Available online at www.sciencedirect.com
SCIENCE DIRECT
Tetrahedron: Asymmetry
Tetrahedron: *Asymmetry* 17 (2006) 330–335

Catalytic asymmetric epoxidation of chalcones under poly(ethylene glycol)-supported *Cinchona* ammonium salt catalyzed conditions

Jian Lv, Xin Wang, Juyan Liu, Liping Zhang and Yongmei Wang*

Department of Chemistry, The State Key Laboratory of Elemento-Organic Chemistry, Nankai University, 300071 Tianjin, China

Received 8 November 2005; revised 27 January 2006; accepted 27 January 2006

Abstract—Dimeric cinchonine, cinchonidine, and quinine have been anchored (via nitrogen) to long linear PEG chains to afford soluble polymer-supported chiral ammonium salts, which were employed as phase-transfer catalysts in the asymmetric epoxidation of chalcones. The highest enantiomeric excess obtained was 86%.

1. Introduction

Optically active epoxides are compounds of well-known interest, and their synthesis by simple and easily scalable procedures represent an important asymmetric challenge that has initiated the development of numerous methodologies, since the asymmetric epoxidation of allylic alcohols, which was reported by Sharpless et al. in 1980.[1] Amongst them, a method utilizing chiral phase-transfer catalysis (PTC) occupies a unique place, featuring many clear synthetic advantages for large-scale procedures including easily available and re-usable chiral catalysts, and environmental benefits.[2] The PTC methodology was applied to the asymmetric epoxidation of electron-deficient olefins and is probably the most simple and easy to scale up. Thus, the advent in the mid 1970s of enantioselective epoxidation of electron-deficient olefins under PTC conditions catalyzed by quaternized *Cinchona* alkaloids,[2c] pioneered by Wynberg et al.[3] and improved by Lygo[4] and Corey,[5] allowed us to obtain impressive degrees of enantioselection using a very simple procedure. Moreover, dimeric *Cinchona* alkaloid-derived catalysts with surfactants,[6] as well as non-*Cinchona*-derived species, such as spiro ammonium salts,[7] polyamino acids,[8] lanthanoid–binaphthol complexes,[9] and chiral crown ethers derived from D-glucose, D-galactose, and D-mannitol[10] have also been used in this kind of asymmetric PTC epoxidation.

Attaching the alkaloid-derived chiral catalysts to a soluble polymers can be considered as the next step beyond development of the PTC methodology due to the ease of separation, possible recycling, good stability and reduced toxicity; the preparation and uses of all kinds of supported reagents will be applied widely in asymmetric catalytic synthesis in the future.[11] Although PEG-supported *Cinchona* alkaloid ligands have been extensively studied for catalytic asymmetric dihydroxylation,[11b,12] only limited studies on asymmetric PTC using those ammonium salt derivatives have been carried out. Our group[13] and Najera et al.[14] have anchored *Cinchona* alkaloids to cross-linked polystyrene for the asymmetric alkylation of benzophenone imine-derived glycine esters. Moreover, Cahard et al.[15] and Benaglia et al.[16] reported the same reaction using PEG-supported chiral *Cinchona* alkaloids. Moreover, for our part, dimeric cinchonine has recently been N-anchored to a long linear PEG chain affording soluble polymer-supported chiral ammonium salts, which were first employed as phase-transfer catalysts in the asymmetric epoxidation of chalcones. The highest enantiomeric excess obtained was 57%.[17]

In this context, we herein report an account of our ongoing studies towards the synthesis of three soluble polymeric PTC catalysts for the asymmetric epoxidation reaction. We also show the N-anchored versions of some

* Corresponding author. Tel./fax: +86 22 2350 2654; e-mail: ymw@nankai.edu.cn

0957-4166/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.tetasy.2006.01.029

natural *Cinchona* alkaloids to long linear chemical modified PEG, and the use of these supported ammonium salts as chiral PTC catalysts in the enantioselective epoxidation of chalcones. Our aim is to provide the best soluble polymeric PTC catalysts, which are to be used in the asymmetric epoxidation of chalcones.

2. Results and discussion

Resin-supported ammonium salts **2a** and **2b** (Fig. 1) were obtained by reaction of diacetamido-PEG_{2000} chloride[18] with an excess (2 equiv) of cinchonidine and quinine, respectively, in refluxing chloroform. After filtration and washing thoroughly diethyl ether, polymer-supported quaternary ammonium chlorides **2a** and **2b** were obtained. Moreover, the cinchonine-derived PEG resin-supported ammonium salt **1** (Fig. 1) was also obtained, as cinchonine has been considered a *pseudoenantiomer* of cinchonidine, its use therefore being a simple way of achieving opposite enantioselection.

