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Manganese(III) complexes of novel chiral unsymmetrical BINOL-Salen ligands: Synthesis, characterization, and application in asymmetric epoxidation of olefins

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ABSTRACT

Several chiral unsymmetrical and C_2-symmetric Mn(III)-BINOL-Salen complexes have been designed, synthesized and applied to the asymmetric epoxidation of non-functionalized alkenes. Experimental results show these complexes are effective in the catalytic asymmetric epoxidation of alkenes. The catalyst **4c** exhibited better enantioselectivity and reactivity than the catalysts **4b** and **4a** due to the steric effect of the ligands. To understand the synergistic effect of the two different chiral centers in the catalyst, the catalyst **6a** has been investigated. By comparison of the enantioselectivity obtained by using **4c** and **6a**, respectively, the positive experimental results have proved that the chiral stereogenic centers in the diaminocyclohexane-derived catalysts played an important role in the current enantioselective epoxidation. Besides, the comparison of enantioselectivity displayed by **4c** and **7a** further demonstrates the significant influence through the cooperation of steric factors and chiral centers in catalyst.

1. Introduction

Chiral epoxid is one of the most important synthetic intermediates for its wide applications in chiral pharmaceuticals and fine chemicals [1–5], and over the past three decades much attention has been devoted to the development of new catalytic systems for the synthesis of chiral epoxides. Among several catalysis systems reported previously, catalytic enantioselective epoxidation of alkenes using chiral metal catalysts has proved to be the most effective method for the synthesis of chiral epoxides [6–9]. Stimulated by an important contribution from Jacobsen and Katsuki, many other chemists have significantly advanced the catalytic asymmetric epoxidation of unfunctionalized alkenes by introducing chiral Mn^{III}-Salen catalysts due to their availability and wide usefulness [10–12]. Although these chiral Mn^{III}-Salen catalysts are excellent catalysts for asymmetric epoxidation of alkenes with high enantiomeric excesses, their utilization to some extent is limited by difficulties in separation of the catalyst from the resultant epoxides as well as the recycling of the often expensive chiral catalyst [13,14]. To address this issue, many attempts have been made to discover the recoverable chiral Mn^{III}-Salen complexes (e.g., catalyst immobilization on inorganic materials [15–17] and polymers [18], catalyst functionalization by ionic liquid [19,20], and catalyst oligomers [21,22]) and highly active Mn^{III}-Salen catalysts [23] for asymmetric epoxidation of alkenes. Due to the fact that the cooperative activation by two or more catalytic centers with proper proximity could greatly increase the reactivity and enantioselectivity of homogeneous chiral catalysts, the catalytic centers is preferentially selected as one component of Mn^{III}-Salen complexes during our investigation on the development of novel effective catalysts for asymmetric epoxidation of alkenes [24–26]. As well known, BINOL-Salen ligand as well as some of its metal complexes have been approved as excellent catalysts for a series of important asymmetric organic transformations [27–31]. Since Katsuki first reported BINOL-Salen-based manganese complexes for the asymmetric epoxidation of alkenes, much attention has been devoted to expand this system [32–36]. To our knowledge, however, there are only a few literatures concerning systematical investigations on the effecting factors of the BINOL-Salen ligand for the asymmetric reactions. Based on these facts, four novel chiral unsymmetrical and one C_2-symmetric BINOL-Salen ligands derived from BINOL as well as the corresponding manganese(III) complexes have been designed and further synthesized. The steric effect and the synergetic effect of multi-chirality of these manganese(III) catalysts have been investigated in the epoxidation reaction. The catalytic activities of corresponding manganese(III)

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complexes towards asymmetric epoxidation of alkenes have been examined systematically with NaClO as the oxidant and PyNO as the axial base, and the positive experimental results have proved that five designed catalysts, especially catalyst **4c**, are effective in the current asymmetric epoxidation of alkenes. To the best of our knowledge, this is the first report of unsymmetrical BINOL-Salen-based manganese complexes with two different chiral centers as catalysts for the asymmetric epoxidation of non-functionalized alkenes.

2. Experimental

General remarks: All starting materials were obtained from commercial supplier used without further purification unless otherwise stated. 2,2-Dimethylchromene and its derivatives were synthesized as described in Ref. [37]. The synthesis of **2a**, **2c** and **5** (Scheme 1) were carried out according to a modified procedure [38–40]. (S)-(+)-3-Formyl-2-hydroxy-2′-methoxy-1,1′-binaphthyl was prepared according to the literature method [41]. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Mercury Plus 400 spectrometer with TMS as internal standard. IR spectra were obtained on a Nicolet 170SX FT-IR spectrophotometer as KBr discs. LC-MS were performed on a Bruker Daltonics Esquire 6000 mass spectrometer. Elemental analyses were taken using a PerkinElmer 240C analytical instrument. All reactions were monitored by TLC. TLC was performed on glass plates coated with silica gel 60 F_{254}. The crude products were purified by flash chromatography. The enantiomeric excesses of the chiral epoxides were determined by chiral High-Performance Liquid Chromatography analysis (Daicel Chiralcel OJ-H and OB-H chiral column, *n*-hexane:*i*-PrOH = 90:10 (v/v), 1.0 mL/min, 254 nm) using a Waters 600 controller with 2996 pholodiode Array detector.

