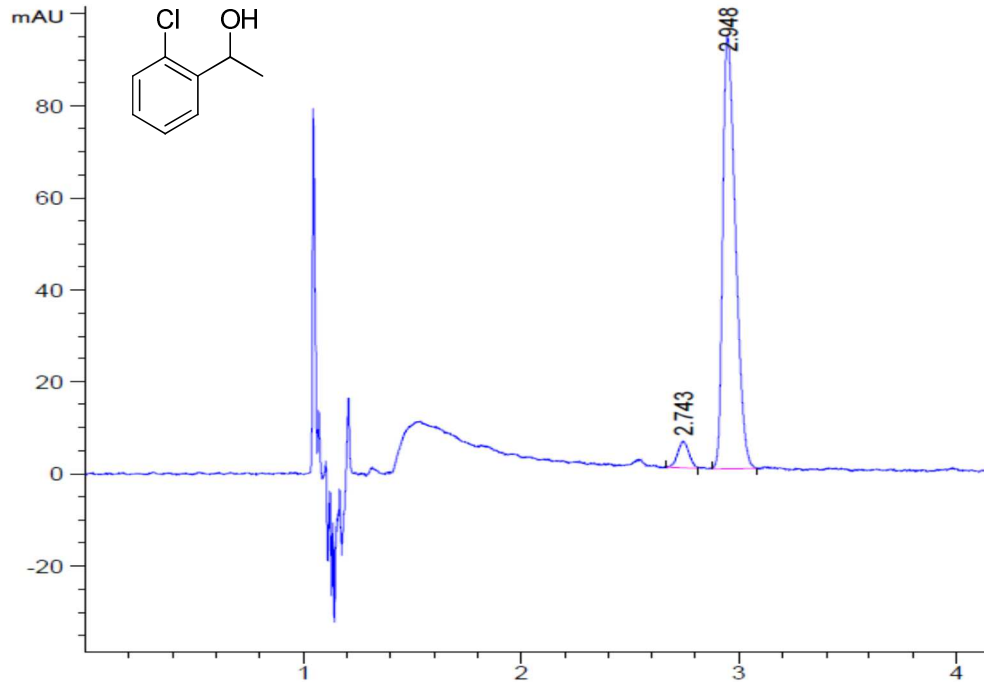


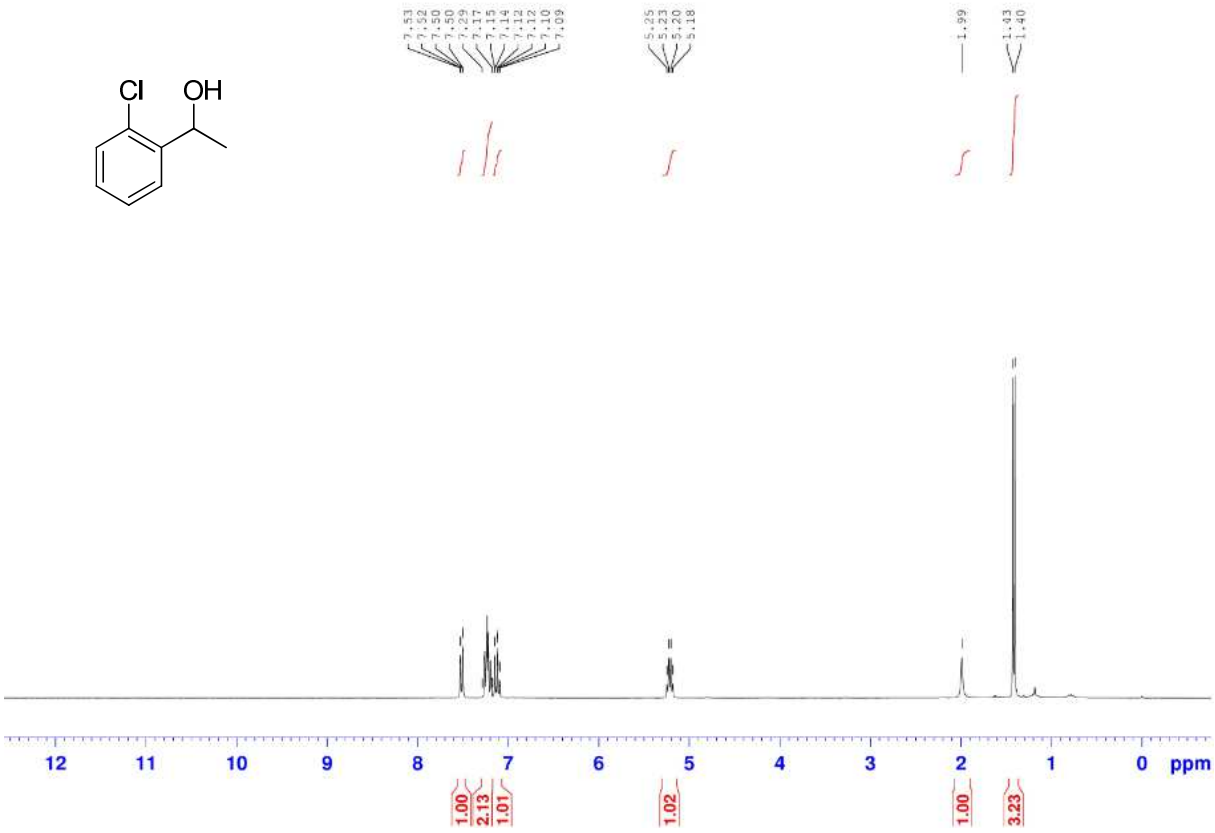
Racemic 1-phenylethanol

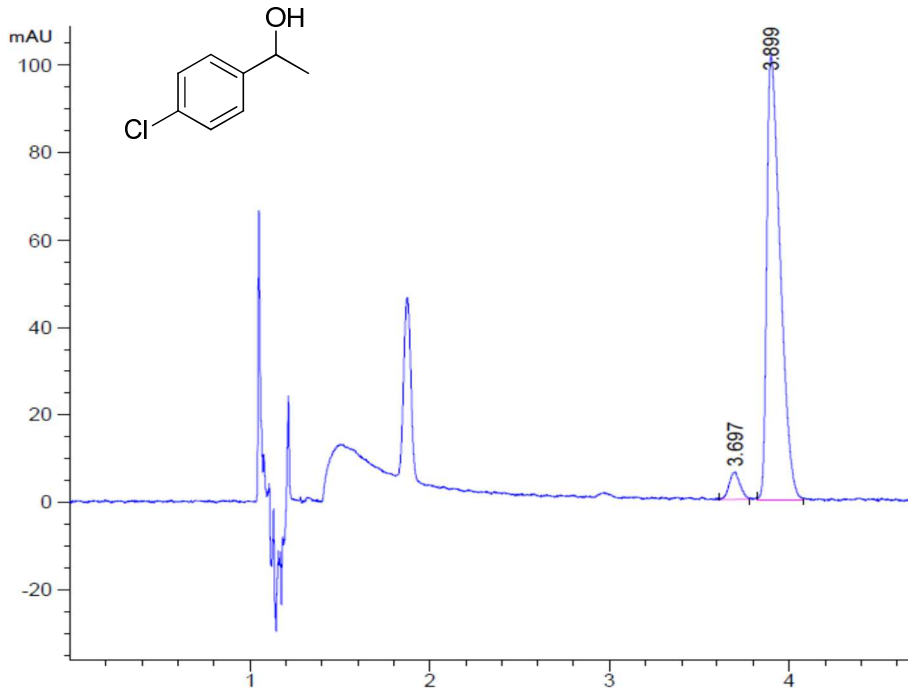



OH
7.42
7.32
7.32
7.25
4.93
4.90
4.88
4.86
2.02
1.51
1.49
12
11
10
9
8
7
6
5
4
3
2
1
0 ppm
4.03
1.00
1.00
0.98
3.07

Substrate scope



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Cl
mAU
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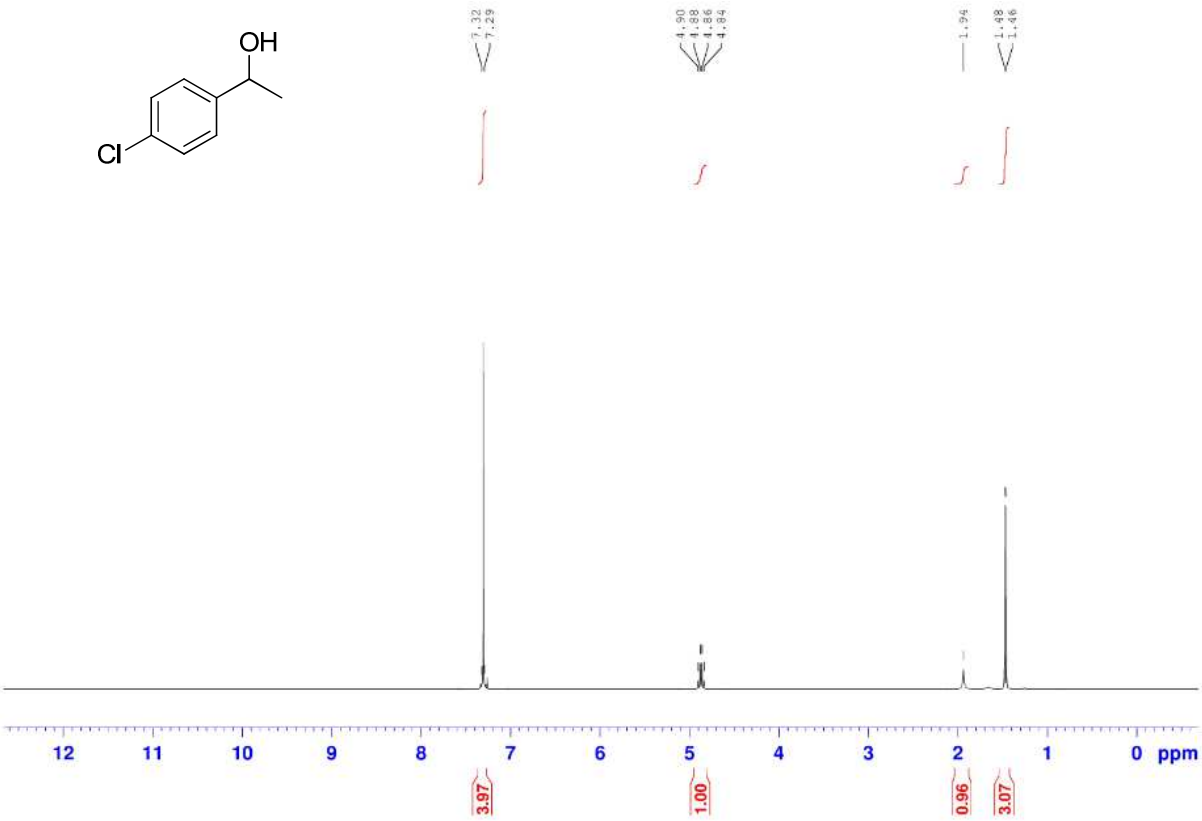
80
60
40
20
0
-20
1
2
3
4
3.899
3.697