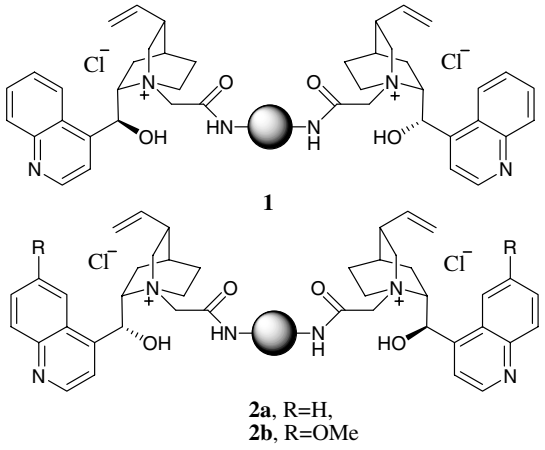


Figure 1.

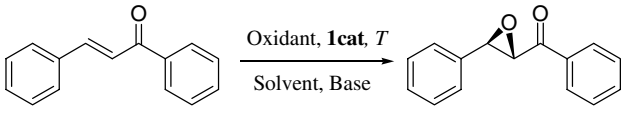
Polymers **1** and **2** were tested as soluble PTC catalysts (0.05 equiv) in the liquid/liquid biphase epoxidation reaction of chalcone derivatives **5** in an organic solvent and using an aqueous base. The search for the optimum reaction conditions was performed using a model epoxidation reaction of chalcone **5a**, and cinchonine-supported salt **1** as PTC catalysts (Table 1).

Thus, when using H_2O_2, *t*-BuOOH and cumylhydroperoxide, respectively, in a system formed by dichloromethane and a 0.25 mL aqueous KOH (1 M) solution at 0 °C, chalcone **5a** was obtained in 34%, 75%, and 42% ee, respectively (Table 1, entries 1–3). However, when the reaction was carried out with NaClO, no product **6a** was obtained (Table 1, entry 4). Thus, *t*-BuOOH was chosen as an oxidant for subsequent epoxidation reactions.

Next, we investigated the effect of solvents and found that dichloromethane was the best choice of solvent (Table 1, entry 2), the use of toluene (Table 1, entry 8) gave rise to lower ee values, whereas coordinating solvents such as THF afforded 6% ee (Table 1, entry 9).

In addition, different alkaline bases, in dichloromethane as an organic solvent at 0 °C were examined (Table 1, entries 2 and 5–7), 0.25 mL KOH (1 M) affording the higher ee (Table 1, entry 2), whereas the use of 2 μL KOH (1 M) gave racemic product. Moreover, solid $LiOH{\cdot}H_2O$ and Cs_2CO_3 were also employed as a base in dichloromethane, respectively, although affording only 30% and 16% ee of compound **6a** (Table 1, entries 6 and 7). Finally, lowering or raising the reaction temperature (−78 °C, Table 1, entry 11 or 25 °C, Table 1, entry 10) gave a notable decrement in the enantioselectivity. Thus, when the model epoxidation reaction was

Table 1. Enantioselective epoxidation of **5a** using polymeric catalyst **1** under PTC conditions

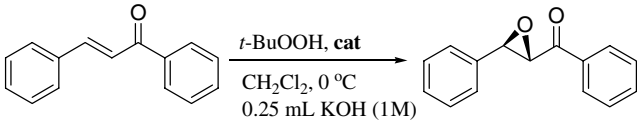


5a **6a**

Entry	Oxidant	Solvent	Base	*T* (°C)	*t* (h)	Yield[a] (%)	ee[b] (%)
1	H_2O_2	CH_2Cl_2	0.25 mL KOH (1 M)	0	48	76	34
2	*t*-BuOOH	CH_2Cl_2	0.25 mL KOH (1 M)	0	48	96	75
3	Cumylhydroperoxide	CH_2Cl_2	0.25 mL KOH (1 M)	0	48	87	42
4	NaOCl	CH_2Cl_2	0.25 mL KOH (1 M)	0	48	Trace	—
5	*t*-BuOOH	CH_2Cl_2	2 μL KOH (1M)	0	48	<8	—
6	*t*-BuOOH	CH_2Cl_2	10.5 mg $LiOH{\cdot}H_2O$(s)	0	48	93	30
7	*t*-BuOOH	CH_2Cl_2	81.5 mg Cs_2CO_3(s)	0	48	58	16
8	*t*-BuOOH	PhMe	0.25 mL KOH (1 M)	0	48	23	11
9	*t*-BuOOH	THF	0.25mL KOH (1 M)	0	16	74	6
10	*t*-BuOOH	CH_2Cl_2	0.25 mL KOH (1 M)	25	48	95	57
11	*t*-BuOOH	CH_2Cl_2	0.25 mL KOH (1 M)	−78	48	58	16

[a] Crude yield determined by ^1H NMR (300 MHz).
[b] Determined by HPLC (Chiralcel OD, hexane/isopropanol, 95:5, 0.8 mL/min, 23 °C, 254 nm), the absolute configuration was (α*S*,β*R*).

