#### Tetrahedron 68 (2012) 5824-5828

Contents lists available at SciVerse ScienceDirect

# Tetrahedron

journal homepage: www.elsevier.com/locate/tet

# Enantioselective water-soluble iron-porphyrin-catalyzed epoxidation with aqueous hydrogen peroxide and hydroxylation with iodobenzene diacetate

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#### ARTICLE INFO

Article history Received 20 March 2012 Received in revised form 27 April 2012 Accepted 3 May 2012 Available online 11 May 2012

Keywords: Asymmetric epoxidation Asymmetric hydroxylation Hydrogen peroxide Iodobenzene diacetate Chiral iron porphyrins Water-soluble iron porphyrins Styrenes

# ABSTRACT

The asymmetric epoxidation of styrene derivatives by H<sub>2</sub>O<sub>2</sub> (or UHP) to give optically active epoxides (ee up to 81%) and hydroxylation of alkanes to give optically active secondary alcohols (ee up to 78%) were carried out in methanol and water using chiral water-soluble iron porphyrins as catalysts. © 2012 Elsevier Ltd. All rights reserved.

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# 1. Introduction

Catalytic asymmetric epoxidation reactions play a major role in organic chemistry since the optically active epoxides are important building blocks.<sup>1–3</sup> In particular, catalytic asymmetric reactions in aqueous solutions are attractive, but rare.<sup>4</sup> Therefore until 2006, results obtained in the asymmetric epoxidation with H<sub>2</sub>O<sub>2</sub> and chiral metal catalysts have been rather disappointing.<sup>5</sup> It should be noted, however, that the Fe-catalyzed asymmetric epoxidation of aromatic alkenes with hydrogen peroxide as the oxygen source and a chiral non-porphyrin ligand has been recently reported, as a nice possibility.6

The discovery that hydrogen peroxide supports catalytic turnover of cytochrome P450 in the absence of electron transfer proteins or cosubstrates has been important for mechanistic studies of this enzyme.<sup>7</sup> In particular, it was proposed that P450's ability to utilize peroxides in place of dioxygen and NAD(P)H to drive hydroxylation via the peroxide shunt pathway could provide a way to confront the cofactor regeneration problem.<sup>8,9</sup> However, generally, the efficiency of this reaction is poor compared with that of reductive activation of molecular oxygen. It should be also noted that there are cytochromes P450s, which can be classified as

a H<sub>2</sub>O<sub>2</sub>-dependent P450s.<sup>10,11</sup> Due to the obvious relevance of cytochrome P450 mechanism, catalytic epoxidation by iron porphyrins has drawn particular attention.<sup>12–14</sup> Since the discovery of iron porphyrin catalyzed epoxidation and hydroxylation,<sup>15</sup> the first asymmetric epoxidation catalyzed by chiral porphyrins was reported by Groves and Myers in 1983.<sup>16</sup> Since then, different chiral iron porphyrins were used by the same authors<sup>17</sup> and others.<sup>13,18–25</sup> The oxidant of choice for these systems is generally iodosylbenzene. Some examples of the use of hydrogen peroxide can be found in the literature with iron porphyrins as catalysts.<sup>26–29</sup> but, to our knowledge, no reports of enantioselectivity.<sup>3</sup> Recently our group reported the asymmetric oxidation of sulfide into sulfoxides with H<sub>2</sub>O<sub>2</sub> in water and methanol using a chiral iron porphyrin.<sup>30</sup> We now want to describe herein chiral epoxidation of alkenes and hydroxylation of alkanes using H<sub>2</sub>O<sub>2</sub> as oxidant catalyzed by optically active water-soluble iron porphyrin (Schemes 1 and 2).



x = H, Me, CF<sub>3</sub>, Cl





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<sup>0040-4020/\$ -</sup> see front matter © 2012 Elsevier Ltd. All rights reserved. doi:10.1016/j.tet.2012.05.014



x = H, Me, Br

Scheme 2. Hydroxylation of alkanes by PhI(OAc)2.

