Factors Affecting the Catalytic Epoxidation of Olefins by Iron Porphyrin Complexes and H₂O₂ in Aprotic Solvents

Wonwoo Nam,‡§ So-Young Oh,† Ying Ji Sun,† Jinheung Kim,† Won-Ki Kim,§ Seung K. Woo,§ and Woonsup Shin†

Department of Chemistry and Division of Nano Sciences, Ewha Womans University, Seoul 120-750, Korea, Department of Chemical Technology, Changwon National University, Kyungnam 641-773, Korea, Department of Pharmacology and Laboratory of Neurodegenerative Diseases, Ewha Institute of Neuroscience, Seoul 120-750, Korea, and Department of Chemistry, Sogang University, Seoul 121-742, Korea

wwnam@ewha.ac.kr

Received April 17, 2003

Abstract: The catalytic epoxidation of cyclohexene by iron(III) porphyrin complexes and H₂O₂ has been investigated in alcohol solvents to understand factors affecting the catalyst activity in aprotic solvents. The yields of cyclohexene oxide and the Fe(III) reduction potentials of iron porphyrin complexes were significantly affected by the aprotic solvents, and there was a close correlation between the product yields and the reduction potentials of the iron porphyrin catalysts. The role of alcohol solvents was proposed to control the electronic nature of iron porphyrin complexes that determines the catalyst activity in the epoxidation of olefins by H₂O₂. We have also demonstrated that an electron-deficient iron porphyrin complex can catalyze the epoxidation of olefins by H₂O₂ under conditions of limited substrate with high conversion efficiency in a solvent mixture of CH₂Cl₂ and CH₂Cl₂.

The importance of iron(III) porphyrin complexes as chemical models of heme-containing enzymes and their use as catalysts for selective and controlled oxygenation reactions have prompted extensive studies of their reactions with a variety of oxidants including iodosylbenzene, peracids, hypochlorite, and hydroperoxides.1 In particular, the reactions of iron porphyrin complexes with hydrogen peroxide have attracted much attention in the literature, the reactions of iron porphyrins and peroxo complexes have been reviewed.17 Recently, we and others have shown that olefin epoxidation and alkane hydroxylation by H₂O₂ can be achieved in aprotic solvents (e.g., CH₂CN) when highly electron-deficient iron porphyrins are used as catalysts. In the studies, oxygenation reactions were found to depend significantly on the electronic nature of the iron porphyrin catalysts. More recently, we have shown that simple counterions of iron porphyrins (e.g., X = Cl or CF₃SO₃ in Fe(Porpx)X) and the presence of imidazoles as axial ligands also affect the oxygenation reactions in aprotic solvents.8,9 Other factors such as pHs in aqueous solution,11 the presence of a proton-shuttle group on iron(III) porphyrin complexes13 were reported to play important roles in the reactions of iron porphyrin complexes and H₂O₂. In the oxidation of olefins by H₂O₂ in a solvent mixture of CH₂Cl₂/H₂O/CH₃OH/H₂O.2 It has been proposed that protic solvents function as general-acid catalysts which facilitates O–O bond heterolysis, resulting in the generation of high-valent oxoiron(V) porphyrin π-cation radicals.2–4 Recently, we and others have shown that olefin epoxidation and alkane hydroxylation by H₂O₂ can be achieved in aprotic solvents (e.g., CH₂CN) when highly electron-deficient iron porphyrins are used as catalysts. In the studies, oxygenation reactions were found to depend significantly on the electronic nature of the iron porphyrin catalysts. More recently, we have shown that simple counterions of iron porphyrins (e.g., X = Cl or CF₃SO₃ in Fe(Porpx)X) and the presence of imidazoles as axial ligands also affect the oxygenation reactions in aprotic solvents.8,9 Other factors such as pHs in aqueous solution,11 the presence of a proton-shuttle group on iron(III) porphyrin complexes13 were reported to play important roles in the reactions of iron porphyrin complexes and H₂O₂. In the oxidation of olefins by H₂O₂ in a solvent mixture of CH₂Cl₂/H₂O/CH₃OH/H₂O.2 It has been proposed that protic solvents function as general-acid catalysts which facilitates O–O bond heterolysis, resulting in the generation of high-valent oxoiron(V) porphyrin π-cation radicals.2–4

1 To whom correspondence should be addressed. Tel: +82-2-3277-2392. Fax: +82-2-3277-2384.

2 Ewha Womans University.
3 Changwon National University.
4 Ewha Institute of Neuroscience.
5 Sogang University.

References:

10.1021/jo044393c CCC: $25.00 © 2003 American Chemical Society
Published on Web 08/27/2003


7903
present work, we have studied the catalytic epoxidation of olefins by iron porphyrin complexes and \( \text{H}_2\text{O}_2 \) in protic solvents, to understand factors affecting the catalyst activity in protic solvents. We found from the studies that the yields of epoxide product and the Fe\( ^{\text{III}}/\text{II} \) reduction potentials of iron porphyrin complexes are significantly influenced by the protic solvents and that there is a close correlation between the product yields and the reduction potentials of the iron porphyrin catalysts. These results led us to propose that alcohol solvents coordinating to iron porphyrins as axial ligands control the electronic nature of iron porphyrin complexes and determine the catalyst activity in the epoxidation of olefins by \( \text{H}_2\text{O}_2 \).