Table 2. Enantioselective epoxidation of **5a** using polymeric catalysts **1**–**4** under PTC conditions



5a **6a**

Entry	Cat.	Yield[a] (%)	Config.	ee[b] (%)
1	**1**	96	α*S*,β*R*	75
2	**2a**	78	α*R*,β*S*	23
3	**2b**	90	α*R*,β*S*	86
4	**3**	54	α*R*,β*S*	15
5	**4**	62	α*S*,β*R*	20

[a] Crude yield determined by ^{1}H NMR (300 MHz).
[b] Determined by HPLC (Chiralcel OD, hexane/isopropanol, 95:5, 0.8 mL/min, 23 °C, 254 nm).

performed at 0 °C (ice bath temperature) the enantioselection was 75% ee (Table 1, compare entries 2, 10, and 11).

With all these optimized parameters, we performed the enantioselective model epoxidation of **5a** using polymeric PTC catalysts **2a** and **2b** (Table 2). The polymeric ammonium salt **2a** seemed to be lower than **1**. Thus, when the polymeric **2a** was used as a PTC catalyst in the epoxidation reaction of **5a**, a much lower ee was obtained for **6a** compared to when the polymeric catalyst **1** was used (Table 2, compare entries 1 and 2). Moreover, the polymeric ammonium salt from quinine **2b** proved to be superior to cinchonine as a PTC catalyst, as shown in the good enantioselectivity achieved for **6a** when **2b** was employed (Table 2, entry 3), and the enantioselection rose to 86% ee.

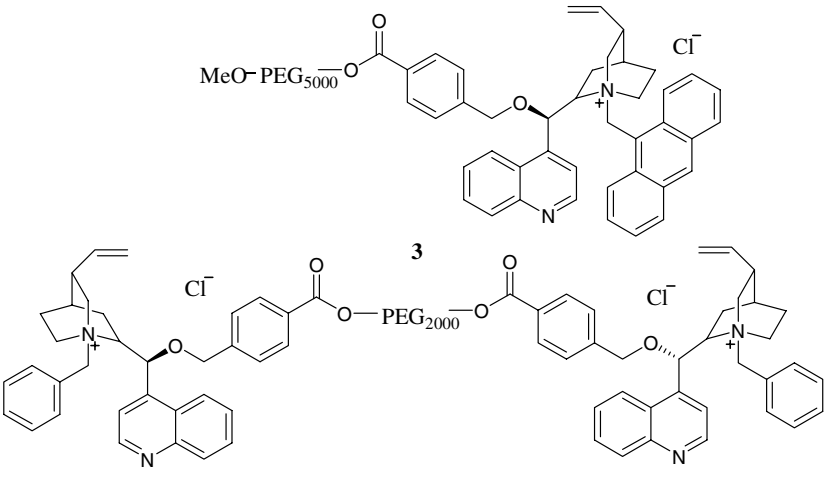
We were also interested in PTC catalysts **3** and **4** (Fig. 2), which were reported to be used in the asymmetric synthesis of α-amino acids.[15] Using the polymeric ammonium salts **3** and **4** seemed to give a notable decrease in the enantioselectivity (Table 2, entries 4 and 5), although they have a good capacity for enantioselection in the asymmetric synthesis of α-amino acids.

The next step was the use of *t*-BuOOH in the epoxidation reaction of various chalcone derivatives using **2b** as the highest enantioselective supported PTC catalysts with 0.25 mL aqueous KOH (1 M) as a base, dichloromethane as a solvent and at 0 °C (Table 3).

Interestingly, all other chalcone derivatives afforded lower ees than the formerly employed **5a** (Table 3). In addition, when positioned on the different groups were aromatic ring (Table 3), a certain dependence upon electronic effects was observed; the presence of a nitro group giving rise to 57% ee (Table 3, entries 2 and 3), whereas a methyl group affording only 49% ee (Table 3, entry 6) and a methoxy group (Table 3, entry 7) giving racemic products. On the other hand, β-alkylated enone **5j** was also easily transformed into the corresponding epoxide, but afforded only 19% (Table 3, entry 10). Moreover, the product of α-naphthoquinone (Table 3, entry 8) and flavone (Table 3, entry 9) were not obtained. PTC catalyst **2b** was separated by adding ether after the reaction and was reused up to three times with almost no loss of activity (Table 3, see footnote b).