## 2. Results and discussion

# 2.1. Epoxidation of alkenes

We previously prepared a water-soluble iron porphyrin<sup>31</sup> from Halterman porphyrin,<sup>32</sup> which has a relatively electron-rich porphyrin ligand due to the presence of bis-ortho and -meta CH<sub>2</sub> substituents. This situation (Fig. 1) prevents the formation of µ-oxo dimers and increases stability with respect to oxidative degradation, which is often encountered with other porphyrins lacking protective ortho-methyl substituents as recently suggested by Wolak and Van Eldik.<sup>29</sup> However, solvent and porphyrin electronic structure affect the selectivity between the heterolytic and homolytic cleavage of the O–O bond of coordinated H<sub>2</sub>O<sub>2</sub>, to favor heterolytic cleavage and thus epoxidation reaction, methanol was used as the solvent of the reaction.<sup>33</sup> Epoxidation of styrene was first examined with this solvent at room temperature in presence of imidazole as cocatalyst. In a typical oxidation, 1 equiv of the iron porphyrin catalyst 1, 100 equiv of hydrogen peroxide, and 1000 equiv of substrate were used under anaerobic conditions. The reaction is fast at room temperature (1 h) and the corresponding epoxide was obtained with good yield (86%) and 60% ee (Table 1, entry 1). Results for the catalytic epoxidation of a number of alkenes are summarized in Table 1. As shown in Table 1, epoxide yields between 10% and 78% were obtained with enantiomeric excess as high as 78% for 1,2-dihydronaphtalene. Small amounts of aldehydes were also detected as by-products. As expected from the reactivity of an electrophilic oxo-iron(IV)-porphyrin cation radical, the best yields were obtained with styrenes bearing electronreleasing substituents whereas no clear trend was evident for optical vields upon changing the para substituent. However, it must be emphasized that both the yields and (slightly) ees were increased when a small amount of acidic water was added in solution (values in parentheses). The key role of imidazole in metalloporphyrincatalyzed oxygenations with H<sub>2</sub>O<sub>2</sub>, evidenced by Mansuy et al. in olefin epoxidation<sup>34,35</sup> with iodosylbenzene is confirmed herein, since only a weak conversion (8%) was detected in absence of this ligand (Table 1, entry 2). 2-Methylimidazole was also tested and found less effective due to possible steric interaction with the chiral porphyrin substituents. Using the hydrophobic catalyst, without any

#### Table 1

Asymmetric oxidation of styrene catalyzed derivatives by Fe HaltS-H<sub>2</sub>O<sub>2</sub>-Imidazole system<sup>a</sup>

Entry	Substrate	Conversion (%) <sup>b</sup>	Epoxide/Aldehyde ratio (%) <sup>b</sup>	Ee (%) <sup>c</sup> (Config) <sup>d</sup>
1	Styrene	86 (98) <sup>e</sup>	93/7 (95/5)	60 (61) (R)
2	Styrene <sup>f</sup>	8	52/48	52 (R)
3	Styrene <sup>g</sup>	24	94/6	59 (R)
4	2-Methylstyrene	72	86/14	55 (R)
5	3-Methylstyrene	69	87/13	58 (R)
6	4-Methylstyrene	67 (86) <sup>e</sup>	88/12 (85/15)	$60(63)^{h}(R)$
7	2-Trifluoromethylstyrene	14	80/20	55 (R)
8	3-Trifluoromethylstyrene	21	99/1	70 (R)
9	4-Trifluoromethylstyrene	17(24) <sup>e</sup>	97/3 (96/4)	65 (63) (R)
10	4-Chlorostyrene	29 (40) <sup>e</sup>	96/4 (95/5)	57 (59) (R)
11	1,2-Dihydronaphtalene	57	_	78 (1 <i>R</i> ,2 <i>S</i> )

<sup>a</sup> Reaction conditions: a mixture containing catalyst (1  $\mu$ mol), Imidazole (10  $\mu$ mol), substrate (1 mmol) and H<sub>2</sub>O<sub>2</sub> (100  $\mu$ mol) in 1 ml distilled CH<sub>3</sub>OH under argon was stirred for 1 h.

