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Synthesis and catalytic activity of new chiral unsymmetrical Mn(III)-Schiff-base complexes containing salicylaldehyde and 1-(2-hydroxyphenyl)ketone units

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Abstract

Two new chiral unsymmetrical (non-C_2-symmetric) Schiff-base ligands containing salicylaldehyde and 1-(2-hydroxyphenyl) ketone units were synthesized from (*R*,*R*)-1,2-diphenylethylenediamine as the chiral diamine using a stepwise approach. The Mn(III) complexes of the ligands were subsequently used as catalysts in asymmetric epoxidation of unfunctionalized alkenes and the results were compared with those obtained using typical C_2-symmetric Mn(III)–salen complexes. Possible reasons for the differences in reactivity and selectivity between the two types of catalysts are briefly discussed.

Keywords: Asymmetric reactions; Epoxidations; Unsymmetrical catalysts; Schiff bases; Salen

1. Introduction

During the last decade, a large number of chiral C_2-symmetric salen-type Schiff-base complexes, such as **1** and **2** in Scheme 1, have been synthesized as catalysts for various asymmetric reactions including enantioselective epoxidation of unfunctionalized alkenes [1–3]. While the synthesis of these symmetrical catalysts is generally highly efficient and straightforward, the unsymmetrical Schiff-base ligands are much less accessible. Accordingly, reports of the chiral unsymmetrical salen ligands have been scarce up to now [4–7]. The published methods involve a stepwise synthesis of non-C_2-symmetric salen ligands containing two different donor units via mono-imines. However, these syntheses are generally unreliable and the mono-imines prepared from salicylaldehyde and 1,2-diamine are always contaminated with various amounts of the C_2-symmetric bis-imine even after attempted purification [6,8]. Very recently, Gilheany and coworkers [6] succeeded to avoid this inherent problem by trapping the mono-aldimine as a tartrate salt; however, further reaction of this salt with a different salicylaldehyde produced the unsymmetrical bis-imine in low yield. The most reliable route so far for preparation of non-C_2-symmetric salen ligands involves the use of a statistical method [9]. Other chiral unsymmetrical salen-like catalysts for asymmetric epoxidation of alkenes reported recently include a biomimetic Mn–dihydrosalen complex [10,11], and Mn–picolinamide–salicylidene complexes [12].

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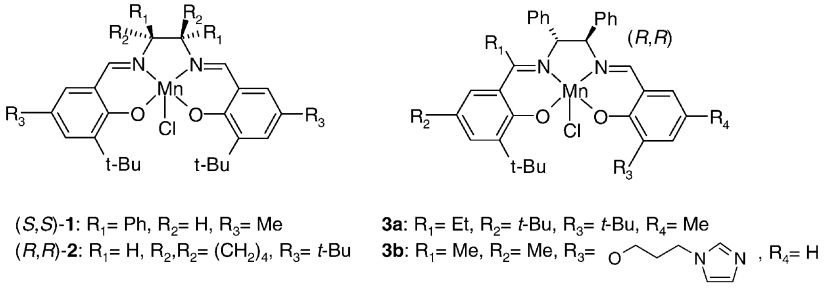


Scheme 1.

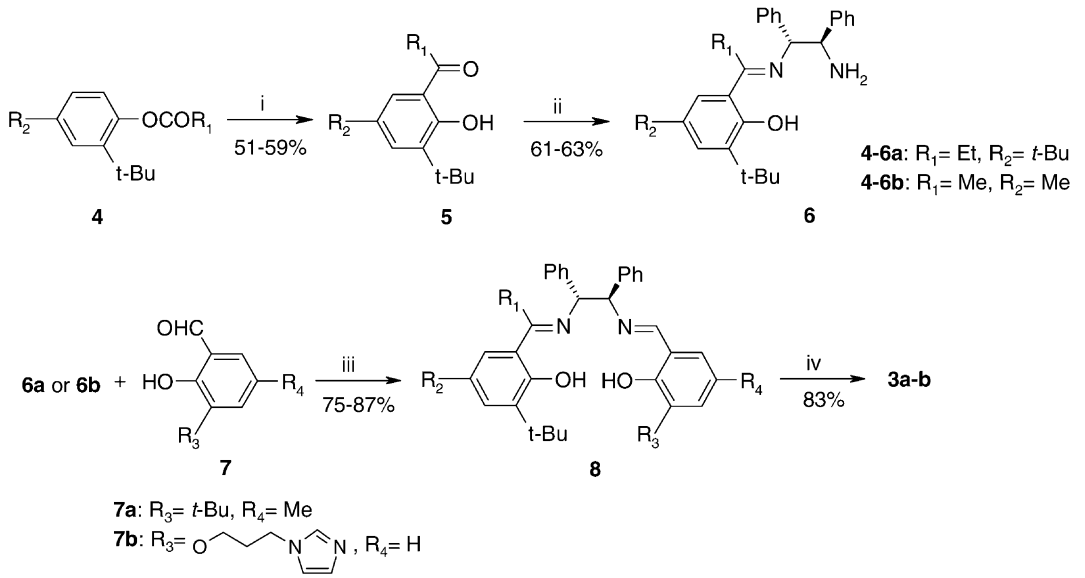
However, to the best of our knowledge, no reports of chiral Schiff-base complexes containing 1-(2-hydroxyphenyl)ketone units as epoxidation catalysts have previously appeared.

