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Rational Design of Mn-Salen Catalyst (2): Highly Enantioselective Epoxidation of Conjugated *cis*-Olefins

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Abstract: On the basis of the newly proposed hypothesis on the mechanism of asymmetric induction, highly efficient (salen)manganese(III) complex (3) was constructed as a catalyst for asymmetric epoxidation. With this catalyst, the highest level of enantioselectivity was realized in the epoxidation of various conjugated *cis*-olefins.

Recent introduction of optically active (salen)manganese(III) catalysts (hereafter referred as Mn-salen catalysts) made a great progress in the asymmetric epoxidation of simple olefins.[1,2] Especially the epoxidation of *cis*-olefins conjugated with alkenyl, alkynyl, or aryl group shows high enantioselectivity. This interesting substrate-specific enantioselectivity observed in salen-catalyzed epoxidation can be explained by the newly proposed pathway **a** for olefin's access to metal oxo species (Fig. 1), wherein two factors, repulsive steric and electronic interactions between the oncoming olefin and the salen ligand, are considered to be responsible for induction of asymmetry: the steric repulsion between C3'-substituent in the salen ligand and an olefinic substituent and π,π-electronic repulsive interaction between the salen benzene ring (**A**) and the olefinic substituent bearing π-bond direct a bulkier and more electron-rich olefinic substituent (**L**) away from the C3'-substituent.[3] (For the convenience' sake, discussions in this paper are limited to the reaction on the β-side of Mn-salen catalysts. The same discussion holds for the reaction on the α-side due to C_2-symmetric structure of the catalysts). Accordingly the above described *cis*-olefins are generally good substrates for salen-catalyzed asymmetric epoxidation. We have already reported that Mn-salen catalysts possessed of axial chirality such as **1** showed good level of enantioselectivity in the epoxidation of conjugated *cis*-olefins.[4,5] In this paper, we describe the construction of more efficient Mn-salen catalysts by the modification of **1** on the ground of our new proposal[3] on the mechanism of asymmetric induction by Mn-salen catalyst and their application to the epoxidation of *cis*-olefins.[6]

Modification of Mn-Salen Catalyst

Salen complex **1** that is characterized by the presence of axial chirality has a wide applicability to the epoxidation of conjugated *cis*-olefins and shows a good level of asymmetric induction (86-91% ee). However, the newly proposed approach **a**[3] suggests that further improvement of enantioselectivity will be achieved by the modification of **1** along the following lines: i) if a sterically bulky and electron-rich group is placed into the space over the C8'-carbon, it causes the strong steric and electronic repulsion against the larger and more electron-rich group on the oncoming olefin with the undesired orientation that leads to the minor enantiomer of epoxides, thus resulting in the increase of enantioselectivity. Fortunately the substituent **X** is directed toward the desired space and, therefore, it is expected that the replacement of the methyl group in **1** (X= Me) with

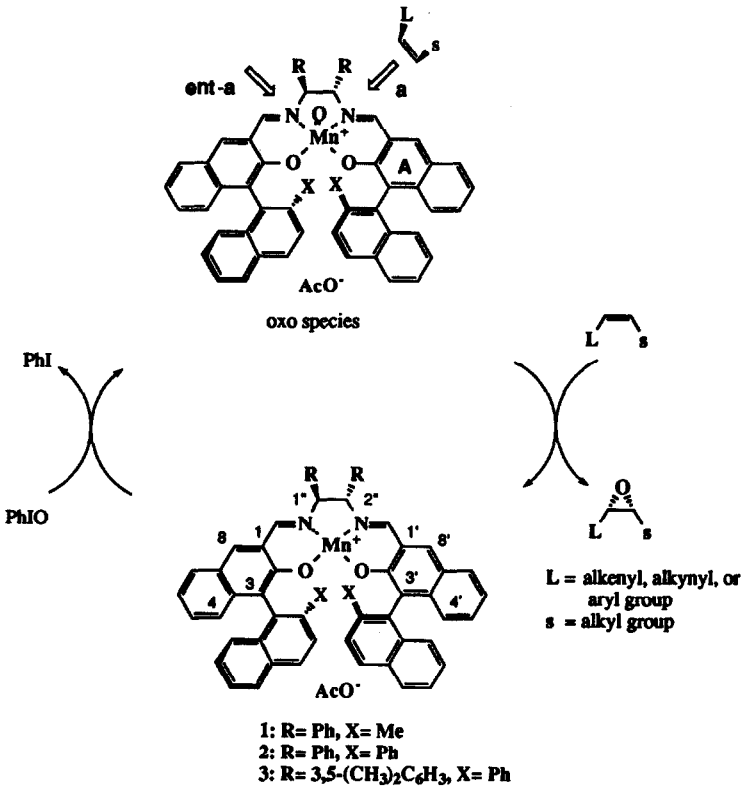


Fig. 1

more electron-rich and bulky group such as phenyl group enhances the enantioselectivity. ii) Although the olefin's approach along another Mn-N bond axis (pathway **ent-a**) that diminishes enantioselectivity is disfavored by the presence of C1"-phenyl group, the phenyl group does not seem possible to block pathway **ent-a** perfectly, since the C1"-substituent takes quasi-equatorial orientation. Accordingly, we can also expect that enantioselectivity is improved by the replacement of C1"(2")-phenyl group with a substituted phenyl group that blocks pathway **ent-a** more effectively. Although *ortho*-substituted phenyl group (R^1= alkyl, R^2=