<sup>b</sup> Determined by GC on the crude reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

<sup>d</sup> Absolute configuration of the epoxide of styrene was determined by comparison with the authentic optically pure (R)-(+)-styrene oxide. Others were deduced from analogy of the GC behavior and of the optical rotatory of (R)-(+)-styrene oxide.

 $^{\rm e}$  Values in parentheses correspond to the experiments in 0.8 ml distilled CH\_3OH+0.2 ml buffer solution (pH 4).

<sup>f</sup> Without imidazole.

<sup>g</sup> Catalyst: FeCl Halt, solvent: 0.5 ml CH<sub>2</sub>Cl<sub>2</sub>+0.5 ml CH<sub>3</sub>OH.

<sup>h</sup> Determined by chiral HPLC on a Chiralcel OD-H column.

sulfonate groups, **2** (Fig. 1) instead of **1** in dichloromethane/methanol solvent gave a low conversion (24%) (Table 1, entry 3).

Our goal was not only to optimize this particular reaction, but to use it as an indicator of the mechanism of oxygen atom transfer. The discovery that hydrogen peroxide supports catalytic turnover of P450 in the absence of electron transfer proteins is important for mechanistic studies.<sup>7</sup> Consequently, a systematic investigation of the effect of water content on the oxidation of styrene at room temperature was first undertaken. The results are summarized in Table 2, showing an interesting phenomenum for the different combination methanol/water. Even when a large amount of water is added, the yields and ees are still maintained and correct. With pure water (pH 6) however, the chemical yields is very poor, 18% whereas the ee is maintained. Gas apparition and catalytic destruction were also observed in the latter case. Hydroxyl and hydroperoxyl radicals are shown to form in homolytic cleavage, and thus these species may be involved in porphyrin degradation and the production of dioxygen.<sup>36</sup> Since the important influence of the acidity of the medium has also been recognized on the mechanism of O–O bond cleavage in these systems.<sup>29</sup> the epoxidation reaction was undertaken at different pH. As can be seen in Table 3, acidic pH gave better conversion, provided that methanol was also present.



Fig. 1. Structure of the iron catalysts.

#### Table 2

Asymmetric oxidation of styrene catalyzed by Fe HaltS–H\_2O\_2–imidazole system in the presence of water  $^{\rm a}$ 

Entry	MeOH:H <sub>2</sub> O (%)	Conversion (%) <sup>b</sup>	Epoxide/Aldehyde ratio (%) <sup>b</sup>	Ee(%) <sup>c</sup>
1	100:0	86	93/7	60
2	75:25	74	92/8	57
3	50:50	60	89/11	56
4	25:75	38	85/15	53
5	0:100	18	85/15	51

 $^a$  Reaction conditions: a mixture containing catalyst (1  $\mu$ mol), imidazole (10  $\mu$ mol), substrate (1 mmol) and H\_2O\_2 (100  $\mu$ mol) in 1 ml CH\_3OH:H\_2O (pH 6) under argon was stirred for 1 h.

<sup>b</sup> Determined by GC after extraction with CH<sub>2</sub>Cl<sub>2</sub> of the reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

#### Table 3

Asymmetric oxidation of styrene catalyzed by Fe HaltS–H $_2O_2$ –Imidazole system at different pH values<sup>a</sup>

Entry	pН	Conversion (%) <sup>b</sup>	Epoxide/Aldehyde ratio (%) <sup>b</sup>	Ee (%) <sup>c</sup>
1	4	98	95/5	61
2 <sup>d</sup>	4	5	85/15	42
3	7	77	92/8	58
4	9	41	87/13	56

<sup>a</sup> Reaction conditions: a mixture containing catalyst (1 µmol), imidazole (10 µmol), substrate (1 mmol) and  $H_2O_2$  (100 µmol) in 0.8 ml distilled CH<sub>3</sub>OH+0.2 ml solution of buffer solution under argon was stirred for 1 h.

<sup>b</sup> Determined by GC on the crude reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

<sup>d</sup> In 1 ml buffer solution (pH 4).

The important influence of the acidity of the medium on the mechanism of O–O bond cleavage in [Fe(Porphyrin)(HOOH)] intermediate to give [Fe(Porphyrin<sup>+</sup>·)(O)] is confirmed in the present study. This pH dependence has usually been interpreted in term of heterolytic O–O bond cleavage.