We want to report a facile synthesis and catalytic use of new chiral unsymmetrical Schiff-base complexes **3a**–**b** containing two different donor units: a salicylaldehyde derivative and 1-(2-hydroxyphenyl)ketone. Aromatic ketones were chosen because they react considerable slower with 1,2-diamines than salicylaldehydes, consequently selective formation of monoketimines was anticipated.

2. Results and discussion

2.1. Synthesis of unsymmetrical Mn(III)-Schiff-base complexes

The synthesis route for non-C_2-symmetric Schiff-base ligands **8a**–**b** is illustrated in Scheme 2. The route involves the initial preparation of chiral half-units **6a**–**b** from substituted 1-(2-hydroxyphenyl)ketones **5a**–**b** and (*R*,*R*)-1,2-diphenylethylenediamine, followed by condensation of **5a**–**b** with salicylaldehyde derivatives **7a**–**b**.

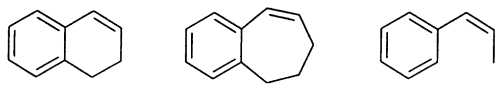


Scheme 2. Reagents and conditions: (i) $TiCl_4$, $MeNO_2$, RT 8 h; (ii) (*R*,*R*)-1,2-diphenylethylenediamine, Na_2SO_4, EtOH, Δ 20 h; (iii) Na_2SO_4, EtOH, Δ 3 h; (iv) $Mn(OAc)_2{\cdot}4H_2O$, LiCl, air, EtOH, Δ 2–3 h.

The condensation reaction proceeded smoothly in the presence of anhydrous Na_2SO_4 as a drying agent to produce the chiral half-units **6a**–**b** in over 60% yield. The crude products were rapidly filtered through a short plug of neutralized silica gel to remove the unreacted diamine because attempted purification of **6a** or **6b** by flash chromatography resulted in the formation of some of the starting ketones. However, attempts to prepare unsymmetrical Schiff-base ligands from the frequently used chiral *trans*-1,2-diaminocyclohexane were not successful, mixtures were instead obtained. Further, reaction of the half-units **6a**–**b** with the salicylaldehyde derivatives **7a**–**b** lead to the facile formation of the unsymmetrical Schiff-base ligands **8a**–**b** (yield 75–83%). Finally, the Mn(III) complexes **3a**–**b** were readily obtained by standard procedure using excess of $Mn(OAc)_2{\cdot}4H_2O$ and LiCl in air [13].

2.2. Asymmetric epoxidations catalyzed with Mn(III) complexes *1*–*3*

The viability of the unsymmetrical complexes **3a** and **3b** as catalysts in the asymmetric epoxidation of typical unfunctionalized alkenes **9**–**11** (see Scheme 3) was subsequently studied and the results were compared with those obtained using analogous symmetrical salen catalysts (results in Table 1).



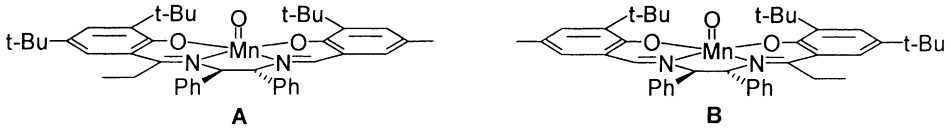
Scheme 3.