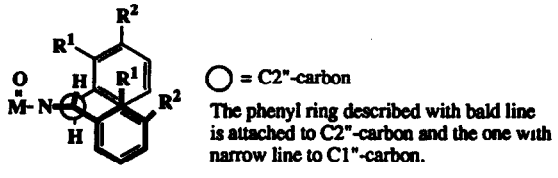


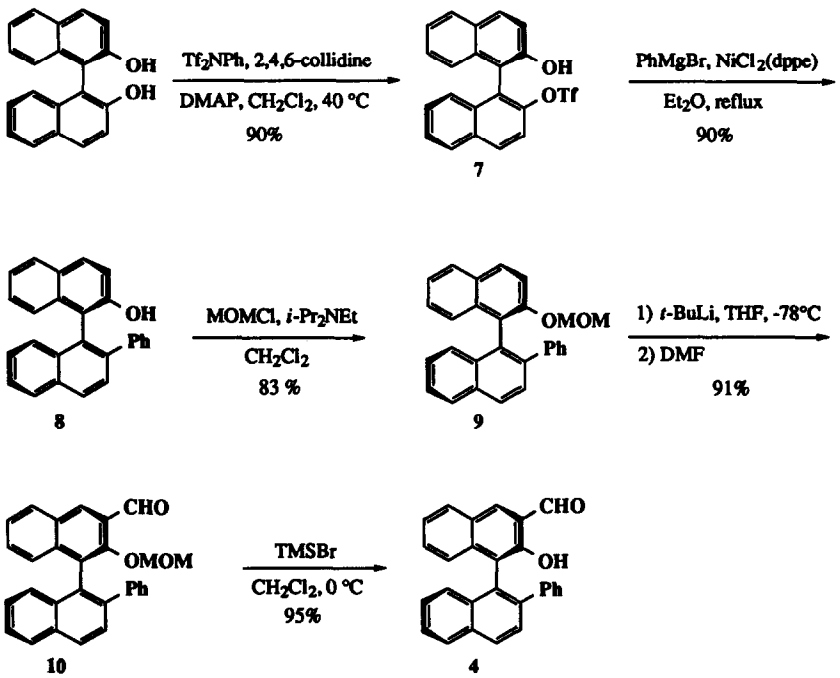
Fig. 2 The side view of the ethylenediamine part of salen complex **1**

H, Fig. 2) seems aprropriate as the substituted phenyl group, its introduction is problematic from following two reasons: i) The *ortho*-substituted phenyl group strongly blocks pathway **ent-a** but it also barrs the pathway **a**. ii) The *ortho*-substituent (R^1) existing near the metal oxo bond probably causes a steric repulsion with the larger substituent on the olefin approaching with the desired orientation and decreases enantioselectivity. On the other hand, a *meta*-substituted phenyl ring (R^1= H, R^2= alkyl) only blocks pathway **ent-a** and, furthermore, R^2 on C1"-phenyl ring locates quite far from the metal-oxo bond so that its steric interaction with the bulkier olefinic substituent should be weak. Based on these considerations, we planned to synthesize the new Mn- salen complexes **2** and **3**.

Synthesis of New Mn-Salen Catalysts 2 and 3

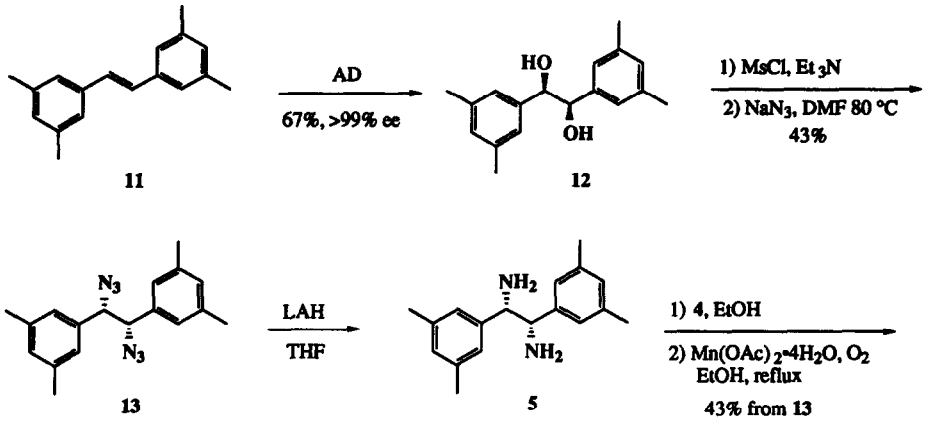
(a*R*)-3-Formyl-2-hydroxy-2'-phenyl-1,1'-binaphthyl (**4**) and (1*S*,2*S*)-1,2-bis(3,5-dimethylphenyl)ethylenediamine (**5**) required for the synthesis of **2** and **3** were synthesized as described in Schemes 1 and 2.

The synthesis of aldehyde **4** started from (a*R*)-binaphthol. Treatment of (a*R*)-binaphthol with *N*-phenylbistrifluoromethanesulfonimide gave monotriflate **7** which was further treated with phenylmagnesium bromide (4 equiv.) in the presence of $NiCl_2(dppe)_2$ to give 2-hydroxy-2'-phenylbinaphthyl **8**. Compound **8** was protected as a MOM ether **9**. Successive treatment of **9** with *t*-butyllithium and *N*,*N*-dimethylformamide afforded aldehyde **10** which was deprotected with trimethylsilyl bromide to give the requisite **4**.