OH
Cl
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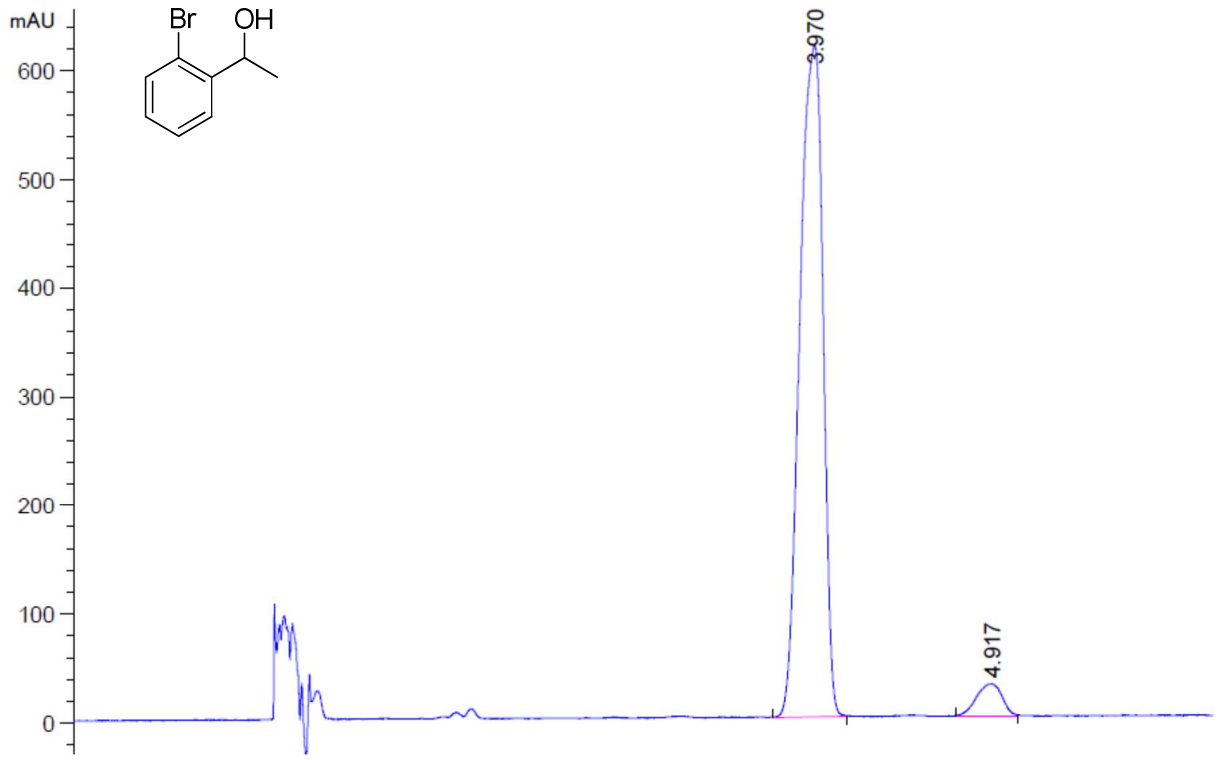
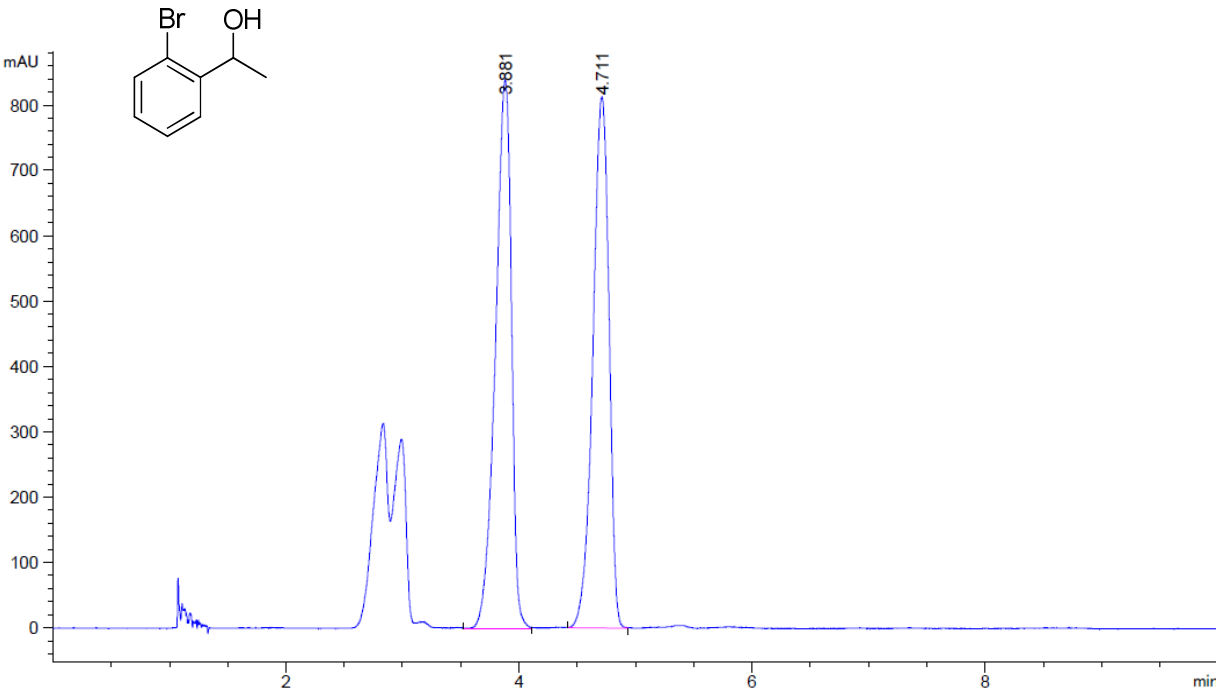
7.29
4.90
4.88
4.86
4.84
1.94
1.48
1.46
12
11
10
9
8
7
6
5
4
3
2
1
0 ppm
3.97
1.00
0.96
3.07