The unsymmetrical Schiff-base complex **3a** was found to be catalytically active and to induce moderate-to-good enantioselectivity (ee 44–79%) in epoxidation of alkenes **9**–**11**. Also, benzocyclic alkenes **9** and **10** produced the corresponding epoxides with almost equal yield with catalyst **3a** compared with catalysts **1** and **2**. However, the catalytic activity of **3a** was lower than activity of the symmetrical catalysts as indicated by the longer reaction times. Also, the enantioselectivities achieved by using **3a** were generally lower than those obtained with the symmetrical complexes. Interestingly, epoxidation of **10** with Bu_4NHSO_5 and **3a** afforded higher ee than the reaction catalyzed by **2**. This is in accordance with our earlier observation that 1,2-diphenylethylenediamine-derived salen complexes (e.g. **1** and **3**) show higher asymmetric

Table 1
Asymmetric epoxidation of unfunctionalized alkenes **9**–**11** catalyzed by Mn(III)-Schiff-base complexes **1**–**3a**

Entry	Alkene	Catalyst	Oxidation system[a]	Temperature (°C)	Time (h)	Yield (%)[b]	ee (%)[c]	Absolute configuration[d]
1	**9**	**1**	A	22	3	55	64	1*S*,2*R*-(−)
2	**9**	**3a**	A	22	6	47 (69)[e]	48	1*R*,2*S*-(+)
3	**9**	**1**	B	2	2.5	49	82	1*S*,2*R*-(−)
4	**9**	**2**	B	2	2.5	45	73	1*R*,2*S*-(+)
5	**9**	**3a**	B	2	6	40	44	1*R*,2*S*-(+)
6	**10**	**1**	C	2	1	59 (72)[f]	89 (90)[f]	5*S*,6*R*-(+)
7	**10**	**2**	C	2	2.5	52	72	5*R*,6*S*-(−)
8	**10**	**3a**	C	−18	4	68	79	5*R*,6*S*-(−)
9	**11**	**1**	C	−18	1	72[g]	87[h]	1*R*,2*S*-(−)
10	**11**	**3a**	C	−18	5	47[i]	50[h]	1*S*,2*R*-(+)

[a] A: 2.5 eq. Bu_4NIO_4 and 0.75 eq. imidazole in CH_2Cl_2; B: 2.0 eq. 0.55 M NaOCl (pH 11) and 0.75 eq. pyridine *N*-oxide in CH_2Cl_2–H_2O; C: 1.6 eq. Bu_4NHSO_5 and 1.0 eq. *N*-methylmorpholine *N*-oxide in CH_3CN.
[b] Yield of the isolated epoxide.
[c] Determined by ^1H NMR in the presence of $Eu(Hfc)_3$.
[d] Determined by comparison of the sign of $[\alpha]_D$ to the literature values.
[e] Yield calculated from the reacted alkene.
[f] Values in parentheses are for reaction conducted at −18 °C.
[g] A mixture of *cis*- and *trans*-epoxides (8.3:1).
[h] Enantioselectivity of the *cis*-epoxide.
[i] A mixture of *cis*- and *trans*-epoxides (4.6:1).



Scheme 4.

induction than their 1,2-diaminocyclohexane-derived counterparts (e.g. **2**) in epoxidations conducted with Bu_4NHSO_5 as the oxidant [14]. In the case of (*Z*)-1-phenylprop-1-ene (**11**), both the enantio- and stereo-selectivity and also yield of the corresponding epoxide were markedly lower when unsymmetrical **3a** was used as the catalyst.

The results obtained here for catalyst **3a** are not surprising since almost all the unsymmetrical Schiff-base complexes studied to date have shown diminished ee in asymmetric epoxidations compared with the analogous C_2-symmetric catalysts [6,10,15]. The diminished ee of **3a**, and other unsymmetrical Schiff-base complexes, could be explained by the formation of diastereomeric Mn(V)-oxo species (**A** and **B**; Scheme 4) [6,12,15].

These isomeric active oxygen transfer species may differ in stability and reactivity, and they may have different selectivity during alkene epoxidation. Also, the presence of the ethyl group in the 1-(2-hydroxyphenyl)propanone unit can change the steric environment of the catalyst **3a**, thereby leading to decreased asymmetric induction compared with the symmetric catalysts.