3. Conclusion

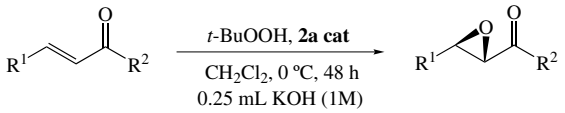
We have prepared chiral polymeric ammonium salts by anchoring a number of *Cinchona*-derived alkaloids to diacetamido-PEG$_{2000}$ chloride. All these ammonium salts have been employed as soluble supported chiral PTC catalysts for the asymmetric epoxidation of chalcones achieving moderate enantioselectivities. The best ees of (α*R*,β*S*)-**6a** (86% ee) were achieved using resin-supported quininium salt **2b**. Furthermore, it was proven that using PTC catalysts **3** and **4**, which were reported to be used in the asymmetric synthesis of α-amino acids, were not suitable for the expoxidation reaction of chalcones, giving lower enantioselectivities.



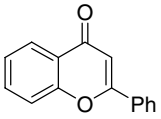
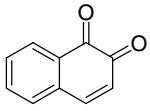
3 **4**

Figure 2.

Table 3. Enatioselective epoxidation of chalcone derivatives **5** using polymeric catalysts **2a** under PTC conditions



5a-j **6a-j**

Entry	R^1	R^2	No.	Yield[a] (%)	ee (%)
1[b]	Ph	Ph	**6a**	90	86
2	3-NO_2–C_6H_4	Ph	**6b**	72	57
3	4-NO_2–C_6H_4	Ph	**6c**	55	57
4	4-Me–C_6H_4	Ph	**6d**	86	49
5	4-MeO–C_6H_4	Ph	**6e**	Trace	—
6	4-Cl–C_6H_4	Ph	**6f**	93	33
7	Ph	4-MeO–C_6H_4	**6g**	77	35
8			**6h**	Trace	—
9			**6i**	Trace	—
10[b]	*i*-Pr	Ph	**6j**	85	19

[a] Crude yield determined by ^{1}H NMR (300 MHz).
[b] Reused up to three times with only 3% lowering in yield and ee between first and third run.

All these supported PTC catalysts could be easily separated from the reaction mixture and reused.

4. Experimental

All the reagents and solvents employed were of the best grade available and used without further purification. The ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AC-P300 instrument in $CDCl_3$. Melting points were determined using an electrothermal apparatus and are uncorrected. Optical rotations were measured on a Perkin–Elmer 341 Polarimeter at 20 °C. Catalysts **3** and **4** were prepared according to reported procedures and the NMR results were consistent to those of the literature.[15] Enones **5a–g** were prepared via aldol condensation according to reported procedures.[19] Enone **5j** was prepared via Wittig reaction again using standard conditions.[20] Enantiomeric excesses were determined by HPLC using Daicel Chiralcel OD, AD-H, OD-H columns with racemic epoxides as standards.

4.1. General procedure for the synthesis of soluble resin-supported ammonium salts 1, 2a, and 2b

To a suspension of cinchonine, cinchonidine, or quinine (2 mmol) in chloroform (20 mL) was added diacetamido-PEG_{2000} chloride (0.5 equiv), and the mixture was stirred at reflux for 100 h. The reaction mixture was cooled to room temperature and the solid was filtered, evaporated in vacuo. Diethyl ether (25 mL) was added in the residue, frozen, and the solid was filtered. The crude product thus obtained was crystallized from dichloromethane–diethyl ether mixture to afford the polymer-supported ammonium salts.

4.1.1. Polymeric ammonium salt 1. A red solid, mp 44–46 °C; $[\alpha]_D^{20} = +45.3$ (*c* 0.4, CH_2Cl_2); IR (KBr) *v* 3404, 3210, 3040, 2956, 1690, 1637, 1590, 1510, 1462, 1425, 1386, 1310, 931, 855, 779 cm^{-1}; ^{1}H NMR: δ 9.39–9.36 (m, 2H), 8.92 (d, 2H, $J = 4.5$ Hz), 8.07–7.92 (m, 4H), 7.85 (d, 2H, $J = 4.5$ Hz), 7.63–7.50 (m, 4H), 6.01–5.82 (m, 2H), 5.57 (d, 2H, $J = 14.7$ Hz), 5.31–5.25 (m, 4H), 4.77–4.64 (m, 4H), 4.46–4.41 (m, 2H), 4.17–4.06 (m, 4H), 3.90–3.86 (m, 2H, PEG), 3.65–3.54 (m, PEG), 3.45–3.39 (m, 2H, PEG), 2.78–2.46 (m, 6H), 2.27–2.19 (m, 2H), 1.97–1.77 (m, 6H), 0.96–0.85 (m, 4H); ^{13}C NMR: δ 163.9, 139.4, 138.6, 135.1, 131.8, 128.7, 124.8, 123.9, 123.8, 118.7, 110.0, 103.0, 70.8, 70.0, 65.9, 61.9, 59.6, 55.7, 38.3, 27.1, 24.1, 21.2.