We first explored the effect of alcohol solvents on the catalytic epoxidation of cyclohexene by an electron-deficient iron(III) porphyrin complex, Fe(TPFPP)Cl (TPFPP = meso-tetrakis(pentafluorophenyl)porphinato dianion), and \( \text{H}_2\text{O}_2 \) in a solvent mixture of alcohol/\( \text{CH}_2\text{Cl}_2 \) at room temperature.\(^2\) The results in Table 1A show that the yields of cyclohexene oxide were markedly influenced by alcohol solvents; the yields were high in \( \text{CH}_3\text{OH} \), \( \text{CH}_3\text{CH}_2\text{OH} \), and \( \text{(CH}_3\text{)}_2\text{CHOH} \) but quite different in \( \text{(CH}_3\text{)}_3\text{OH} \). The Fe\( ^{\text{III}}/\text{II} \) reduction potentials of Fe(TPFPP)Cl were determined with cyclic voltammetry under the identical reaction conditions employed in the epoxidation reactions,\(^3a\) the Fe\( ^{\text{III}}/\text{II} \) reduction potentials results from the coordination of alcohol solvents as axial ligands (vide infra).

B. Effect of 5-Chloro-1-methylimidazole as an Axial Ligand\(^{b,c}\)

In \( \text{CH}_3\text{OH} \) and \( \text{(CH}_3\text{)}_2\text{CHOH} \), the Fe\( ^{\text{III}}/\text{II} \) reduction potentials shifted to less negative values (Supporting Information, Table S1), indicating that the iron porphyrin complex became more electron-deficient with the increase of methanol concentrations.\(^1\) Based on the amounts of \( \text{H}_2\text{O}_2 \) added, the reduction potentials of Mn(TPP)Cl (TPP = meso-tetraphenylporphinato dianion) were dependent on methanol concentrations, and this phenomenon was illustrated with the replacement of an axial chloride ligand by \( \text{CH}_3\text{OH} \) upon the increase of methanol concentrations.\(^1\)

To probe that the alcohol solvent effect was resulted from the coordination of alcohol solvents as axial ligands, the Fe\( ^{\text{III}}/\text{II} \) reduction potentials results from the coordination of alcohols as axial ligands (vide infra).

Then, the effect of alcohol concentration on the epoxidation of cyclohexene by Fe(TPFPP)Cl and \( \text{H}_2\text{O}_2 \) was investigated in \( \text{CH}_3\text{OH} \) and \( \text{(CH}_3\text{)}_2\text{CHOH} \). Figure 1 shows that epoxide yields increased with the increase of alcohol concentrations and the increase of the product yields was faster in \( \text{CH}_3\text{OH} \) than in \( \text{(CH}_3\text{)}_2\text{CHOH} \). In addition, the increase of alcohol concentrations shifted the Fe\( ^{\text{III}}/\text{II} \) reduction potentials to less negative values (Supporting Information, Table S1), indicating that the iron porphyrin complex became more electron-deficient with the increase of the amounts of alcohols in reaction solutions. As we have discussed above, the results of the concentration effect on the product yields and the Fe\( ^{\text{III}}/\text{II} \) reduction potentials are illustrated with the axial ligand effect. Indeed, it has been reported that the reduction potentials of Mn(TPP)Cl (TPP = meso-tetraphenylporphinato dianion) were dependent on methanol concentrations, and this phenomenon was illustrated with the replacement of an axial chloride ligand by \( \text{CH}_3\text{OH} \) upon the increase of methanol concentrations.\(^1\)