While complex **3a** was catalytically active, the complex **3b** with a tethered imidazole group showed no catalytic activity with any of the oxidants studied, with or without added donor ligands. One possible explanation for the inactivity of catalyst **3b** might be intermolecular coordination, contrary to the desired intramolecular coordination [10,11], of the tethered imidazole moiety of one Schiff-base complex with the metal center of another catalyst molecule. This could eventually result in the occupation of most of the coordination sites, which renders the catalyst inactive.

In conclusion, a new type of epoxidation catalyst was developed by a facile stepwise procedure. This synthesis method could give the opportunity to develop other chiral unsymmetric Schiff-base complexes having different steric and electronic properties on the different subunits. While the enantioselectivities obtained in epoxidations performed using the non-C_2-symmetric catalyst **3a** were only moderate, this type of complexes could well be suitable catalysts for other asymmetric reactions traditionally catalyzed by C_2-symmetric salen complexes [1]. Studies towards these goals are underway.

3. Experimental

3.1. General

The NMR spectra were obtained on a Varian Gemini 2000 spectrometer (200 MHz) in $CDCl_3$ with Me_4Si as internal standard. IR spectra were acquired by use of a Perkin Elmer Spectrum One spectrometer. Optical rotation was measured with a Jasco DIP-1000 polarimeter at ambient temperature. EI-MS was acquired by use of a JEOL JMS-SX102 mass spectrometer. Elemental analyses were performed by the Analytische Laboratorien Prof. Dr. H. Malissa und G. Reuter GmbH in Lindlar, Germany. TLC was conducted on Merck Al-plates coated with silica gel 60 F_{254}. Flash chromatography and dry column flash chromatography were performed using Merck silica gel 60 (230–400 mesh ASTM). Silica gel was neutralized with Et_3N before use. Catalyst **2** was purchased from Fluka Chemie. Catalyst **1** and alkenes **9**–**10** were prepared as previously described [16]. Alkene **11** was obtained from Tokyo Chemical Industry.

3.2. Preparation of the aryl esters *4a–b*

A mixture of the phenol (1 mol eq.), carboxylic acid anhydride (1.9 mol eq.) and pyridine (3.8 mol eq.) was stirred at 60–90 °C for 24 h. The cooled mixture was diluted with water and ethylacetate, and phases were separated. The organic phase was washed successively with water, 2 M HCl, water, 2 M NaOH, water and saturated NaCl solution, dried over anhydrous Na_2SO_4, and concentrated.

*3.2.1. 2,4-Di-tert-butylphenyl propanoate (**4a**)*

Prepared from 2,4-di-*tert*-butylphenol and propionic anhydride. Yellowish oil, yield 95%, solidifies on standing (lit. [17], m.p. 40 °C). ^{1}H NMR: δ 1.29 (3H, t, $J = 7.6$ Hz), 1.31 (9H, s), 1.34 (9H, s), 2.62 (2H, q, $J = 7.6$ Hz), 6.90 (1H, d, $J = 8.4$ Hz), 7.22 (1H, dd, $J = 8.4$ and 2.4 Hz), 7.39 (1H, d, $J = 2.4$ Hz) ppm.

*3.2.2. 2-tert-Butyl-4-methylphenyl acetate (**4b**)*

Prepared from 2-*tert*-butyl-4-methylphenol and acetic anhydride. Oil, yield 94%, b.p. 90 °C/2 mmHg (lit. [18], b.p. 81–82 °C/1.5 mmHg). ^{1}H NMR: δ 1.34 (9H, s), 2.32 (3H, s), 6.87 (1H, d, $J = 8.1$ Hz), 7.02 (1H, dd, $J = 8.1$ and 2.0 Hz), 7.18 (1H, d, $J = 2.0$ Hz) ppm.

*3.3. Preparation of the 1-(2-hydroxyphenyl) ketones **5a–b***

The 1-(2-hydrophenyl)ketones were prepared from the corresponding aryl esters **4a–b** by $TiCl_4$-induced Fries rearrangement [19].

