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Asymmetric alkene epoxidation catalysed by a novel family of chiral metalloporphyrins: effect of structure on catalyst activity, stability and enantioselectivity

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A selection of alkenes has been epoxidised with iodosylbenzene, catalysed by three related iron(III) tetraarylporphyrins: **1***, **2*** and **3*** with four 2,6-di(1-phenylbutoxy)phenyl groups, with one pentafluorophenyl and three 2,6-di(1-phenylbutoxy)phenyl groups and with two pentafluorophenyl and two 2,6-di(1-phenylbutoxy)phenyl groups, respectively. **1*** is very sterically hindered and prone to self-oxidation which makes it a relatively poor epoxidation catalyst. Introducing the smaller pentafluorophenyl groups, in place of 2,6-di(1-phenylbutoxy)phenyl, increases catalyst reactivity, stability and selectivity. This change allows easier access of the substrates to the active oxidant and also, by decreasing the electron density on the porphyrin ligand, increases the reactivity of the oxoiron intermediate and its stability towards self-oxidation. A family of five homochiral catalysts, **1**, **2** and **3**, [the analogues of **1***, **2*** and **3***, prepared from (*R,R*)-2,6-di(1-phenylbutoxy)benzaldehyde] and catalyst **4** with three pentafluorophenyl and one (*R,R*)-2,6-di(1-phenylbutoxy)phenyl group and **5** the manganese(III) analogue of **3** have been used to epoxidise three prochiral alkenes. All the reactions give low enantioselectivities. Using styrene as the substrate, (*S*)-styrene epoxide is the major enantiomer obtained with all the catalysts except **1** which leads to the (*R*)-styrene epoxide being preferred. In contrast *cis*-hept-2-ene and 2-methylbut-2-ene give the same major epoxide enantiomer with all the catalysts. The dependence of the ee values on catalyst and substrate structure, temperature and solvent is examined and discussed.

Introduction

The substantial success of Jacobsen and Katsuki and their co-workers,[1] with designing effective chiral manganese(III) salen catalysts for asymmetric epoxidation of unfunctionalised alkenes, has provided a strong stimulus for the development of other catalytic chiral metal ligand systems. In particular, chiral metalloporphyrins have and continue to be an active field for catalyst development.[2] Since the first report, twenty years ago, by Groves and Myers[3] of enantioselective epoxidation of styrene using a chiral picket fence porphyrin, a wide variety of metalloporphyrins with a chiral superstructure has been prepared and tested.[4] The target remains; a simple synthesis of chiral metalloporphyrins which are robust and efficient catalysts for asymmetric oxygen-transfer from cheap oxidants, such as dioxygen, hydrogen peroxide and hypochlorite, to prochiral substrates.

Systematic studies aimed at optimising the design of new homochiral porphyrin ligands involve comparing the catalytic performance of their metal complexes (typically iron, manganese and ruthenium). The ligands are usually prepared by one of two approaches: attaching the chiral superstructure to each of the four atropisomers of a parent tetraarylporphyrin[4p] or modifying the substituents on a single atropisomer.[4o,4q] Less commonly, a family of closely related tetraarylporphyrins with one to four chiral aryl groups have been synthesised and studied.[5] The latter procedure was used for this study.

We have recently described the preparation of an efficient and short synthetic route to a new family of metalloporphyrins, with pentafluorophenyl and (*R,R*)-2,6-di(1-phenylbutoxy)-phenyl groups on the porphyrin *meso* positions.[6] In this paper we report the use of these to catalyse alkene epoxidation by iodosylbenzene and show that the position and number of pentafluorophenyl groups on the macrocycle ring has a marked effect on the catalyst's activity, stability and enantioselectivity.

Results and discussion

Effect of porphyrin structure on catalyst stability and efficiency in alkene epoxidation

Initially, the catalytic efficiencies of the optically inactive iron(III) porphyrins **1***, **2*** and **3***† in alkene epoxidations were investigated. These three catalysts, with respectively four, three and two 2,6-di(1-phenylbutoxy)phenyl groups, were selected to evaluate the effect of the different steric and electronic environments of each on the oxidation processes and on the fate of the catalyst. The epoxidations were carried out in dry dichloromethane at room temperature with iodosylbenzene, using catalyst, oxidant and substrate in the molar proportions 1 : 100 : 1000. Eight alkenes were used as substrates, namely, styrene, three cyclic alkenes (cyclooctene, cyclohexene and cyclopentene), and four acyclic alkenes (oct-1-ene, *cis*-hept-2-ene, 2,3-dimethylbut-2-ene and 2-methylbut-2-ene). Subsequently, four iron(III) porphyrins **1**, **2**, **3** and **4** and the manganese(III) porphyrin **5** were used for the asymmetric epoxidation of styrene, *cis*-hept-2-ene and 2-methylbut-2-ene and the reaction conditions were systematically varied to improve the enantioselectivity of the epoxidations.