Scheme 1

The synthesis of diamine **5** started from *trans*-3,3',5,5'-tetramethylstilbene **11** which was readily prepared from commercial 3,5-dimethylbenzoic acid via 3,5-dimethylbenzyl alcohol in a conventional manner. Sharpless asymmetric dihydroxylation[7] gave (*R,R*)-diol **12** with high enantioselectivity. Compound **12** was mesylated and subsequently treated with sodium azide to give (*S,S*)-diazide **13** stereospecifically. LAH reduction of **13** gave diamine **5** which was unstable and hence used for the preparation of complex **3** without purification. Complexes **2** and **3** were prepared from **4** and (*S,S*)-diphenylethylenediamine and from **4** and **5**, respectively, according to the literature procedure[1a] with slight modification.



Scheme 2

Asymmetric Epoxidation with Catalysts 1-3

With these complexes **1-3** at hand, we first examined the epoxidation of *trans*-stilbene and dihydronaphthalene using iodosylbenzene as a terminal oxidant (Table 1). Enantioface selectivity of *trans*-stilbene was only slightly improved by the use of the catalyst **3** (entries 1 and 2). This result seems to be reasonable from our proposal: *trans*-olefins approach metal-oxo bond along Mn-N bond axis not from the side but from the upper side for steric reason.[3a] Since C1"-substituent takes quasi-equatorial orientation as discussed above, it can not disturb the approach of *trans*-olefins along the pathway **ent-a** leading to formation of the opposite enantiomer of the epoxide. Accordingly the enantioselectivity observed with catalysts **1** and **3** are poor. On the other hand, enatioface selectivity of dihydronaphthalene was improved by the use of modified catalysts up to 97% ee (entries 3-6). Use of sodium hypochlorite[2e] as a terminal oxidant in the epoxidation of dihydronaphthalene was found to slightly improve enantioselectivity up to 98% ee (entry 7). We also synthesized catalyst **14**[8] in which the substituent in binaphthyl moiety is 3,5-dimethylphenyl group, expecting further improvement of enantioselectivity in the epoxidation of *cis*-olefins. Contrary to our expectation, however, **14** showed the diminished enantioselectivity (entry 8). 3,5-Dimethylphenyl group is probably too bulky as a binaphthyl substituent.

Based on these results, we next examined the epoxidation of various conjugated *cis*-olefins with **3** as a catalyst (Table 2). All the reactions with iodosylbenzene as an oxidant proceeded smoothly with high enantioselectivity even at -20 °C (entries 2, 5 and 8), except for the epoxidation of *cis*-β-methylstyrene.

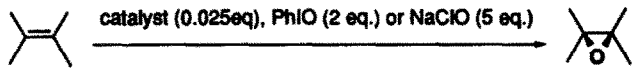
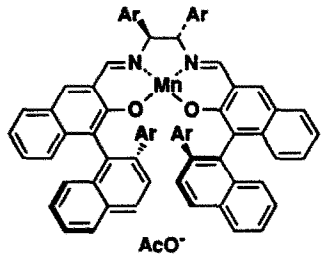


Table 1 Epoxidation of dihydronaphthalene and *trans*-stilbene using Mn-salen catalyst **1**, **2**, **3**, or **14**[a]

entry	olefin	catalyst	oxidant	time (h)	temp	yield (%)	% ee (confign.)	(% ee)[b]
1	Ph, Ph	**1**	PhIO	24	r.t.	52	0[c] (-)	(66)[d]
2	"	**3**	"	24	r.t.	27	15[c] (1*R*,2*R*)	
3		**1**	PhIO	24	r.t.	77	86[e] (1*S*,2*R*)	(91)[f]
4	"	**2**	"	24	r.t.	96	93 (1*S*,2*R*)	
5	"	**3**	"	24	r.t.	61	96 (1*S*,2*R*)	
6		**3**	"	4	0 °C	80	97 (1*S*,2*R*)	
7	"	**3**	NaClO	4	0 °C	78	98 (1*S*,2*R*)	
8	"	**14**	"	24	r.t.	48	85 (1*S*,2*R*)	

a) Reactions were carried out in acetonitile in the presence of pyridine *N*-oxide by using PhIO as a terminal oxidant or in dichloromethane in the presence of 4-phenyl-pyridine*N*-oxide by using NaClO as a terminal oxidant.
b) The highest % ee reported to date for catalytic asymmetric epoxidation.
c) Determined by HPLC (DAICEL CHIRALCEL OJ, hexane/*i*-PrOH = 9/1).
d) Reference 3a.
e) For the determination of % ee, see the experimental part.
f) Reference 2a.