Br
OH
mAU
600
500
400
300
200
100
0
3.970
4.917

Racemic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OH
mAU
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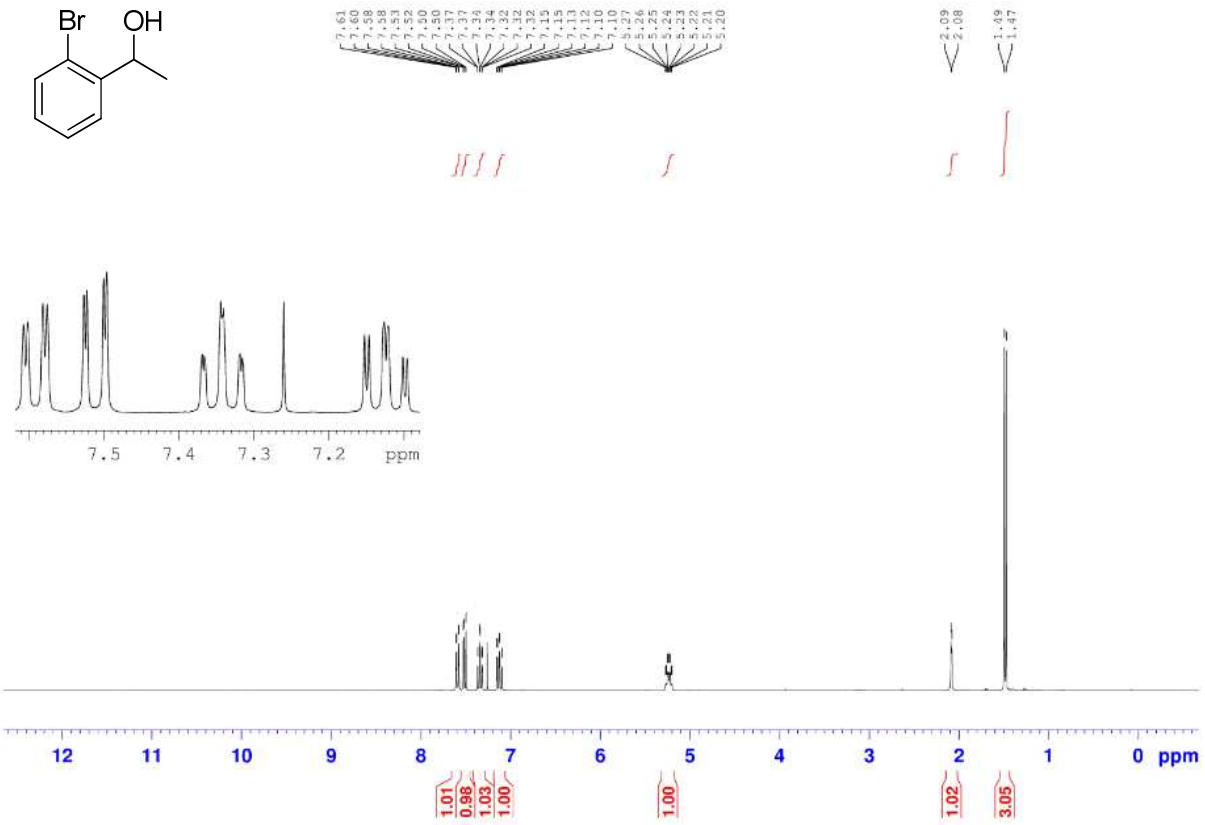
700
600
500
400
300
200
100
0
3.881
4.711
2
4
6
8
min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7.3
7.2
ppm
12
11
10
9
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0 ppm
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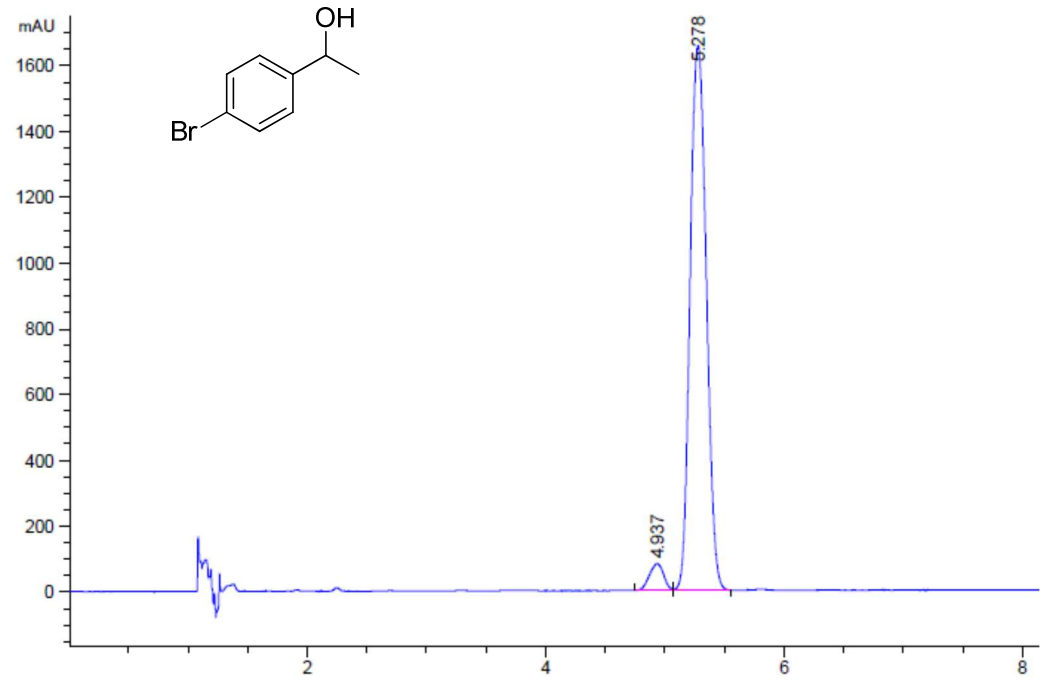
0.98
1.03
1.00
1.00
1.02
3.05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Br
mAU
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1200
1000
800
600
400
200
0
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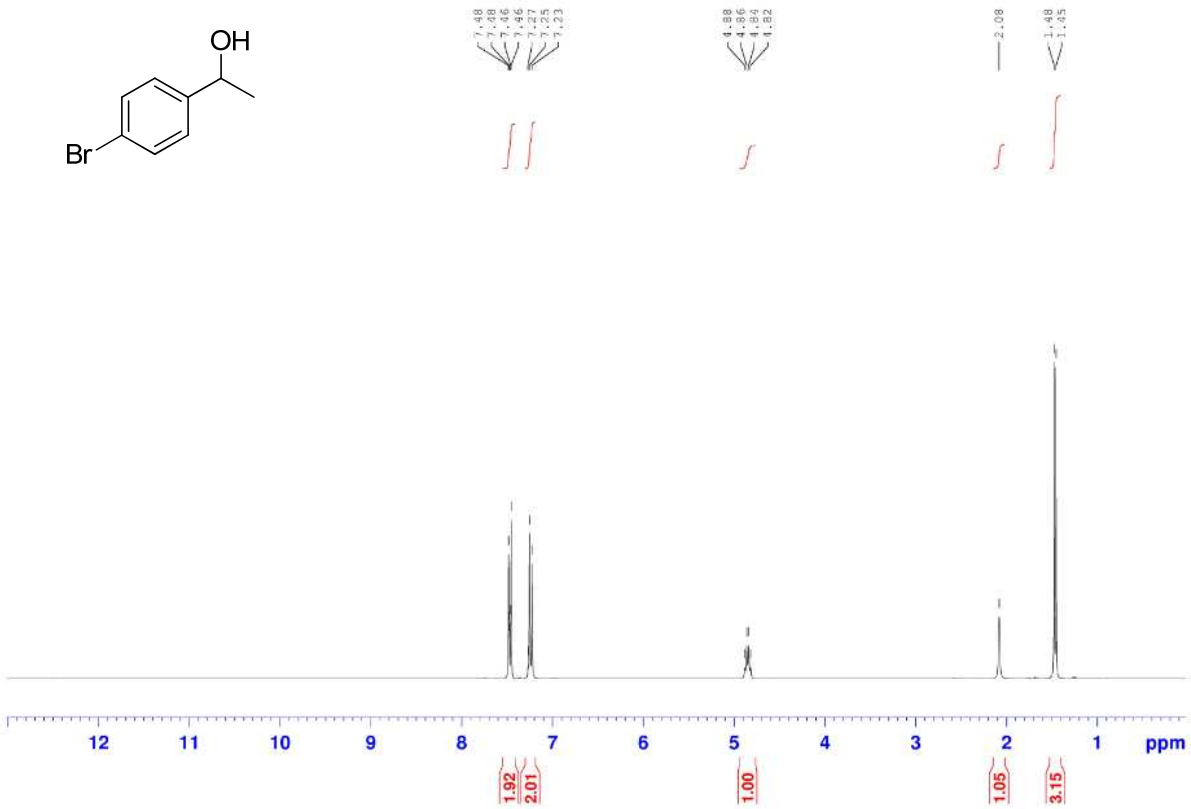
2
4
6
8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Br
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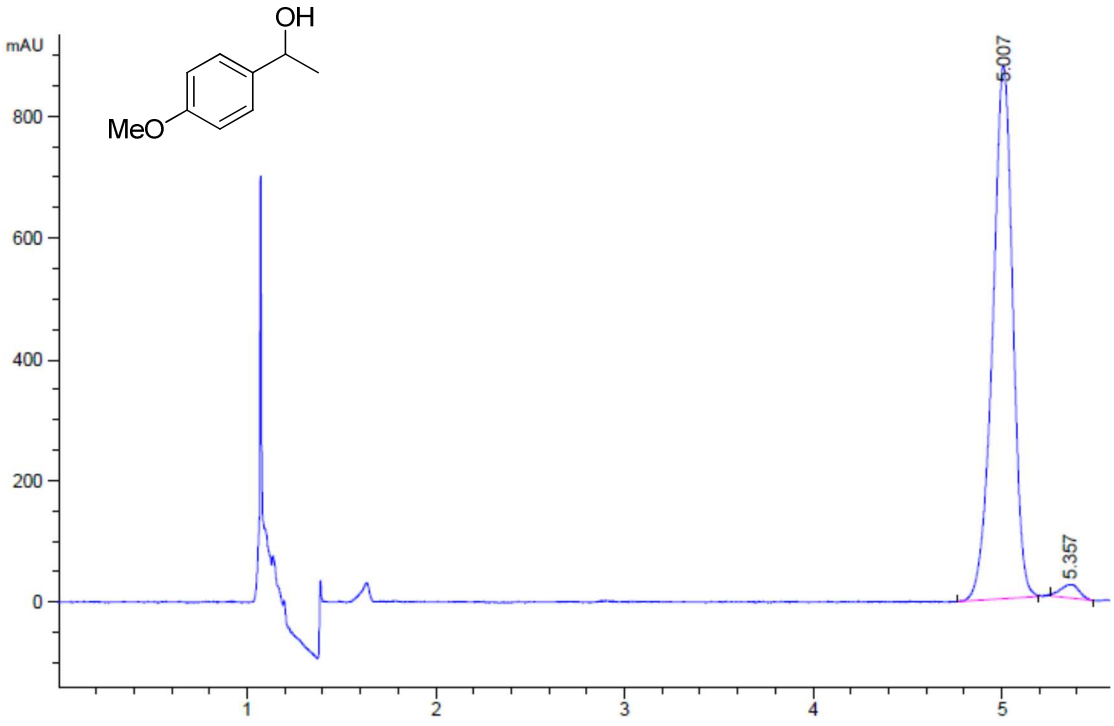
7.48
7.46
7.46
7.27
7.25
7.23
4.88
4.86
4.84
4.82
2.08
1.48
1.45
12
11
10
9
8
7
6
5
4
3
2
1
ppm
1.92
2.01
1.00
1.05
3.15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MeO
mAU
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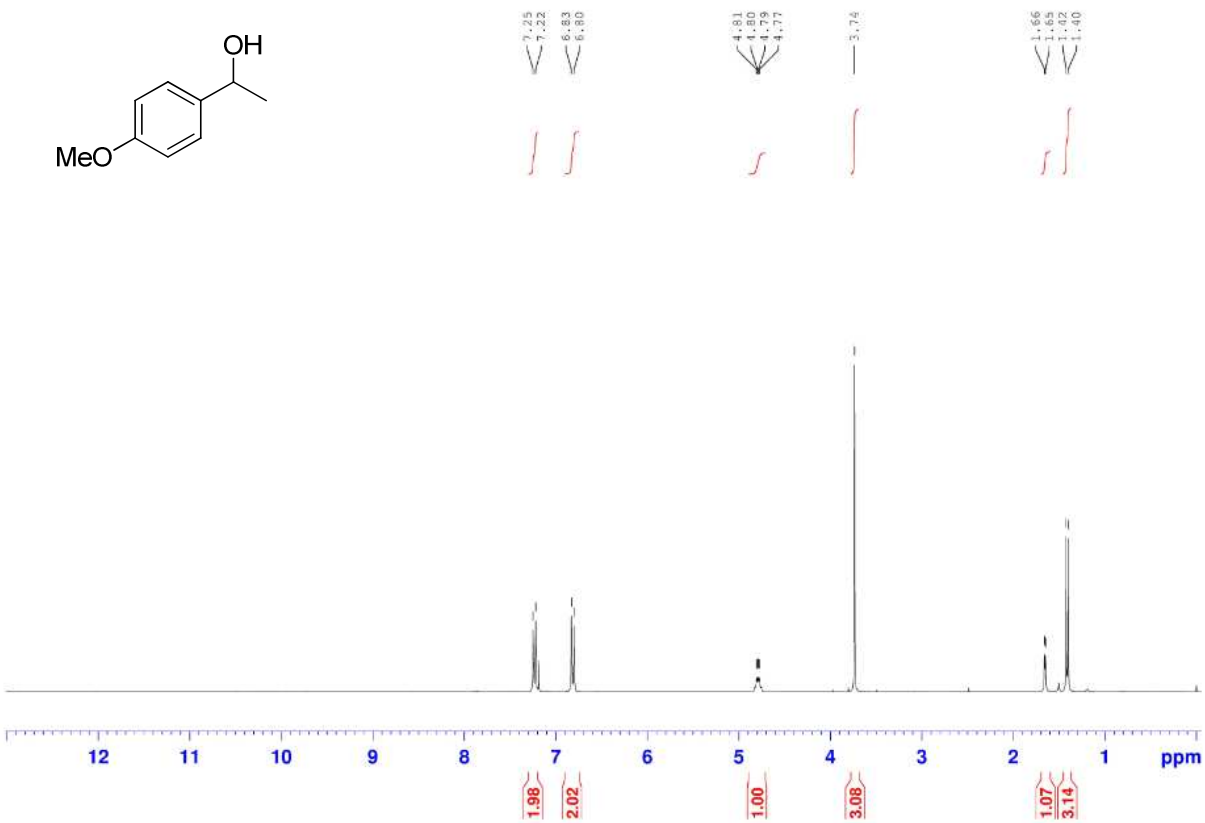
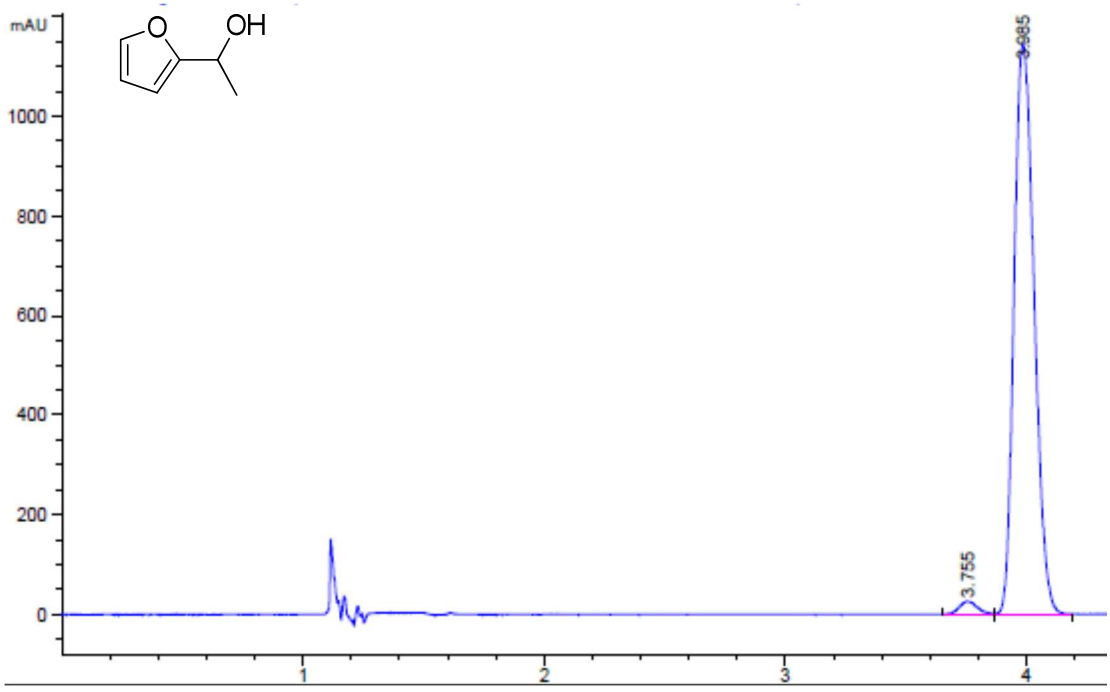
600
400
200
0
5.007
5.357
1
2
3
4
5


OH
MeO
7.25
7.22
6.83
6.80
4.81
4.80
4.79
4.77
3.74
1.66
1.65
1.42
1.40
12
11
10
9
8
7
6
5
4
3
2
1
ppm
1.98
2.02
1.00
3.08
1.07
3.14