In these systems, iodosylbenzene generates the active oxidant, oxoiron(IV) porphyrin π radical cation or oxomanganese(V) porphyrin[7] which is consumed in three competing pathways, epoxidation, catalyst destruction and iodosylbenzene disproportionation (illustrated for the iron porphyrins in Scheme 1). The product distributions and oxidation yields, based on iodosylbenzene, (path a, Scheme 1) were monitored with time by capillary GC analysis and the final yields were measured after 70–90 min. Despite the large excess of alkene over catalyst,

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† Catalysts **1***, **2*** and **3*** are optically inactive analogues of **1**, **2** and **3** and were prepared from (±)-1-phenylbutanol.[6]

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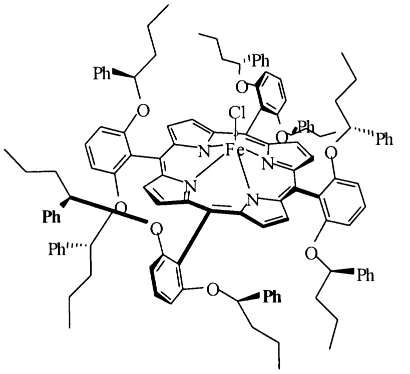

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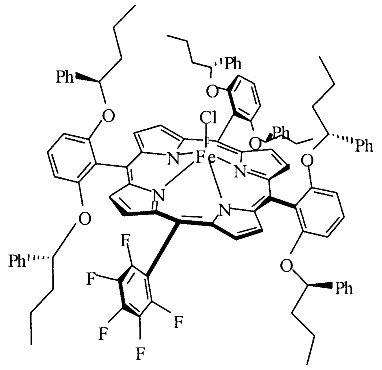

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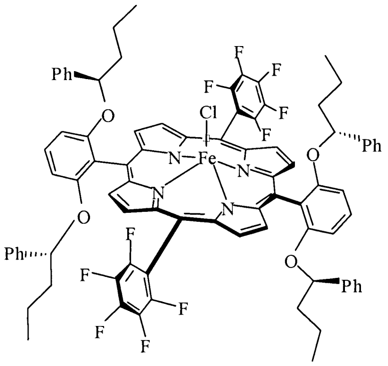

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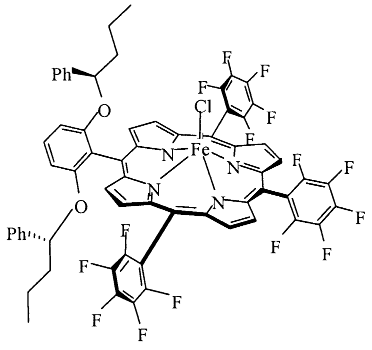

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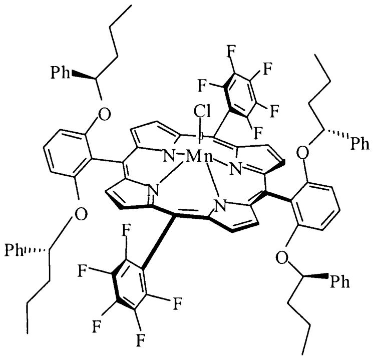

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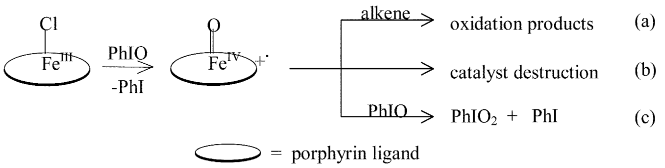


Scheme 1

catalyst destruction, by inter- and/or intramolecular oxidations, was an important side-reaction (path b, Scheme 1). The catalyst's stability during the epoxidations was determined by analysing aliquots from the reaction mixture by UV–Vis spectroscopy. The catalysed disproportionation of iodosylbenzene to iodoxybenzene and iodobenzene (path c, Scheme 1) was monitored, at the end of the reaction, by measuring the yield of iodoxybenzene by iodometric titration and by comparing the yields of iodobenzene and epoxide (GC analysis). Fig. 1 clearly shows that during the epoxidation of 2,3-dimethylbut-2-ene with catalyst **1*** and iodosylbenzene, the rate of formation and the yield of iodobenzene are higher than those of 2,3-dimethylbut-2-ene epoxide. This arises largely from the catalysed disproportionation of iodosylbenzene. With a catalyst to oxidant ratio of 1 : 100 in the reactions, oxidant consumption arising from catalyst destruction is unlikely to exceed a few percent. Similar graphs have been obtained with all the substrates. The % yield of epoxide, iodobenzene and iodoxybenzene at the end of each reaction was measured and the oxidant balance was determined in terms of iodobenzene, [PhI], and oxidant, [O] (equations 1 and 2, respectively). The oxidant accountability in the reactions was generally good showing that no significant oxidation products had been missed (see for example Table 1).

$$\text{Total}\ \%\ [\text{PhI}] = \text{yield PhI}\ (\%) + \text{yield PhIO}_2\ (\%) \qquad (1)$$

$$\text{Total}\ \%\ [\text{O}] = \text{yield epoxide}\ (\%) + 2 \times \text{yield PhIO}_2\ (\%) \qquad (2)$$

The rates of epoxidation, product yields and catalyst stability depend on the structure of the porphyrin ligand, thus

Table 1 The accountability of iodosylbenzene in epoxidation of cyclohexene, oct-1-ene and 2-methylbut-2-ene catalysed by iron(III) porphyrin, **2**

Substrate	Oxidation yield (%)	Iodobenzene (%)	Iodoxybenzene (%)	[PhI] (%)[a]	[O] (%)[a]
Cyclohexene	81.3[b]	89.0	11.2	100.2	103.7
Oct-1-ene	32.0	66.2	29.7	95.8	91.4
2-Methylbut-2-ene	80.0	92.8	3.5	96.3	87.0

[a] The estimated error in the accountability is ~5%. [b] Total yield of cyclohexene epoxide, cyclohex-2-en-1-ol and cyclohex-2-en-1-one.