14 Ar= 3,5-dimethylphenyl

Reaction at -20 °C showed a slightly improved asymmetric induction as compared with that at room temperature (cf. entries 4 and 5). However, in accord with the epoxidation of dihydronaphthalene, the reactions with sodium hypochlorite as a terminal oxidant generally showed further improved enantioselectivity which was the highest ones reported for the each substrate to date (entries 1, 3, 6, 7, and 9), except for the epoxidation of *cis*-β-methylstyrene. The low enantioselectivity observed for *cis*-β-methylstyrene especially in acetonitrile is surprising (entry 10), since even **1** showed much better asymmetric induction of 89% ee for the *cis*-epoxide. This suggests that an attractive force is operating between the olefinic phenyl group and the phenyl group in the binaphthyl moiety. Recently it has been reported that two benzene rings which can partially stack in parallel to each other interact attractively.[9] Since the phenyl ring of *cis*-β-methylstyrene is

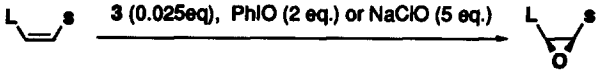
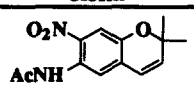
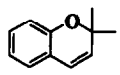
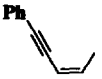


Table 2 Epoxidation of conjugated *cis*-olefins using Mn-salen complex 3 as a catalyst[a)]

entry	olefin	oxidant	time (h)	temp	yield (%)	% ee (confign.)	(% ee)[b)]
1		NaClO	0.7	0 °C	80	>99[c)] (3*S*,4*S*)	96[d)]
2		PhIO	24	-20 °C	60	>99[e)] (-)[f)]	98[g)]
3	"	NaClO	2	0 °C	75	99[e)] (-)[f)]	
4		PhIO	24	rt	53	92[h)] (1*S*,2*R*)	88[i)]
5	"	PhIO	24	-20 °C	82	94[h)] (1*S*,2*R*)	
6	"	NaClO	3	0 °C	55	98[h)] (1*S*,2*R*)	
7		NaClO	3	0 °C	80[j)]	96 (3*R*,4*R*)[k)] 92 (3*S*,4*R*)[k)]	93[l)]
8		PhIO	24	-20 °C	41	70[h)] (-)[f)]	57[m)]
9	"	NaClO	1	0 °C	40	77[h)] (-)[f)]	
10		PhIO	3	0 °C	25[n)]	43 (1*R*,2*R*)[h)] 64 (1*S*,2*R*)[h)]	92[g)]
11	"	NaClO	1.5	0 °C	16[o)]	40 (1*R*,2*R*)[h)] 90 (1*S*,2*R*)[h)]	
12	"	PhIO[p)]	2	0 °C	16[q)]	51 (1*R*,2*R*)[h)] 73 (1*S*,2*R*)[h)]	
13	"	PhIO[r)]	4	0 °C	14[s)]	80 (1*R*,2*R*)[h)] 66 (1*S*,2*R*)[h)]	

a) Reactions were carried out in acetonitile in the presence of pyridine *N*-oxide by using PhIO as a terminal oxidant or in dichloromethane in the presence of 4-phenyl-pyridine*N*-oxide by using NaClO as a terminal oxidant, unless otherwise mentioned.
b) The highest % ee reported to date for catalytic asymmetric epoxidation.
c) Determined by HPLC analysis (DAICEL CHIRALCEL OJ, hexane/*i*-PrOH = 1/1).
d) Reference 1b.
e) For the determination of % ee, see the experimental part.
f) The absolute configuration has not been determined.
g) Reference 2a.
h) Determined by ^{1}H NMR analysis in $CDCl_3$ using Eu(hfc)$_3$ as a chiral shift reagent.
i) Reference 2g.
j) A mixture of (3*S*,4*R*)- and (3*R*,4*R*)-poxides in a ratio of 2:1.
k) Determined by ^{1}H NMR analysis in C_6D_6 using Eu(hfc)$_3$ as a chiral shift reagent.
l) The enantiomeric excess of the (3*R*,4*R*)-epoxide (Reference 2c). The enantiomeric excess of (3*S*,4*R*)-epoxide was 58% ee.
m) Reference 2f.
n) A mixture of (1*S*,2*R*)- and (1*R*,2*R*)-epoxides in a ratio of 2.4:1.
o) A mixture of (1*S*,2*R*)- and (1*R*,2*R*)-epoxides in a ratio of 8.5:1.
p) Reaction was carried out in dichloromethane.
q) A mixture of (1*S*,2*R*)-and (1*R*,2*R*)-epoxides in a ratio of 1.9:1.
r) Reaction was carried out in acetonitrile in the presence of phosphate buffer.
s) A mixture of (1*S*,2*R*)-and (1*R*,2*R*)-epoxides in a ratio of 1:3.8.

perpendicular to the double bond due to allylic strain, it can partially stack in parallel with the phenyl group at the binaphtyl moiety on its way to the oxo bond. We speculated that the attractive interaction between these two phenyl rings cancels out the above described steric and electronic repulsion, resulting in the decrease of enantioselectivity. In contrast to the reaction in acetonitrile, the reaction in dichloromethane with aqueous sodium hypochlorite as an oxidant showed a considerably improved enantioselectivity (entry 11). This result is probably attributable to that, in the reaction in a mixed solvent of dichloromethane and water, CH-π interaction (CH_2Cl_2) or OH-π interaction (H_2O) competes with the partial stacking of two phenyl rings. This is supported from the results that the use of dichlorometane as a solvent or the addition of small amount of water to acetonitrile improves the enantioselectivity to some extent even when iodsobenzene is used as an oxidant (entries 12 and 13).

In conclusion, we could show that the Mn-salen complex **3** synthesized based on the newly proposed asymmetry-inducing mechanism,[3] was so far the best catalyst for the epoxidation of conjugated *cis*-olefins.

