Pergamon

Tetrahedron: *Asymmetry* 12 (2001) 2043–2047

TETRAHEDRON: *ASYMMETRY*

Efficient synthesis of optically active β-hydroxy *p*-tolylsulfones with very high enantiomeric excess via CBS–oxazaborolidine-catalyzed borane reduction

Byung Tae Cho* and Dong Jun Kim

Department of Chemistry, Hallym University, Chunchon 200-702, Republic of Korea

Received 16 July 2001; accepted 9 August 2001

Abstract—A simple, efficient synthesis of optically active β-hydroxy *p*-tolylsulfones with >99% e.e. by employing CBS–oxazaborolidine-catalyzed asymmetric borane reduction of β-keto *p*-tolylsulfones using *N*-ethyl-*N*-*iso*-propylaniline–borane complex as the borane carrier has been established.

1. Introduction

Optically active β-hydroxy phenyl or *p*-tolylsulfones are extremely useful chiral building blocks for the synthesis of a variety of chiral organic compounds, because the α-carbon atom of arylsulfonyl groups of the compounds can be further functionalized and, moreover, the sulfonyl groups can be easily removed from the skeleton without racemization.[1,2] Indeed, they have been successfully used as starting materials in the synthesis of optically active γ-butenolides,[2a–c] γ-butyrolactones,[2b–d] δ-valerolactones,[2c] 2,5-disubstituted tetrahydrofurans[2e] and allylic alcohols.[2f] Methods for the synthesis of β-hydroxy phenyl or *p*-tolylsulfones include the asymmetric reduction of β-keto sulfones using mediated by either baker's yeast[3,4] or a fungus cell,[5] the Ru(II)-catalyzed enantioselective hydrogenation of β-keto phenylsulfones,[6] kinetic resolution of racemic β-hydroxy sulfones[7] and/or kinetically controlled oxidation of racemic β-hydroxy sulfoxides[8] using biocatalysts. However, baker's yeast-mediated reduction of β-keto sulfones was highly dependent on the size of the groups adjacent to the carbonyl group. For example, the reduction of 1-phenylsulfonyl-2-propanone provided the corresponding β-hydroxy sulfone with 95% e.e. In contrast, the reduction of 1-phenylsulfonyl-2-heptanone and 1-phenylsulfonyl-2-phenylethanone afforded the product β-hydroxy sulfones with 10% e.e.[4] and 15% e.e.,[2e] respectively and 1-phenylsulfonyl-2-octanone was not reduced by baker's yeast.[9] In the case of catalytic enantioselective hydrogenation, the reduction of aromatic keto analogues required high pressure condition (75 bar) to obtain high optical purity. Kinetic resolution and oxidation of racemic substrates by biocatalysts both suffer from the fact that the theoretical yields are limited to 50%.

Recently, we have reported highly efficient oxazaborolidine-catalyzed asymmetric borane reductions of α-functionalized ketones, including α-sulfonyloxy ketones,[10a,b] α-triorganosilyloxy- or α-tetrahydropyranyloxy ketones[10c,d] and α-keto acetals.[10e,f] From these studies, we have found that the use of *N*-ethyl-*N*-*iso*-propylaniline–borane complex **2** instead of borane–tetrahydrofuran, borane–dimethyl sulfide and catechol borane commonly employed as borane carriers for such a reduction is more useful for large-scale applications. As part of an ongoing program on the asymmetric reduction of functionalized ketones, we have recently studied an efficient synthesis of optically active alcohols containing a sulfur functionality via asymmetric reduction.[11] We wish to report herein a convenient synthesis of optically active β-hydroxy *p*-tolylsulfones with very high enantiomeric purity via oxazaborolidine-catalyzed asymmetric reduction using the amine–borane reagent **2** as borane carrier.