Table 2 Yields of epoxide obtained from the corresponding alkenes using catalysts **1***, **2*** and **3*** and iodosylbenzene

	Yields (%)		
	1*	**2***	**3***
Cyclooctene epoxide	51.1	68.9	100.0
Styrene epoxide	48.5	79.5	91.5
Cyclopentene epoxide	48.9	48.8	59.3
Oct-1-ene epoxide	6.8	31.9	67.6
2-Methylbut-2-ene epoxide	45.1	80.0	81.6
2,3-Dimethylbut-2-ene epoxide	50.5	62.3	90.1
Cyclohexene epoxide	48.3	67.9	81.9
cis-2-Heptene epoxide	32.4	68.5	80.3

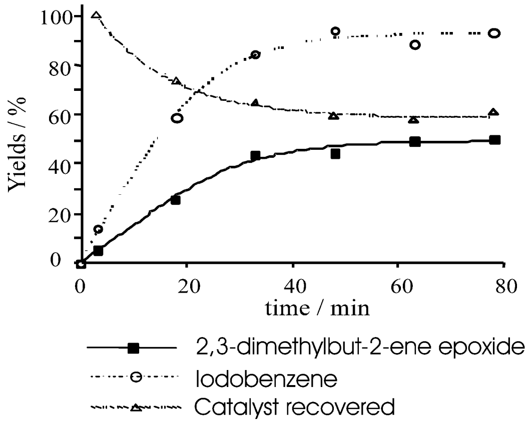


Fig. 1 Formation of 2,3-dimethylbut-2-ene epoxide and iodobenzene and catalyst degradation with time in the epoxidation of 2,3-dimethylbut-2-ene with catalyst **1*** and iodosylbenzene.

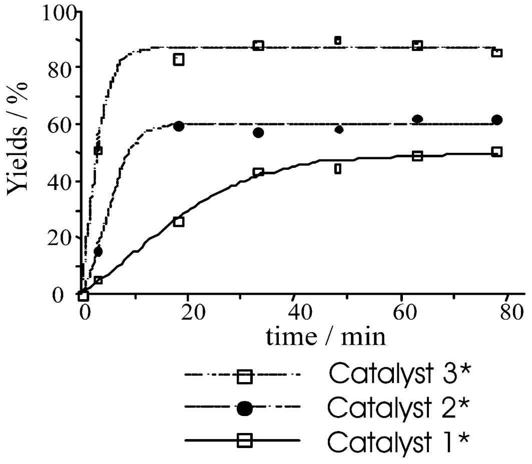


Fig. 2 Formation of cyclohexene epoxide as a function of time, in the epoxidation of cyclohexene with iodosylbenzene catalysed by **1***, **2***, **3***.

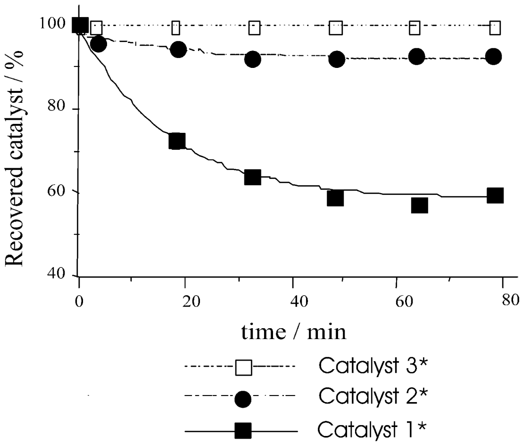
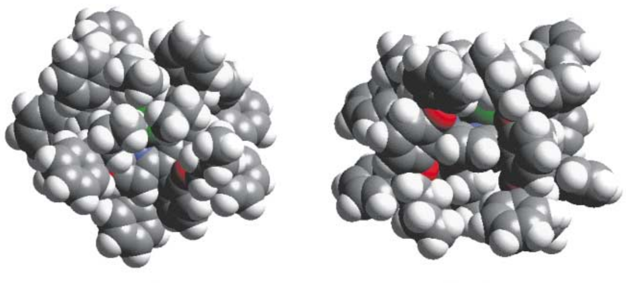


Fig. 3 Degradation of catalysts **1***, **2*** and **3*** *versus* time during the epoxidation of 2,3-dimethylbut-2-ene with iodosylbenzene.