*3.3.1. 1-(3,5-Di-tert-butyl-2-hydroxyphenyl) propan-1-one (**5a**)*

Yellowish solid, yield 59%, m.p. 64–66 °C (lit. [17], m.p. 68 °C). ^{1}H NMR: δ 1.25 (3H, t, $J = 7.3$ Hz), 1.32 (9H, s), 1.43 (9H, s), 3.07 (2H, q, $J = 7.3$ Hz), 7.54 (1H, d, $J = 2.4$ Hz), 7.61 (1H, d, $J = 2.4$ Hz), 12.9 (1H, s) ppm. ^{13}C NMR: δ 8.7, 29.5, 31.5, 32.0, 34.4, 35.3, 118.4, 123.6, 131.1, 138.2, 140.1, 160.2 and 208.0 ppm.

*3.3.2. 1-(3-tert-Butyl-5-methyl-2-hydroxyphenyl) ethan-1-one (**5b**)*

Yellowish solid, yield 51%, m.p. 59–60 °C (lit. [20], m.p. 58 °C). ^{1}H NMR: δ 1.41 (9H, s), 2.30 (3H, s), 2.62 (3H, s), 7.30 (1H, d, $J = 1.9$ Hz), 7.40 (1H, d, $J = 2.0$ Hz), 12.7 (1H, s) ppm. ^{13}C NMR: δ 21.0, 27.2, 29.4, 35.0, 119.2, 126.7, 128.3, 134.8, 138.4, 160.1 and 205.0 ppm.

*3.4. Preparation of the mono-imines **6a–b***

A mixture of the 1-(2-hydroxyphenyl)ketone **5a–b** (0.8 mmol), (*R*,*R*)-1,2-diphenylethylenediamine (1.0 mmol) and anhydrous Na_2SO_4 (0.7 g) was refluxed in dry EtOH (10 ml) for 20 h. Upon filtration and evaporation of the filtrate, the residue was purified by filtration through a short plug of neutralized silica gel eluting with hexane–EtOAc. After evaporation, the mono-imine **6a–b** was obtained as a yellow semisolid contaminated with a small amount of ketone **5a–b**.

*3.4.1. (R,R)-N-[1-(3,5-Di-tert-butyl-2-hydroxyphenyl) propylidene]-1,2-diphenylethylenediamine (**6a**)*

Yield 63%. ^{1}H NMR: δ 0.99 (3H, dt, $J = 7.6$ and 7.8 Hz), 1.29 (9H, s), 1.52 (9H, s), 2.72 (2H, m), 4.50 (1H, d, $J = 7.2$ Hz), 4.83 (1H, d, $J = 7.2$ Hz), 7.10–7.43 (12H, m), 12.7 (1H, bs) ppm.

*3.4.2. (R,R)-N-[1-(3-tert-Butyl-2-hydroxy-5-methylphenyl)ethylidene]-1,2-diphenylethylenediamine (**6b**)*

Yield 61%. ^{1}H NMR: δ 1.50 (9H, s), 2.19 (3H, s), 2.27 (3H, s), 4.51 (1H, d, $J = 7.1$ Hz), 4.84 (1H, $J = 7.1$ Hz), 7.09–7.26 (12H, m), 12.7 (1H, bs) ppm.

*3.5. Preparation of 2-hydroxy-3-(3-imidazol-1-ylpropoxy)benzaldehyde (**7b**)*

2-Allyloxy-3-hydroxybenzaldehyde [21] (0.40 g, 2.24 mmol) dissolved in dry DMF (6 ml) was added to a suspension of NaH (50%, 0.13 g, 2.71 mmol) in dry DMF (6 ml). Freshly prepared *N*-(3-bromopropyl)imidazole [22,23] (0.92 g, 3.72 mmol) dissolved in DMF (5 ml) was added and the mixture was stirred at room temperature for 18 h. The reaction mixture was quenched with water and extracted with $CHCl_3$. The organic phase was washed with 2 M NaOH and extracted with 2 M HCl (3×). The collected HCl fractions were neutralized with 2 M NaOH and extracted with $CHCl_3$ (3×). The combined $CHCl_3$ extracts were dried with anhydrous Na_2SO_4 and the solvents evaporated. The residue was filtered through a short plug of silica gel eluting with $CHCl_3$–EtOH (10:1) to afford yellowish oil, yield 0.49 g. Subsequent deallylation using the procedure of Yamada et al. [24] afforded aldehyde **7b** as yellowish powder, which was recrystallized from 2-propanol. Yield 0.27 g, 49% from 2-allyloxy-3-hydroxybenzaldehyde, m.p. 138–139 °C. ^{1}H NMR: δ 2.27 (2H, quint, $J = 6.2$ Hz), 3.95 (2H, t, $J = 5.7$ Hz), 4.26 (2H, t, $J = 6.6$ Hz), 7.07 (5H, m), 7.50 (1H, s), 9.92 (1H, s), 11.2 (1H, s) ppm. ^{13}C NMR: δ 30.7, 43.3, 65.5, 119.0, 119.7, 120.7, 121.2, 125.7, 129.7, 137.5, 147.1, 152.2 and 196.7 ppm. HRMS (EI) *m/z*: calcd. for $C_{13}H_{14}N_2O_3$ 246.1004, found 246.0989.

