Participation of Two Distinct Hydroxylating Intermediates in Iron(III) Porphyrin Complex-Catalyzed Hydroxylation of Alkanes

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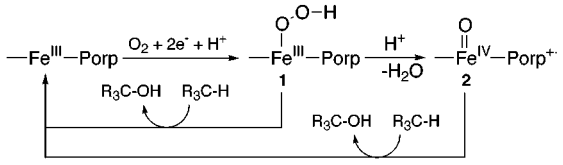
Abstract: We have obtained evidence that acylperoxo-iron(III) porphyrin complexes **1a** are involved as reactive hydroxylating intermediates in the hydroxylation of alkanes by *m*-chloroperoxybenzoic acid (*m*-CPBA) catalyzed by electron-deficient iron(III) porphyrin complexes containing chloride as an anionic axial ligand in a solvent mixture of CH_2Cl_2 and CH_3CN at −40 °C. In addition to the intermediacy of **1a**, oxoiron(IV) porphyrin cation radical complexes **2** are formed as the reactive hydroxylating intermediates in the alkane hydroxylations by *m*-CPBA catalyzed by the iron(III) porphyrin complexes containing triflate ($CF_3SO_3^-$) as an anionic axial ligand under the same reaction conditions. In line with the recent proposal by Newcomb, Coon, Vaz, and co-workers for cytochrome P-450 reactions, these results suggest that two distinct electrophilic oxidants such as **1a** and **2** effect the alkane hydroxylations in iron porphyrin models, depending on the reaction conditions such as the nature of the anionic axial ligands of iron(III) porphyrin complexes.

Introduction

Elucidation of the structure of reactive intermediates responsible for oxygen atom transfer in the catalytic hydroxylation of alkanes by cytochrome P-450 enzymes and their iron(III) porphyrin models has been the continuing interest in biological and bioinorganic chemistry.[1,2] It has been generally believed for a long time that oxoiron(IV) porphyrin cation radical intermediates **2** are the sole reactive species capable of activating the energetically difficult C−H bonds of alkanes (Scheme 1).[1]

Scheme 1



Considerable indirect evidence for the intermediacy of **2** in the catalytic hydroxylation of alkanes by iron porphyrin complexes has been reported.[3] Also, several oxoiron(IV) porphyrin cation radical complexes generated at low temperature were directly used in the reactivity studies of alkane hydroxylation reactions.[4]

In addition to the intermediacy of **2**, it has been proposed recently that hydroperoxo-iron(III) porphyrin intermediates **1** are able to hydroxylate alkanes prior to the formation of **2** (Scheme 1).[5,6] Notably, Newcomb, Coon, Vaz, and co-workers reported elegant results consistent with the involvement of two distinct electrophilic oxidants such as **1** (or iron(III)-hydrogen peroxide (Fe^{III}-H_2O_2) intermediate) and **2** in the hydroxylation of alkanes by cytochrome P-450 enzymes and their mutants

† Ewha Womans University.

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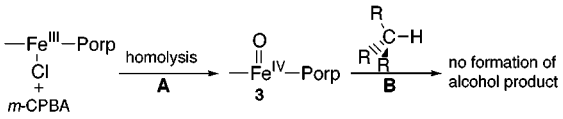
Scheme 2



lacking threonine in the active site.[5] In addition, Lippard, Newcomb, and co-workers recently provided compelling evidence that a hydroperoxo-iron(III) species is a plausible hydroxylating intermediate in methane monooxygenase enzymes as well.[7] In iron porphyrin models, although a number of reports appeared recently that **1** is a viable reactive species capable of oxygenating easily oxidized substrates such as olefins,[8] it has not been shown clearly that **1** is able to activate the C−H bonds of alkanes to give alcohol products in iron porphyrin-catalyzed hydroxylation of alkanes.[9] In the present study, we report evidence for the first time that acylperoxo-iron(III) porphyrin complexes [(Porp)Fe^{III}-OOC(O)R, **1a**] hydroxylate alkanes to yield the corresponding alcohols in iron(III) porphyrin-catalyzed hydroxylation of alkanes by *m*-chloroperoxybenzoic acid (*m*-CPBA) at low temperature. We also show in this study that, as Newcomb, Coon, Vaz, and co-workers have proposed in cytochrome P-450 reactions, two distinct electrophilic oxidants such as **1a** and **2** are involved as reactive hydroxylating intermediates in iron porphyrin-catalyzed hydroxylation of alkanes.