Experimental

NMR spectra were recorded at 400 MHz on a JEOL GX-400, at 270 MHz on a JEOL EX-270, or at 90 MHz on a JEOL FX-90Q instrument. All signals were expressed as ppm down field from tetramethylsilane used as an internal standard (δ-value in $CDCl_3$). IR spectra were obtained with a JASCO IR-700 instrument. Optical rotation was measured with a JASCO DIP-360 automatic digital polarimeter. Column chromatography was conducted on Silica Gel 60, 70-230 mesh ASTM, available from E. Merck. Preparative thin layer chromatography was performed on 0.5 mm x 20 cm x 20 cm E. Merck silica gel plate (60 F-254). Solvents were dried and distilled shortly before use. Reactions were carried out under an atmosphere of nitrogen if necessary.

(a*R*)-2-Hydroxy-2'-trifluoromethanesulfonyloxy-1,1'-binaphthyl (7)

To a solution of (*R*)-(-)binaphthol (286 mg, 1.0 mmol) in CH_2Cl_2 (4 ml) was added 2,4,6-collidine (132 µl, 1.0 mmol), 4-(*N*,*N*-dimethylamino)pyridine (15 mg, 0.12 mmol), and Tf_2NPh (357 mg, 1.0 mmol) and the resulting mixture was refluxed for 12 h. The mixture was cooled and then concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, toluene) to give **7** (378 mg, 90%) as an oil. $[\alpha]_D^{25}$ +12.59° (*c* 4.01, $CHCl_3$). ^1H NMR (270 MHz): δ 8.13 (d, *J*= 9.24, 1H), 8.02 (d, *J*= 8.25, 1H), 7.97 (d, *J*= 8.90, 1H), 7.88 (d, *J*= 7.59, 1H), 7.61 (d, *J*= 9.24, 1H), 7.60 (dd, *J*= 8.25 and 8.25 Hz, 1H), 7.45 (d, *J*= 3.63, 2H), 7.39-7.26 (m, 3H), 7.02 (d, *J*= 8.25, 1H), 5.04 (br s, 1H). IR (KBr): 3537, 3061, 2928, 1622, 1599, 1508, 1420, 1383, 1346, 1271, 1213, 1169, 1140, 1069, 974, 951, 862, 835, 814, 750, 677, 619, 496 cm^{-1}. HRFABMS m/z. Calcd. for $C_{21}H_{13}F_3O_4S$: 418.0487. Found 418.0488 (M^+).

(a*R*)-2-Hydroxy-2'-phenyl-1,1'-binaphthyl (8)

To a mixture of **7** (209 mg, 0.5 mmol) and $NiCl_2$(dppe) (5.3 mg, 0.01 mmol) was slowly added an ethereal phenylmagnesium bromide solution (0.8 M, 2.5 ml, 2.0 mmol). The resulting mixture was refluxed for 1 h and then quenched with aqueous NH_4Cl. The reaction mixture was extracted with Et_2O, washed successively with aqueous $NaHCO_3$ and brine, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/toluene=4/6) to give **8** (156 mg 90%) as colorless crystals. m.p. 174 °C. $[\alpha]_D^{24}$ +27.2° (*c* 1.00, $CHCl_3$). ^1H NMR (400 MHz): δ 8.10 (d, *J*= 8.30 Hz, 1H), 7.79

(d, *J*= 8.30 Hz, 1H), 7.78 (d, *J*= 9.28 Hz, 2H), 7.72 (d, *J*= 8.79 Hz, 1H), 7.54-7.50 (m, 1H), 7.36-7.20 (m, 4H), 7.15-7.04 (m, 7H), 4.82 (s, 1H). IR (KBr): 3483, 3418, 3057, 3020, 1618, 1597, 1518, 1493, 1468, 1379, 1354, 1265, 1205, 1184, 1148, 1128, 816, 748, 698, 586 cm^{-1}. HRFABMS m/z. Calcd. for $C_{26}H_{18}O$: 346.1358. Found 346.1358 (M^+).

(a*R*)-2-Methoxymethoxy-2'-phenyl-1,1'-binaphthyl (9)

To a solution of **8** (365 mg, 1.1 mmol) in CH_2Cl_2 (4 ml) was added *N,N*-diisopropylethylamine (530 µl, 3.0 mmol) and chloromethyl methyl ether (230 µl, 3.0 mmol). The resulting mixture was stirred for 24 h at room temperature and quenched with water. The mixture was extracted with CH_2Cl_2, washed with water, dried over Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/Et_2O=19/1) to give **9** (346 mg, 83%) as colorless crystals. m.p. 86-88 °C. $[\alpha]_D^{20}$ +59.6° (*c* 0.55, $CHCl_3$). ^1H NMR (90 MHz): δ 8.22-7.00 (m, 17H), 4.90 (ABq, *J*= 7.07 Hz, 2H), 3.11 (s, 3H). IR (KBr): 3055, 2891, 1622, 1591, 1506, 1474, 1240, 1200, 1148, 1084, 1057, 1036, 1015, 922, 820, 764, 750, 702 cm^{-1}. Anal. Calcd for $C_{28}H_{22}O_2$: C, 86.13; H, 5.68. Found: C, 85.92; H, 5.77.