3.6. Preparation of the non-C_2-symmetric Schiff-base ligands **8a–b**

The mono-imine **6a–b** (0.45 mmol) and salicylaldehyde derivative **7a–b** (0.47 mmol) were dissolved in dry EtOH (10 ml), Na_2SO_4 (0.4 g) was added and the mixture was refluxed for 3 h. After filtration and evaporation of the filtrate, the residue was purified by flash chromatography (eluent hexane–EtOAc) to afford **8a–b** as yellow foam.

3.6.1. Schiff-base ligand **8a**

Prepared from **6a** and 3-*tert*-butyl-2-hydroxy-5-methylbenzaldehyde **7a** [13], yield 87%. ^{1}H NMR: δ 0.92 (3H, dt, J = 7.6 and 6.0 Hz), 1.25 (9H, s), 1.40 (9H, s), 1.49 (9H, s), 2.18 (3H, s), 2.70 (2H, dq, J = 7.7 and 6.1 Hz), 4.76 (1H, d, J = 7.8 Hz), 5.12 (1H, d, J = 7.8 Hz), 6.85 (1H, d, J = 1.9 Hz), 7.05 (1H, d, J = 2.0 Hz), 7.08–7.30 (11H, m), 7.34 (1H, d, J = 2.2 Hz), 8.48 (1H, s), 13.7 (1H, s), 16.2 (1H, s) ppm. ^{13}C NMR: δ 11.9, 22.7, 29.3, 29.6, 31.4, 34.1, 34.7, 35.2, 69.9, 81.5, 116.7, 118.3, 122.3, 126.4, 127.1, 127.3, 127.4, 127.9, 128.0, 128.1, 128.2, 130.4, 130.5, 136.6, 137.6, 137.8, 139.8, 139.9, 157.9, 161.5, 166.9 and 177.5 ppm. HRMS (EI) *m/z*: calcd. for $C_{43}H_{54}N_2O_2$ 630.4174, found 630.4162.

3.6.2. Schiff-base ligand **8b**

Prepared from **6b** and **7b**, yield 75%. ^{1}H NMR: δ 1.43 (9H, s), 2.19 (3H, s), 2.21 (3H, s), 2.24 (2H, m), 3.95 (2H, t, J = 5.7 Hz), 4.25 (2H, t, J = 6.8 Hz), 4.81 (1H, d, J = 8.2 Hz), 5.11 (1H, d, J = 8.2 Hz), 6.71–7.20 (17H, m), 7.52 (1H, s), 8.55 (1H, s), 13.7 (1H, s), 16.4 (1H, s) ppm. ^{13}C NMR: δ 16.1, 21.0, 29.5, 31.0, 34.9, 43.5, 65.2, 70.5, 81.4, 116.7, 118.1, 118.9, 119.0, 124.6, 124.8, 126.2, 127.3, 127.5, 127.8, 128.1, 128.2, 129.4, 130.5, 137.3, 137.7, 139.2, 139.3, 146.7, 151.5, 160.2, 166.1 and 172.9 ppm. HRMS (EI) *m/z*: calcd. for $C_{40}H_{44}N_4O_3$ 628.3413, found 628.3427.