2. Results and discussion

We selected a commercially available CBS–oxazaborolidine **1**[12] as a representative catalyst. The reduction was carried out by slow addition of β-keto *p*-tolylsulfones **3** over 1 h to a solution of 1.0 equiv. of the reagent **2** in the presence of 10 mol% of **1** in THF at

* Corresponding author. E-mail: btcho@sun.hallym.ac.kr

0957-4166/01/$ - see front matter
PII: S0957-4166(01)00359-7

25°C. The reduction afforded the corresponding β-hydroxy sulfones **4** in high yields (Scheme 1). The e.e.s of the products were determined by HPLC analysis using Chiralcel OD, Chiralcel OD-H and Whelk-O1 columns. As shown in Table 1, the reduction of aromatic β-keto sulfones **3a**–**g** bearing phenyl, *p*-substituted phenyl (*p*-XC_6H_4; X = Me, MeO, F, Cl and NO_2) and 2-naphthyl groups furnished the corresponding β-hydroxy sulfones **4a**–**g** with very high enantioselectivity (approaching 100% e.e.). Inductive effects of the substituent groups of phenyl ring on the enantioselectivity were not observed (entries 1–6). For a heterocyclic analogue bearing a furan ring, we also obtained the product **4h** with very high enantiomeric excess. Although the reduction of aliphatic analogues having ethyl and *n*-undecyl groups gave products with somewhat lower e.e.s compared with those obtained from the aromatic analogues, the case of more hindered aliphatic analogues containing *tert*-butyl and cyclohexyl groups again proceeded with very high enantioselectivities (entries 9–12). Interestingly these results indicate that enantioselection is not significantly affected by the bulk of the *p*-tolylsulfonyl group of the β-keto sulfone. The reason for this is unclear at this time.[15]

3. Conclusion

In summary, we have established a simple and efficient synthetic method for obtaining near enantiopure aromatic and hindered aliphatic β-hydroxy *p*-tolylsulfones by employing CBS–oxazaborolidine-catalyzed asymmetric borane reduction of the corresponding β-keto sulfones using *N*-ethyl-*N*-*iso*-propylaniline–borane complex as the borane carrier. Further applications of this methodology are under investigation and will be reported in due course.

4. Experimental

4.1. General

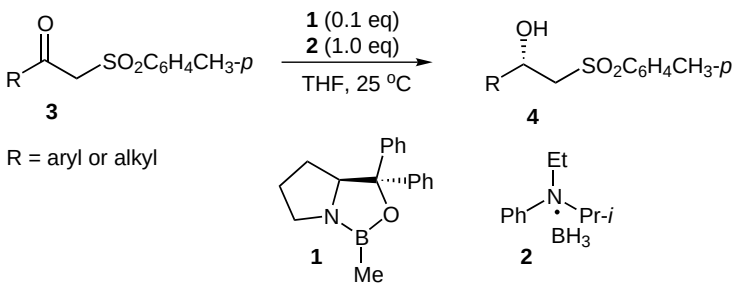
All operations with air-sensitive materials were carried out under a nitrogen atmosphere with oven-dried glassware. Liquid materials were transferred with a double-ended needle. The reactions were monitored by TLC using silica gel plates and the products were purified by flash-column chromatography on silica gel (Merck; 230–400 mesh). NMR spectra were recorded at 400 MHz for ^1H and 100 or 125 MHz for ^{13}C using Me_4Si as the internal standard in $CDCl_3$. Optical rotations were measured with a high-resolution digital polarimeter. Melting points were uncorrected. Enantiomeric excesses (% e.e.) of the product β-hydroxy *p*-tolylsulfones were determined with an HPLC apparatus fitted with a 25 cm Chiralcel OD or OD-H column (Daicel) and a Whelk-O1 column (Regis).

4.2. Materials

Most of the organic compounds utilized in this study were commercial products of the highest purity. They were further purified by distillation when necessary. THF was distilled over sodium benzophenone ketyl and stored in ampules under a nitrogen atmosphere. The CBS reagent **1** and *N*-ethyl-*N*-*iso*-propylaniline–borane complex **2** were purchased from the Aldrich Chemical Company. β-Keto *p*-tolylsulfones **3** were prepared from [(*p*-toluenesulfonyl)methylene]dilithium and the corresponding esters or acid chlorides with sodium *p*-tolylsulfinate according to the known procedure.[13]