on changing the catalysts in the order **1***, **2*** and **3*** the reactions become faster (see for example the epoxidation of cyclohexene, Fig. 2), the maximum yields increase (Table 2 and Fig. 1) and the catalysts become more stable (see for example the epoxidation of 2,3-dimethylbut-2-ene, Fig. 3). It is well documented that the reactivity of iron porphyrins, as oxidation catalysts, is very dependent on the structure of the macrocyclic ligand,[8] and that iron(III) tetra(pentafluorophenyl)porphyrin is a significantly better catalyst than the non-fluorinated analogue, iron(III) tetraphenylporphyrin.[8a] It is clear, from the results presented here, that replacing a 2,6-di(1-phenylbutoxy)-phenyl group by pentafluorophenyl leads to a marked improvement in catalyst efficiency and stability. The presence of a pentafluorophenyl group on the porphyrin ring can increase the catalytic activity in three ways: first, the electron-withdrawing fluorines activate the electrophilic high-valent oxoiron intermediate.[8,9] Secondly, by removing electron density from the macrocyclic ring, the halogens also make the porphyrin less susceptible to attack by the active oxidant leading to less catalyst self-destruction.[8,9] Finally, since a pentafluorophenyl group is considerably less bulky than 2,6-di(1-phenylbutoxy)-phenyl not only does this allow easier access of the substrate to the oxoiron centre during the catalytic cycle but it also removes oxidisable 1-phenylbutoxy groups, reducing intramolecular catalyst destruction. It is difficult to determine which of these effects is the most important, however, it is likely that all three play a role in these oxidations.

The structures of the catalysts were investigated using computer molecular modelling. To simplify these calculations only the chiral analogues of the optically inactive catalysts **1***, **2*** and **3*** (**1**, **2** and **3**) were used (Figs. 4–6). The structures show the marked difference in access to the metal centre in the three



Top view Side view

Fig. 4 Molecular models of top and side views of chiral catalyst **1** showing full van der Waals radii. The oxygens are drawn in red, the nitrogens in blue and the chlorine atom is in green.

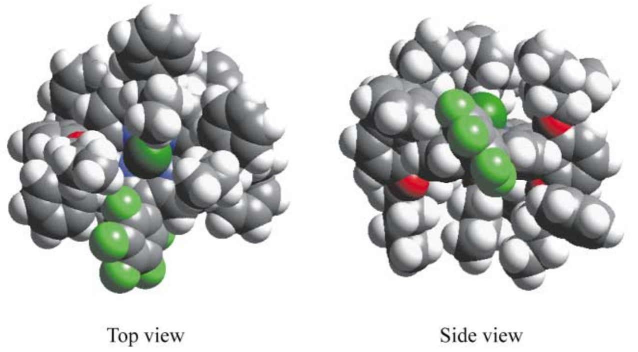


Fig. 5 Molecular models of top and side views of chiral catalyst **2** showing full van der Waals radii. The oxygens are drawn in red, the nitrogens in blue, the chlorine is in dark green and the fluorines in light green.

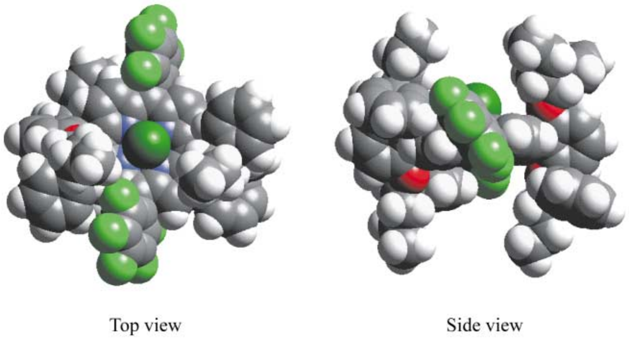
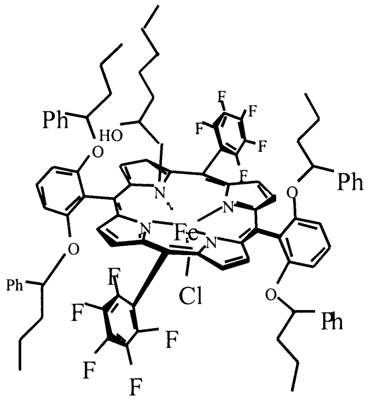


Fig. 6 Molecular models of top and side views of chiral catalyst **3** showing full van der Waals radii. The oxygens are drawn in red, the nitrogens in blue, the chlorine is in dark green and the fluorines in light green.

iron(III) porphyrins. With **1**, the catalyst core is completely buried by the substituents; this provides a very constrained environment which allows intramolecular catalyst destruction to compete effectively with alkene epoxidation. Replacing one of the 2,6-di(1-phenylbutoxy)phenyl groups by pentafluorophenyl (catalyst **2**) creates a space on each porphyrin face, accounting for the increased rate of epoxidation with catalyst **2***. In catalyst **3** the alternating pentafluorophenyl and 2,6-di-(1-phenylbutoxy)phenyl groups on the porphyrin *meso* positions generate a well defined corridor, on each porphyrin face, for the substrate to approach the metal centre. This results in a further increase in the rate of epoxidation at the expense of catalyst destruction.