3.7. Preparation of the non-C_2-symmetric Mn(III)-Schiff-base complexes **3a–b**

3.7.1. Mn(III)-Schiff-base complex **3a**

A mixture of the ligand **8a** (0.38 mmol) and $Mn(OAc)_2{\cdot}4H_2O$ (0.8 mmol) in dry EtOH (6 ml) was refluxed in air for 90 min. Solid LiCl (1.7 mmol) was added and the mixture was further refluxed for 3 h. The mixture was concentrated, the residue dissolved in CH_2Cl_2 and transferred to a separatory funnel containing water. The organic phase was washed with water and saturated NaCl solution, dried over Na_2SO_4 and concentrated. The residue was purified by flash chromatography (eluent CH_2Cl_2 and CH_2Cl_2–MeOH) to afford **3a** as a dark brown powder. Yield 83%, m.p. 180 °C. IR (neat): 3062, 3030, 3004, 2953, 2907, 2868, 1603, 1538, 1520, 1408, 1388, 1306, 1252, 1204, 824, 701 cm^{-1}. MS (EI) *m/z*: 718 (M^+), 683 (M^+-Cl). Anal. calcd. for $C_{43}H_{52}ClMnN_2O_2{\cdot}CH_3OH$: C, 70.43; H, 7.39; N, 3.73. Found: C, 70.65; H, 7.09; N, 3.72.

3.7.2. Mn(III)-Schiff-base complex **3b**

Prepared as above from ligand **8b**, reaction time 2 h. Product was precipitated from the reaction mixture by adding a small amount of water. Drying in air overnight afforded **3b** as a dark brown powder, yield 83%, m.p. >300 °C. IR (neat): 3059, 3030, 3004, 2949, 2907, 2868, 1602, 1523, 1433, 1303, 1243, 1216, 1084, 827, 740, 703 cm^{-1}. MS (EI) *m/z*: 681 (M^+-Cl). Anal. calcd. for $C_{40}H_{42}ClMnN_4O_3{\cdot}1.5H_2O$: C, 64.56; H, 6.09; N, 7.53. Found: C, 64.79; H, 6.10; N, 7.26.

3.8. Typical procedures for the asymmetric epoxidation catalyzed by Mn(III) complex **3a**

3.8.1. Bu_4NIO_4 as the oxidant [25]

To a solution of 1,2-dihydronaphthalene (65 mg, 0.5 mmol), imidazole (25 mg, 0.37 mmol) and catalyst **3a** (21.5 mg, 0.03 mmol) in CH_2Cl_2 (2.5 ml) was added solid Bu_4NIO_4 (0.54 g, 1.25 mmol). The mixture was stirred at room temperature and monitored by TLC. After 6 h, the mixture was filtered through a pad of silica gel and the filtrate concentrated. The residue was purified by flash chromatography (eluent hexane–EtOAc) to give the corresponding epoxide, yield 34 mg (47%). The ee of the epoxide was determined to be 48% by ^{1}H NMR analysis in the presence of the chiral shift reagent tris[3-(heptafluoropropylhydroxymethylene)-(+)-camphorato]europium, Eu(hfc)$_3$. The absolute configuration was determined to be 1*R*,2*S*-(+) by polarimetry.

3.8.2. NaOCl as the oxidant

To a cooled (2 °C) solution of 1,2-dihydronaphthalene (66 mg, 0.51 mmol), pyridine *N*-oxide (36 mg,

0.38 mmol), and catalyst **3a** (19 mg, 0.026 mmol) in CH_2Cl_2 (2 ml) was added a pre-cooled solution of 0.55 M NaOCl (1.9 ml, pH 11.3). The mixture was stirred at 2 °C for 6 h and then diluted with CH_2Cl_2 and water. Phases were separated and the organic phase was washed with saturated NaCl solution, dried over Na_2SO_4, and concentrated. Flash chromatography (eluent hexane–EtOAc) provided the epoxide, yield 30 mg (40%). The ee of the epoxide was 44%.

3.8.3. Bu_4NHSO_5 as the oxidant [14]

To a cooled (−18 °C) solution of 6,7-dihydro-5*H*-benzocyclohexene (60.5 mg, 0.42 mmol), NMO (49 mg, 0.42 mmol), and catalyst **3a** (21 mg, 0.029 mmol) was added Bu_4NHSO_5 (purity 88%, 0.27 g, 0.67 mmol) and the mixture was stirred at −18 °C. After 4 h, the reaction was quenched with Me_2S (ca. 1.0 mmol), excess solid K_2CO_3 was added, the mixture was allowed to reach room temperature, filtered and the filtrate concentrated. The residue was purified by flash chromatography (eluent hexane–EtOAc) to afford the epoxide, yield 46 mg (69%). The ee of the epoxide was determined to be 79% and the absolute configuration 5*R*,6*S*-(−).

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