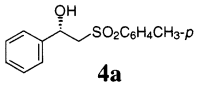
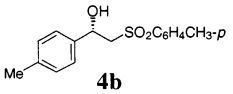
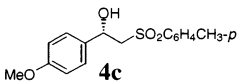
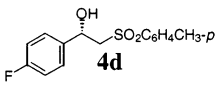
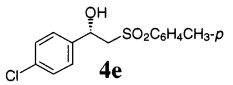
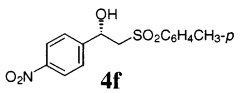
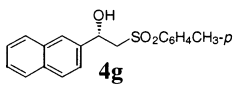
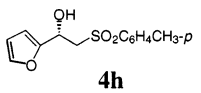
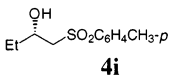
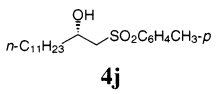
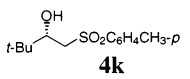
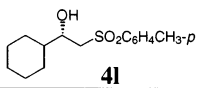
4.3. General procedure for CBS–oxazaborolidine-catalyzed borane reduction of β-keto *p*-tolylsulfones 3

To a solution of **1** (0.2 M, 1.0 mL, 0.2 mmol) in THF was added a solution of *N*-ethyl-*N*-*iso*-propylaniline–borane complex **2** (2.0 M, 1.0 mL, 2.0 mmol) in THF. To this was added slowly a THF solution of **3** (1 M, 2 mL, 2 mmol) over a period of 1 h using a syringe pump at 25°C. After the addition, the reaction mixture was stirred for 10 min, quenched cautiously with methanol (0.5 mL), and stirred for an additional 30 min. The solvent was evaporated under reduced pressure. The crude products **4** obtained were further purified by flash-column chromatography on silica gel (230–400 mesh) using hexane/ethyl acetate (1/1) as the eluent, unless otherwise indicated.



Scheme 1.

Table 1. CBS–oxazaborolidine-catalyzed asymmetric borane reduction of β-keto *p*-tolylsulfones **3**[a]

Entry	Product **4**	Yield (%)[b]	$[\alpha]_D^{20}$ in $CHCl_3$	E.e. (%)	Config
1	 **4a**	98	+20.6 (*c* 1.02)	>99[d]	S[c]
2	 **4b**	98	+11.8 (*c* 1.04)	98[d]	*S*[c]
3	 **4c**	98	+10.8 (*c* 1.12)	98[d]	*S*[c]
4	 **4d**	97	+20.0 (*c* 1.24)	98[d]	*S*[c]
5	 **4e**	98	+10.1 (*c* 1.04)	99[d]	*S*[c]
6	 **4f**	97	+33.7 (*c* 1.07)[h]	98[e]	*S*[c]
7	 **4g**	99	+6.0 (*c* 1.02)	>99[d]	*S*[c]
8	 **4h**	98	+5.8 (*c* 1.02)	97[f]	*S*[c]
9	 **4i**	96	+17.6 (*c* 1.07)	73[g]	*S*[i]
10	 **4j**	97	+11.0 (*c* 1.03)	87[g]	*S*[c]
11	 **4k**	98	+42.5 (*c* 0.97)	99[g]	*S*[c]
12	 **4l**	99	+21.8 (*c* 1.05)	>99[g]	*S*[c]

[a] **[3]**:**[2]**:**[1]** = 1:1:0.1. **[3]** = 0.5 M.
[b] Isolated and purified yields.
[c] The absolute configuration is unknown, but is probably *S* based on comparison of the order of elution of HPLC analysis using a chiral column and the sign of the optical rotation with that of the phenylsulfonyl analogue: Ref. 6.
[d] Determined by HPLC analysis using a Whelk-O1 column; eluent: hexane–*iso*-PrOH 9:1.
[e] Determined by HPLC analysis using a Chiralcel OD-H column; eluent: hexane–*iso*-PrOH 4:1.
[f] Determined by HPLC analysis of its benzoate using a Whelk-O1 column; eluent: hexane–*iso*-PrOH 9:1.
[g] Determined by HPLC analysis using a Chiralcel OD column; eluent: hexane–*iso*-PrOH 9:1.
[h] In acetone.
[i] Based on $[\alpha]_D^{25}$ +16.4 (*c* 2.1, $CHCl_3$), *S*: Ref. 14.