4.1.2. Polymeric ammonium salt 2a. A light yellow solid, mp 48–50 °C; $[\alpha]_D^{20} = -15.6$ (*c* 0.4, CH_2Cl_2). IR (KBr) *v* 3422, 3218, 3068, 2885, 1678, 1590, 1510, 1467, 1360, 1344, 1281, 1242, 1112, 1061, 963, 842, 779 cm^{-1}; ^{1}H NMR: δ 9.37–9.34 (m, 2H), 8.92 (d, 2H, $J = 4.5$ Hz), 8.10 (d, 2H, $J = 8.4$ Hz), 7.97 (d, 2H,$J = 7.5$ Hz), 7.83 (d, 2H, $J = 4.5$ Hz), 7.66 (d, 2H, $J = 8.1$ Hz), 7.59 (d, 2H, $J = 6.9$ Hz), 5.58–5.44 (m, 2H), 5.24 (d, 2H, $J = 17.1$ Hz), 5.00 (d, 2H, $J = 10.2$ Hz), 4.92–4.89 (m, 2H), 4.79–4.71 (m, 2H), 4.42–4.27 (m, 4H), 3.89–3.71 (m, 2H, PEG), 3.66–3.53 (m, PEG), 3.41–3.37 (m, 2H, PEG), 2.77–2.76 (m, 2H), 2.26–1.92 (m, 16H), 1.15–1.07 (m, 2H), 0.81–0.76 (m,

2H); ^{13}C NMR: δ 164.6, 139.1, 136.9, 136.8, 130.3, 128.1, 124.8, 123.6, 123.1, 117.4, 110.0, 106.4, 70.7, 69.0, 65.7, 65.0, 61.8, 59.8, 56.4, 38.0, 26.3, 25.7, 21.9.

4.1.3. Polymeric ammonium salt 2b. A light brown solid, mp 45–46 °C; $[\alpha]_D^{20} = -20.2$ (c 0.4, CH_2Cl_2). IR (KBr) ν 3421, 3210, 3077, 2884, 1677, 1621, 1588, 1560, 1508, 1467, 1359, 1344, 1280, 1241, 1112, 963, 841, 779 cm^{-1}; ^{1}H NMR: 9.26–9.20 (m, 2H), 8.77 (d, 2H, $J = 4.8$ Hz), 8.09 (d, 2H, $J = 9$ Hz), 7.96–7.87 (m, 4H), 7.41–7.37 (m, 2H), 5.62–5.52 (m, 2H), 5.29 (d, 2H, $J = 17$ Hz), 5.07 (d, 2H, $J = 12$ Hz), 4.95–4.84 (m, 2H), 4.57–4.51 (m, 2H), 4.09–4.06 (m, 4H), 3.89–3.80 (m, 4H, PEG), 3.66–3.51 (m, PEG), 3.47 (s, 6H), 2.80–2.70 (m, 4H), 2.18–1.81 (m, 14H), 1.11–0.95 (m, 4H); ^{13}C NMR: δ 164.8, 158.6, 137.4, 137.3, 137.0, 131.2, 126.2, 122.9, 120.5, 117.1, 110.0, 101.4, 70.7, 69.0, 66.2, 63.6, 61.7, 59.7, 57.5, 56.9, 37.9, 26.4, 25.8, 22.3.

4.2. Enantioselective epoxidation of 2,4-diarylenones 5 using 1 or 2, as catalysts under PTC conditions

To a stirred mixture of **5** (0.125 μmol), polymeric catalyst **1**, or **2** (6.25 μmol) in the appropriate solvent (4 mL) at the selected temperature (see Table 1), was added the corresponding oxidant (H_2O_2, 30%, 0.2 mL; t-BuOOH, 70%, 0.07mL; cumylhydroperoxide, 70%, 0.08mL; NaOCl, 10%, 0.1 mL). The corresponding base was then added after 10 min. The reaction mixture was stirred vigorously at the selected temperature until the starting material had been consumed (TLC, 48 h). The mixture was diluted with dichloromethane (15 mL), washed with water (2 × 10 mL), dried over $MgSO_4$, filtered off, and evaporated in vacuo. Diethyl ether (25 mL) was added in the residue, shaken, and then stilled. The polymeric catalyst was filtered and reclaimed. The solution was evaporated in vacuo. Purification of the residue by flash column chromatography on silica gel (hexane–ethyl acetate, 10:1) afforded the pure product **6.**

