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## Polymer-Bound Chiral (Salen)Mn(III) Complex as Heterogeneous Catalyst in Rapid and Clean Enantioselective Epoxidation of Unfunctionalised Olefins

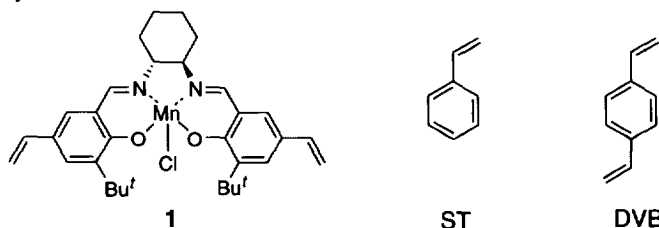
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**Abstract:** The application of a new polystyrene-divinylbenzene system containing an optically active (salen)Mn(III) complex in asymmetric epoxidation of unfunctionalised olefins is reported. This system showed a remarkably high reaction speed in the conditions described. Reaction outcomes drastically varied, in terms of enantioselectivity and *cis-trans* isomerization extent, upon the terminal oxidant employed (*m*CPBA/NMO and MMPP). Reuse of the catalyst was extremely efficient for several cycles. Interesting values of ee were obtained for styrene (15%) and *cis*- $\beta$ -methylstyrene (41%).  
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Asymmetric epoxidation of unfunctionalised olefins catalyzed by chiral (salen)Mn(III) complexes has proved to be one of the most useful reactions discovered in last decade.<sup>1</sup> The reaction provides chiral epoxides, which are versatile synthetic intermediates, with high levels of enantioselectivity. Such manganese complexes can be easily synthesized,<sup>2</sup> and keep their efficiency with a large variety of oxidant systems.<sup>3</sup> The increasing interest towards this reaction brought some authors to develop polymer-bound (salen)Mn(III) catalysts, capable to perform heterogeneous asymmetric epoxidation.<sup>4</sup> Some advantages can be expected in heterogeneous catalysis: a) the chiral catalyst can be recovered and reused for a large number of cycles; b) the degradation of Mn-salen, *via* formation of  $\mu$ -oxo-manganese(IV) dimers, can be avoided because of the spatial distribution of the Mn-complex molecules in the polymeric chain. On the other hand, the main disadvantage is that performances, in terms of reaction speed and stereoselectivity, are not always as good as in homogeneous catalysis.



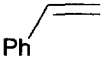

In the light of these considerations, we prepared a chiral Mn(III)-salen complex (**1**) bearing two vinyl

groups. As already reported, these kind of complexes can give radical promoted copolymerization with other suitable monomers.<sup>4</sup> The synthesis started from 3-*t*-butyl-5-vinylsalicylaldehyde<sup>5</sup> that was treated with (R,R)-*trans*-1,2-diaminocyclohexane. Complex **1** was subsequently obtained by inserting the manganese atom according to literature procedures.<sup>3b</sup> Copolymerization of **1** with styrene (ST) and divinylbenzene (DVB) was carried out in toluene at 100°C, using AIBN as radical initiator. The monomer ratio in the reaction mixture was 10:75:15 for **1**, ST and DVB respectively. The polymer was obtained as a dark brown solid, which was extracted for 48h in a Soxhlet device with acetonitrile (the solvent used in catalytic reactions, see below), until no complex molecules were detectable (UV) in the solvent. Elemental analysis confirmed that polymer composition was almost identical to the initial monomer mixture. This agreed with comparable polymerization rates for the three monomers.

Several oxidant systems were tested in the epoxidation of two typical unfunctionalised olefins, styrene and *cis*- $\beta$ -methylstyrene. Iodosylbenzene (PhIO) gave only sluggish reactions with both substrates, using our polymeric catalyst. Moreover, it was not possible to completely clean the polymer from PhIO<sub>2</sub>, a disproportionation product of PhIO, which was insoluble in all the solvents used. Thereupon the recycle of the catalyst was not very efficient.

Recently, Jacobsen *et al.* reported a new oxidant system, a combination of *m*-chloroperbenzoic acid (*m*CPBA) and *N*-methylmorpholine-*N*-oxide (NMO) in dichloromethane, which proved to be very efficient with homogeneous catalysts even at low temperatures.<sup>6</sup> The same terminal oxidant was employed with our heterogeneous catalyst **1**-ST-DVB in acetonitrile and the results are shown in Table 1.

**Table 1.** Epoxidation of Styrene and *cis*- $\beta$ -Methylstyrene catalyzed by **1**-ST-DVB in CH<sub>3</sub>CN.<sup>7</sup>

Entry	Substrate	Oxidant	Temp (°C)	Time	Conversion (%)	Yield(%) <sup>a</sup>	Ee(%) <sup>b</sup>
1		<i>m</i> CPBA / NMO <sup>c</sup>	0	30 min	96	99	14
2		"	-30	1h	84	99	15
3		MMPP (H <sub>2</sub> O) <sup>d</sup>	0	4h	76	80	6
4		MMPP / NMO <sup>e</sup>	0	22h	74	71	8
5		<i>m</i> CPBA / NMO <sup>c</sup>	0	1h	78	96 <sup>f</sup>	41 <sup>j</sup>
6		"	-30	2h	73	95 <sup>g</sup>	41 <sup>j</sup>
7		MMPP (H <sub>2</sub> O) <sup>d</sup>	0	7h	67	97 <sup>h</sup>	8 <sup>j</sup>
8		MMPP / NMO <sup>e</sup>	0	22h	69	78 <sup>i</sup>	4 <sup>j</sup>