4.3.1. (*S*)-1-Phenyl-2-(*p*-toluenesulfonyl)ethanol 4a. White solid; mp 94–96°C (EtOH); $[\alpha]_D^{20}$ +20.6 (*c* 1.02, $CHCl_3$); HPLC analysis using a Whelk-O1 column showed it to be >99% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, t_R(*S*) 21.84 min and t_R(*R*) 26.12 min]; IR (KBr, cm^{-1}) 3491, 1285, 1135; ^1H NMR (400 MHz, $CDCl_3$): δ 2.40 (s, 3 H), 3.25 (dd, 1 H, *J* = 1.84 and 14.51 Hz), 3.40 (dd, 1 H, *J* = 10.01 and 14.17 Hz), 3.69 (brs, 1 H), 5.18 (dd, 1 H, *J* = 1.6 and 10.11 Hz), 7.19–7.33 (m, 7 H), 7.77 (d, 2 H, *J* = 7.83 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.67, 63.99, 68.44, 125.63, 128.00, 128.30, 128.74, 130.10, 136.11, 140.64, 145.27. Anal. calcd for $C_{15}H_{16}O_3S$: C, 65.19; H, 5.84; S, 11.60. Found: C, 65.14; H, 5.90; S, 11.63%.

4.3.2. (*S*)-1-*p*-Tolyl-2-(*p*-toluenesulfonyl)ethanol 4b. White solid; mp 57–59°C (EtOH); $[\alpha]_D^{20}$ +11.8 (*c* 1.04, $CHCl_3$); HPLC analysis using a Whelk-O1 column showed it to be 98% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, $t_R(S)$ 23.86 min and $t_R(R)$ 31.02 min]; IR (KBr, cm^{-1}) 3502, 1284, 1134; ^1H NMR (400 MHz, $CDCl_3$): δ 2.24 (s, 3 H), 2.39 (s, 3 H), 3.23 (dd, 1 H, J = 2.0 and 14.39 Hz), 3.40 (dd, 1 H, J = 10.51 and 14.39 Hz), 3.59 (brs, 1 H), 5.13 (d, 1 H, J = 10.03 Hz), 7.04–7.11 (m, 4 H), 7.31 (d, 2 H, J = 6.83 Hz), 7.76 (d, 2 H, J = 7.79 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.08, 21.66, 63.96, 68.30, 125.57, 127.99 129.37, 130.05, 136.16, 137.71, 138.10, 145.19. Anal. calcd for $C_{16}H_{18}O_3S$: C, 66.18; H, 6.25; S, 11.04. Found: C, 66.18; H, 6.18; S, 11.14%.

4.3.3. (*S*)-1-*p*-Methoxyphenyl-2-(*p*-toluenesulfonyl)ethanol 4c. White solid; mp 84–86°C (EtOH); $[\alpha]_D^{20}$ +10.8 (*c* 1.12, $CHCl_3$); HPLC analysis using a Whelk-O1 column showed it to be 98% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, $t_R(S)$ 38.45 min and $t_R(R)$ 57.33 min]; IR (KBr, cm^{-1}) 3442, 1302, 1144; ^1H NMR (400 MHz, $CDCl_3$): δ 2.38 (s, 3 H), 3.22 (dd, 1 H, J = 1.70 and 14.39 Hz), 3.40 (dd, 1 H, J = 10.11 and 14.27 Hz), 3.60 (brs, 1 H), 3.70 (s, 3 H), 5.12 (d, 1 H, J = 9.28 Hz), 6.77 (d, 2 H, J = 8.55 Hz), 7.14 (d, 2 H, J = 8.75 Hz), 7.31 (d, 2 H, J = 8.51 Hz), 7.76 (d, 2 H, J = 8.79 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.66, 55.28, 63.94, 68.07, 114.95, 126.95, 127.94, 130.06, 132.81, 136.17, 145.19, 159.52. Anal. calcd for $C_{16}H_{18}O_4S$: C, 62.72; H, 5.92; S, 10.47. Found: C, 62.80; H, 6.01; S, 10.44%.