We next explore the effect of UHP in alcohol solvents on the catalytic epoxidation of alkene by the chiral iron porphyrin **1** and  $H_2O_2$ . Actually, adducts of hydrogen peroxide with urea have been used as a convenient source of anhydrous  $H_2O_2$ . The catalytic reaction undertaken with this system has approximately the same activity as the free  $H_2O_2$  system (see Tables 1 and 4). Moreover, the formation of aldehyde as by-product is slightly decreased when UHP is used. It should be also noted that the use of UHP cannot be problematic due to its solubility: it is entirely soluble in methanol solvent in these experimental conditions. A decrease of the

#### Table 4

Asymmetric oxidation of styrene derivatives catalyzed by Fe HaltS–UHP–imidazole system  $^{\rm a}$ 

Entry	Substrate	Conversion (%) <sup>b</sup>	Epoxyde/Aldehyde ratio (%) <sup>b</sup>	Ee (%) <sup>c</sup> Config) <sup>d</sup>
1	Styrene	99	96/4	62 (R)
2	Styrene <sup>e</sup>	47	91/9	55 (R)
3	2-Methylstyrene	97	90/10	54 (R)
4	3-Methylstyrene	98	94/6	61 (R)
5	4-Methylstyrene	99	82/18	$60^{f}(R)$
6	2-Trifluoromethylstyrene	22	81/19	54 (R)
7	3-Trifluoromethylstyrene	42	98/2	71 (R)
8	4-Trifluoromethylstyrene	27	98/2	70 (R)
9	4-Chlorostyrene	97	99/1	68 (R)
10	1,2-Dihydronaphtalene	99	_	80(1 <i>R</i> ,2 <i>S</i> )

 $^a$  Reaction conditions: a mixture containing catalyst (1  $\mu mol$ ), imidazole (10  $\mu mol$ ), substrate (1 mmol) and UHP (100  $\mu mol$ ) in 1 ml distilled CH\_3OH under argon was stirred for 1 h.

<sup>b</sup> Determined by GC on the crude reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

<sup>d</sup> Absolute configuration of the epoxide of styrene was determined by comparison with the authentic optically pure (R)-(+)-styrene oxide. Others were deduced from

analogy of the GC behavior and of the optical rotatory of (R)-(+)-styrene oxide.

e Without imidazole.

<sup>f</sup> Determined by chiral HPLC on a Chiralcel OD-H column.

temperature to 0 °C increases slightly the ee to 81% for oxidation of 1,2-dihydronaphtalene.

The nature of the active oxygen complex, which is able to transfer its oxygen atom to alkenes and hydrocarbons, although not completely established, is generally considered to be a high-valent Feoxo porphyrin radical cation, at least formally, a  $Fe^{IV} = 0$  species. although a Fe<sup>III</sup>–OOH could be invoked.<sup>29</sup> In order to characterize the oxidizing species, in the chiral Fe system, we have compared the yield and enantiomeric excess using different oxidants (Table 5). Using an identical concentration of oxidant and styrene (Fe/imidazole/oxidant/styrene=1/10/100/1000), Table 5 shows that there is an increase of the yield when the oxidants employed are iodobenzene diacetate, H<sub>2</sub>O<sub>2</sub> and UHP (from 80 to 99%). Because the oxidation yield depends of the efficiency of the oxygen-atom transfer, and the degree of asymmetry induction depends on the chirality of the catalyst, we can infer the state of the catalyst from its catalytic activity and different oxidants. Herein, it is remarkable that, with three different oxidants, UHP, H<sub>2</sub>O<sub>2</sub>, and PhI(OAc)<sub>2</sub>, the enantiomeric excesses are similar according to a probable commun optically active intermediate.