2.1. Preparation of half-unit ligands (*2b*)

2.1.1. Synthesis of N-(2-hydroxyl-3-tert-butylbenzaldehyde)-1-amino-2-cyclohexaneimine (*2b*)

3-Tert-butylsalicylaldehyde (0.18 g, 1.0 mmol) in chloroform (50 mL) was added dropwise to the vigorously stirred solution of (1*R*,2*R*)-(−)-diaminocyclohexane (0.12 g, 1.0 mmol) in chloroform (150 mL) containing 4 Å molecular sieves at 0 °C. The reaction mixture was stirred for 48 h, and then the solvent was removed under reduced pressure to give the crude product. The crude product was then purified by flash chromatography on silica gel (petroleum ether/EtOAc = 4:1) affording a yellow oil (0.25 g, 91% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 13.85 (1H, s, OH); 8.28 (1H, s, CHN); 7.24 (1H, d–d, J = 6.4 Hz, J = 1.6 Hz, ArH); 6.98 (1H, d–d, J = 6 Hz, J = 1.6 Hz, ArH); 6.71(1H, t, J = 7.6 Hz, ArH); 3.32 (1H, m, CH); 1.99-1.73 (9H, m, CH—CH_2); 1.39 (9H, s, $C(CH_3)_3$). ^{13}C NMR (100 MHz, $CDCl_3$): δ 165.5; 160.3; 137.1; 129.8; 129.2; 118.6; 117.7; 72.4; 34.8; 33.1; 29.7; 29.3; 24.3. LC-MS: *m*/*z* 275.3 $[M+H]^+$. Anal. calcd for $C_{17}H_{26}N_2O$: C, 74.41; H, 9.55; N, 10.21. Found: C, 74.44; H, 9.60; N, 10.24.

2.2. General procedure for the preparation of new unsymmetrical BINOL-Salen ligands (*3a*–*3c* and *6*)

To a solution of half-unit ligands (**2a**–**2c** and **5**) (1.0 mmol) in ethanol (40 mL) was added dropwise a solution of (*S*)-(+)-3-formyl-2-hydroxy-2′-methoxy-1,1′-binaphthyl (1.0 mmol) in ethanol (40 mL). The reaction mixture was stirred under refluxing for 12 h, and then cooled to room temperature. The solvent of the resulting mixture was removed under reduced pressure, and the crude product was then purified by flash chromatography on silica gel (petroleum ether/EtOAc) affording a yellow solid.

2.2.1. Compound *3a*

Pale yellow solid (0.42 g, 79% yield) which was purified by flash column chromatography using petroleum ether: ethyl acetate (4:1) as eluent. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.52 (1H, s, CHN); 8.23 (1H, s, CHN); 7.88 (1H, d, J = 8.4 Hz, ArH); 7.81 (1H, d, J = 11.6 Hz, ArH); 7.77 (1H, s, ArH); 7.73 (1H, d, J = 3.8 Hz, ArH); 7.45 (2H, d, J = 9.2 Hz, ArH); 7.33–7.03 (7H, m, ArH); 6.89 (1H, d, J = 8.2 Hz, ArH); 6.73 (1H, t, ArH); 3.79 (3H, s, OCH_3); 3.38 (1H, m, CH); 3.26 (1H, m, CH); 2.09–1.65 (8H, m, CH_2). ^{13}C NMR (100 MHz, $CDCl_3$): δ 169.8; 164.9; 154.5; 155.4; 154.1; 138.2; 131.4; 130.9; 129.6; 129.3; 129.1; 128.9; 128.8; 128.1; 126.4; 125.4; 124.8; 123.8; 123.6; 120.3; 118.2.; 117.7; 114.7; 73.3; 72.5; 71.8; 34.8; 31.9; 22.7; 19.2. LC-MS: *m*/*z* 529.4 $[M+H]^+$. Anal. calcd for $C_{35}H_{32}N_2O_3$: C, 79.52; H, 6.10; N, 5.30. Found: C, 79.56; H, 6.11; N, 5.33. FT-IR (KBr): 3425, 2929, 2842, 1731, 1633, 1455, 1376, 1257, 1191, 913, 811, 744, 654 cm^{-1}.