4.2.1. *trans*-2,3-Epoxy-1,3-diphenylpropan-1-one 6a. Yield: 90%; mp 74–75 °C; $[\alpha]_D^{20} = +177.4$ (c 1, CH_2Cl_2), 86% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak OD column, hexane/isopropanol = 95:5, flow rate = 0.8 mL/min, $t_R = 24.92$ min (2R,3S), $t_R = 27.24$ min (2S,3R); ^{1}H NMR: δ 8.02–8.00 (m, 2H), 7.65–7.38 (m, 8H), 4.30 (d, 1H, $J = 1.5$ Hz), 4.09 (d, 1H, $J = 1.5$ Hz).

4.2.2. *trans*-2,3-Epoxy-3-(3-nitrophenyl)-1-phenylpropan-1-one 6b. Yield: 72%; mp 115–116 °C, $[\alpha]_D^{20} = +142.5$ (c 1, CH_2Cl_2), 57% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak OD column, hexane/isopropanol = 95:5, flow rate = 0.6 mL/min, $t_R = 59.73$ min (2R,3S), $t_R = 68.85$ min (2S,3R); ^{1}H NMR: δ 8.03 (d, 2H, $J = 7.2$ Hz), 7.73 (d, 1H, $J = 7.6$ Hz), 7.66–7.61 (m, 2H), 7.54–7.50 (m, 2H), 4.32 (d, 1H, $J = 1.5$ Hz), 4.22 (d, 1H, $J = 1.5$ Hz).

4.2.3. *trans*-2,3-Epoxy-3-(4-nitrophenyl)-1-phenylpropan-1-one 6c. Yield: 55%; mp 138–140 °C, $[\alpha]_D^{20} = +140.6$ (c 1, CH_2Cl_2), 57% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak OD column, hexane/isopropanol = 95:5, flow rate = 0.5 mL/min, $t_R = 79.04$ min (2R,3S), t_R 89.36 min (2S,3R); ^{1}H NMR: δ 8.30–8.28 (m, 2H), 8.01–7.99 (m, 2H), 7.70–7.64 (m, 1H), 7.58–7.50 (m, 4H), 4.30 (d, 1H, $J = 1.7$ Hz), 4.18 (d, 1H, $J = 1.1$ Hz).

4.2.4. *trans*-2,3-Epoxy-3-(4-methylphenyl)-1-phenylpropan-1-one 6d. Yield: 86%; mp 77–78 °C; $[\alpha]_D^{20} = +116.7$ (c 1, CH_2Cl_2), 49% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak OD column, hexane/isopropanol = 99:1, flow rate = 0.8 mL/min, $t_R = 42.84$ min (2R,3S), $t_R = 45.41$ min (2S,3R); ^{1}H NMR: δ 8.00 (d, 2H, $J = 7.2$ Hz), 7.61 (t, 2H, $J = 7.2$ Hz), 7.48 (t, 2H, $J = 7.2$ Hz), 7.28–7.20 (m, 4H), 4.28 (d, 1H, $J = 1.8$ Hz), 4.04 (d, 1H, $J = 1.3$ Hz), 2.37 (s, 3H).

4.2.5. *trans*-2,3-Epoxy-3-(4-chlorophenyl)-1-phenylpropan-1-one 6f. Yield: 93%; mp 64–66 °C; $[\alpha]_D^{20} = +66.7$ (c 1, CH_2Cl_2), 33% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak OD column, hexane/isopropanol = 95:5, flow rate = 1.0 mL/min, $t_R = 19.63$ min (2R,3S), $t_R = 21.57$ min (2S,3R); ^{1}H NMR: δ 8.03–8.01 (m, 2H), 7.68–7.65 (m, 1H), 7.54–7.50 (m, 2H), 7.35–7.31 (m, 2H), 7.21–7.26 (m, 2H), 4.30 (d, 1H, $J = 1.5$ Hz), 4.05 (d, 1H, $J = 1.5$ Hz).