To probe that the alcohol solvent effect was resulted from the coordination of alcohol solvents as axial ligands, the Fe\( ^{\text{III}}/\text{II} \) reduction potentials results from the coordination of alcohol solvents as axial ligands (vide infra).
the catalytic epoxidation of cyclohexene by Fe(TPFPP)-Cl and H2O2 was carried out in the presence of 5-chloro-1-methylimidazole (5-Cl-1-MeIm) in alcohol solvents.2b The binding of 5-Cl-1-MeIm to the Fe(TPFPP)+ complex was monitored by taking UV–vis spectra of the reaction solutions (data not shown).3b,17 The results in Table 1B show that when the epoxidation reactions were carried out in the presence of 5-Cl-1-MeIm, the yield of cyclohexene oxide increased from 17% to 70% in CF3CH2OH solution and high yields of epoxide product were obtained in CH3OH, CH3CH2OH, and (CH3)2CHOH. In (CH3)2OH solution, the yield of cyclohexene oxide increased from 3% to 35%, and this result was ascribed to a fast degradation of the Fe(TPFPP)Cl catalyst under the reaction condition (data not shown). In addition, the Fe1111 reduction potentials of the imidazole-bound low-spin Fe(TPFPP)(5-Cl-1-MeIm)2 were identical (~0.32 V) in all alcohol solvents.5b On the basis of the observations that the alcohol solvent effect disappeared when the axial positions of the Fe(TPFPP)+ complex were coordinated by imidazoles, we conclude that the chloride ligand of Fe(TPFPP)Cl is replaced by alcohol solvents and the Fe(TPFPP)+ complexes binding different alcohols show different reactivities in the epoxidation of olefins by H2O2.18

The electronic effect of iron porphyrin complexes on the catalytic epoxidation of cyclohexene by H2O2 was also investigated with iron porphyrins bearing different substituents on meso-phenyls and pyrrole positions of porphyrin ligand in CH3OH (Supporting Information, Figure S1 for the structures of iron porphyrin complexes).19 As we have shown previously,18 electron-rich iron porphyrins did not produce cyclohexene oxide in the epoxidation of cyclohexene by H2O2 (see data of 1 and 2 in Table 1C). As the iron porphyrin catalysts became electron-deficient, the yields of cyclohexene oxide increased (see data of 3–5 in Table 1C). Interestingly, the epoxide yields diminished as the iron porphyrins became more electron-deficient (see data of 6 and 7 in Table 1C).20 These results indicate that iron complexes of electron-rich or too electron-deficient porphyrin ligands are poor catalysts. This trend is also seen in the studies of alcohol solvent effect, in which the Fe(TPFPP)+ complex in (CH3)2OH and CF3-CH2OH is the most electron-rich and -deficient, respectively, and in these solvents, the yields of epoxide product are low (see Table 1A). On the basis of the results, we conclude that alcohol solvents coordinating as axial ligands play an important role in controlling the electronic nature of iron porphyrin complexes and that the electronic nature of iron porphyrin catalysts is an important factor in determining the catalyst activity.21

Finally, the catalytic epoxidation of olefins by Fe(TPFPP)Cl and H2O2 was attempted under conditions of limiting substrate (catalyst/substrate/H2O2 = 1:2000:2400), since the development of efficient and practical methods that utilize environmentally benign and inexpensive H2O2 as a terminal oxidant is an important objective in preparative oxidation chemistry.22 Treatment of olefins with 1.2 equiv of H2O2 in the presence of 0.05 mol % catalyst in a solvent mixture of CH3OH/CH2Cl2 afforded the complete conversion of olefins with high product yields and stereoselectivity (Table 2). By taking UV–vis spectra of reaction solutions before and after the addition of the oxidant, the destruction of the iron porphyrin catalyst was found to be minimal (i.e., less than 5%). These results demonstrate that the Fe(TPFPP)Cl complex can catalyze the epoxidation of olefins by H2O2 efficiently and selectively under conditions of limiting substrate.

In summary, we have shown here that the electronic nature and catalytic activity of iron porphyrin complexes are markedly influenced by alcohol solvents. This phenomenon was illustrated with the binding of alcohols as axial ligands that controls the electronic nature of iron porphyrin complexes. We have also demonstrated that the electronic nature of iron porphyrin catalysts is an important factor in determining the catalyst activity and that an electron-deficient iron porphyrin complex can catalyze the epoxidation of olefins by H2O2 under conditions of limiting substrate with high conversion efficiency.

**Experimental Section**

**Materials and Instrumentation.** All reagents purchased from Aldrich Chemical Co. were the best available purity and used without further purification unless otherwise indicated.

**Table 2. Catalytic Epoxidation of Olefins by Fe(TPFPP)Cl and H2O2 under Conditions of Limiting Substrate**

<table>
<thead>
<tr>
<th>substrate</th>
<th>conversion (%)</th>
<th>products</th>
<th>yields (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyclohexene</td>
<td>99 ± 1</td>
<td>cyclohexene oxide</td>
<td>90 ± 5</td>
</tr>
<tr>
<td>cyclohexene</td>
<td>5 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cyclohexene</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cyclooctene</td>
<td>99 ± 1</td>
<td>cyclooctene oxide</td>
<td>95 ± 5</td>
</tr>
<tr>
<td>cis-stilbene</td>
<td>99 ± 1</td>
<td>cis-stilbene oxide</td>
<td>95 ± 4</td>
</tr>
<tr>
<td>trans-stilbene</td>
<td>2 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>benzaldehyde</td>
<td></td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

*See the Experimental Section for detailed reaction conditions.