4.3.4. (*S*)-1-*p*-Fluorophenyl-2-(*p*-toluenesulfonyl)ethanol 4d. White solid; mp 74–76°C (EtOH); $[\alpha]_D^{20}$ +20.0 (*c* 1.24, $CHCl_3$); HPLC analysis using a Whelk-O1 column showed it to be 98% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, $t_R(S)$ 20.09 min and $t_R(R)$ 23.50 min]; IR (KBr, cm^{-1}) 3583, 1298, 1133; ^1H NMR (400 MHz, $CDCl_3$): δ 2.40 (s, 3 H), 3.21 (dd, 1 H, J = 1.96 and 14.15 Hz), 3.37 (dd, 1 H, J = 10.23 and 14.39 Hz), 3.75 (d, 1 H, J = 1.96 Hz), 5.17 (d, 1 H, J = 9.75 Hz), 6.93 (t, 2 H, J = 8.77 Hz), 7.18–7.22 (m, 2 H), 7.32 (d, 2 H, J = 7.55 Hz), 7.76 (d, 2 H, J = 8.55 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.66, 63.94, 67.83, 115.50, 115.72, 127.38, 127.46, 127.98, 130.12, 135.99, 136.44, 136.47, 145.38, 161.24, 163.69. Anal. calcd for $C_{15}H_{15}FO_3S$: C, 61.21; H, 5.14; S, 10.89. Found: C, 61.26; H, 5.07; S, 10.73%.

4.3.5. (*S*)-1-*p*-Chlorophenyl-2-(*p*-toluenesulfonyl)ethanol 4e. White solid; mp 83–85°C (EtOH); $[\alpha]_D^{20}$ +10.1 (*c* 1.04, $CHCl_3$); HPLC analysis using a Whelk-O1 column showed it to be 99% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, $t_R(S)$ 20.97 min and $t_R(R)$ 25.83 min]; IR (KBr, cm^{-1}) 3469, 1283, 1151; ^1H NMR (400 MHz, $CDCl_3$): δ 2.40 (s, 3 H), 3.21 (dd, 1 H, J = 1.84 and 14.27 Hz), 3.35 (dd, 1 H, J = 10.23 and 14.39 Hz), 3.77 (brs, 1 H), 5.16 (dd, 1 H, J = 1.58 and 10.13 Hz), 7.14–7.22 (m, 4 H), 7.31 (d, 2 H, J = 8.03 Hz), 7.75 (d, 2 H, J = 8.55 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.66, 63.78, 67.80, 127.04, 127.95, 128.84, 130.11, 134.00, 135.93, 139.12, 145.39. Anal. calcd for $C_{15}H_{15}ClO_3S$: C, 57.97; H, 4.86; S, 10.32. Found: C, 57.93; H, 4.98; S, 10.39%.

4.3.6. (*S*)-1-*p*-Nitrophenyl-2-(*p*-toluenesulfonyl)ethanol 4f. Light yellow solid; mp 143–145°C (EtOH); $[\alpha]_D^{20}$ +33.7 (*c* 1.07, acetone); HPLC analysis using a Chiralcel OD-H column showed it to be 98% e.e. [*iso*-PrOH/hexane = 1/4, flow rate = 0.5 mL/min, $t_R(R)$ 28.04 min and $t_R(S)$ 30.48 min];IR (KBr, cm^{-1}) 3446, 1343, 1138; ^1H NMR (400 MHz, $CDCl_3$): δ 2.48 (s, 3 H), 3.32 (dd, 1 H, J = 1.84 and 14.32 Hz), 3.43 (dd, 1 H, J = 9.89 and 14.29 Hz), 4.03 (s, 1 H), 5.40 (d, 1 H, J = 9.77 Hz), 7.41 (d, 2 H, J = 8.19 Hz), 7.50 (d, 2 H, J = 8.77 Hz), 7.84 (d, 2 H, J = 8.26 Hz), 8.18 (d, 2 H, J = 8.72 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.68, 63.55, 67.65, 123.92, 126.58, 127.98, 130.25, 135.75, 145.71, 147.62, 147.69. Anal. calcd for $C_{15}H_{15}NO_5S$: C, 56.06; H, 4.70; N, 4.36; S, 9.98. Found: C, 56.07; H, 4.67; N, 4.41; S, 9.93%.