#### Table 5

Asymmetric oxidation of styrene catalyzed by Fe HaltS–Imidazole system in the presence of different oxidants<sup>a</sup>

Entry	Oxidant	Conversion (%) <sup>b</sup>	Epoxide/Aldehyde ratio (%)	Ee(%) <sup>c</sup>
1	H <sub>2</sub> O <sub>2</sub>	86	93/7	60
2	UHP	99	96/4	62
3	PhI(OAc) <sub>2</sub>	80	88/12	59

 $^a$  Reaction conditions: a mixture containing catalyst (1  $\mu$ mol), imidazole (10  $\mu$ mol), substrate (1 mmol) and oxidant (100  $\mu$ mol) in 0.9 ml CH\_3OH+0.1 ml H\_2O under argon was stirred for 1 h.

<sup>b</sup> Determined by GC after extraction with CH<sub>2</sub>Cl<sub>2</sub> of the reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

#### 2.2. Hydroxylation of arylalkanes

The functionalization of C–H bonds is one of the most difficult transformation in synthetic chemistry.<sup>37,38</sup> The different parameters involved in the activation of hydrogen peroxide by iron porphyrins have been studied by the groups of Bruice<sup>39</sup> and Traylor.<sup>40</sup> Later, it was demonstrated that electron-deficient iron porphyrin complexes show tendency to cleave the hydroperoxide O-O bond heterolytically but, in contrast, homolysis can be important with electron-rich iron porphyrin complexes.<sup>27</sup> Despite this detrimental situation, we first studied the hydroxylation reaction catalyzed by metalloporphyrin 1, which is clearly an electron-rich iron porphyrin, using H<sub>2</sub>O<sub>2</sub> as oxidant. The results are summarized in Tables 6 and 7. Treatment of ethylbenzene (10 equiv) with hydrogen peroxide (1 equiv) and a catalytic quantity of catalyst 1 in H<sub>2</sub>O/MeOH (1/5) at room temperature for 1 h afforded in a very low yield (5% conversion) as a mixture of (S)-1-phenylethanol (47%) acetophenone (53%). The enantiopurity of the phenylethanol was determined to be 15% by chiral capillary GC analysis (Table 6, entry 4). Cyclic alkanes, such as indane and tetrahydronaphtalene are more reactive substrates since a higher conversion was obtained after 1 h, 51% and 20%, respectively, and enantioselectivities was determined to be 38% and 63%, respectively, (Table 6, entries 10 and 12). Because iodobenzene diacetate (PhI(OAc)<sub>2</sub>) is an efficient terminal oxidant in iron(III)porphyrin complex-catalyzed oxygenation reactions in presence of water,<sup>41</sup> similar reactions were undertaken, using PhI(OAc)<sub>2</sub> instead of H<sub>2</sub>O<sub>2</sub>, for comparison. The results, which are also summarized in Table 6, show that this oxidant converted ethylbenzene to the corresponding secondary alcohol with a better yield (46%) and much higher ee (75%). Similar yields and ees were obtained for the hydroxylation of indane and tetrahydronaphtalene (Table 6, entries 9 and 11).

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 Table 6

 Asymmetric hydroxylation catalyzed by Fe HaltSCl–Imidazole–PhI(OAc)<sub>2</sub> system<sup>a</sup>

Entry	Substrate	Conversion (%) <sup>b</sup>	Alcohol/Ketone ratio (%) <sup>b</sup>	Ee (%) <sup>c</sup> (Config) <sup>d</sup>
1	Ethylbenzene	46	91/9	75 (S)
2	Ethylbenzene <sup>e</sup>	32	83/17	78 (S)
3	Ethylbenzene <sup>f</sup>	62	91/9	73 (S)
4	Ethylbenzene <sup>g</sup>	5	47/53	15 (S)
5	2-Ethyltoluene	24	95/5	7 (R)
6	3-Ethyltoluene	32	85/15	60 (S)
7	4-Ethyltoluene	54	90/10	75 (S)
8	1-Bromo-4	47	95/5	76 (S)
	-ethylbenzene			
9	Indane	82	84/16	50 <sup>h</sup>
10	Indane <sup>g</sup>	51	73/27	38 <sup>h</sup>
11	Tetrahydronaphtalene	80	96/4	62 <sup>h</sup>
12	Tetrahydronaphtalene <sup>g</sup>	20	94/6	63 <sup>h</sup>

<sup>a</sup> Reaction conditions: a mixture containing catalyst (1  $\mu$ mol), imidazole (10  $\mu$ mol), substrate (1 mmol) and Phl(OAc)<sub>2</sub> (100  $\mu$ mol) in 1 ml distilled CH<sub>3</sub>OH+0.2 ml H<sub>2</sub>O under argon was stirred for 1 h.