2.2.2. Compound *3b*

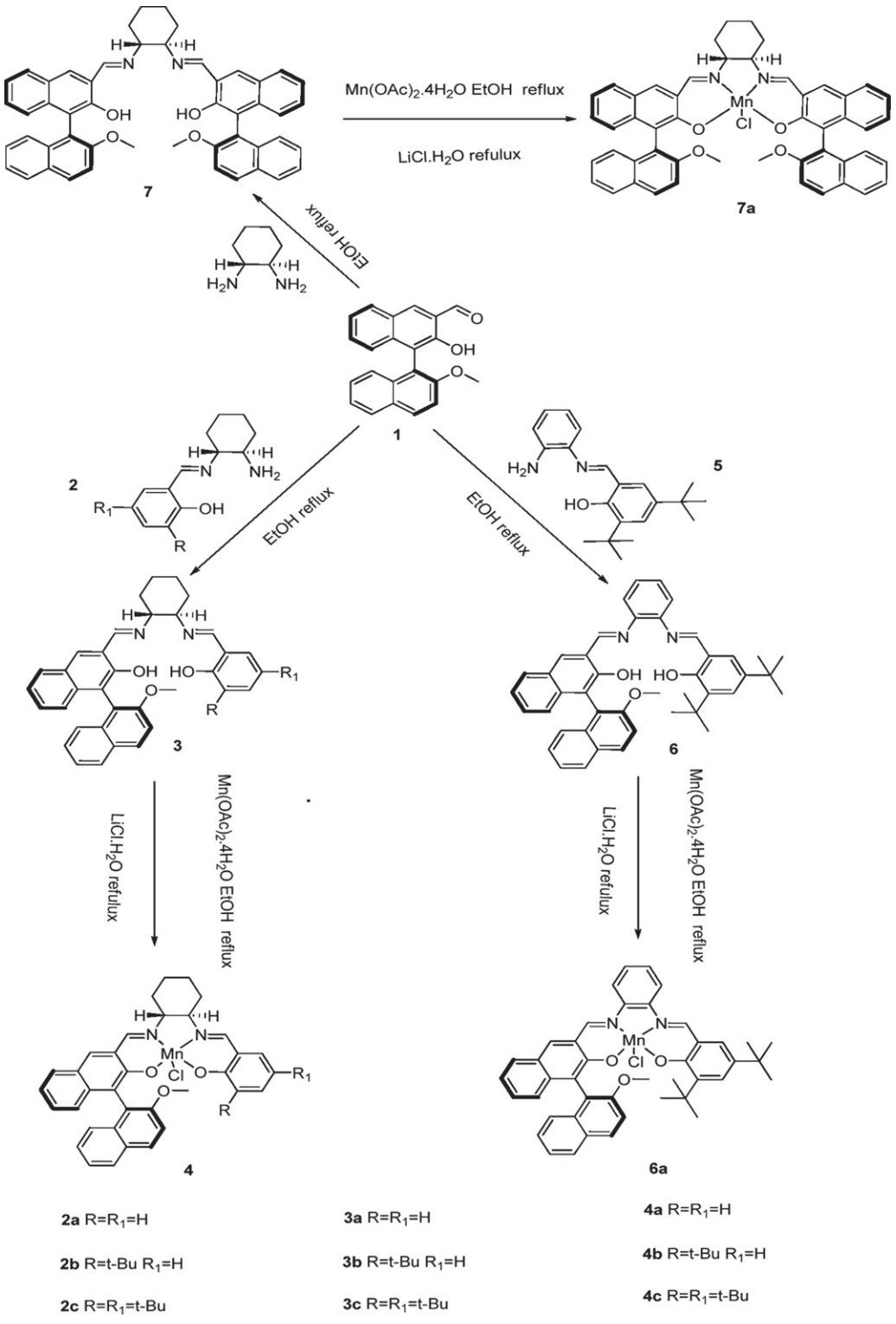
Pale yellow solid (0.48 g, 82% yield) which was purified by flash column chromatography using petroleum ether: ethyl acetate (6:1) as eluent. ^{1}H NMR (400 MHz, $CDCl_3$): δ 13.91 (1H, s, OH); 13.01 (1H, s, OH); 8.56 (1H, s, CHN); 8.23 (1H, s, CHN); 7.97 (1H, d, J = 8.6 Hz, ArH); 7.86 (2H, d, J = 8.2 Hz, ArH); 7.81 (1H, s, ArH); 7.77 (1H, d, J = 3.2 Hz, ArH); 7.45 (2H, d, J = 8.6 Hz, ArH); 7.33–6.95 (7H, m, ArH); 6.93 (2H, t, ArH); 3.68 (3H, s, OCH_3); 3.41 (1H, m, CH); 3.25 (1H, m, CH); 2.01–1.66 (8H, m, CH_2); 1.43 (9H, s, $C(CH_3)_3$). ^{13}C NMR (100 MHz, $CDCl_3$): δ 165.7; 165.1; 160.3; 155.2; 154.5; 137.1; 133.8; 133.2; 129.7; 129.6; 129.3; 128.9; 128.7; 128.0; 127.9; 127.3; 126.4; 125.1; 124.8; 123.6; 123.1; 120.7; 118.6.; 117.7; 114.7; 72.9; 72.2; 71.8; 34.8; 33.1; 31.9; 29.4; 22.7; 19.2. LC-MS: *m*/*z* 585.5 $[M+H]^+$. Anal. calcd for $C_{39}H_{40}N_2O_3$: C, 80.11; H, 6.89; N, 4.79. Found: C, 80.13; H, 6.92; N, 4.81. FT-IR (KBr): 3433, 2924, 2866, 1624, 1507, 1376, 1258, 1195, 1080, 1017, 913, 800, 745 cm^{-1}.