(a*R*)-3-Formyl-2-methoxymethoxy-2'-phenyl-1,1'-binaphthyl (10)

t-Butyllithium (1.5 M in pentane, 530 µl, 0.8 mmol) was added to a solution of **9** (140 mg, 0.36 mmol) in THF (1.5 ml) at -78 °C and the mixture was stirred for 3 h at the same temperature. After *N,N*-dimethylformamide (140 µl, 1.8 mmol) was added, the reaction mixture was allowed to warm to room temperature and stirred for 1 h. The reaction mixture was quenched with aqueous NH_4Cl, extracted with Et_2O, washed successively with aqueous $NaHCO_3$ and brine, dried over Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/Et_2O=19/1) to give **10** (139 mg, 91%) as a yellow oil. $[\alpha]_D^{20}$ -12.6° (*c* 0.17, $CHCl_3$). ^1H NMR (90 MHz): δ 10.42 (s, 1H), 8.50 (s, 1H), 8.18-7.00 (m, 15H), 4.53 (ABq, *J*= 6.17 Hz, 2H), 2.94 (s, 3H). IR (KBr): 1690, 1653, 1618, 1587, 1558, 1541, 1506, 1501, 1456, 1157, 1069, 964, 924, 764, 700 cm^{-1}. HREIMS m/z. Calcd. for $C_{29}H_{22}O_3$: 418.1568. Found 418.1552 (M^+).

(a*R*)-3-Formyl-2-hydroxy-2'-phenyl-1,1'-binaphthyl (4)

Bromotrimethylsilane (195 µl, 1.5 mmol) was added to a mixture of **10** (154 mg, 0.37 mmol) and MS 4Å in CH_2Cl_2 (1.5 ml) and stirred for 1 h. The mixture was quenched with aqueous $NaHCO_3$, extracted with CH_2Cl_2, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/toluene=3/7) to give **4** (132 mg, 95%) as yellow crystals. m.p. 205 °C. $[\alpha]_D^{22}$ -50.7° (*c* 1.00, $CHCl_3$). ^1H NMR (400 MHz): δ 10.41 (s, 1H), 10.10 (s, 1H), 8.17 (s, 1H), 8.05 (d, *J*= 8.30 Hz, 1H), 7.97 (d, *J*= 8.30 Hz, 1H), 7.85 (d, *J*= 7.81 Hz, 1H), 7.65 (d, *J*= 8.30 Hz, 1H), 7.49 (dd, *J*= 3.42 Hz, 1H), 7.34-7.19 (m, 6H), 7.12 (d, *J*= 9.27 Hz, 1H), 7.02-7.00 (m, 3H). IR (KBr): 3180, 3051, 1657, 1630, 1504, 1460, 1441, 1412, 1385, 1342, 1292, 1248, 1180, 1148, 1115, 1026, 939, 893, 860, 822, 793, 751, 702, 683, 505 cm^{-1}. Anal. Calcd for $C_{27}H_{18}O_2$: C, 86.61; H, 4.85. Found: C, 86.33; H, 4.85.

(*R,R*)-1,2-Bis(3,5-dimethylphenyl)ethane-1,2-diol (12)

A mixture of *t*-BuOH (20 ml) and H_2O (20 ml), $K_2OsO_2(OH)_4$ (11.1 mg, 0.03 mmol), and **11** (709 mg, 3.0 mmol) were added to a mixture of hydroquinidine 4-chlorobenzoate (186 mg, 0.4 mmol), $K_3Fe(CN)_6$ (2.96 g,

9.0 mmol), and K_2CO_3 (1.24 mg, 9.0 ml) and stirred for 24 h at room temperature. After Na_2SO_3 (15 g, 119 mmol) was added, the reaction mixture was stirred for another 30 min. The organic layer was separated and the water layer was extracted with CH_2Cl_2. The organic layers were combined and concentrated *in vacuo*. The residue was diluted with AcOEt, washed successively with 1M H_2SO_4, aqueous $NaHCO_3$, and brine, then dried over Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/AcOEt=9/1 to 7/3) to give **12** (550 mg, 67%) as colorless crystals. The optical purity of **12** was determined to be >99% ee by HPLC analysis (DAICEL CHIRALCEL OD, hexane/*i*-PrOH=15/1). m.p. 106-107 °C. $[\alpha]_D^{24}$ +65.60° (*c* 1.00, $CHCl_3$). ^1H NMR (270 MHz): δ 6.89 (s, 2H), 6.83 (s, 4H), 4.67 (s, 2H), 2.65 (br s, 2H), 2.26 (s, 12H). IR (KBr): 3885, 2909, 2860, 1647, 1636, 1609, 1464, 1159, 1072, 849, 727, 704, 687 cm^{-1}. Anal. Calcd for $C_{18}H_{22}O_2$: C, 79.96; H, 8.20. Found: C, 79.89; H, 8.14.

(*S*,*S*)-1,2-Diazido-1,2-bis(3,5-dimethylphenyl)ethane (13)

Triethylamine (610 μl, 4.4 mmol) and methanesulfonyl chloride (340 μl, 4.4 mmol) were added to a solution of **12** (550 mg, 2.0 mmol) in CH_2Cl_2 (8 ml) and stirred for 3 h. The reaction mixture was quenched with water and extracted with CH_2Cl_2. The organic layer was dried over Na_2SO_4 and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, Et_2O) to give the corresponding mesylate (839 mg, 98%) as colorless crystals. ^1H NMR (90 MHz): 7.10-6.80 (m, 6H), 5.74 (s, 2H), 2.86 (s, 6H), 2.23 (s, 12H). Since the mesylate was unstable at room temperature, it was used immediately for the next reaction.