The competition of epoxidation and catalyst destruction (Scheme 1) for the oxoiron(IV) porphyrin π radical cation is well illustrated by catalysts **1***, **2*** and **3***. Thus as the catalyst becomes less involved in self-oxidation reaction paths, the rate of the epoxidation and the yields increase. This is apparent both when different substrates are epoxidised by the same catalyst and when a single substrate is epoxidised by different catalysts. The latter is well illustrated by the epoxidation of 2,3-dimethylbut-2-ene, where the increased epoxidation yields that arise from changing the catalyst from **1*** to **2*** to **3*** (Table 2) parallel a decrease in catalyst deactivation. Fig. 3 shows that during the reaction, catalyst **1*** is significantly destroyed whilst the concentration of **2*** is only slightly affected and **3*** is unchanged. This trend is observed with all the substrates used in this study. It appears that alkene epoxidation is particularly sensitive to steric effects around the porphyrin macrocycle so that, if the oxoiron centre is not readily accessible to the substrate, the side-reactions (destruction of the catalyst and formation of iodoxybenzene) can compete with the epoxidation.

With all three catalytic systems, particularly those using **1*** and **2***, the yield of epoxide from oct-1-ene compared with those from the other substrates is low (Table 2). This arises in part from the lower reactivity of terminal alkenes[10] but also from catalyst deactivation, by *N*-alkylation of one of the pyrrole rings of the porphyrin macrocycle by the substrate, that occurs during the oxidation process. To investigate the latter reaction further, at the end of the epoxidation of oct-1-ene using catalyst **3***, the reaction mixture was passed through a short silica gel column (using dichloromethane as eluant) and the porphyrin fraction was analysed by ESI-mass spectroscopy. The mass spectrum had a base peak at *m*/*z* 1604 (abundance 100%) which corresponds to the molecular structure **6**, with molecular formula of $C_{92}H_{83}ClFeF_{10}N_4O_5$. The literature reports several examples of deactivation of metalloporphyrins during terminal alkene epoxidation by iodosylbenzene.[11] In these reactions, a pyrrole nitrogen traps an intermediate, diverting it from epoxide to give an *N*-hydroxyalkyl-derivative of the porphyrin. This generates a less active catalyst and leads to demetallation.[11] It is likely that the same deactivation of the catalyst takes place in the analogous reactions of **1*** and **2***. In agreement with this conclusion, each of the reactions with oct-1-ene shows a large amount of the catalyst degradation (>80%).



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The oxygen transfer from the active oxoiron species of catalyst **1*** gives approximately a 50% yield of epoxide with all the alkenes, except oct-1-ene (Table 2). This lack of discrimination between the alkenes is unexpected and not observed with the other two catalysts. With the two less hindered catalysts, **2*** and **3***, where the active oxidant is more accessible to the substrates, the epoxide yields are higher and show a greater discrimination in substrate reactivity. The results also reveal an interesting example of tuning of the catalyst's properties. With the least hindered catalyst **3***, as expected the more electron-rich 2,3-dimethylbut-2-ene gives a higher epoxide yield than 2-methylbut-2-ene,[10] however, with the more hindered catalyst **2*** the less electron-rich alkene is more reactive. This reversal of reactivity can be accounted for in terms of steric effects outweighing electronic preferences, since the less hindered 2-methylbut-2-ene is able to approach the more hindered oxoiron active centre of catalyst **2*** more readily than 2,3-dimethylbut-2-ene.

Enantioselective epoxidations

Styrene, *cis*-hept-2-ene and 2-methylbut-2-ene were used in enantioselective epoxidations catalysed by the chiral metalloporphyrins **1**, **2**, **3**, **4** and **5**. These prochiral substrates were chosen as representative of three different types of alkene. Styrene has been widely used previously as a substrate to compare the enantioselective efficiency of different metalloporphyrin-catalysed epoxidations,[4] whereas aliphatic alkenes have been much less extensively studied.[4n] For each epoxidation, the product distribution was monitored several times, by chiral

Table 3 Effect of temperature on the yield and ee value of styrene epoxidation (catalyst **1** and **3**) and *cis*-hept-2-ene (catalyst **2**) with iodosylbenzene in dichloromethane

Substrate	Catalyst	T/°C	Epoxide yield(%)	Epoxide ee(%)
Styrene	**1**	20	48.5	16.3
Styrene	**1**	0	39.5	15.0
Styrene	**3**	20	91.5	16.6
Styrene	**3**	0	99.0	23.2
cis-Hept-2-ene	**2**	20	68.5	16.4
cis-Hept-2-ene	**2**	0	76.7	20.0
cis-Hept-2-ene	**2**	−20	65.4	21.0

GC analysis, during the course of the reaction and when the oxidation was complete.