2.2.3. Compound *3c*

Yellow solid (0.56 g, 88% yield) which was purified by flash column chromatography using petroleum ether: ethyl acetate (5:1) as eluent. ^{1}H NMR (400 MHz, $CDCl_3$): δ 13.71 (1H, s, OH); 12.99 (1H, s, OH); 8.55 (1H, s, CHN); 8.22 (1H, s, CHN); 7.96 (1H, d, J = 9.2 Hz, ArH); 7.85 (1H, d, J = 8.4 Hz, ArH); 7.79 (1H, s, ArH); 7.75 (1H, d, J = 8 Hz, ArH); 7.44 (1H, d, J = 8.6 Hz, ArH); 7.32–7.14 (6H, m, ArH); 7.03 (1H, d, J = 7.2 Hz, ArH); 6.91 (1H, s, ArH); 3.66 (3H, s, OCH_3); 3.43 (1H, m, CH); 3.23 (1H, m, CH); 1.99–1.53 (8H, m, CH_2); 1.44 (9H, s, $C(CH_3)_3$); 1.19 (9H, s, $C(CH_3)_3$). ^{13}C NMR (100 MHz, $CDCl_3$): δ 165.9; 165.1; 157.9; 154.5; 139.9; 136.4; 133.3; 130.9; 129.6; 129.5; 128.9; 128.7; 128.0; 127.9; 127.3; 126.9; 126.4; 125.9; 125.2; 124.7; 123.6; 123.1; 120.8.; 119.1; 117.8; 114.6; 73.0; 72.2; 71.7; 34.9; 33.3; 32.9; 31.9; 29.5; 29.4; 22.7; 19.2. LC-MS: *m*/*z* 641.5 $[M+H]^+$. Anal. calcd for $C_{43}H_{48}N_2O_3$: C, 80.59; H, 7.55; N, 4.37. Found: C, 80.62; H, 7.58; N, 4.41. FT-IR (KBr): 3386, 2972, 2925, 1629, 1451, 1380, 1266, 1087, 1049, 881, 804, 736 cm^{-1}.

2.2.4. Compound *6*

Yellow solid (0.51 g, 80% yield) which was purified by flash column chromatography using petroleum ether: ethyl acetate (6:1) as eluent. ^{1}H NMR (400 MHz, $CDCl_3$): δ 13.38 (1H, s, OH); 12.55 (1H, s, OH); 8.95 (1H, s, CHN); 8.63 (1H, s, CHN); 8.07 (1H, s, ArH); 7.96 (1H, d, J = 8.8 Hz, ArH); 7.85 (2H, d, J = 8.4 Hz, ArH); 7.45 (1H, d, J = 8.8 Hz, ArH); 7.38 (1H, d, J = 2 Hz, ArH); 7.33–7.09 (11H, m, ArH); 3.76 (3H, s, OCH_3); 1.29 (9H, s, $C(CH_3)_3$); 1.26 (9H, s, $C(CH_3)_3$). ^{13}C NMR (100 MHz, $CDCl_3$): δ 165.3; 164.8; 164.7; 158.6; 154.5; 142.0; 134.8; 130.9; 130.2; 129.7; 129.6; 128.8; 128.4; 128.2; 127.9; 127.5; 127.3; 126.8; 126.7; 126.5; 125.3; 125.2; 124.9; 124.2; 123.7; 123.5; 123.2; 121.9; 121.3; 119.9; 114.5; 35.1; 31.5; 31.4; 29.4; 29.2. LC-MS: *m*/*z* 635.5 $[M+H]^+$. Anal. calcd for $C_{43}H_{42}N_2O_3$: C, 81.36; H, 6.67; N, 4.41. Found: C, 81.40; H, 6.68; N, 4.45. FT-IR (KBr): 3433, 2924, 2854, 1613, 1566, 1459, 1368, 1269, 1179, 1080, 1021, 800, 752 cm^{-1}.



Scheme 1. Preparation of ligands and corresponding manganese(III) complexes.

*2.3. Synthesis of (1R,2R)-(−)-N,N′-Bis((S)-1,1′-2-hydroxy-2′-methoxy-3-naphthylidene)-1,2-cyclohexanediamine (**7**)*

The chiral 1,2-cyclohexanediammonium mono-L-tartrate (0.50 mmol) and K_2CO_3 (1.0 mmol) were dissolved in 1.2 mL 50% ethanol. The obtained solution was then added dropwise to the solution of (*S*)-(+)-3-formyl-2-hydroxy-2′-methoxy-1,1′-binaphthyl (1.0 mmol) in ethanol (5 mL) and stirred under reflux for 6 h. After the removal of the solvent under reduced pressure, the crude product was purified by flash chromatography on silica gel (petroleum ether/EtOAc = 4:1) affording a yellow solid (0.64 g, 87% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.48 (2H, s, CHN); 7.98 (2H, d, J = 8.8 Hz, ArH); 7.86 (2H, d, J = 8.4 Hz, ArH); 7.74 (2H, s, ArH); 7.73 (2H, d, J = 2.4 Hz, ArH); 7.53 (2H, d, J = 8.2 Hz, ArH); 7.43 (2H, d, J = 8.8 Hz, ArH); 7.33–7.17 (8H, m, CH_2); 7.04 (2H, d,