Results and Discussion

We have shown recently that the reactions of electron-deficient iron(III) porphyrin complexes containing chloride as an anionic axial ligand such as Fe(TPFPP)Cl (TPFPP = *meso*-tetrakis(pentafluorophenyl)porphinato dianion) and Fe(TDFPP)-Cl (TDFPP = *meso*-tetrakis(2,6-difluorophenyl)porphinato dianion) with *m*-CPBA gave the formation of oxoiron(IV) porphyrin complexes **3** in a solvent mixture of CH_2Cl_2 and CH_3CN at −40 °C [Scheme 2, pathway A; see Figure 1A for the UV−vis spectral change upon the addition of *m*-CPBA to a reaction solution containing Fe(TPFPP)Cl].[10] The oxoiron(IV) porphyrin complexes such as (TPFPP)Fe^{IV}═O and (TDFPP)-Fe^{IV}═O were found to be incapable of hydroxylating alkanes at the reaction temperature (Scheme 2, pathway B).[11,12] These results indicate that we would not expect to observe the formation of alcohol products in the hydroxylation of alkanes by the electron-deficient iron(III) porphyrin complexes containing chloride as an axial ligand and *m*-CPBA, since **3** is formed

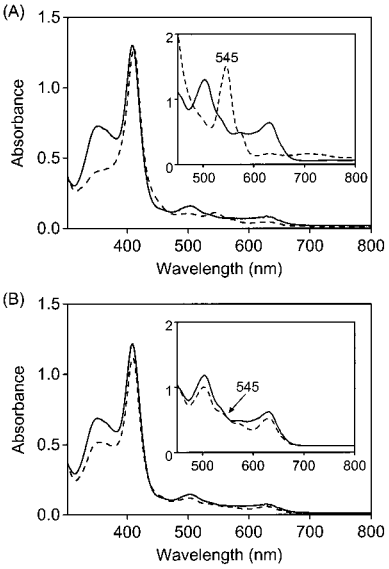


Figure 1. UV-vis spectral changes upon the addition of *m*-CPBA to a reaction solution containing Fe(TPFPP)Cl in the absence and presence of cyclohexane. (A) *m*-CPBA (1.5×10^{-4} mmol, diluted in 50 μL of CH_3CN) was added to a 0.1-cm UV cell containing Fe(TPFPP)Cl (5×10^{-5} mmol, —) in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:1) at −40 °C. The completion of the formation of (TPFPP)Fe^{IV}═O (— — —) took 10 min. Inset: UV−vis spectra of Fe(TPFPP)Cl (—) and (TPFPP)Fe^{IV}═O (— — —) taken in the reaction of Fe(TPFPP)Cl (5×10^{-4} mmol) with 3 equiv of *m*-CPBA (1.5×10^{-4} mmol). (B) The reaction procedures were the same as described in (A) except that cyclohexane (0.3 mmol) was present in the reaction solution.

in the *m*-CPBA reactions and this intermediate is not able to hydroxylate alkanes. However, it has been often reported previously that the Fe(TPFPP)Cl complex is an effective catalyst in the hydroxylation of alkanes by peracids in aprotic solvent, giving high yields of alcohol products.[13] Therefore, we were curious about how the alcohol products are produced in the hydroxylation of alkanes by the iron(III) porphyrin complex and *m*-CPBA. We therefore carried out the *m*-CPBA reactions with Fe(Porp)Cl complexes in the presence of cyclohexane under the identical reaction conditions described above. Interestingly, we observed a complete inhibition of the formation of **3** (see Figure 1B for the UV−vis spectral change upon the addition of *m*-CPBA to a reaction solution containing Fe(TPFPP)Cl and cyclohexane) with a high yield of cyclohexanol formation (∼70% based on *m*-CPBA added). This result suggests that a reactive species different from **3** was generated as a hydroxylating intermediate in the reactions of the iron porphyrin complexes and *m*-CPBA.

More interestingly, the formation of **3** and the amounts of cyclohexanol formed in the *m*-CPBA reactions were found to depend on the concentration of cyclohexane present in the reaction solutions. As the concentration of the alkane increased, the formation of **3** decreased, while the yield of cyclohexanol product increased (Figure 2). In addition to the concentration effect, the amounts of **3** and alcohol products formed in the *m*-CPBA reactions were found to depend on the C−H bond strength of alkanes. When the C−H bond strength of alkanes was weak (e.g., *cis*-1,2-dimethylcyclohexane), the formation of **3** was not detected but a high yield of alcohol formation was observed (Table 1 and Figure 3). As the C−H bond strength of alkanes became stronger (e.g., cyclohexane-d_{12}), the formation of **3** was detected with a lower yield of alcohol formation (Table

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(11) No formation of cyclohexanol was observed when cyclohexane was added to reaction solutions containing in situ generated (TPFPP)Fe^{IV}═O and (TDFPP)Fe^{IV}═O complexes.

(12) It has been shown by Groves and co-workers that the reactivity of oxoiron(IV) porphyrin complexes [e.g., (TMP)Fe^{IV}═O] is low and different from that of oxoiron(IV) porphyrin cation radicals [e.g., (TMP)$^{+\bullet}$Fe^{IV}═O]: Groves, J. T.; Gross, Z.; Stern, M. K. *Inorg. Chem.* **1994**, *33*, 5065−5072.