<sup>b</sup> Determined by GC on the crude reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

<sup>d</sup> Absolute configuration of the alcohol of styrene was determined by comparison with the authentic optically pure (S)-(-)-1-phenylethanol. Others were deduced from analogy of the GC behavior and of the optical rotatory of (S)-(-)-1-Phenylethanol.

<sup>e</sup> Without imidazole.
 <sup>f</sup> Catalyst: FeCl Halt, solvent: 0.5 ml CH<sub>2</sub>Cl<sub>2</sub>+0.5 ml CH<sub>3</sub>OH.

<sup>g</sup> With  $H_2O_2$  (100 µmol).

<sup>h</sup> Determined by chiral HPLC on a Chiralcel OB-H column.

#### Table 7

Asymmetric oxidation of ethylbenzene catalyzed by Fe HaltS-imidazole-Phl(OAc)<sub>2</sub> system in the presence of water<sup>a</sup>

Entry	MeOH:H <sub>2</sub> O (%)	Conversion (%) <sup>b</sup>	Epoxide/Aldehyde ratio (%) <sup>b</sup>	Ee(%) <sup>c</sup>
1	80:20	46	91/9	75
2	50:50	41	87/13	77
3	20:80	9	36/64	56

<sup>a</sup> Reaction conditions: a mixture containing catalyst (1  $\mu$ mol), imidazole (10  $\mu$ mol), substrate (1 mmol) and Phl(OAc)<sub>2</sub> (100  $\mu$ mol) in 1 ml CH<sub>3</sub>OH:H<sub>2</sub>O under argon was stirred for 1 h.

<sup>b</sup> Determined by GC after extraction with CH<sub>2</sub>Cl<sub>2</sub> of the reaction mixture.

<sup>c</sup> Determined by GC on a chiral CP-Chirasil-Dex column.

The two main obstacles when using hydrogen peroxide are the high activity of many first-row transition metals in its decomposition thereof, the so-called catalase reaction<sup>5</sup> and the catalyst destruction by hydroxyl radicals readily released by homolytic H<sub>2</sub>O<sub>2</sub> decomposition. Many iron porphyrin-H<sub>2</sub>O<sub>2</sub> systems have been studied to get information on the mechanism and nature of the active intermediates.<sup>12,27,42</sup> Thus, mechanistic studies on peroxide activation by a water-soluble iron<sup>III</sup> porphyrin was reported by Wolak and van Eldick.<sup>29</sup> They used a water-soluble iron(III) complex with a relatively electron-rich porphyrin ligand tetrakis (3-sulfonatomesityl)porphyrin. After initial formation of the peroxy complex {Fe(P)[(H)OOR]} intermediates, the nature of the metalloporphyrin product from the reaction with all the three oxidants (m-chloroperoxybenzoic acid, iodosylbenzene and hydrogen peroxide) changed from the oxo-iron<sup>IV</sup> porphyrin cation radical to the oxo-iron(IV) porphyrin at pH>7.5 whereas a mixture of both species was formed in the intermediate pH range of 5.5-7.5. Bell and Groves<sup>43</sup> subsequently reported the detection and kinetic characterization of [FeO-TMPyP]<sup>+</sup> (TMPyP: tetrakis(*N*-methylpyridinium)porphyrin), which shows extraordinary rates for C-H hydroxylation at pH 4.7. This electropositively charged watersoluble complex is orders of magnitude more reactive that the well-studied tetramesityl analogs.44,45 Besides oxometalloporphyrins, other species, such as iron peroxo complexes were proposed as the reaction intermediates in epoxidation and alkane hydroxylation, for example, the ferric hydroperoxo porphyrin intermediate.<sup>46–48</sup> However, although this species can serve as a second electrophilic oxidant, it seems that oxoferryl P450 is the best catalyst both for olefin epoxidation and alkane hydroxylation.<sup>48</sup>