J = 3.6 Hz, ArH); 3.51 (6H, s, OCH_3); 3.31 (2H, d, J = 10 Hz, CH_2); 1.97–1.56 (8H, m, CH_2). ^{13}C NMR (100 MHz, $CDCl_3$): δ 165.3; 155.2; 154.4; 135.4; 133.8; 133.2; 130.9; 129.6; 129.5; 128.8; 128.5; 127.9; 127.4; 126.3; 125.2; 124.7; 123.6; 120.6; 119.3; 117.11; 114.8; 73.03; 31.5; 24.1; 19.2. LC-MS: m/z 735.4 $[M+H]^+$. Anal. calcd for $C_{50}H_{42}N_2O_4$: C, 81.72; H, 5.76; N, 3.81. Found: C, 81.75; H, 5.80; N, 3.84. FT-IR (KBr): 3468, 2921, 2842, 1625, 1503, 1455, 1376, 1262, 1179, 1088, 808, 744 cm^{-1}.

2.4. General procedure for the preparation of the corresponding Mn(III)-BINOL-Salen complexes (**4a**–**4c**, **6a** and **7a**)

The ethanol solution of new ligands (**3a**–**3c**, **6** and **7**) (1.0 mmol) was stirred with the ethanol solution of $Mn(OAc)_2{\cdot}4H_2O$ (3.0 mmol) under nitrogen atmosphere with refluxing for 6 h. The reaction mixture was cooled to room temperature. Lithium chloride (6.0 mmol) was added and the resulting mixture was refluxed for additional 2 h while exposed to air. The solvent was removed under reduced pressure and the residue was extracted with dichloromethane (3 × 10 mL). The extract was washed with water (2 × 10 mL), brine and dried over anhydrous Na_2SO_4, and then concentrated to give the crude product. The crude product was recrystallized with petroleum ether affording the desired complexes.

2.4.1. Compound **4a**

Dark brown powder (0.55 g, 89% yield). LC-MS: m/z 581.4 $[M-Cl]^+$. Anal. calcd for $C_{35}H_{30}ClMnN_2O_3$: C, 68.13; H, 4.90; N, 4.54. Found: C, 68.17; H, 4.96; N, 4.60. FT-IR (KBr): 3433, 2927, 2855, 1608, 1442, 1342, 1263, 1147, 1018, 906, 810, 755, 689 cm^{-1}.

2.4.2. Compound **4b**

Dark brown powder (0.51 g, 76% yield). LC-MS: m/z 637.4 $[M-Cl]^+$. Anal. calcd for $C_{39}H_{38}ClMnN_2O_3$: C, 69.59; H, 5.69; N, 4.16. Found: C, 69.64; H, 5.70; N, 4.23. FT-IR (KBr): 3417, 2944, 2850, 1613, 1545, 1328, 1263, 1195, 1083, 1022, 891, 808, 752 cm^{-1}.

2.4.3. Compound **4c**

Dark brown powder (0.63 g, 86% yield). LC-MS: m/z 693.4 $[M-Cl]^+$. Anal. calcd for $C_{43}H_{46}ClMnN_2O_3$: C, 70.82; H, 6.36; N, 3.84. Found: C, 70.90; H, 6.39; N, 3.88. FT-IR (KBr): 3448, 2953, 2850, 1610, 1530, 1433, 1388, 1082, 1023, 839, 807, 749 cm^{-1}.

2.4.4. Compound **6a**

Brown powder (0.61 g, 85% yield). LC-MS: m/z 687.4 $[M-Cl]^+$. Anal. calcd for $C_{43}H_{40}ClMnN_2O_3$: C, 71.42; H, 5.58; N, 3.87. Found: C, 71.44; H, 5.64; N, 3.90. FT-IR (KBr): 3425, 2953, 2850, 1598, 1573, 1560, 1385, 1248, 1178, 1083, 1017, 807, 747 cm^{-1}.

2.4.5. Compound **7a**

Brown powder (0.72 g, 87% yield). LC-MS: m/z 787.4 $[M-Cl]^+$. Anal. calcd for $C_{50}H_{40}ClMnN_2O_4$: C, 72.95; H, 4.90; N, 3.40. Found: C, 72.98; H, 4.93; N, 3.49. FT-IR (KBr): 3472, 2921, 2842, 1609, 1577, 1423, 1342, 1245, 1188, 1081, 806, 748 cm^{-1}.

2.5. General procedure for the asymmetric epoxidation of olefins

The substrate (2.0 mmol) and PyNO (0.30 mmol) as the axial ligand were added to the dichloromethane (4 mL) solution of Mn(III)-Binol-Salen complex (0.10 mmol). After the addition of buffered NaOCl solution (4.0 mmol, pH 11.3) as the oxidant at 0 °C, the resulting mixture was stirred vigorously and monitored by TLC. After the reaction was totally completed, the mixture was diluted with CH_2Cl_2 (2 × 10 mL). The organic layer was separated, washed with water and brine, and then dried with $MgSO_4$. The solvent was removed under reduced pressure, and the crude product was purified by flash chromatography on silica gel (petroleum ether/CH_2Cl_2 = 2:1) affording the corresponding epoxide. The enantiomeric excesses of the chiral epoxide were determined by chiral High-Performance Liquid Chromatography analysis.