O
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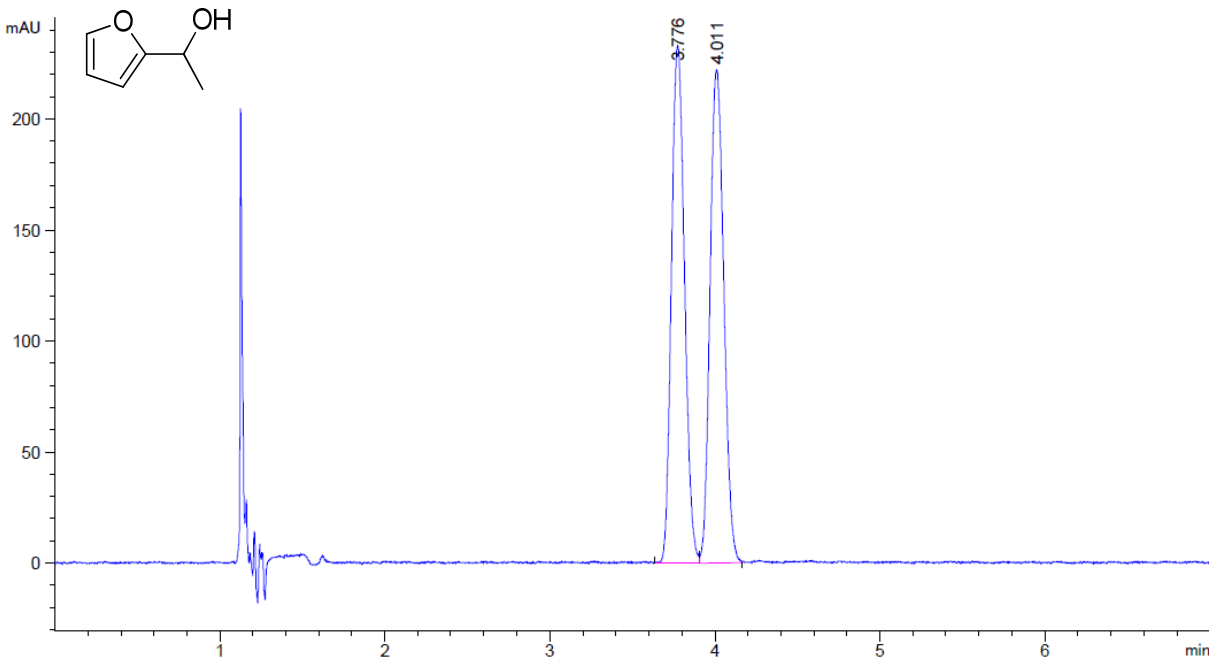
mAU
1000
800
600
400
200
0
3.755
3.985
1
2
3
4

Racemic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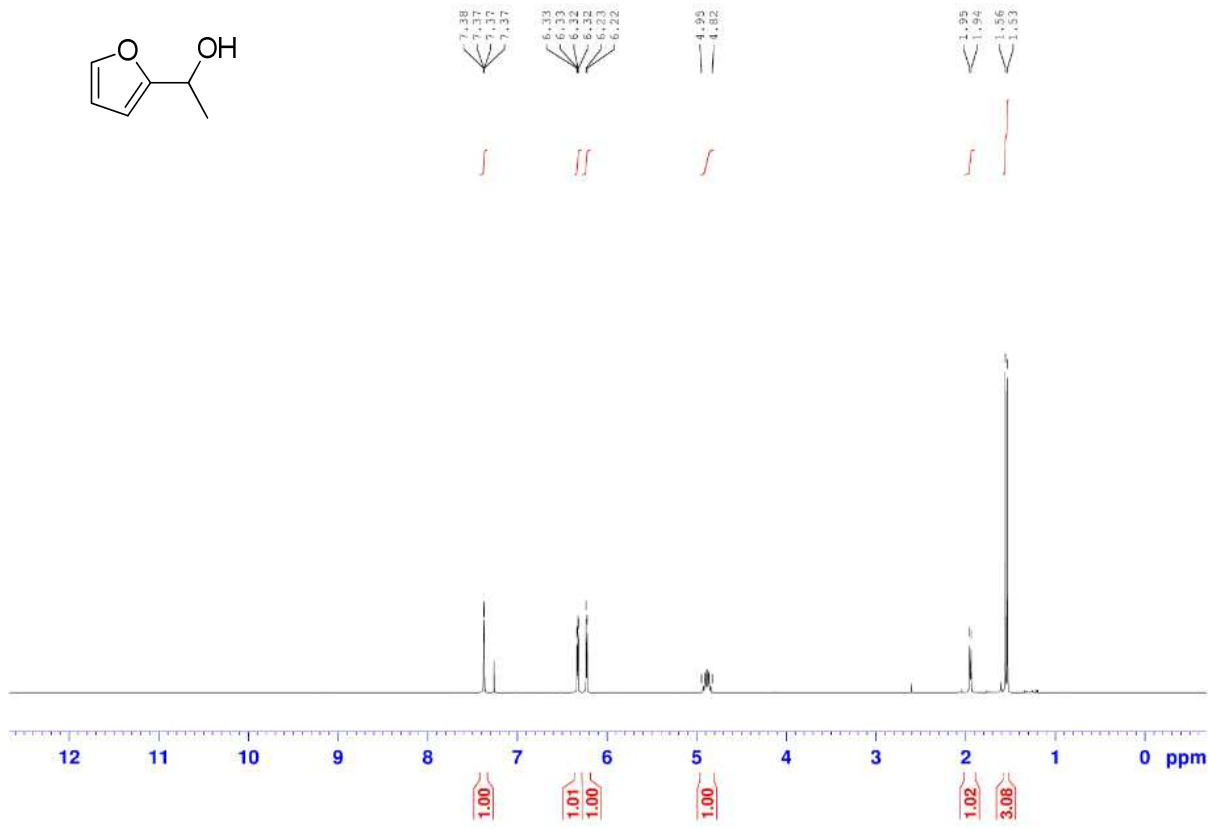
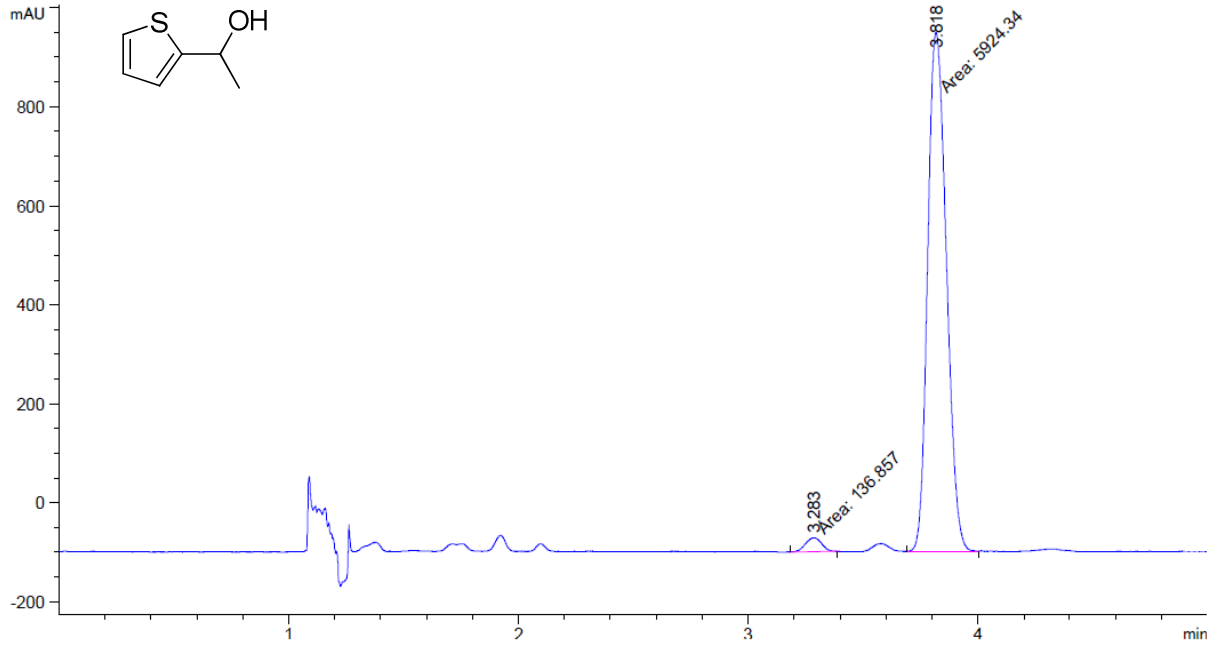
mAU
200
150
100
50
0
3.776
4.011
1
2
3
4
5
6
min


OH
7.38
7.37
7.37
7.37
6.33
6.33
6.32
6.32
6.23
6.22
4.95
4.82
1.95
1.94
1.56
1.53
12
11
10
9
8
7
6
5
4
3
2
1
0 ppm
1.00
1.01
1.00
1.00
1.02
3.08