The catalysed epoxidations of styrene and *cis*-hept-2-ene were initially carried out at room temperature, using iodosylbenzene and **1**, **2**, **3**, **4** and **5**. The yields for the iron(III) porphyrin-catalysed oxidations of both substrates increase on going from catalyst **1** to **4** (Figs. 7 and 8), as discussed above, this is attributable to a decrease of steric hindrance around the catalytic centre and the increased stability of the catalysts arising from the electron-withdrawing effects of the pentafluorophenyl groups. Low enantiomeric excesses of the product epoxides were obtained with all the catalysts, with the highest values for styrene arising from **1** and **3** (16.3 and 16.6%, respectively) and for *cis*-hept-2-ene from **2** (16.4%) (Figs. 7 and 8). The most interesting feature of the styrene oxidations is that, with catalyst **1**, the (*R*)-styrene epoxide is favoured whereas with all the other catalysts, the (*S*)-isomer predominates. With *cis*-hept-2-ene, all the catalysts gave the same epoxide enantiomer as the major product although its configuration was not determined. The manganese(III) catalyst, **5**, with both styrene and *cis*-hept-2-ene gave comparable epoxide yields to its iron(III) analogue, **3**, however, it was less stereoselective giving ee values approximately half those from **3**.

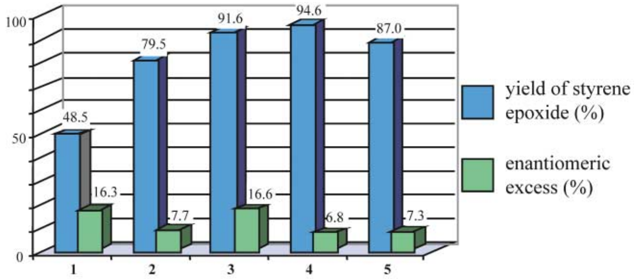


Fig. 7 Yields and enantiomeric excesses of styrene epoxide obtained in the epoxidation of styrene by iodosylbenzene catalysed by **1**, **2**, **3**, **4** and **5**.

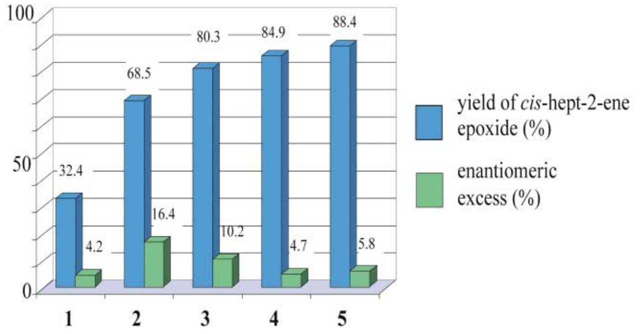


Fig. 8 Yields and enantiomeric excesses of *cis*-hept-2-ene epoxide obtained with catalysts **1**, **2**, **3**, **4** and **5** and iodosylbenzene at room temperature.

To assess whether or not the enantioselectivity of the oxygen transfer was maintained throughout the epoxidation process, the products were monitored at selected times during the course of the reactions. The enantiomeric excesses with each chiral catalyst remained effectively constant (or even increased slightly). It was expected that catalyst self-oxidation might involve the chiral 1-phenylbutoxy groups, since heteroatoms on the chiral appendages of metalloporphyrins are reported to facilitate the oxidative degradation of the superstructure,[2c] and this would lead to less selective iron porphyrin catalysts and to a decrease in the enantioselectivity as the reactions progressed. However, this was not observed and we conclude that the main pathway for loss of **1** and to a lesser extent with **2** is oxidative destruction of the porphyrin macrocycle.[1a,2a,8c,12]

2-Methylbut-2-ene was epoxidised using catalysts **1**, **2** and **3** and the same major enantiomer (unidentified) was produced in each reaction (Fig. 9). The small size of the alkyl groups attached to the double bond makes chiral selectivity with this alkene extremely challenging and not surprisingly, of the three substrates studied, 2-methylbut-2-ene gave the lowest ee values. The most sterically hindered catalyst **1** gave the highest ee value (10.1%) whereas catalyst **3**, with more open access to the active oxidant, led to negligible asymmetric induction. For this reason the study was not extended to include catalysts **4** and **5**.

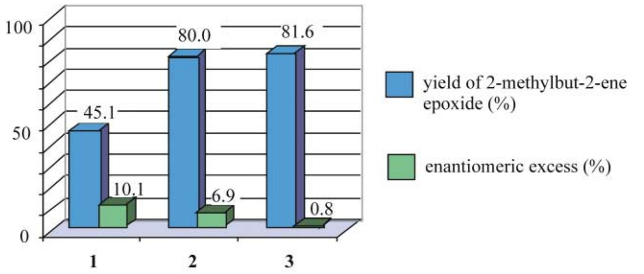


Fig. 9 Yields and enantiomeric excesses of 2-methylbut-2-ene epoxide obtained with catalysts **1**, **2** and **3** and iodosylbenzene in dichloromethane at room temperature.

Effect of temperature on asymmetric epoxidation. The effect of temperature on the yield and enantioselectivity of the epoxidation of styrene and *cis*-hept-2-ene was examined using the most selective catalysts for each substrate (styrene, catalysts **1** and **3** and *cis*-hept-2-ene, catalyst **2**) (Table 3). With catalysts **3** and **2**, lowering the temperature from 20 to 0 °C resulted in a higher overall epoxidation yield and a small but significant increase in the ee values. Improved enantioselectivities were anticipated based on previous work on epoxidations using high valent oxometalloporphyrins[4i,13] and can be attributed to a slower more selective epoxidation mechanism which leads to an increased differentiation between the *Re* and *Si* faces of the prochiral alkene. Interestingly the epoxidation of styrene using the very hindered catalyst **1** led to a decrease in the overall yield and no improvement in the enantioselectivity. Lowering the temperature of the *cis*-hept-2-ene epoxidation further to −20 °C led to a further small increase in the ee value but the overall yield was reduced.