**In conclusion**, we have developed an efficient and enantioselective epoxidation of terminal alkenes using a safe and easily accessible oxidant catalyzed by water-soluble chiral iron porphyrins. Hydrogen peroxide is relatively cheap and gives water as the only co-product. One limitation is that the system needs an excess of alkene versus oxidant. In contrast, asymmetric hydroxylation of alkanes using hydrogen peroxide as oxidant is still difficult to proceed without electron-deficient chiral metalloporphyrins. Works in these directions are under progress in our laboratory.

## 3. Experimental

#### 3.1. General

All reactions were performed under argon and were magnetically stirred. Solvents were distilled from appropriate drying agent prior to use: MeOH from turning Mg. Commercially available reagents were used without further purification unless otherwise stated. Gas chromatography analysis was performed on a Varian CP-3380 gas chromatography using flame ionization detector and equipped with a CP-Chirasil-Dex CB column (25 m×0.25 mm I.D.). Conditions used: 80 °C (1 min), 2.5 °C min<sup>-1</sup>, 180 °C (60 min); injector temperature, 200 °C; detector temperature, 220 °C. HPLC analysis was realized on a Varian Prostar 218 system equipped with a Chiralcel OD-H column. The optical rotations were measured on a Perkin Elmer 341 polarimeter. The porphyrins were synthesised by literature methods. The corresponding iron porphyrins were prepared as previously reported.<sup>49</sup>

## 4. Catalytic oxidation procedures

#### 4.1. Epoxidation reaction

Iron porphyrin complex **1** (1.6 mg, 1 µmol) and imidazole (0.68 mg, 10 µmol) was placed in a test tube under argon. Then, 1 ml of distilled methanol was added, followed by styrene (104 mg, 1 mmol). Aqueous  $H_2O_2$  (35%), (9.7 mg, 100 µmol) was added over a period of 15 mn. After the addition of all the  $H_2O_2$ , the reaction was allowed to stir for an additional 45 mn. The mixture was analysed by GC for oxidation yield, 86%, based on  $H_2O_2$ , and for epoxide enantiomeric excess, 60%. Polarimetric measurement of the oxidation product determined that (*R*)-(+)-styrene oxide was formed in excess. In addition to expected styrene oxide, phenylacetaldehyde was also observed.

The reaction and analysis of the other susbtrates in Table 1 were carried out in a manner identical with that used for styrene oxidation except for 4-methylstyrene, which enantiomeric excess was determined by chiral HPLC with a Chiralcel OD-H column: *n*-hexane/isopropanol=98/2; flow rate=0.3 ml min<sup>-1</sup>; wavelength=220 nm.

The epoxidations with urea $-H_2O_2$  adduct (UHP) oxygen source were carried out in a manner similar to that described above for  $H_2O_2$ .

#### 4.2. Hydroxylation reaction

Iron porphyrin complex **1** (1.6 mg, 1  $\mu$ mol) and imidazole (0.68 mg, 10  $\mu$ mol) was placed in a test tube under argon. Then, 0.8 ml of distilled methanol and 0.2 ml H<sub>2</sub>O were added, followed by ethylbenzene (106 mg, 1 mmol). PhI(OAc)<sub>2</sub>, (32 mg, 100  $\mu$ mol) in 0.2 ml methanol was added over a period of 45 mn. After 1 h, the mixture was analysed by GC for oxidation yield, 46%, based on oxidant, and for epoxide enantiomeric excess, 75%. Polarimetric

measurement of the oxidation product determined that (S)-(-)-1phenylethanol was formed in excess. In addition to expected phenylethanol, acetophenone was also observed.

The reaction and analysis of the other susbtrates in Table 1 were carried out in a manner identical with that used for ethylbenzene oxidation except for indane and tetrahydronaphtalene. In the latter case, enantiomeric excess was determined by chiral HPLC with a Chiralcel OB-H column: n-hexane/isopropanol=95/5; flow rate- $=0.5 \text{ ml min}^{-1}$ ; wavelength=220 nm.

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