<sup>a</sup> Yields were determined by capillary GC, by integration of product peaks against an internal quantitative standard (*n*-dodecane), correcting for response factors and for the extent of olefin conversion. <sup>b</sup> Ee's were determined by capillary GC using a commercial chiral column (SGE Cydex-B column, 25m X 0.33 mm i.d., 0.25  $\mu$ m film). <sup>c</sup> 5 eq NMO. <sup>d</sup> 0.5 ml of water were added to the reaction mixture (see ref. 7). <sup>e</sup> 1 eq NMO. <sup>f-i</sup> *cis:trans* epoxide ratio = <sup>f</sup> 73:27. <sup>g</sup> 69:31. <sup>h</sup> 93:7. <sup>i</sup> 91:9. <sup>j</sup> Ee's are referred to *cis* epoxide.

Several tries in dichloromethane gave, at the end of the reaction, colloidal mixtures from which the catalyst could not be recovered by simple filtration. On the contrary, in acetonitrile the polymeric catalyst was perfectly undissolved, and its recovery was, in every case, extremely handy and efficient.<sup>8</sup> It is worth noting that the catalyst preserved its unmodified efficiency, both in terms of yields and ee's, after 5 recycles.

For both substrates epoxidations with *m*CPBA/NMO were incredibly fast, compared to previously reported analogous heterogeneous epoxidations,<sup>4</sup> even at low temperatures (-30°C). At 0°C high conversions were reached within 30 min (entry 1) or 1h (entry 5), and the reaction showed to be highly chemoselective towards epoxidation. In fact, no detectable amounts of side products were present in the reaction mixtures.

Enantioselectivity degrees found in these conditions (15% for styrene oxide and 41% for *cis*- $\beta$ -methylstyrene oxide) can be considered promising, especially in the light of the previously reported ee's using an analogous polymeric catalyst (< 2% with styrene and  $\leq$  30% with all *cis* olefins tested, ref. 4).

In contrast to homogenous catalysis,<sup>6</sup> noticeable degrees of *cis-trans* isomerization occurred in epoxidation of *cis*- $\beta$ -methylstyrene, that could not be reduced even at lower temperatures (entries 5 and 6). As noticed by Jacobsen *et al.*,<sup>6a</sup> this unwanted process can also account for lower enantioselectivities observed for the terminal olefin (compare entries 1 and 5), since the same isomerization path induces racemization in styrene substrates.

The results drastically changed upon use of magnesium monoperoxyphthalate (MMPP) as oxidant. As already noticed in homogeneous catalytic systems,<sup>6</sup> this oxidant showed to be much less active than *m*CPBA. Longer times were needed to get agreeable conversions (entries 4 and 8). Reaction speed was improved by addition of a small amount of water to reaction mixture (entries 3 and 7).

Differently to what happened with *m*CPBA, epoxidation of *cis*- $\beta$ -methylstyrene with MMPP was highly *cis*-diastereoselective, giving rise to the formation of only small amount of *trans* epoxide (entries 7 and 8). Unfortunately, the higher diastereoselectivity achieved did not coincide with an expected higher enantioselectivity. Ee's actually never reached the values attained with *m*CPBA. These contradictory findings may be explained as follows. While blank reaction with *m*CPBA/NMO did not proceed at all, even after 22h at rt, a certain amount of epoxide (18% yield) was produced after 7h at rt by MMPP alone, upon the addition of water. This uncatalyzed process proceeds in a complete *cis*-diastereoselective fashion, according to a concerted one-step mechanism common to most epoxidations carried out by peracids.<sup>9</sup> Adding 1-ST-DVB to MMPP system, the reaction speed greatly increased (see entries 3 and 7). Then, according to the low ee's and high *cis/trans* ratios obtained, we think that uncatalyzed direct reaction of MMPP is somehow enhanced by the presence of our polymeric Mn-catalyst. On the contrary, in homogeneous systems<sup>6</sup> both *m*CPBA and MMPP seem to follow the catalytic cycle. Such a different behaviour of heterogeneous (salen)Mn(III) catalysts from homogeneous ones is under current investigation.

In conclusion, a new heterogeneous catalytic system, containing a chiral salen-manganese complex bound into a polystyrene-divinylbenzene polymer, showed to be effective in asymmetric epoxidation of both styrene and *cis*- $\beta$ -methylstyrene, with promising enantioselectivities. Reactions with *m*CPBA/NMO were extremely rapid and clean. The catalyst could effectively be recovered and reused several times without loss of activity and stereoselectivity.

## References and Notes

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5. Synthetic details and spectroscopic data will be reported elsewhere.
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7. General experimental procedure: A solution containing 1.0 mmol of olefin and 5.0 mmol of NMO in acetonitrile (10 ml), precooled at the indicated temperature, was treated with 80 mg of polymeric catalyst (containing 0.050 mmol of complex, 5mol%). *m*CPBA (2.0 mmol) was then added. Upon consumption of the olefin, the catalyst was filtered off and washed with Et<sub>2</sub>O. The filtrate, diluted with Et<sub>2</sub>O, was washed with 2N NaOH, water, and dried over Na<sub>2</sub>SO<sub>4</sub>. The crude product, obtained after evaporation under vacuum of the solvent, was purified by column chromatography on silica gel (Hex/Et<sub>2</sub>O).
8. The polymeric catalyst recovered as in ref. 7, was thoroughly washed with acetonitrile and dried under vacuum. Its recovery was always ≥ 96%.
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