4.2.6. *trans*-2,3-Epoxy-1-(4-methoxyphenyl)-3-phenylpropan-1-one 6g. Yield: 77%; mp 78–80 °C; $[\alpha]_D^{20} = +73.7$ (c 1, CH_2Cl_2), 35% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak AD-H column, hexane/isopropanol = 95:5, flow rate = 0.8 mL/min, $t_R = 38.924$ min (2R,3S), $t_R = 42.60$ min (2S,3R); ^{1}H NMR: δ 8.02–8.00 (d, 2H), 7.41–7.36 (m, 5H), 6.94–6.96 (m, 2H), 4.30 (d, 1H, $J = 2.0$ Hz), 4.06 (d, 1H, $J = 2.0$ Hz), 3.90 (s, 3H).

4.2.7. *trans*-2,3-Epoxy-4-methylbutanophenone 6j. Yield: 85%, a colorless oil; $[\alpha]_D^{20} = +5.0$ (c 1, CH_2Cl_2), 19% ee; enantiomeric excess was determined by HPLC analysis, using Chiralpak OD-H column, hexane/isopropanol = 95:5, flow rate = 0.5 mL/min, $t_R = 11.47$ min (2R,S), $t_R = 13.36$ min (2S,3R); ^{1}H NMR: δ 8.02 (d, 2H, $J = 8.6$ Hz), 7.66–7.58 (m, 1H), 7.56–7.47 (m, 2H), 4.07 (d, 1H, $J = 2.0$ Hz), 2.97 (dd, 1H, $J = 2.0$, 6.0 Hz); 1.84–1.72 (m, 1H), 1.11 (d, 3H, $J = 6.9$ Hz), 1.07 (d, 3H, $J = 6.9$ Hz).

Acknowledgements

This work was financially supported by 973Project (No. 2002CB211800, China) and the National Natural Science Foundation of China (Grant No. 20472032, China). We also thank Nankai University, State Key Laboratory of Elemento-Organic Chemistry, for support.