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Table 1. Dependence of the Yields of Oxygenated Products and the Formation of Intermediate **3** on the C−H Bond Energy of Alkanes in the Hydroxylation of Various Alkanes by Fe(TDFPP)Cl and *m*-CPBA

substrate	products	yields (%) of products[a,c]	formation (%) of **3**[b,c]	C−H bond energy (kcal/mol)[d]
cis−1,2-dimethyl-cyclohexane	*cis*−1,2-dimethyl-cyclohexanol	72 ± 4	0	∼96
	trans−1,2-dimethyl-cyclohexanol	0		
	2,3- and 3,4-dimethyl-cyclohexanol	5 ± 1		
cyclohexane	cyclohexanol	70 ± 4	4 ± 2	99.3
	cycloohexanone	2 ± 1		
cyclohexane-d_{12}	cyclohexanol-d_{12}	40 ± 3	50 ± 3	100.6

[a] See Experimental Section for detailed experimental procedures of hydroxylation reactions. [b] See footnote in Figure 3 for detailed experimental procedures of UV−vis spectroscopic studies. [c] Based on *m*-CPBA added. [d] See Table 5 in ref 4.

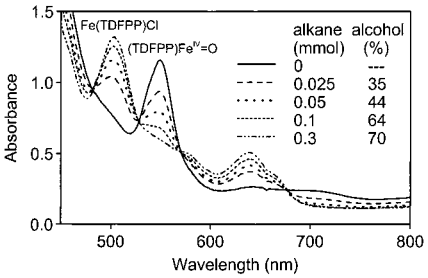


Figure 2. Concentration effect of alkane on the formation of **3** and alcohol product in the reaction of Fe(TDFPP)Cl and *m*-CPBA. Reaction conditions: *m*-CPBA (6×10^{-4} mmol, diluted in 50 μL of CH_3CN) was added to a 0.1-cm UV cell containing Fe(TDFPP)Cl (5×10^{-4} mmol) and various amounts of cyclohexane in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:1) at −40 °C. Spectral changes were directly monitored by UV−vis spectroscopy, and the percent yields of cyclohexanol (based on *m*-CPBA added) were determined by analyzing the reaction solutions with GC.

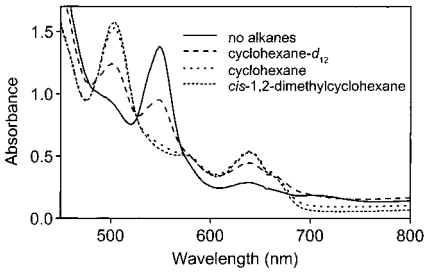
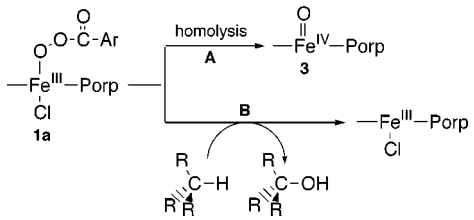


Figure 3. Effect of C−H bond strength of alkanes on the formation of **3** and alcohol products in the reactions of Fe(TDFPP)Cl and *m*-CPBA. Reaction conditions: *m*-CPBA (6×10^{-4} mmol, diluted in 50 μL of CH_3CN) was added to a 0.1-cm UV cell containing Fe(TDFPP)Cl (5×10^{-4} mmol) and alkanes (0.3 mmol) in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:1) at −40 °C. Spectral changes were directly monitored by UV−vis spectroscopy, and the percent yields of products in Table 1 were determined by analyzing the reaction solutions with GC.

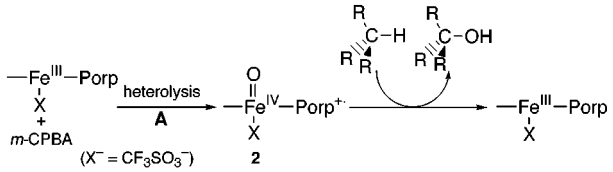
1 and Figure 3). On the basis of the results that the formation of **3** depends on the concentration and C−H bond strength of alkanes, we conclude that the formation of **3** is inhibited by the competitive reaction of an intermediate with alkanes. Since **1a** is presumed to be the sole intermediate present in the course of the formation of **3** via O−O bond homolysis (Scheme 3, pathway A), we suggest that **1a** is the reactive species that effects the hydroxylation of alkanes by Fe(Porp)Cl and *m*-CPBA in a solvent mixture of CH_2Cl_2 and CH_3CN at −40 °C (Scheme 3, pathway B).[14]