3. Results and discussion

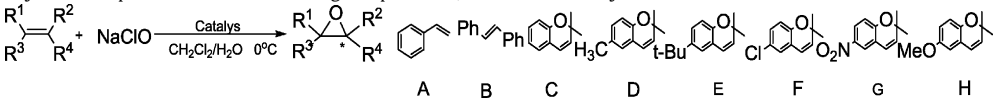
3.1. Synthesis of the novel chiral BINOL-Salen ligands and corresponding Mn(III) complexes

Taking into consideration the above-described previous studies, we synthesized four novel chiral unsymmetrical BINOL-Salen ligands (**3a**–**3c**, and **6**), which bear a tert-butyl group or phenyl group as the bulky substituent on the half-unit ligand moiety (as show in Scheme 1). The BINOL-Salen ligands were synthesized by two-step procedure, wherein we first prepared the half-unit ligands bearing a Schiff base framework according to the reported procedure, [37–39] *N*-(2-hydroxylbenzaldehyde)-1-amino-2-cyclohexaneimine (**2a**) *N*-(2-hydroxyl-3-tert-butylbenzaldehyde)-1-amino-2-cyclohexaneimine (**2b**), *N*-(2-hydroxyl-3,5-di-tert-butylbenzaldehyde)-1-amino-2-cyclohexaneimine (**2c**) and *N*-(2-hydroxyl-3,5-di-tert-butylbenzaldehyde)-1-amino-2-benzeneimine (**5**). Then the half-unit ligands reacted with (*S*)-(+)-3-formyl-2-hydroxy-2′-methoxy-1,1′-binaphthyl, respectively, in a 1:1 molar ratio affording unsymmetrical BINOL-Salen ligands. To elucidate steric effect and chiral center effect of this catalytic reaction systematically, one C_2-symmetric BINOL-Salen ligand (**7**) was also prepared (as show in Scheme 1). With these ligands in hand, the corresponding Mn(III) complexes (**4a**–**4c**, **6a** and **7a**) were synthesized, respectively (as show in Scheme 1). All of the synthesized ligands and complexes were well characterized by NMR, LC-MS, FT-IR, and Elemental analyses.

3.2. The catalytic performance of unsymmetrical Mn(III)-BINOL-Salen complexes **4a**, **4b** and **4c**

To understand the steric effect of the unsymmetrical Mn(III)-BINOL-Salen complexes for asymmetric epoxidation of alkenes, the ligands were altered with only substituent group of the salicylaldehyde framework. With the unsymmetrical Mn(III)-BINOL-Salen complexes (**4a**, **4b** and **4c)** in hand, the asymmetric epoxide reactions were systematically investigated with the substrates of styrene (A), *trans*-stilbene (B), 2,2-dimethylchromene (C), 2,2,6-trimethylchromene (D), 6-tert-butyl-2,2-dimethylchromene (E), 6-chloro-2,2-dimethylchromene (F), 6-nitro-2,2-dimethylchromene (G), and 6-methoxy-2,2-dimethylchromene (H). As is known to all, the organic co-catalyst plays an important role in the Jacobsen epoxidation. Based on this point, Pyridine *N*-oxide was used as co-catalyst since it has remarkable effects on both the activity and enantioselectivity of the enantioselcetive epoxidation. Table 1 summarizes the catalytic performance of the complexes **4a**, **4b** and **4c** in the enantioselective epoxidation of alkenes with NaClO as the oxidant and PyNO as the axial base. The positive experimental results show these complexes are effective catalysts for the asymmetric epoxidation of alkenes. As expected, the reaction with **4a** proceeded at 0 °C in CH_2Cl_2, giving high entantioselectivity and chemical yield, especially for 2,2-dimethylchromene (9–91% ee, 64–82% yield) (Table 1, entries 1–8). Using catalyst **4b** instead of **4a** led to remarkable enhanced entantioselectivity and chemical yield (73–91% yield, 16–95% ee) (Table 1, entries 9–16). This feature can be attributed to complex **4b** bearing a tert-butyl group as the bulky substituent on the salicylaldehyde moiety at the 3 position. This result supports the assumption that steric bulk at the 3,3′-position of the Salen ligand can enhance entantioselectivity of alkenes [4]. To understand the steric effects and electronic effects of catalyst in the

Table 1
Asymmetric epoxidation of alkenes using complexes **4a**, **4b** and **4c** as catalysts[a] .