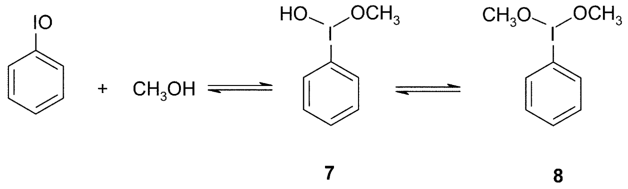
Solvent dependence of the enantioselective epoxidation of styrene and *cis*-hept-2-ene. The influence of solvent on the catalysed asymmetric epoxidations was examined with styrene (with **1** and **3**) and *cis*-hept-2-ene (with **2**) at 0 °C in dichloro-

Table 4 Solvent dependence of the yield and enantiomeric excess of epoxidation of styrene (catalysts **1** and **3**) and *cis*-hept-2-ene (catalyst **2**) by iodosylbenzene at 0 °C

Substrate	Catalyst	Solvent	Epoxide yield(%)	Epoxide ee(%)	Major enantiomer
Styrene	**1**	CH_2Cl_2	39.5	15.0	(*R*)
Styrene	**1**	Toluene	64.3	17.5	(*R*)
Styrene	**1**	CH_3OH	4.5	0.0	
Styrene	**1**	CH_3CN	68.5	15.5	(*R*)
Styrene	**3**	CH_2Cl_2	99.0	23.2	(*S*)
Styrene	**3**	Toluene	84.0	9.7	(*S*)
Styrene	**3**	CH_3OH	67.8	12.9	(*S*)
Styrene	**3**	CH_3CN	86.5	16.3	(*S*)
cis-Hept-2-ene	**2**	CH_2Cl_2	76.7	21.0	—
cis-Hept-2-ene	**2**	Toluene	69.5	18.5	—
cis-Hept-2-ene	**2**	CH_3OH	36.7	26.2	—
cis-Hept-2-ene	**2**	CH_3CN	72.5	18.0	—

methane, toluene, methanol, and acetonitrile (Table 4). Although the overall yields and ee values showed significant solvent dependence, the major enantiomer formed with each substrate/catalyst combination was unaffected by the changes. Interestingly no single solvent was optimum for all three systems. Styrene with **1** gave the best epoxide yields in acetonitrile or toluene and the highest ee value in the latter. In contrast with **3**, dichloromethane led to a virtually quantitative yield of epoxide and the highest ee value. With *cis*-hept-2-ene and **2**, methanol gave the highest ee value but the overall yield was less than half that of the reaction in dichloromethane.

Methanol is not an innocent solvent for these oxidations. It reacts with iodosylbenzene (Scheme 2)[14] giving (hydroxymethoxyiodo)benzene (**7**) and (dimethoxyiodo)benzene (**8**) and the former is thought to be the species that transfers oxygen to the metalloporphyrin to generate the active oxidant.[15] Furthermore, it is a competing substrate for the active oxidant and consequently epoxidation yields in methanol are generally lower than those in more robust solvents.[15] The particularly low epoxide yield from styrene with catalyst **1** probably arises from steric hindrance restricting the bulky iodosylbenzene derivative **7** from approaching the metal centre.



Scheme 2

Previous work on the solvent effects on oxidations with metalloporphyrin systems has used aprotic solvents and found that aromatic hydrocarbons, such as benzene or toluene, give the highest ee values.[4i,13] This has been interpreted as arising from solvent induced changes of the structure of the chiral cavity surrounding the oxo-metal group of the active oxidant, leading to greater enantioselectivity. In the present study, however, the best solvent is dependent on the chiral catalyst and shows no obvious trends with solvent type or polarity.

General discussion on catalyst design

In designing chiral metalloporphyrin catalysts for asymmetric alkene epoxidation, Collman and co-workers[2a,4n] and Campbell and Kodadek[2c] have pointed out that, to optimise enantioselectivity without losing epoxide yields, there is a balance between control of the approach of the substrate by the porphyrin superstructure and access to the active oxidant. Systematic studies of the influence of metalloporphyrin structure on catalytic activity and enantioselectivity have led to the conclusion that the failure of some catalysts arises from the hindrance of both enantioapproaches of the prochiral substrate to the metal centre.[5] These restrictions can make highly substituted metalloporphyrins both inefficient and unselective catalysts whereas, by contrast, analogues with more open access to the metal centre can be both effective and selective.[4n,4p,5]

Rose and Collman and co-workers[5] synthesised a series of chiral metallotetraarylporphyrins based on the parent, double picket fenced iron(III) tetra-(2,6-di-Mosher's amidophenyl)-porphyrin, with one to three of the four chiral 2,6-disubstituted aryl groups systematically replaced by pentafluorophenyl rings. Comparison of these as catalysts for the asymmetric epoxidation of styrene showed that, despite the low ee values obtained (<6%), there was a trend; the least hindered catalyst with three pentafluorophenyl substituents gave the highest and the most hindered parent compound the lowest enantioselectivity. It was argued that placing fewer chiral groups on each face of a porphyrin can, by allowing better access to the metal centre, generate a more selective catalyst. The ee values from the present study show that no one catalyst is optimum for the epoxidation for all three types of alkene used. This emphasises the importance of substrate–catalyst interactions in differentiating between the *Re* and *Si* faces of the alkene. It also suggests that to obtain optimum ee values a specific catalyst may need to be designed for the epoxidation of each class of alkene.