mAU
800
600
400
200
0
-200
1
2
3
4
min
S
OH
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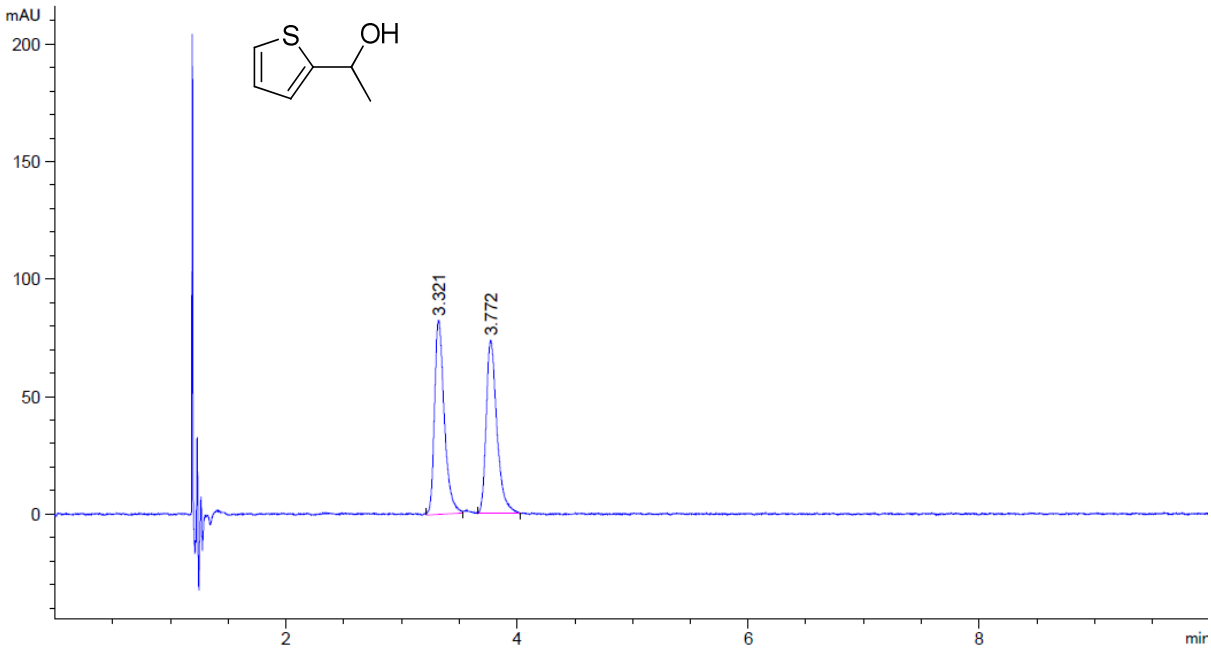
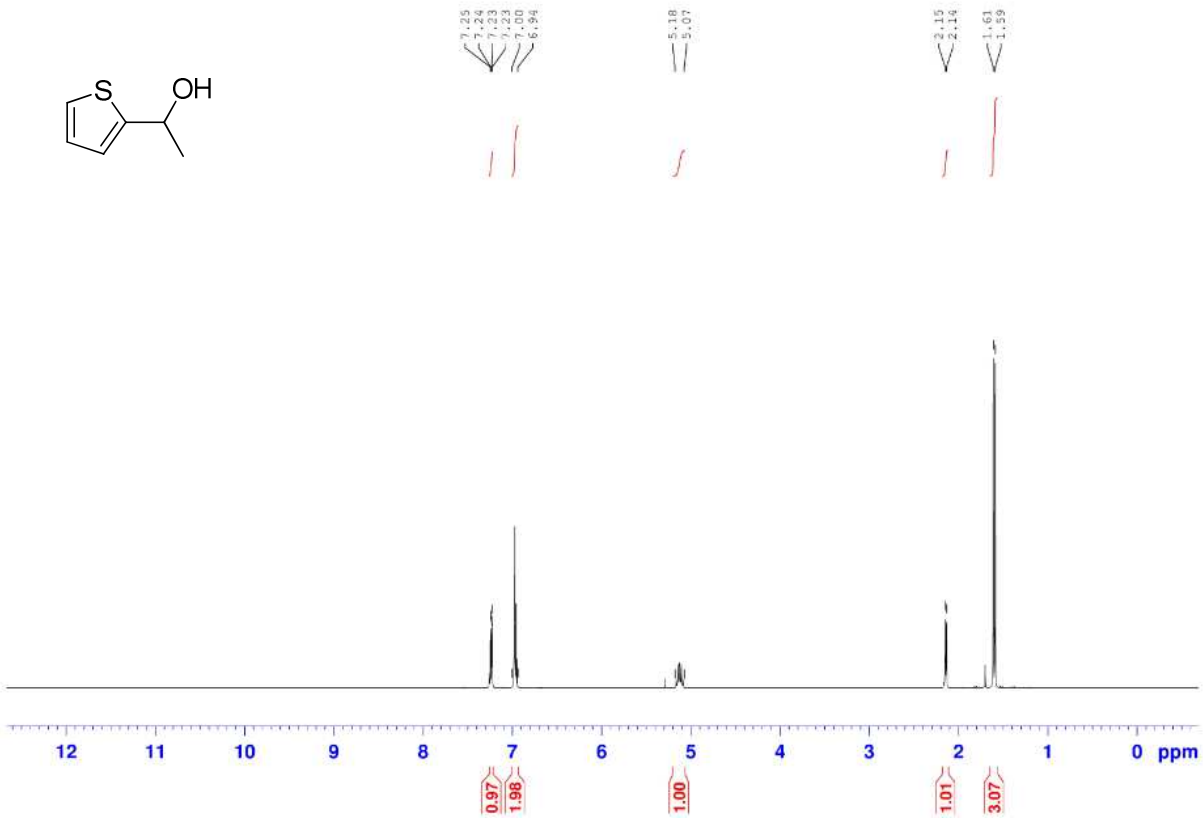
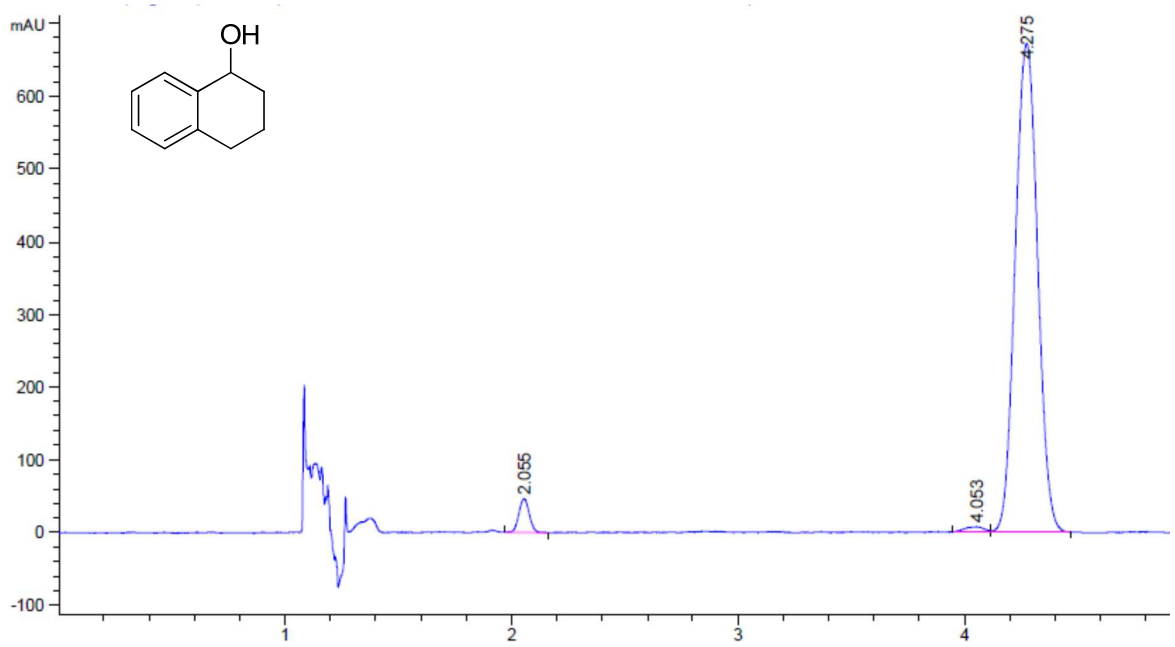
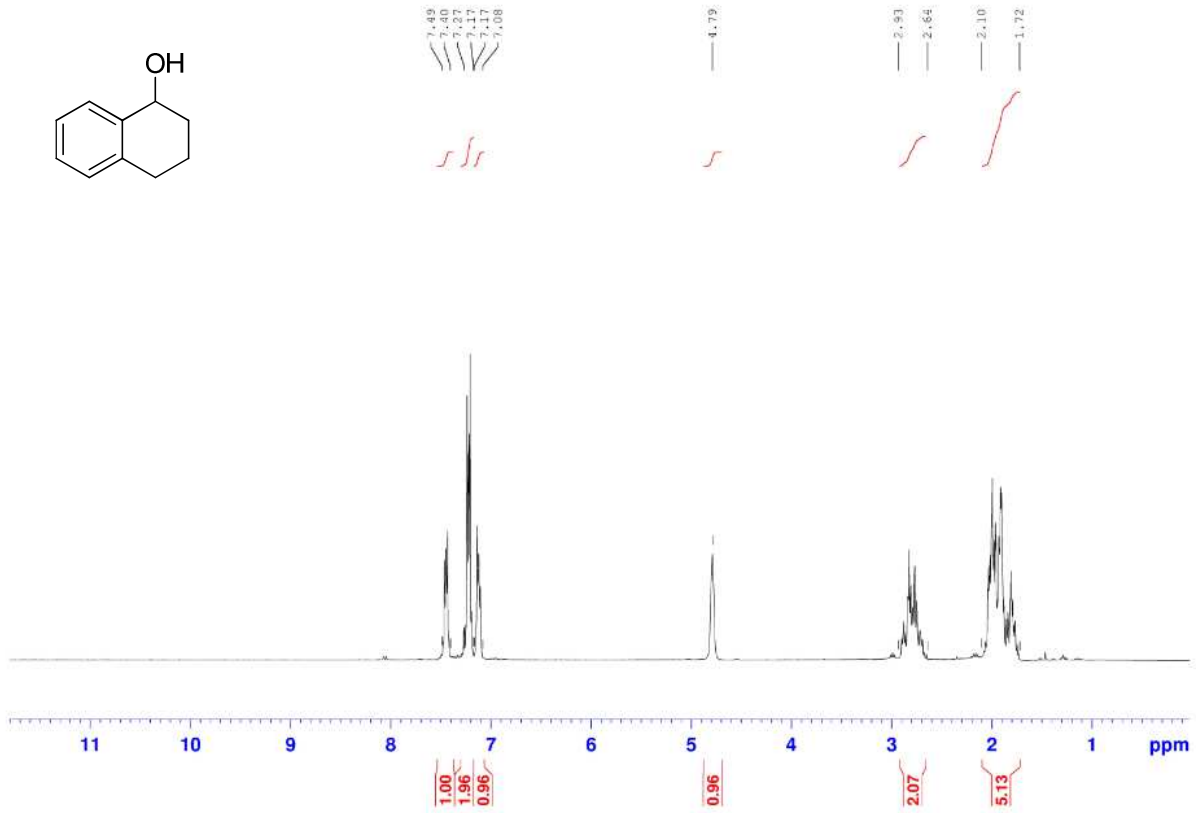
Area: 5924.34
3.283
Area: 136.857