A mixture of the mesylate (1.7 g, 4.0 mmol) and NaN_3 (572 mg, 8.8 mmol) in *N*,*N*-dimethylformamide (16 ml) was stirred for 7 h at 80 °C and cooled to room temperature. After water was added, the mixture was extracted with AcOEt. The organic layer was dried over Na_2SO_4 and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane) to give **13** (568 mg, 44%) as colorless crystals. m.p. 39-41 °C. $[\alpha]_D^{26}$ +140.9° (*c* 1.00, $CHCl_3$). ^1H NMR (90 MHz): δ 7.00 (br s, 2H), 6.84 (br s, 4H), 4.63 (s, 2H), 2.28 (s, 12H). IR (KBr): 3314, 3015, 2920, 2864, 2480, 2118, 2073, 1609, 1464, 1377, 1304, 1290, 1244, 934, 849, 739, 694, 627, 554 cm^{-1}. Anal. Calcd for $C_{18}H_{20}N_6$: C, 67.48; H, 6.29; N, 26.23. Found: C, 67.65; H, 6.26; N, 26.17.

(Salen)manganese(III) complex (3)

To a solution of **13** (32 mg, 0.1 mmol) in THF (1 ml) was added LAH (7.6 mg, 0.2 mmol) at 0 °C. The mixture was stirred for 30 min at room temperature and quenched with aqueous KF (1.59 N, 380 μl, 0.6 mmol). The suspension was filtered through a pad of Celite and extracted with AcOEt. The organic layer was dried over Na_2SO_4 and concentrated *in vacuo*. To the concentrate including **5** were added **4** (75.8 mg, 0.2 mmol) and EtOH (4 ml) and the mixture was stirred for 1 h at room temperature. The mixture was concentrated *in vacuo* to dryness and to the concentrate was added a solution of $Mn(OAc)_2 \cdot 4H_2O$ (24.6 mg, 0.1 mmol) in EtOH (4 ml). The mixture was refluxed in air for 6 h and allowed to cool to room temperature. The dark brown crystals were separated from the solution by filtration, washed successively with EtOH and hexane. The filtrate was concentrated to dryness and the residue was recrystalized from CH_2Cl_2-hexane. The combined first and second crops of **3** weighed 47.0 mg (43% from **13**). IR (KBr): 3053, 2920, 1599, 1493, 1425, 1333, 1296, 1223, 1188, 1148, 1128, 1045, 1028, 953, 860, 733, 700, 575, 548 cm^{-1}. Anal. Calcd for $C_{74}H_{57}N_2O_4Mn \cdot 2H_2O$: C, 78.70; H, 5.45; N, 2.48. Found: C, 78.93; H, 5.68; N, 2.41.

(Salen)manganese(III) complex (2)

To a solution of **4** (25.3 mg, 68 μmol) in CH_2Cl_2 (1 ml) was added (1*S*,2*S*)-(-)-1,2-diphenylethylenediamine (7.2 mg, 34 μmol) followed by addition of a solution of $Mn(OAc)_2 \cdot 4H_2O$ (8.3 mg, 34 mmol) in EtOH (1 ml) dropwise over 10 min and the mixture was stirred in air for 24 h at room temperature. The dark brown crystals were separated from the solution by filtration, washed with water, and dried under vaccum to give **2** (12.4 mg, 35%). The filtrate was concentrated to dryness and recrystallized from CH_2Cl_2-EtOH to yield the second crop (12.9 mg, 37%). IR (KBr): 3431, 3053, 1599, 1493, 1443, 1425, 1385, 1333, 1296, 1223, 1188, 1148, 1128, 1090, 1072, 1045, 1028, 999, 953, 860, 733, 700, 681, 575, 548 cm^{-1}. Anal. Calcd for $C_{70}H_{49}N_2O_4Mn \cdot 1.5H_2O$: C, 79.01; H, 4.93; N, 2.63. Found: C, 78.94; H, 5.06; N, 2.53.

General procedure for asymmetric epoxidation using complex 3 as a catalyst

(The procedure using iodosylbenzene as a terminal oxidant)

Compound **3** (2.7 mg, 2.5 μmol) was added to a solution of 2,2-dimethylchromene (16.0 mg, 0.1 mmol) and pyridine *N*-oxide (2.4 mg, 25 μmol) in acetonitrile (1.25 ml) and the mixture was cooled to -20 °C. Iodosylbenzene (44.0 mg, 0.2 mmol) was added at the same temperature and the whole mixture was stirred for 24 h, then allowed to warm to room temperature, and filtered through a pad of Celite. The filtrate was concentrated and the residue was purified by column chromatography (SiO_2, pentane/ether=1/0 to 19/1) to give the corresponding epoxide (10.6 mg, 60%). The optical purity of this sample was determined to be >99% ee by HPLC (DAICEL CHIRALCEL OJ, hexane/2-propanol=15/1).