*a* Based on the amount of substrates used.

---


(18) When the anionic chloride ligand of Fe(TPFPP)Cl was replaced by nonligating anions such as CF3SO3− and ClO4−, the catalytic efficiency of the iron porphyrin complex increased markedly and the yields of oxygenated products were high in olefin epoxidation and alkane hydroxylation reactions by HO2 in aprotic solvents.

(19) Abbreviations of porphyrin ligands: β-C1(TPFPP) = β-octachloro-meso-tetrakis(pentafluorophenyl)porphinothiazin; β-C1(TDCA) = β-octachloro-meso-tetrakis(2,6-dichlorophenyl)porphinothiazin; TDFP = meso-tetrakis(2,6-dichlorophenyl)porphinothiazin; TDPCP = meso-tetrakis(2,6-difluorophenyl)porphinothiazin; TDPP = meso-tetrakis(2,6-dichlorophenyl)porphinothiazin; TFP = meso-tetrakis(2,6-dichlorophenyl)porphinothiazin.

(20) In these reactions, the iron catalysts degraded at a fast rate, confirming a previous observation that iron porphyrin complexes bearing halogen-substituents on pyrrole positions lose their stability against oxidative degradation. Poirié, E.; Bondol, A.; Leroy, J. Tetrahedron Lett. 1998, 39, 4829–4830.

(21) At this moment, we do not rule out the possibility that the polarity and acidity of alcohol solvents also play an important role in determining the catalytic activity of iron porphyrin complexes in H2O2 reactions.2,4

Methanol (anhydrous) and dichloromethane (anhydrous) were purified by distillation over CaH₂ prior to use. H₂O₂ (30% aqueous) was purchased from Aldrich. Fe(TPFPP)Cl and Fe(TPP)Cl were purchased from Aldrich Chemical Co. Other iron(III) porphyrin complexes were obtained from Mid-Century Chemicals. The purity of the iron porphyrins was examined by ¹H NMR in CD₂Cl₂.

Product analyses were performed on either a Hewlett-Packard 5890 II Plus gas chromatograph equipped with a FID detector using 30-m capillary column (Hewlett-Packard, HP-1 and HP-5) or a SUMMIT HPLC (DIONEX) with a variable-wavelength UV 170S and a Phenomenex LUNA C18 reversed-phase column. UV–vis spectra were recorded on a Hewlett-Packard 8453 spectrophotometer. ¹H NMR spectra were recorded on a Bruker AM 250. All electrochemical experiments were performed under N₂ atmosphere in a glovebox using BAS 50W voltammetric analyzer.

Reaction Conditions. Reactions were performed at ambient temperature under argon atmosphere unless otherwise indicated. All reactions were run in at least triplicate, and the data reported represent the averages of these reactions. In general, an iron porphyrin complex (1.25 × 10⁻³ mmol) was dissolved in a solvent mixture (2.5 mL) of alcohol/CH₂Cl₂ (3:1) containing cyclohexene (1 mmol). H₂O₂ (0.1 mmol, 30% aqueous, diluted in 0.2 mL of CH₃OH/CH₂Cl₂ (3:1)) was slowly added to the reaction solution over a period of 3 min, and the resulting solution was stirred for 10 min. An aliquot of the reaction mixture was directly analyzed by GC or GC/MS, and product yields were determined by comparison against standard curves prepared with known authentic samples.

The catalytic epoxidation reactions under conditions of limiting substrate were carried out as follows: H₂O₂ (3 mmol, diluted in a solvent mixture (0.5 mL) of CH₃OH/CH₂Cl₂ (3:1)) was added via syringe pump over 40 min to a reaction solution containing Fe(TPFPP)Cl (1.25 × 10⁻³ mmol) and substrate (2.5 mmol) in a solvent mixture (5 mL) of CH₃OH/CH₂Cl₂ (3:1). The reaction mixture was further stirred for 10 min and directly analyzed by GC or HPLC.

Acknowledgment. We thank the Ministry of Science and Technology of Korea through the Creative Research Initiatives Program, the Korea Science and Engineering Foundation (R02-2003-000-100), and the Korea Research Foundation (Grant No. DP0270) for financial support.

Supporting Information Available: Table S1 reports the yields of cyclohexene oxide and the Fe(III/II) reduction potentials of Fe(TPFPP)Cl determined in different alcohol concentrations. Figure S1 shows structures of iron(III) porphyrin complexes used in this study. This material is available free of charge via the Internet at http://pubs.acs.org.