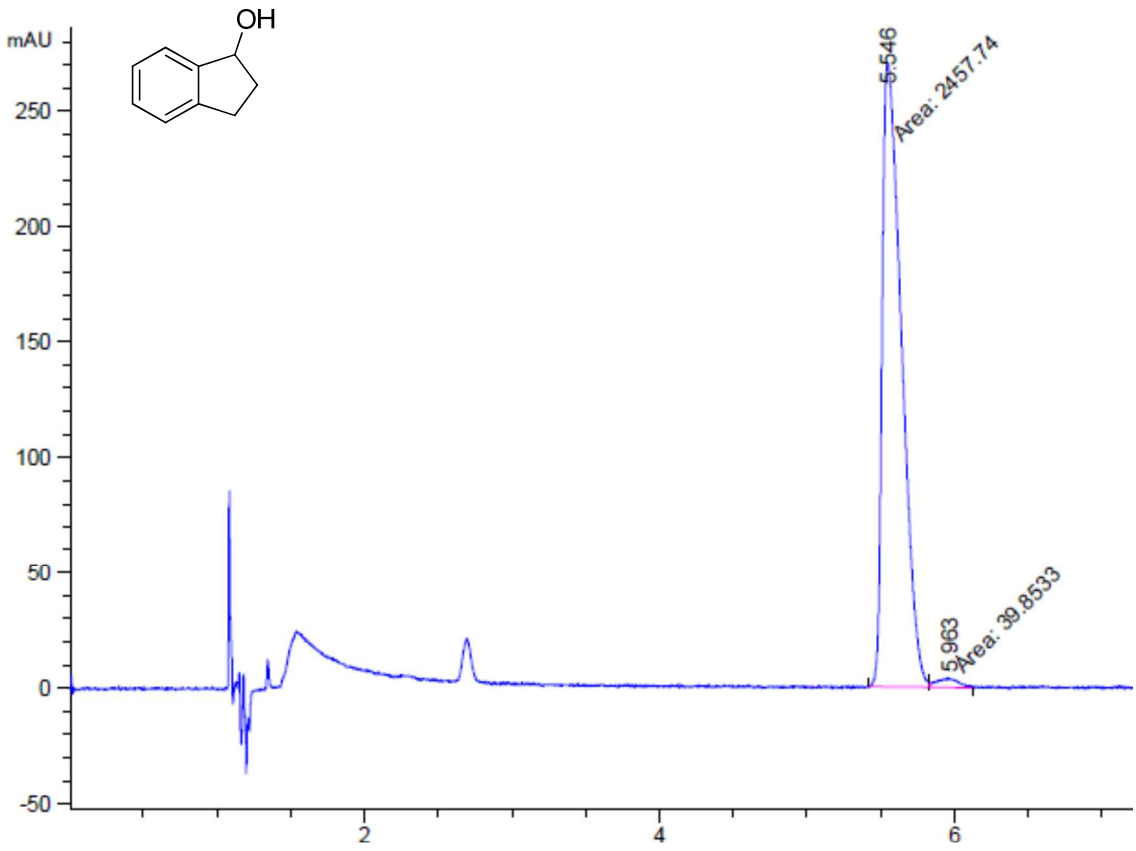
Racemic


mAU
200
150
100
50
0
2
4
6
8
mir
S
OH
3.321
3.772

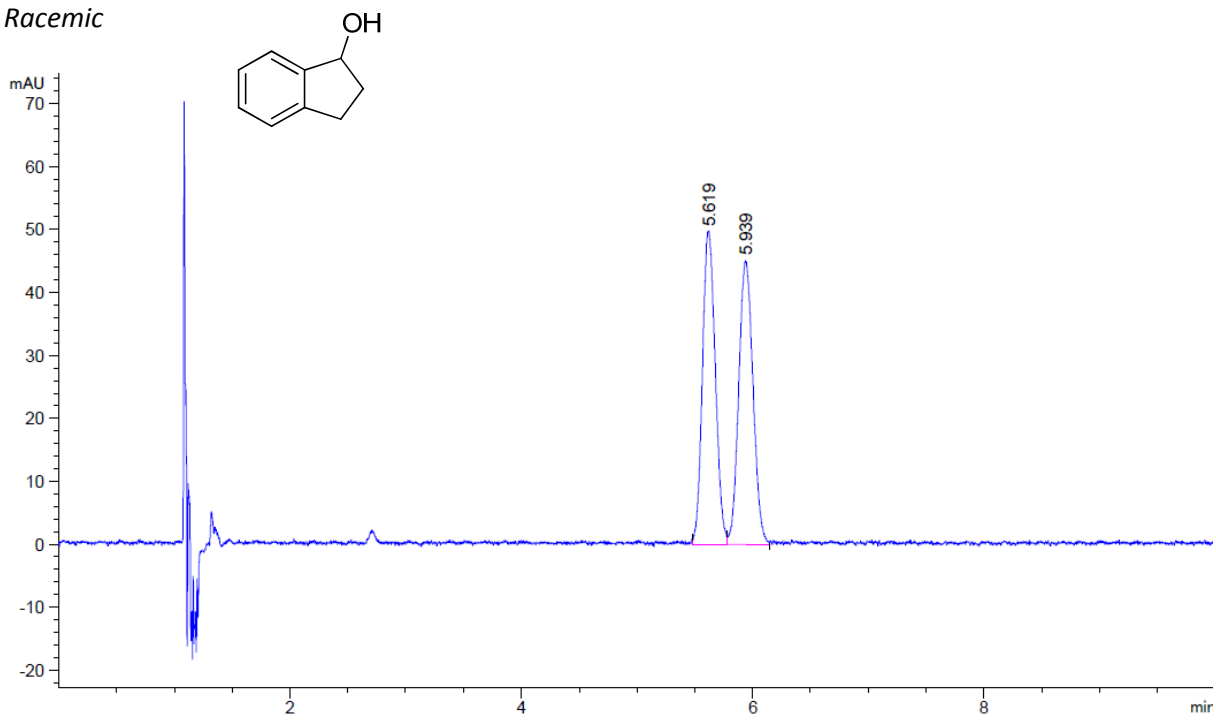

S
OH
7.25
7.24
7.23
7.23
7.00
6.94
5.18
5.07
2.15
2.14
1.61
1.59
12
11
10
9
8
7
6
5
4
3
2
1
0 ppm
0.97
1.98
1.00
1.01
3.07

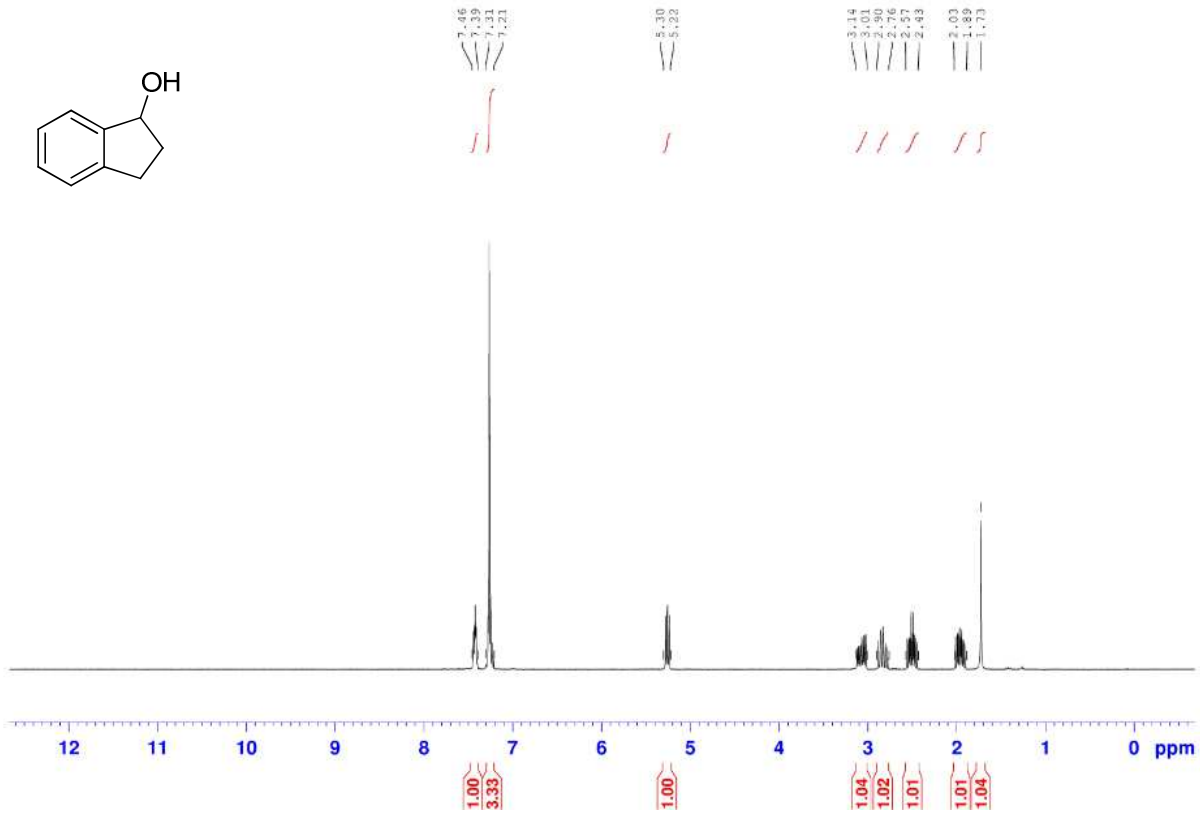

OH
mAU
600
500
400
300
200
100
0
-100
2.055
4.053
4.275
1
2
3
4

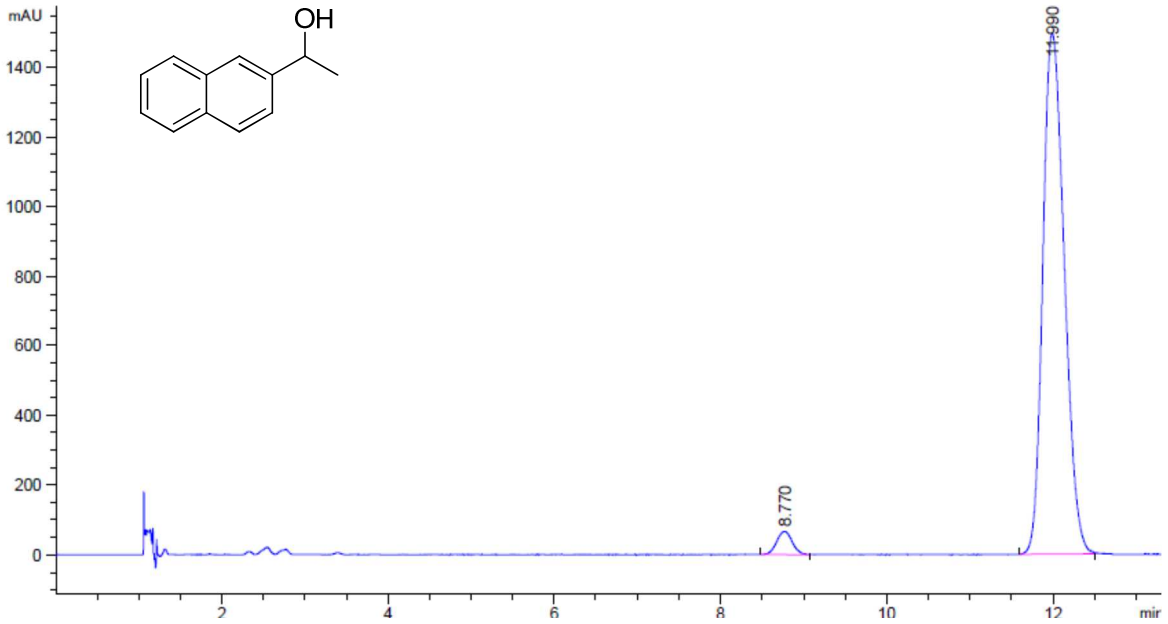

OH
7.49
7.40
7.27
7.17
7.17
7.08
4.79
2.93
2.64
2.10
1.72
11
10
9
8
7
6
5
4
3
2
1
ppm
1.00
1.96
0.96
0.96
2.07
5.13