The low ee values obtained in this study most probably arise from a lack of structural rigidity of the chiral appendages, leading to poor spatial definition of the catalytic site. Collman *et al.*[4n] have shown that iron porphyrins with a rigid chiral superstructure, even with relatively open access to the metal centre, can be very efficient and selective catalysts for asymmetric epoxidation. In the present study, attempts to improve control of the approach of the substrate to the active oxidant by restricting access to the metal centre, led to lower epoxide yields and more catalyst destruction. This is well illustrated for the epoxidation of *cis*-hept-2-ene where catalysts **1** and **4** gave effectively the same ee values although there was a marked difference in yield. With **1** the yield was 32.4% because the active site of the catalyst is masked by the presence of four bulky chiral substituents limiting the access of the substrate whereas with **4**, more ready access, led to an 84.9% yield.

Comparison of the results obtained with **3** and **5** shows that although the manganese catalyst gives similar epoxide yields to the iron analogue it is less stereoselective. Comparable observations have been reported previously for the asymmetric epoxidation of styrene using chiral strapped[4i] and chiral wall metalloporphyrins.[16] However, this not a general phenomenon since chiral manganese(III) porphyrins[4] and the extensively studied chiral manganese(III) salens[1] can be very effective catalysts for asymmetric alkene epoxidation. We suspect that the difference we and others have observed will be dependent on the structure of the porphyrin and may reflect a different approach of the substrate towards the oxo-metal active oxidant with the iron and manganese complexes (see for example reference 13*b*).

Experimental

Instrumental methods

UV–Visible spectra were recorded on a Hewlett Packard model HP8453 diode array spectrophotometer and analysed using a PC running Hewlett Packard A.02.05 UV–Vis ChemStation software.

Isothermal and temperature-programmed gas chromatography was carried out on an AMS94 gas chromatograph with a flame ionisation detector and helium as the mobile phase. The data were analysed on a PC with Jones Chromatography JCL6000 (revision 005) analytical software. The non-chiral analyses used an Alltech Carbowax capillary column (30 m, i.d. 0.25 mm, film thickness 0.25 µm) and the chiral separations employed a Chiraldex γ-cyclodextrin propionyl capillary column (50 m, i.d. 0.25 mm) or a Supelco β-DEX 120 capillary column (30 m, i.d. 0.25 mm, film thickness 0.25 µm). The methods were optimised and calibrated using racemic epoxides. The (*R*) and (*S*) styrene epoxides were identified by comparison of retention times of authentic samples. The product yields were quantified using 1,3-dichlorobenzene as the internal standard. The identities of all the oxidation products were confirmed by GC-MS using a VG Autospec S Series A027 mass spectrometer linked to a Hewlettt Packard 5890 Series 2 gas chromatograph. The spectra were analysed using a VAX3100 Workstation.

The molecular models for the metalloporphyrins **1**–**5** were generated using the program Cerius^{2}™ (BIOSYM/Molecular Simulations) and minimised using the Universal force field.[17]

Materials

All reagents and solvents were used as purchased (Aldrich, Lancaster) unless otherwise stated. Iodosylbenzene was prepared from iodobenzene diacetate as described previously.[14c] The syntheses of the metalloporphyrin catalysts have been reported.[6] The alkenes were purified by passing them through a short column of activated alumina prior to use and their purities were checked by GC analysis.

Oxidation systems

The achiral epoxidations were carried out at room temperature by adding iodosylbenzene (22 mg, 0.1 mol) to a solution of the substrate (1 mmol), metalloporphyrin (1×10^{-6} mol) and 1,3-dichlorobenzene (0.01 cm^3, GC internal standard) in dry dichloromethane (3.1 cm^3). For chiral epoxidations the quantities employed were a fifth of those above. The product distributions and yields were monitored by removing aliquots from the alkene oxidations, with a syringe at selected time intervals, and analysing them by GC. The final yields of epoxide, based on iodosylbenzene, were calculated after 70–90 min.

The catalyst stabilities during the epoxidations were determined by diluting aliquots (50 µl) from the reaction mixtures with dichloromethane (3 cm^3) and analysing them by UV–Vis spectroscopy by monitoring the metalloporphyrin Soret band.

The yield of iodoxybenzene was determined by adding glacial acetic acid (30 cm^3), excess of potassium iodide (10% aqueous solution) and ice to the reaction mixture dissolved in methanol (20 cm^3). After 30 min in the dark with occasional shaking, the solution was titrated against sodium thiosulfate solution using starch as indicator.[18]

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