References

1. Katsuki, T.; Sharpless, K. B. *J. Am. Chem. Soc.* **1980**, *102*, 5974–5976.

2. For recent representative review, see: (a) O' Donnell, M. J. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; Verlag Chemie, 1993; Chapter 8; (b) Shioiri, T.; Arai, S. In *Stimulating Concepts in Chemistry*; Vogtle, F., Stoddart, J. F., Shibasaki, M., Eds.; Wiley-VCH: Weinheim, 2000; pp 123–130; (c) Porter, M. J.; Skidmore, J. *Chem. Commun.* **2000**, 1215–1225.
3. (a) Helder, R.; Hummelen, J. C.; Laane, R. W. P. M.; Wiering, J. S.; Wynberg, Hans *Tetrahedron Lett.* **1976**, *17*, 1831–1834; (b) Wynberg, Hans; Greijdanus, B. *J. Chem. Soc., Chem. Commun.* **1978**, 427–428; (c) Hummelen, J. C.; Wynberg, Hans *Tetrahedron Lett.* **1978**, *19*, 1089–1091; (d) Wynberg, Hans; Marsman, B. *J. Org. Chem.* **1980**, *45*, 158–161; (e) Pluim, H.; Wynberg, Hans *J. Org. Chem.* **1980**, *45*, 2498–2502.
4. (a) Lygo, B.; Wainwright, P. G. *Tetrahedron Lett.* **1998**, *39*, 1599–1602; (b) Lygo, B.; Wainwright, P. G. *Tetrahedron* **1999**, *55*, 6289–6300; (c) Lygo, B.; To, D. C. M. *Tetrahedron Lett.* **2001**, *42*, 1343–1346.
5. Corey, E. J.; Zhang, F.-Y. *Org. Lett.* **1999**, *1*, 1287–1290.
6. Jew, S.-S.; Lee, J.-H.; Jeong, B.-S.; Yoo, M.-S.; Kim, M.-J.; Lee, Y.-J.; Choi, S.-H.; Lee, K.; Lah, M. S.; Park, H.-G. *Angew. Chem., Int. Ed.* **2005**, *44*, 1383–1385.
7. Ooi, T.; Ohara, D.; Tamura, M.; Maruoka, K. *J. Am. Chem. Soc.* **2004**, *126*, 6844–6845.
8. (a) Juliá, S.; Masana, J.; Vega, J. C. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 929–933; (b) Coffey, P. E.; Drauz, K.-H.; Roberts, S. M.; Skidmore, J.; Smith, J. A. *Chem. Commun.* **2001**, 2330–2331; (c) Berkessel, A.; Gasch, N.; Glaubitz, K.; Koch, C. *Org. Lett.* **2001**, *3*, 3839–3842; (d) Geller, T.; Krüger, C. M.; Militzer, H.-Ch. *Tetrahedron Lett.* **2004**, *45*, 5069–5071; (e) Kelly, D. R.; Meek, A.; Roberts, S. M. *Chem. Commun.* **2004**, 2021–2022; (f) Yi, H.; Zou, G.; Li, Q.; Chen, Q.; Tang, J.; He, M.-Y. *Tetrahedron Lett.* **2005**, *46*, 5665–5668.
9. (a) Shibasaki, M.; Sasai, H.; Arai, T. *Angew. Chem., Int. Ed.* **1997**, *36*, 1236–1256; (b) Yamada, K.; Arai, T.; Sasai, H.; Shibasaki, M. *J. Org. Chem.* **1998**, *63*, 3666–3672; (c) Wantanabe, S.; Arai, T.; Sasai, H.; Bougauchi, M.; Shibasaki, M. *J. Org. Chem.* **1998**, *63*, 8090–8091; (d) Nemoto, T.; Ohshima, T.; Shibasaki, M. *Tetrahedron Lett.* **2000**, *41*, 9565–9568; (e) Nemoto, T.; Ohshima, T.; Yamaguchi, K.; Shibasaki, M. *J. Am. Chem. Soc.* **2001**, *123*, 2725–2732.
10. (a) Bakó, T.; Bakó, P.; Keglevich, G.; Bombicz, P.; Kubinyi, M. *Tetrahedron: Asymmetry* **2004**, *15*, 1589–1595; (b) Bako, P.; Bako, T.; Meszaros, A.; Keglevich, G.; Szoellosy, A.; Bodor, S.; Mako, A.; Toke, L. *Synlett* **2004**, 643–646.
11. (a) Bayer, E.; Mutter, M. *Nature* **1972**, *237*, 512; (b) Toy, P. H.; Janda, K. D. *Acc. Chem. Rev.* **2000**, *33*, 546–554; (c) Dicherson, T. J.; Reed, N. N.; Janda, K. D. *Chem. Rev.* **2002**, *102*, 3325–3344; (d) Bergbreiter, D. E. *Chem. Rev.* **2002**, *102*, 3345–3384.
12. (a) Han, H.; Janda, K. D. *J. Am. Chem. Soc.* **1996**, *118*, 7632–7633; (b) Kuang, Y.-Q.; Zhang, Sh.-Y.; Wei, L.-L. *Synth. Commun.* **2003**, *33*, 3545–3550; (c) Jiang, R.; Kuang, Y. Q.; Sun, X. L.; Zhang, Sh. Y. *Tetrahedron: Asymmetry* **2004**, *15*, 743–746; (d) Yang, X. W.; Liu, H. Q.; Xu, H. Q.; Xu, M. H.; Lin, G. Q. *Chin. J. Chem.* **2005**, *23*, 68–70.
13. (a) Wang, Y. M.; Zhang, Zh. P.; Wang, Zh.; Meng, J. B.; Hodge, P. *Chin. J. Polym. Sci.* **1998**, *16*, 356–361; (b) Zhang, Zh. P.; Wang, Y. M.; Wang, Zh.; Hodge, P. *React. Funct. Polym.* **1999**, *41*, 37–43.
14. (a) Chinchilla, R.; Mazón, P.; Nájera, C. *Adv. Synth. Catal.* **2004**, *346*, 1186–1194; (b) Chinchilla, R.; Mazón, P.; Nájera, C. *Molecules* **2004**, *9*, 349–364; (c) Guillena, G.; Kreiter, R.; van de Coevering, R.; Gebbink, R. J. M. K.; van Koten, G.; Mazón, P.; Chinchilla, R.; Nájera, C. *Tetrahedron: Asymmetry* **2003**, *14*, 3705–3712.
15. Thierry, B.; Plaguevent, J.-C.; Cahard, D. *Tetrahedron: Asymmetry* **2003**, *14*, 1671–1677.
16. Danelli, T.; Annunziata, R.; Benaglia, M.; Cinquini, M.; Cozzi, F.; Tocco, G. *Tetrahedron: Asymmetry* **2003**, *14*, 461–467.
17. Liu, J. Y. *Graduation Thesis of Master in Nankai University*, 2005; pp 35–51.
18. (a) Meumann, M.; Geckeler, K. E. *React. Funct. Polym.* **1997**, *33*, 173–184; (b) Smith, P. A. S.; Hall, J. H.; Kan, T. O. *J. Am. Chem. Soc.* **1962**, *84*, 485–489; (c) Pattison, F. L. M. *J. Am. Chem. Soc.* **1956**, *78*, 2556–2559.
19. Kohler, E. P.; Chadwell, H. M. *Org. Synth. Coll. Vol. 1* **1941**, 78.
20. Chaffee, A. L.; Cooke, R. G.; Dagley, I. J.; Perlmutter, P.; Thomas, R. L. *Aust. J. Chem.* **1981**, *34*, 587–598.