A B C D E F G H

Entry	Alkene[b]	Catalyst	Time (h)[c]	Yield (%)[d]	ee (%)[e]	Configuration[f]
1	A	**4a**	4	81	27	*R*-(+)
2	B	**4a**	4	77	9	*R*-(+)
3	C	**4a**	4	81	91	3*R*,4*R*-(+)
4	D	**4a**	4	68	89	3*R*,4*R*-(+)
5	E	**4a**	4	82	82	3*R*,4*R*-(+)
6	F	**4a**	4	64	65	3*R*,4*R*-(+)
7	G	**4a**	4	82	52	3*R*,4*R*-(+)
8	H	**4a**	4	68	86	3*R*,4*R*-(+)
9	A	**4b**	4	88	36	*R*-(+)
10	B	**4b**	4	83	26	*R*-(+)
11	C	**4b**	4	91	95	3*R*,4*R*-(+)
12	D	**4b**	4	73	90	3*R*,4*R*-(+)
13	E	**4b**	4	83	91	3*R*,4*R*-(+)
14	F	**4b**	4	82	93	3*R*,4*R*-(+)
15	G	**4b**	4	83	89	3*R*,4*R*-(+)
16	H	**4b**	4	74	92	3*R*,4*R*-(+)
17	A	**4c**	4	91	40	*R*-(+)
18	B	**4c**	4	83	26	*R*-(+)
19	C	**4c**	4	95	97	3*R*,4*R*-(+)
20	D	**4c**	4	88	91	3*R*,4*R*-(+)
21	E	**4c**	4	89	93	3*R*,4*R*-(+)
22	F	**4c**	4	93	95	3*R*,4*R*-(+)
23	G	**4c**	4	87	94	3*R*,4*R*-(+)
24	H	**4c**	4	79	97	3*R*,4*R*-(+)

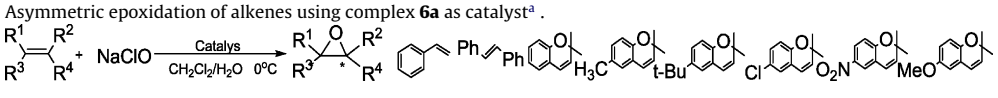
[a] Reaction conditions: substrate (2 mmol), catalyst (5 mol%), NaOCl (4 mmol), PyNO (15 mol%).
[b] A: styrene; B: trans-stilbene; C: 2,2-dimethylchromene; D: 2,2,6-trimethylchromene; E: 6-tert-butyl-2,2-dimethylchromene; F: 6-chloro-2,2-dimethylchromene; G: 6-nitro-2,2-dimethylchromene; H: 6-methoxy-2,2-dimethylchromene.
[c] Monitored by TLC every other 20 min.
[d] Isolated yield.
[e] Determined by HPLC on chiral OJ-H and OB-H column.
[f] Absolute configuration was determined by comparison of the sign of $[\alpha]_D$ with the literature value.

catalytic reaction systematically, we also examined the asymmetric epoxidation of alkenes with **4c** as the catalyst under the same condition. It was also noteworthy that complex **4c** derived from chiral unsymmetrical BINOL-Salen (**3c**) gave higher entantioselectivity on alkenes epoxidation than its analogue catalysts (**4a** and **4b**) (79–95% yield, 26–97% ee) (Table 1, entries 17–24). The remarkable improvement in the performance of **4c** can be attributed to the two tert-butyl groups as the bulky substituent on the salicylaldehyde moiety at the 3,5-position. This result supports the assumption that steric bulk at the 5,5′-position of the Salen ligand has an equally profound effect of entantioselectivity [42]. With comparison of the activities of **4a** and **4b** with that of **4c**, we conclude that different attachment positions of chiral unsymmetrical Mn(III)-BINOL-Salen complex had crucial effects on the catalytic performance of the corresponding Mn(III) complex. It demonstrates that steric factors play an important role in the related asymmetric catalysis.

3.3. The catalytic performance of unsymmetrical Mn(III)-BINOL-Salen complex ***6a***

To further investigate the synergistic effect of two different chiral centers in the unsymmetrical Mn(III)-BINOL-Salen

Table 2
Asymmetric epoxidation of alkenes using complex **6a** as catalyst[a] .

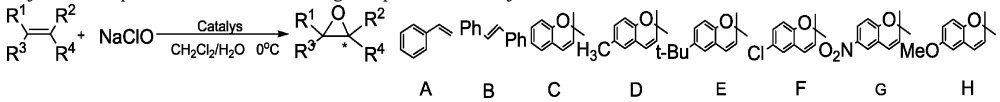


A B C D E F G H

Entry	Alkene[b]	Catalyst	Time (h)[c]	Yield (%)[d]	ee (%)[e]	Configuration[f]
1	A	**6a**	4	82	21	*R*-(+)
2	B	**6a**	4	78	8	*R*-(+)
3	C	**6a**	4	73	24	3*R*,4*R*-(+)
4	D	**6a**	4	64	21	3*R*,4*R*-(+)
5	E	**6a**	4	88	25	3*R*,4*R*-(+)
6	F	**6a**	4	91	10	3*R*,4*R*-(+)
7	G	**6a**	4	84	11	3*R*,4*R*-(+)
8	H	**6a**	4	93	22	3*R*,4*R*-(+)

[a] Reaction conditions: substrate (2 mmol), catalyst (5 mol%), NaOCl (4 mmol), PyNO (15 mol%).
[b] A: styrene; B: trans-stilbene; C: 2,2-dimethylchromene; D: 2,2,6-trimethylchromene; E: 6-tert-butyl-2,2-dimethylchromene; F: 6-chloro-2,2-dimethylchromene; G: 6-nitro-2,2-dimethylchromene; H: 6-methoxy-2,2-dimethylchromene.
[c] Monitored by TLC every other 20 min.
[d] Isolated yield.
[e] Determined by HPLC on chiral OJ-H and OB-H column.
[f] Absolute configuration was determined by comparison of the sign of $[\alpha]_D$ with the literature value.