4.3.7. (*S*)-1-(2-Naphthyl)-2-(*p*-toluenesulfonyl)ethanol 4g. White solid; mp 122–124°C (EtOH); $[\alpha]_D^{20}$ +6.0 (*c* 1.02, $CHCl_3$); HPLC analysis using a Whelk-O1 column showed it to be >99% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, $t_R(S)$ 23.80 min and $t_R(R)$ 41.64 min]; IR (KBr, cm^{-1}) 3503, 1283, 1135; ^1H NMR (400 MHz, $CDCl_3$): δ 2.44 (s, 3 H), 3.40 (dd, 1 H, J = 1.86 and 14.34 Hz), 3.55 (dd, 1 H, J = 9.91 and 14.36 Hz), 3.84 (brs, 1 H), 5.41 (d, 1 H, J = 9.83 Hz), 7.33–7.36 (m, 3 H), 7.44–7.49 (m, 2 H), 7.77–7.84 (m, 6 H); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.66, 63.90, 68.63, 123.29, 124.77, 126.28, 126.42, 127.67, 127.99, 128.02, 128.66, 130.08, 133.13, 133.18, 135.17, 137.97, 145.25. Anal. calcd for $C_{19}H_{18}O_3S$: C, 69.91; H, 5.56; S, 9.82. Found: C, 69.89; H, 5.60; S, 9.85%.

4.3.8. (*S*)-1-(2-Furyl)-2-(*p*-toluenesulfonyl)ethanol 4h. White solid; mp 75–77°C (EtOH); $[\alpha]_D^{20}$ +5.8 (*c* 1.02, $CHCl_3$); HPLC analysis of its benzoate using a Whelk-O1 column showed it to be 97% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 1.0 mL/min, $t_R(S)$ 41.77 min and $t_R(R)$ 47.71 min]; IR (KBr, cm^{-1}) 3469, 1298, 1146; ^1H NMR (400 MHz, $CDCl_3$): δ 2.46 (s, 3 H), 3.51 (dd, 1 H, J = 2.44 and 14.46 Hz), 3.56 (brs, 1 H), 3.64 (dd, 1 H, J = 9.56 and 14.38 Hz), 5.25 (d, 1 H, J = 9.27 Hz), 6.28–6.31 (m, 2 H), 7.30 (d, 1 H, J = 0.73 Hz), 7.39 (d, 2 H, J = 8.16 Hz), 7.81 (d, 2 H, J = 8.23 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 22.07, 61.07, 63.19, 107.70, 110.84, 128.46, 130.47, 136.49, 142.99, 145.66, 152.99. Anal. calcd for $C_{13}H_{14}O_4S$: C, 58.63; H, 5.30; S, 12.04. Found: C, 58.70; H, 5.42; S, 12.00%.

4.3.9. (*S*)-1-(*p*-Toluenesulfonyl)butan-2-ol 4i. Colorless viscous oil; $[\alpha]_D^{20}$ +17.6 (*c* 1.07, $CHCl_3$); HPLC analysis using a Chiralcel OD column showed it to be 73% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 0.5 mL/min, $t_R(S)$ 33.02 min and $t_R(R)$ 37.00 min]; IR (neat, cm^{-1}) 3505, 2932, 1288, 1141; ^1H NMR (400 MHz, $CDCl_3$): δ 0.92 (t, 3 H, J = 7.45 Hz), 1.53–1.63 (m, 2 H), 2.47 (s, 3 H), 3.17–3.20 (m, 2 H), 3.37 (d, 1 H, J = 2.23 Hz), 4.06 (m, 1 H), 7.38 (d, 2 H, J = 8.20 Hz), 7.81 (d, 2 H, J = 8.32 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 9.34, 21.69, 29.46, 62.03, 67.18, 127.98, 130.12, 136.35, 145.18. Anal. calcd for $C_{11}H_{16}O_3S$: C, 57.87; H, 7.06; S, 14.05. Found: C, 57.89; H, 7.07; S, 13.96%.