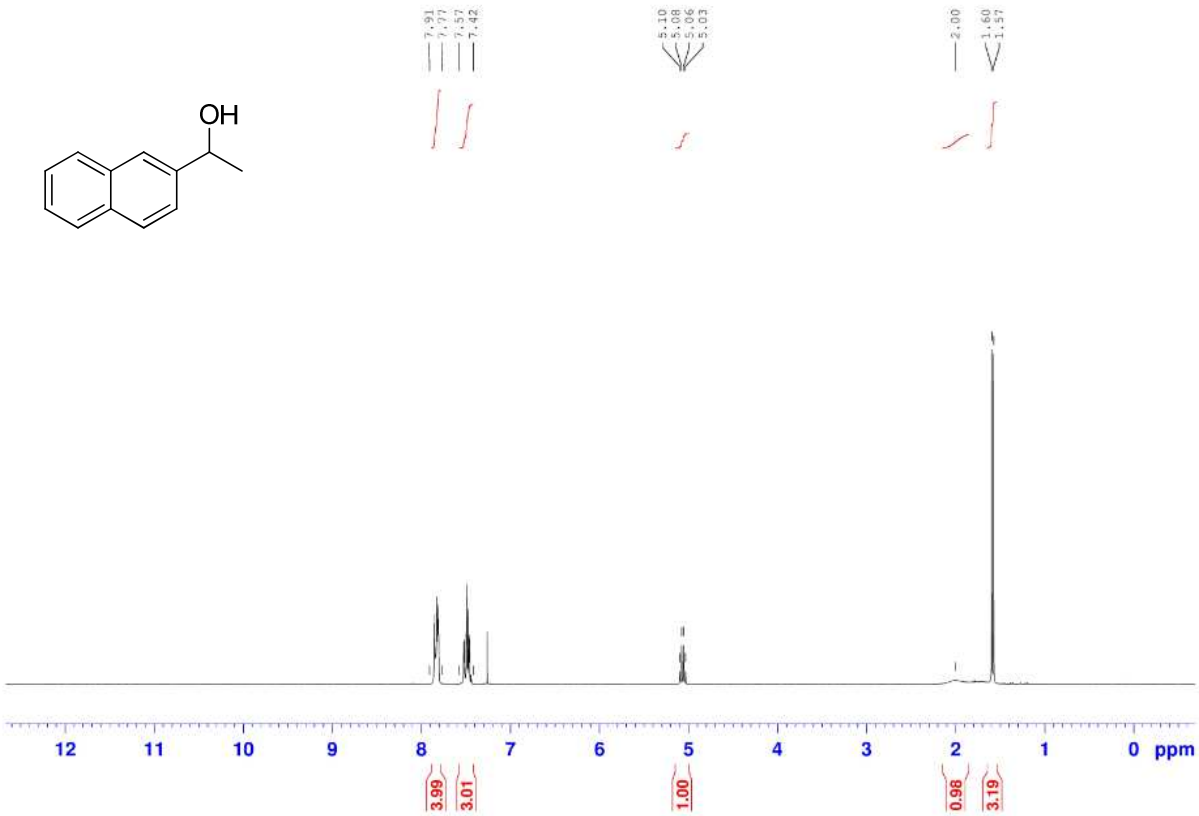

OH
mAU
250
200
150
100
50
0
-50
2
4
6
5.546
Area: 2457.74
5.963
Area: 39.8533

Racemic


OH
mAU
70
60
50
40
30
20
10
0
-10
-20
5.619
5.939
2
4
6
8
min

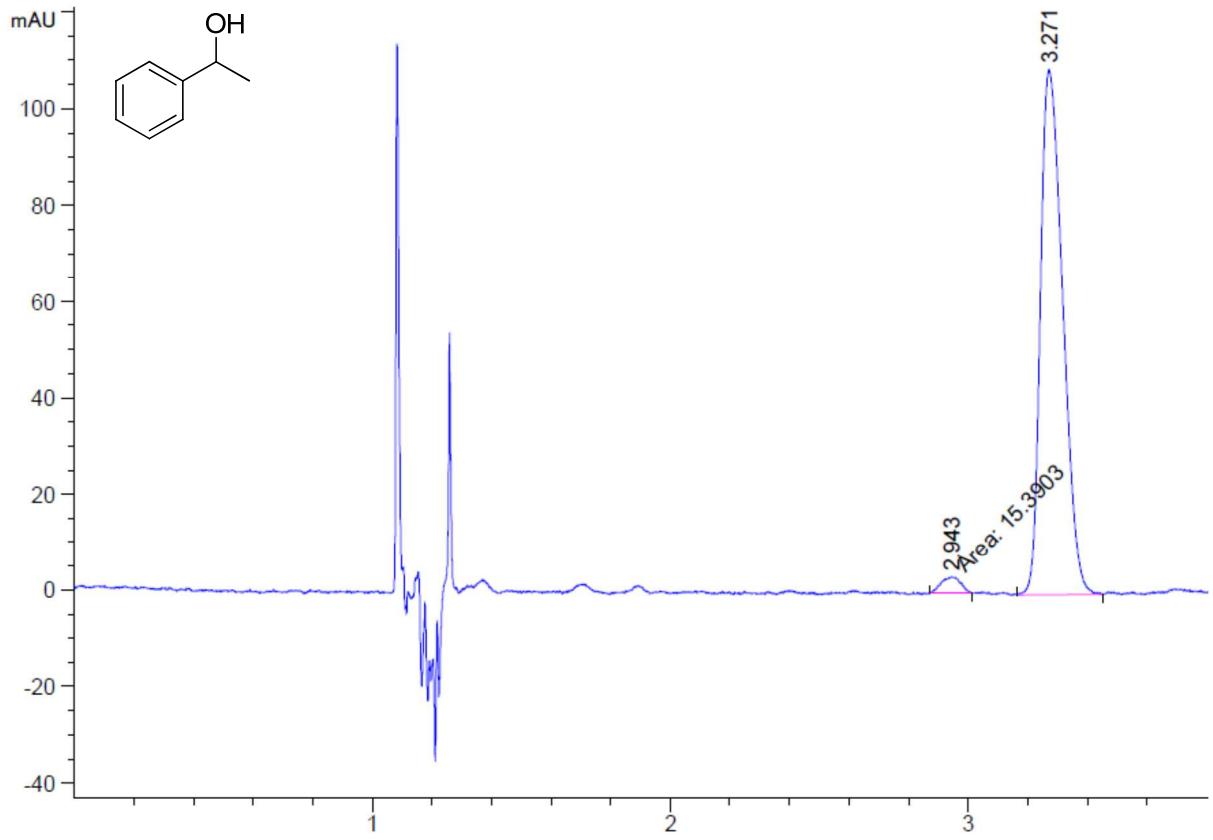

OH
7.46
7.39
7.31
7.21
5.30
5.22
3.14
3.01
2.90
2.76
2.57
2.43
2.03
1.89
1.73
12
11
10
9
8
7
6
5
4
3
2
1
0 ppm
1.00
3.33
1.00
1.04
1.02
1.01
1.01
1.04


OH
mAU
1400
1200
1000
800
600
400
200
0
8.770
11.990
2
4
6
8
10
12
mir

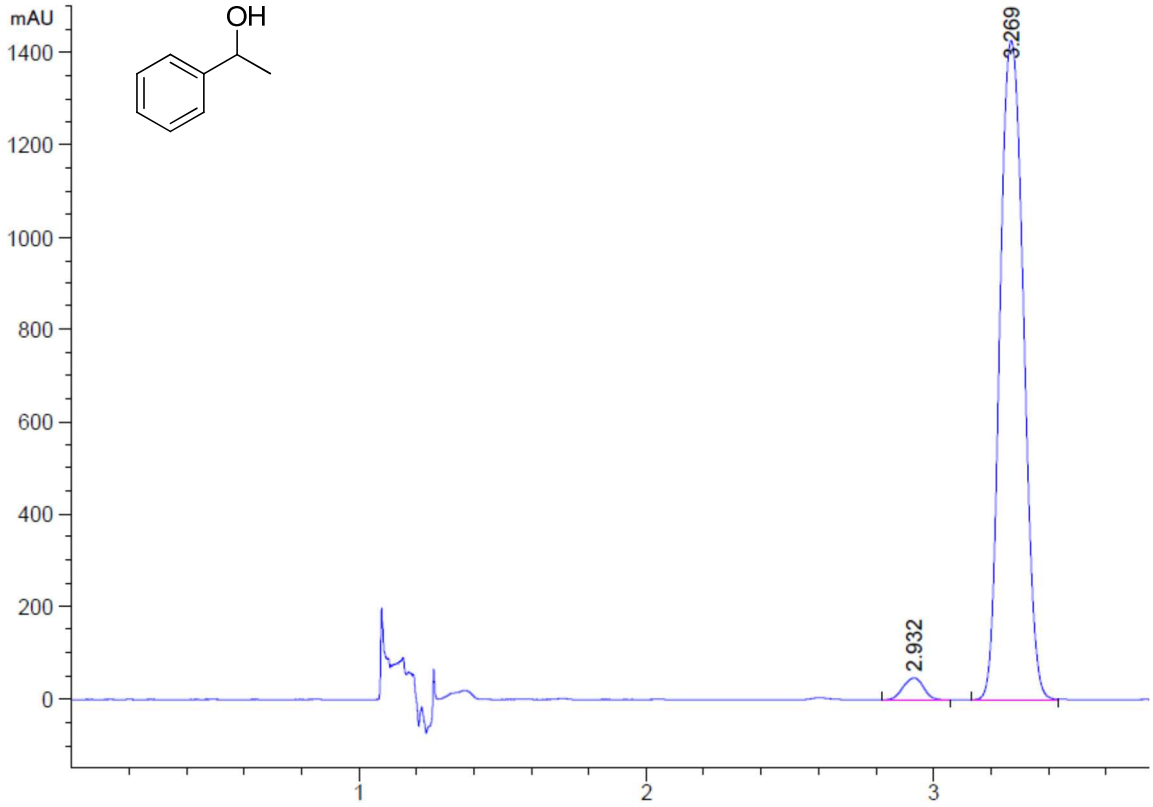

OH
7.91
7.77
7.57
7.42
5.10
5.08
5.06
5.03
2.00
1.60
1.57
12
11
10
9
8
7
6
5
4
3
2
1
0 ppm
3.99
3.01
1.00
0.98
3.19