(The procedure using sodium hypochlorite as a terminal oxidant)

To a solution of 1,2-dihydronaphthalene (12.8 mg, 0.08 mmol) and 4-phenylpyridine *N*-oxide (3.4 mg, 0.02 mmol) in CH_2Cl_2 (0.5 ml) was added **3** (2.2 mg, 2 μmol) and the mixture was cooled to 0 °C followed by addition of NaOCl in phosphate buffer (0.588 M, pH= 11.37) (0.7 ml) at the same temperature. The two phase solution was stirred for 4 h, then allowed to warm to room temperature, and separated. The aqueous phase was extracted with dichloromethane and the combined organic phase was dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (SiO_2, pentane/ether=1/0 to 49/1) to give the correspondig epoxide (9.1 mg, 78%). The optical purity of this sample was determined to be 98% ee by GC (SUPELCO β-DEX 120 fused silica capillary column, 30 m x 0.25 mm ID, 0.25 μm film, col. temp.: 120 °C).

NMR and chiroptical data of the obtained epoxides

(1*S*,2*R*)-1,2-Epoxy-1,2,3,4-tetrahydronaphthalene (98% ee);$[\alpha]_D^{25}$ -144.9° (*c* 0.33, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ 7.40 (dd, *J*= 1.47 and 7.33 Hz, 1H), 7.28-7.18 (m, 2H), 7.09 (d, *J*= 7.33 Hz, 1H), 3.85 (d, *J*= 4.39 Hz, 1H), 3.73 (m, 1H), 2.77 (ddd, *J*= 6.83, 14.65, and 14.65 Hz, 1H), 2.55 (dd, *J*= 5.86 and 14.65 Hz, 1H), 2.42 (m, 1H), 1.77 (ddd, *J*= 5.86, 14.65, and 14.65 Hz, 1H).

(3*S*,4*S*)-6-Acetamido-3,4-epoxy-2,2-dimethyl-7-nitrochromene (>99% ee);$[\alpha]_D^{25}$ +23.2° (*c* 0.25, $CHCl_3$). ^1H NMR (400 MHz, CDCl3): δ 10.09 (br s, 1H), 8.79 (s, 1H), 7.63 (s, 1H), 3.97 (d, *J*= 4.40 Hz, 1H), 3.55 (d, *J*= 4.40 Hz 1H), 2.28 (s, 3H), 1.59 (s, 3H), 1.27 (s, 3H).

3,4-Epoxy-2,2-dimethylchromene (99% ee);[10]$[\alpha]_D^{25}$ -0.60° (*c* 0.93, $CHCl_3$). ^1H NMR (270 MHz, $CDCl_3$): δ 7.33 (dd, *J*= 1.82 and 7.43 Hz, 1H), 7.23 (ddd, *J*= 1.82, 7.10, and 7.72 Hz, 1H), 6.92 (ddd, *J*= 0.91, 7.10, and

7.43 Hz, 1H), 6.64 (dd, *J*= 0.91 and 7.72 Hz, 1H), 3.90 (d, *J*= 4.13 Hz, 1H), 3.49 (d, *J*= 4.13 Hz, 1H), 1.58 (s, 3H), 1.25 (s, 3H).

(1*S*,2*R*)-1,2-Epoxyindan (98% ee); $[\alpha]_D^{25}$ +12.6° (*c* 0.23, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ 7.50 (d, *J*= 7.32, 1H), 7.32-7.17 (m, 3H), 4.27 (dd, *J*= 0.97 and 2.93 Hz, 1H), 4.14 (dd, *J*= 2.93 and 2.93 Hz, 1H), 3.22 (d, *J*= 17.82 Hz, 1H), 2.98 (dd, *J*= 2.93 and 17.82 Hz, 1H).

(3*S*,4*R*)-*cis*-3,4-Epoxy-1-phenyl-1-pentyne; ^1H NMR (270 MHz, $CDCl_3$): δ 7.48-7.28 (m, 5H), 3.64 (d, *J*= 3.94 Hz, 1H), 3.25 (dq, *J*= 3.94 and 4.95 Hz, 1H), 1.51 (d, *J*= 4.95 Hz, 3H).

(3*R*,4*R*)-*trans*-3,4-Epoxy-1-phenyl-1-pentyne; ^1H NMR (270 MHz, $CDCl_3$): δ 7.45-7.42 (m, 2H), 7.34-7.27 (m, 3H), 3.30-3.23 (m, 2H), 1.39 (d, *J*= 5.28 Hz, 3H).

3,4-Epoxycyclooctene (77% ee);[10] $[\alpha]_D^{25}$ -13.3° (*c* 0.50, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$): δ 5.80-5.74 (m, 1H), 5.59 (d, *J*= 11.23 Hz, 1H), 3.47-3.45 (m, 1H), 3.14-3.09 (m, 1H), 2.33-2.27 (m, 1H), 2.12-2.01 (m, 2H), 1.79-1.75 (m, 1H), 1.69-1.60 (m, 2H), 1.50-1.38 (m, 1H), 1.31-1.25 (m, 1H).

(1*S*,2*R*)-*cis*-1,2-Epoxy-1-phenylpropane; ^1H NMR (400 MHz, $CDCl_3$): δ 7.38-7.25 (m, 5H), 4.07 (d, *J*= 4.39 Hz, 1H), 3.35 (dq, *J*= 4.35 and 5.37 Hz, 1H), 1.09 (d, *J*= 5.37 Hz, 3H).

(1*R*,2*R*)-*trans*-1,2-Epoxy-1-phenylpropane; ^1H NMR (400 MHz, $CDCl_3$): δ 7.36-7.25 (m, 5H), 3.58 (d, *J*= 2.20 Hz, 1H), 3.04 (dq, *J*= 2.20 and 5.13 Hz, 1H), 1.46 (d, *J*= 5.13 Hz, 3H).

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