4.3.10. (*S*)-1-(*p*-Toluenesulfonyl)tridecan-2-ol 4j. White solid; mp 51–53°C (80% EtOH); $[\alpha]_D^{20}$ +11.0 (*c* 1.03, $CHCl_3$); HPLC analysis using a Chiralcel OD column showed it to be 87% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 0.6 mL/min, $t_R(S)$ 19.28 min and $t_R(R)$ 24.71 min]; IR (neat) 3530, 2921, 1284, 1138; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.80 (t, 3 H, J = 6.94 Hz), 1.16–1.56 (m, 20 H), 2.40 (s, 3 H), 3.06–3.16 (m, 2 H), 3.31 (d, 1 H, J = 2.44 Hz), 4.05 (m, 1 H), 7.31 (d, 2 H, J = 8.80 Hz), 7.74 (d, 2 H, J = 8.55 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 14.10, 21.65, 22.66, 24.94, 29.28, 29.31, 29.44, 29.49, 29.58, 31.88, 36.39, 62.28, 65.95, 127.92, 130.06, 136.27, 145.11. Anal. calcd for $C_{20}H_{34}O_3S$: C, 67.75; H, 9.67; S, 9.04. Found: C, 67.52; H, 9.87; S, 9.29%.

4.3.11. (*S*)-1-(*p*-Toluenesulfonyl)-3,3-dimethylbutan-2-ol 4k. White solid; mp 66–67°C (80% EtOH); $[\alpha]_D^{20}$ +42.5 (*c* 0.97, $CHCl_3$); HPLC analysis using a Chiralcel OD column showed it to be 99% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 0.6 mL/min, $t_R(S)$ 15.62 min and $t_R(R)$ 18.63 min]; IR (KBr, cm^{-1}) 3530, 1280, 1135; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.90 (s, 9 H), 2.40 (s, 3 H), 3.03 (dd, 1 H, J = 9.87 and 14.27 Hz), 3.16 (s, 1 H), 3.19 (brs, 1 H), 3.68(d, 1 H, J = 10.99 Hz), 7.32 (d, 2 H, J = 7.31 Hz), 7.75 (d, 2 H, J = 9.03 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.66, 25.35, 34.85, 58.80, 73.21, 127.93, 130.04, 136.20, 145.05. Anal. calcd for $C_{13}H_{20}O_3S$: C, 60.91; H, 7.86; S, 12.51. Found: C, 60.92; H, 7.95; S, 12.48%.

4.3.12. (*S*)-1-Cyclohexyl-2-(*p*-toluenesulfonyl)ethanol 4l. White solid, mp 72–73°C (80% EtOH); $[\alpha]_D^{20}$ +21.8 (*c* 1.05, $CHCl_3$); HPLC analysis using a Chiralcel OD column showed it to be >99% e.e. [*iso*-PrOH/hexane = 1/9, flow rate = 0.6 mL/min, $t_R(S)$ 22.34 min and $t_R(R)$ 26.74 min]; IR (KBr, cm^{-1}) 3514, 2927, 1288, 1140; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.87–1.17 (m, 5 H), 1.29–1.46 (m, 1 H), 1.54–1.67 (m, 5 H), 2.39 (s, 3 H), 3.11 (s, 1 H), 3.13 (d, 1 H, J = 1.20 Hz), 3.21 (d, 1 H, J = 2.92 Hz), 3.83–3.87 (m, 1 H), 7.31 (d, 2 H, J = 7.55 Hz), 7.74 (d, 2 H, J = 8.27 Hz); ^{13}C NMR (100, MHz, $CDCl_3$): δ 21.65, 25.86, 25.95, 26.21, 27.51, 28.44, 43.10, 60.29, 69.78, 127.91, 130.03, 136.25, 145.06. Anal. calcd for $C_{15}H_{22}O_3S$: C, 63.80; H, 7.85; S, 11.35. Found: C, 63.78; H, 7.97; S, 11.48%.

Acknowledgements

This work was supported from Grant No. 2000-1-12300-002-1 from the Basic Research Program of the Korea Science and Engineering Foundation.