Recycling catalysis without catalyst precipitation

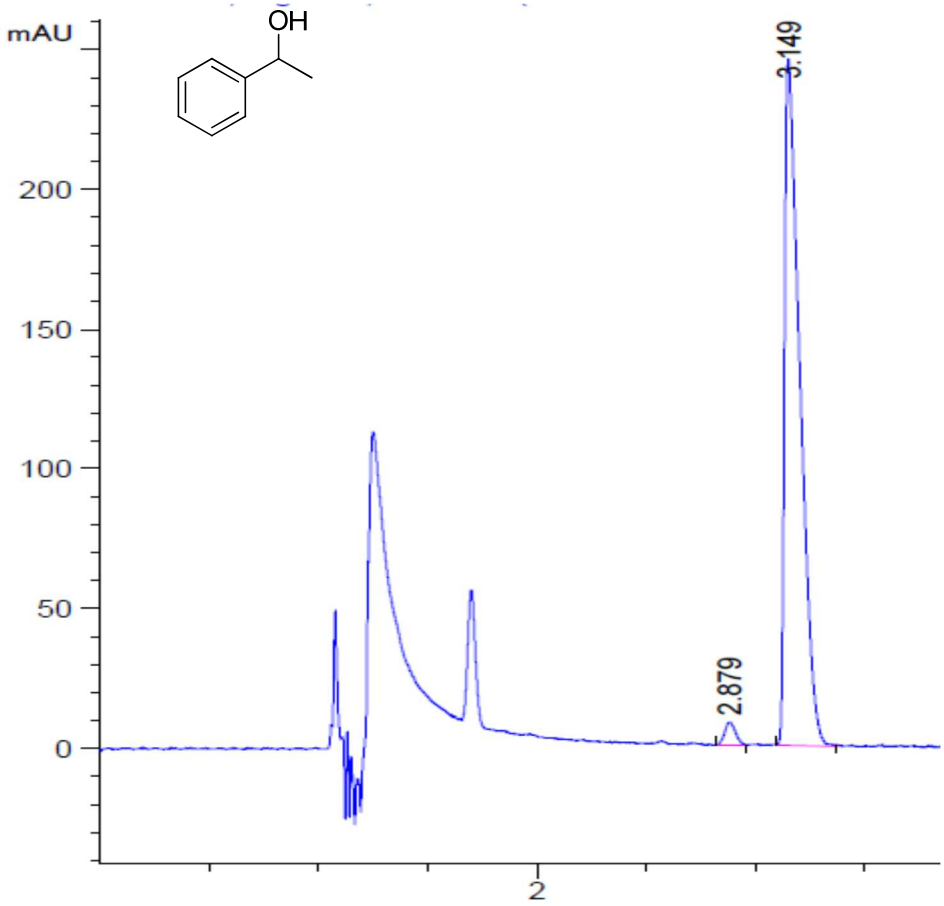
1st cycle



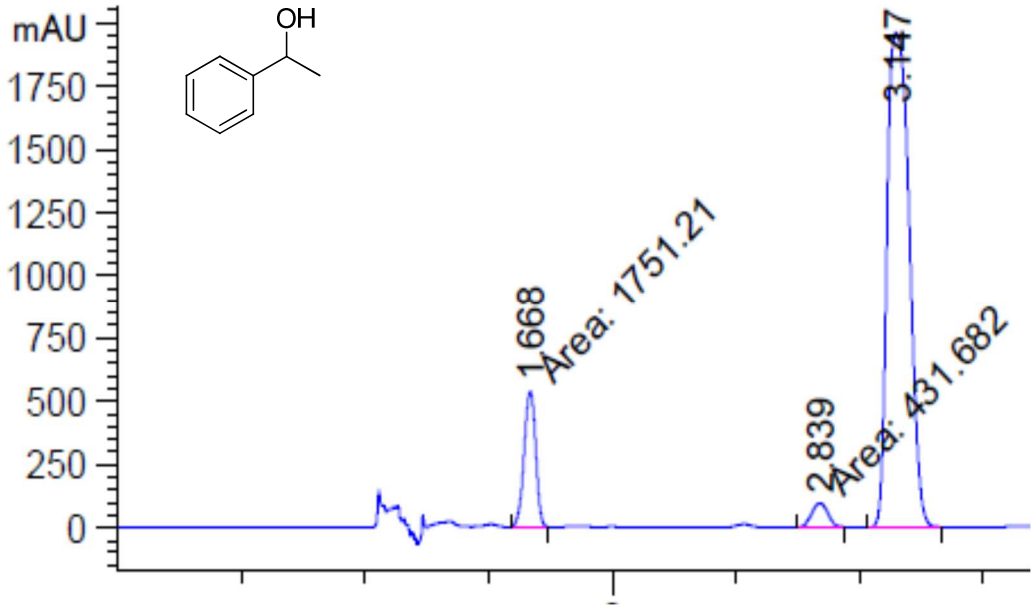
2nd cycle



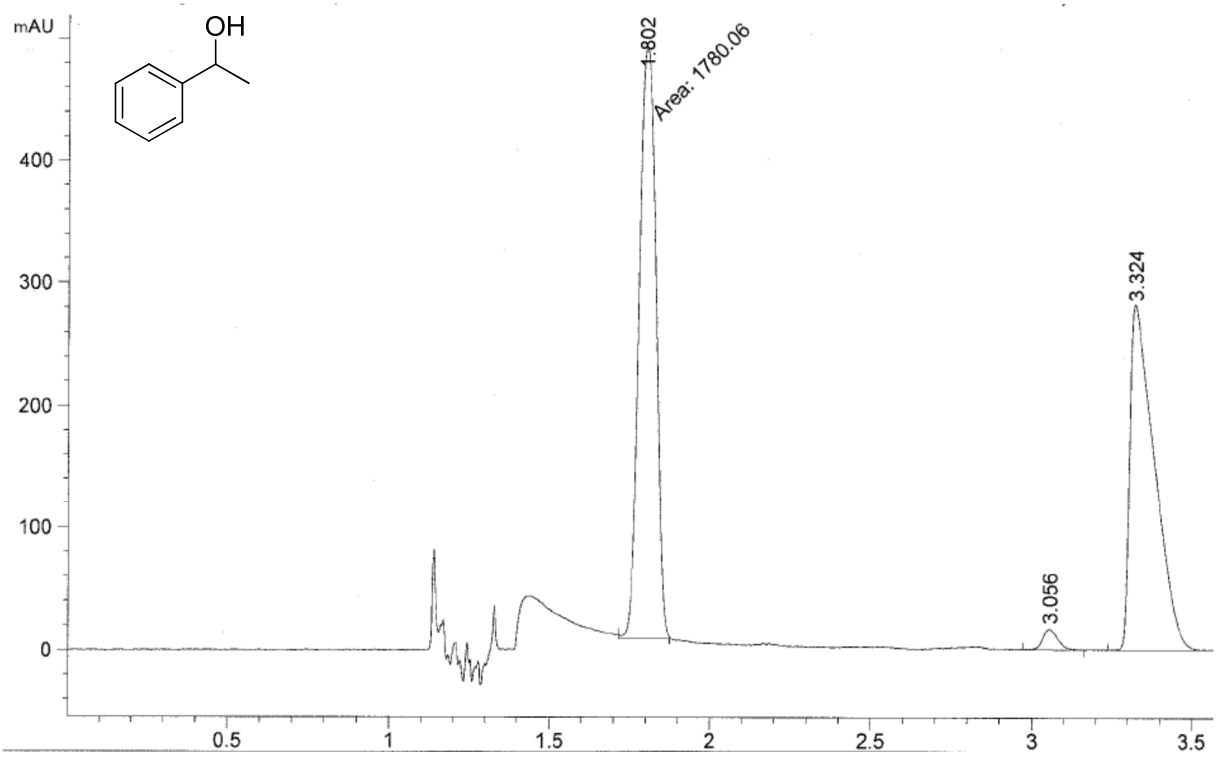
3rd cycle



4th cycle

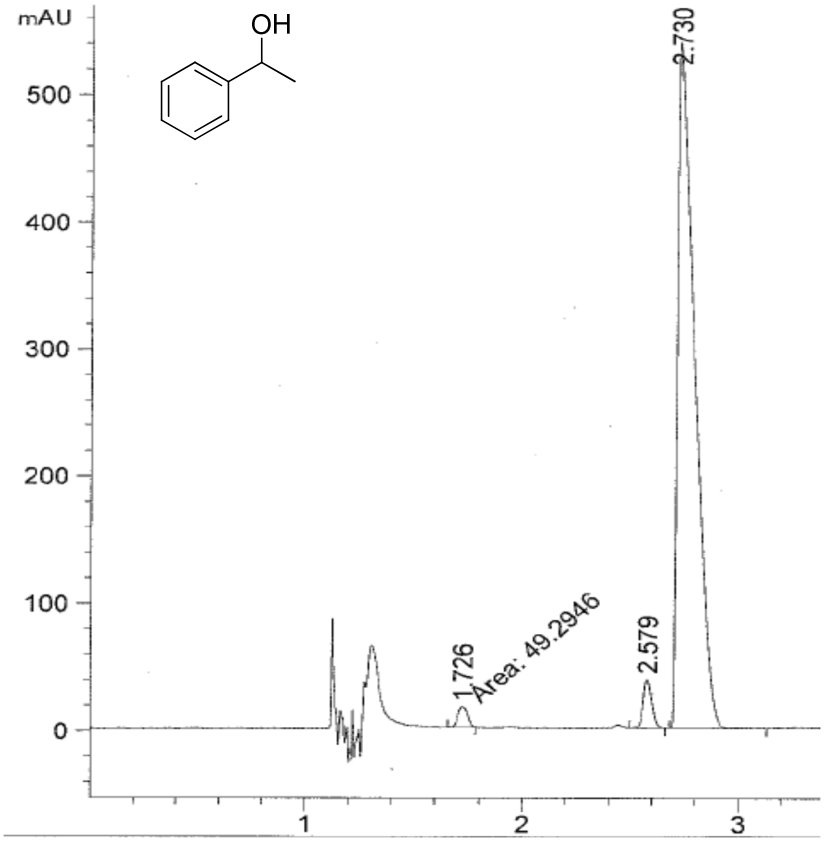


5th cycle

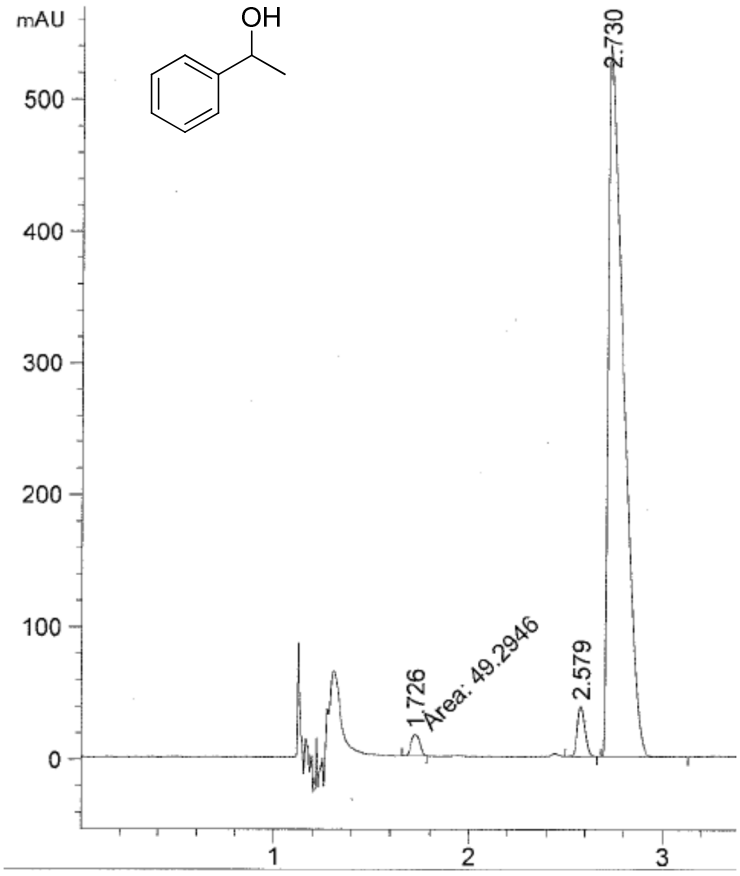


Recycling catalysis with catalyst precipitation

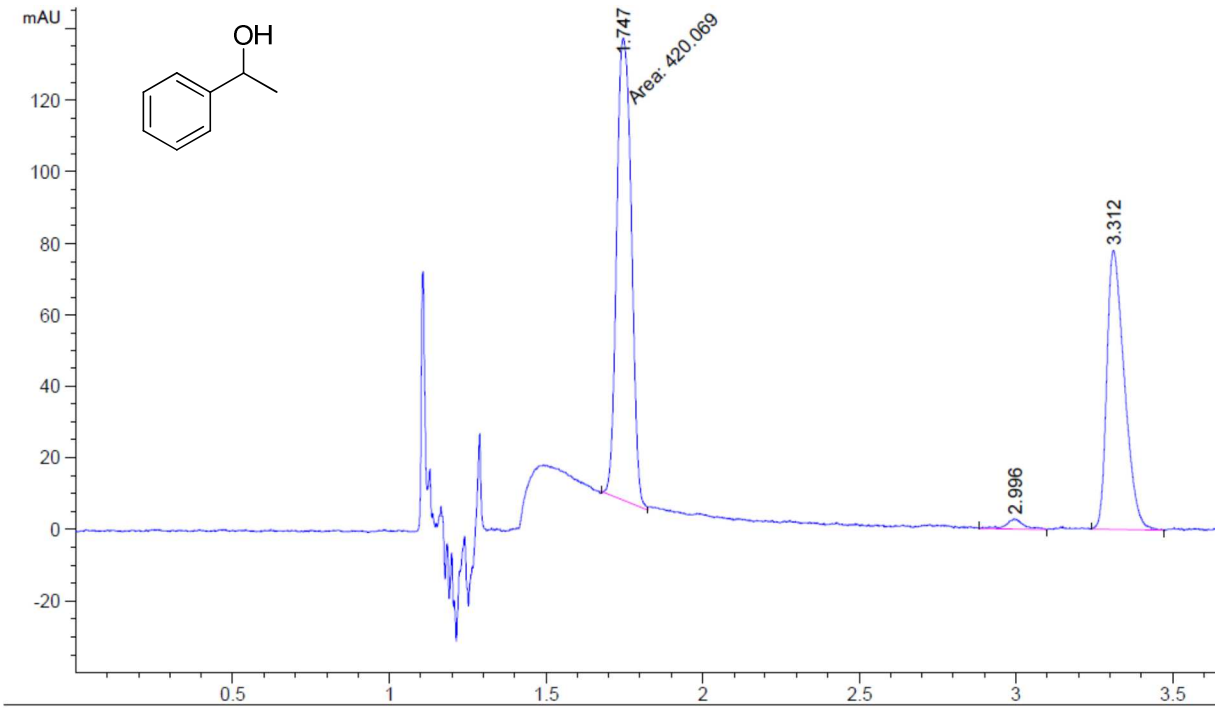
1st cycle



2nd cycle



3rd cycle



7. References

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