Table 3
Asymmetric epoxidation of alkenes using complex **7a** as catalyst[a].



Entry	Alkene[b]	Catalyst	Time (h)[c]	Yield (%)[d]	ee (%)[e]	Configuration[f]
1	A	**7a**	4	82	31	*R*-(+)
2	B	**7a**	4	85	13	*R*-(+)
3	C	**7a**	4	78	94	3*R*,4*R*-(+)
4	D	**7a**	4	76	90	3*R*,4*R*-(+)
5	E	**7a**	4	89	91	3*R*,4*R*-(+)
6	F	**7a**	4	79	92	3*R*,4*R*-(+)
7	G	**7a**	4	81	80	3*R*,4*R*-(+)
8	H	**7a**	4	69	91	3*R*,4*R*-(+)

[a] Reaction conditions: substrate (2 mmol), catalyst (5 mol%), NaOCl (4 mmol), PyNO (15 mol%).
[b] A: styrene; B: trans-stilbene; C: 2,2-dimethylchromene; D: 2,2,6-trimethylchromene; E: 6-tert-butyl-2,2-dimethylchromene; F: 6-chloro-2,2-dimethylchromene; G: 6-nitro-2,2-dimethylchromene; H: 6-methoxy-2,2-dimethylchromene.
[c] Monitored by TLC every other 20 min.
[d] Isolated yield.
[e] Determined by HPLC on chiral OJ-H and OB-H column.
[f] Absolute configuration was determined by comparison of the sign of $[\alpha]_D$ with the literature value.

complex, the asymmetric epoxidation of alkenes with catalyst **6a** were examined. Table 2 summarizes the catalytic performance of the unsymmetrical Mn(III)-BINOL-Salen complex **6a** in the enantioselective epoxidation of alkenes under the controlled condition, displaying lower entantioselectivity (8–25% ee) (Table 2, entries 1–8). From the results in Tables 1 and 2, it could be seen that the different asymmetric induction observed in the epoxidation with complexes **4c** and **6a** might attribute to the different chiral centers in **4c** and **6a**. These results, to some extent, support the assumption that the catalytic activity and entantioselectivity in the present epoxidation were related to the synergistic effect of chiral centers of catalyst.

3.4. The catalytic performance of C_2-symmetric Mn(III)-BINOL-Salen complex **7a**

To further understand the cooperation of steric factors and chiral centers in the Mn(III)-BINOL-Salen complex, the epoxidation of alkenes with catalyst **7a** was also tested. As summarized in Table 3, the catalytic performance of the C_2-symmetric Mn(III)-BINOL-Salen complexe **7a** in the enantioselective epoxidation of alkenes gave the high chemical yield and entantioselectivity (69–89% yield, 13–94% ee) (Table 3, entries 1–8). Compared with the activities of **6a** and **4c** as catalyst, the catalytic results from **7a** apparently show that the cooperation of steric factors and chiral centers of Mn(III)-BINOL-Salen complex has an important influence on the current catalytic asymmetric epoxidation, and this fact is consistent with that observed by others [9,43].

4. Conclusion

In conclusion, one C_2-symmetric and four unsymmetrical chiral Mn(III)-BINOL-Salen complexes have been synthesized. These complexes, especially **4c**, with NaClO as the oxidant and PyNO as the axial base constitute the catalytic system for the asymmetric epoxidation of non-functionalized alkenes with good-to-excellent chemical yields and enantioselectivity. The attachment positions of chiral Mn(III)-BINOL-Salen complex had crucial effects on the catalytic performance of the corresponding Mn(III) complex. The chiral unsymmetrical Mn(III)-BINOL-Salen complex **4c** bearing two tert-butyl groups as the bulky substituent on the salicylaldehyde moiety at the 3,5-position exhibited the best catalytic activity in the present asymmetric epoxidation reaction. Moreover, the catalytic activity and entantioselectivity were related to the synergistic effect of chiral center of catalyst. These observations suggested that the cooperation of steric factors and chiral centers of Mn(III)-BINOL-Salen complex play an important role in the catalytic performances. Notably, this work emphasizes a combinational strategy to encourage more attempts to explore new highly effective catalyst for the enantioselective epoxidation of nonfunctional olefins, and the further optimizations and studies of the scope and mechanism of the asymmetric olefin epoxidation catalyzed by the designed chiral BINOL-Salen complexes are ongoing in our laboratory.

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