References

1. Metzner, P.; Thuillier, A. *Sulfur Reagents in Organic Synthesis*; Academic Press: New York, 1994.
2. (a) Solladié, G.; Frechou, C.; Demailly, G.; Greck, C. *J. Org. Chem.* **1986**, *51*, 1912–1914; (b) Robin, S.; Huet, F.; Fauve, A.; Veschambre, H. *Tetrahedron: Asymmetry* **1993**, *4*, 239–246; (c) Kozikowski, A. P.; Mugrage, B. B.; Li, C. S.; Felder, L. *Tetrahedron Lett.* **1986**, *27*, 4817–4820; (d) Sato, T.; Okumura, Y.; Itai, J.; Fujisawa, T. *Chem. Lett.* **1988**, 1537–1540; (e) Tanikaga, R.; Hosoya, K.; Kaji, A. *J. Chem. Soc., Perkin Trans. 1* **1987**, 1799–1803; (f) Tanikaga, R.; Hosoya, K.; Kaji, A. *Chem. Lett.* **1987**, 829–832.
3. For reviews, see (a) Servi, S. *Synthesis* **1990**, 1–25; (b) Csuk, R.; Glänzer, B. I. *Chem. Rev.* **1991**, *91*, 49–97; (c) Robert, S. M. *J. Chem. Soc., Perkin Trans. 1* **1999**, 1–21.
4. Crumbie, R. L.; Deol, B. S.; Nemorin, J. E.; Ridley, D. D. *Aust. J. Chem.* **1978**, *31*, 1965–1980.
5. Goto, V.; Rebolledo, F.; Liz, R. *Tetrahedron: Asymmetry* **2001**, *12*, 513–515.
6. Bertus, P.; Phansavath, P.; Ratovelomanana-Vidal, V.; Genêt, J.-P.; Touati, A. R.; Homri, T.; Ben Hassine, B. *Tetrahedron Lett.* **1999**, *40*, 3175–3178 and *Tetrahedron: Asymmetry* **1999**, *10*, 1369–1380.
7. Chinchilla, R.; Nájera, C.; Pardo, J.; Yus, M. *Tetrahedron: Asymmetry* **1990**, *1*, 575–578.
8. Ohta, H.; Kato, Y.; Tsuchihashi, G. *J. Org. Chem.* **1987**, *52*, 2735–2739.
9. Nakmura, K.; Ushio, K.; Oka, S.; Ohno, A.; Yasui, S. *Tetrahedron Lett.* **1984**, *25*, 3979–3982.
10. (a) Cho, B. T.; Yang, W. K.; Choi, O. K. *J. Chem. Soc., Perkin Trans. 1* **2001**, 1204–1211; (b) Choi, O. K.; Cho, B. T. *Org. Proc. Prep. Int.* **2000**, *32*, 493–497; (c) Cho, B. T.; Chun, Y. S. *J. Org. Chem.* **1998**, *63*, 5280–5282; (d) Cho, B. T.; Chun, Y. S. *Tetrahedron: Asymmetry* **1999**, *10*, 1843–1846; (e) Cho, B. T.; Chun, Y. S. *Bull. Korean Chem. Soc.* **1999**, *20*, 397; (f) Cho, B. T.; Chun, Y. S. *J. Chem. Soc., Perkin Trans. 1* **1999**, 2095–2100.
11. For a recent review, see: Cho, B. T.; Chun, Y. S. In *Organoboranes for Syntheses (ACS Symposium Series 783)*; Ramachandran, P. V.; Brown, H. C., Eds.; American Chemical Society: Washington, DC, 2001; Chapter 8, pp. 122–135.
12. Corey, E. J.; Bakshi, R. K.; Shibata, S.; Chen, C.-P.; Singh, V. K. *J. Am. Chem. Soc.* **1987**, *109*, 7925–7926.
13. Thomsen, M. W.; Handwerker, B. M.; Katz, S. A.; Belser, R. B. *J. Org. Chem.* **1988**, *53*, 906–907.
14. Chinchilla, R.; Nájera, C.; Pardo, J.; Yus, M. *Tetrahedron: Asymmetry* **1990**, *1*, 575–578.
15. In the same reduction of α-oxygenated prochiral ketones, such as α-sulfonyloxy ketones,[10a,b] α-siloxy ketones[10c,d] and α-keto acetals,[10e,f] we also observed that the effects of the size of the oxygen-containing groups on enantioselection was insignificant.