We then studied the *m*-CPBA reactions with iron(III) porphyrin complexes containing triflate ($CF_3SO_3^-$) as an anionic axial ligand. As we have observed previously,[10] **2** was formed in the reactions of *m*-CPBA with Fe(TPFPP)(CF_3SO_3) and Fe(TDFPP)(CF_3SO_3) in a solvent mixture of CH_2Cl_2 and

Scheme 3



Scheme 4



CH_3CN at −40 °C (Scheme 4, pathway A). When the identical reactions were performed in the presence of cyclohexane, we found that the formation of **2** was not inhibited by the presence of the alkane (Figure 4). This result is different from that observed in the reactions of Fe(Porp)Cl with *m*-CPBA, in which the formation of **3** was inhibited by the presence of cyclohexane (vide supra). Although **2** was relatively stable in the absence of cyclohexane at the reaction temperature ($t_{1/2}$ = ∼5 min), **2** disappeared faster in the presence of the alkane (Figure 4, $t_{1/2}$ = ∼0.7 min). GC analysis of the resulting solutions revealed that good amounts of cyclohexanol were yielded (∼40% based on *m*-CPBA used). On the basis of the results presented above, we conclude that **2** is formed as a hydroxylating intermediate in the hydroxylation of alkanes by Fe(Porp)(CF_3SO_3) complexes and *m*-CPBA in a solvent mixture of CH_2Cl_2 and CH_3CN at −40 °C (Scheme 4).

To gain further evidence that **1a** and **2** were generated as reactive hydroxylating intermediates in the reactions of *m*-CPBA with the Fe(Porp)Cl and Fe(Porp)(CF_3SO_3) complexes, respectively, we carried out isotopically labeled water, $H_2{}^{18}O$, experiments[4,15] in the hydroxyation of cyclohexane by *m*-CPBA

(14) We rule out a possibility that the hydroxylation reactions proceed via free radical mechanism with the following observations. The alkane hydroxylations were highly stereospecific, in which the hydroxylation of *cis*-1,2-dimethylcyclohexane afforded *cis*-1,2-dimethylcyclohexanol with no formation of *trans*-1,2-dimethylcyclohexanol (Table 1) and the hydroxylation of *trans*-1,2-dimethylcyclohexane gave *trans*-1,2-dimethylcyclohexanol (12%) and 2,3- and 3,4-dimethylcyclohexanol (44%). No formation of *cis*-1,2-dimethylcyclohexanol was detected in the latter reaction. Another evidence that supports ruling out the involvement of radical chemistry is the high alcohol-to-ketone ratio obtained in the hydroxylation of cyclohexane performed in air (Table 1), since hydroxylation of alkanes via free radical pathways usually affords equal amounts of alcohol and ketone products: (a) Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981. (b) MacFaul, P. A.; Ingold, K. U.; Wayner, D. D. M.; Que, L., Jr. *J. Am. Chem. Soc.* **1997**, *119*, 10594−10598.

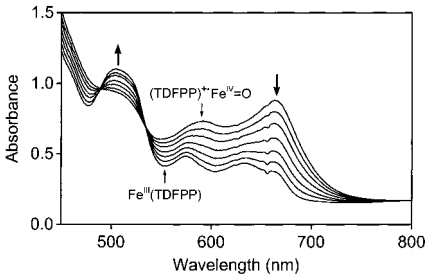


Figure 4. UV-vis spectral changes upon the addition of *m*-CPBA to a reaction solution containing Fe(TDFPP)(CF_3SO_3) and cyclohexane. *m*-CPBA (6×10^{-4} mmol, diluted in 50 μL of CH_3CN) was added to a 0.1-cm UV cell containing Fe(TDFPP)(CF_3SO_3) (5×10^{-4} mmol) and cyclohexane (0.3 mmol) in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:1) at −40 °C. The completion of the reaction took 4 min.

Table 2. Percentages of ^{18}O Incorporated from $H_2{}^{18}O$ into Cyclohexanol Product[a,b]

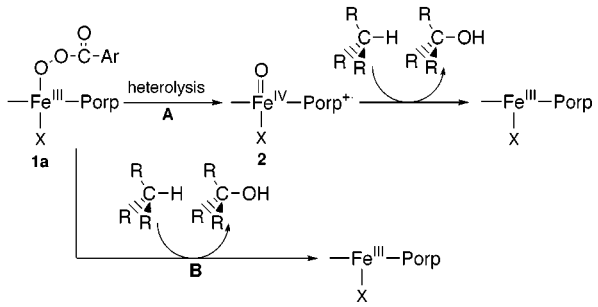
entry	reactions	^{18}O (%) in cyclohexanol	yield (%) of cyclohexanol[c]
1	$(TPFPP)^{+\bullet}Fe^{IV}$═O	31 ± 3	43 ± 5
2	Fe(TPFPP)(CF_3SO_3) + *m*-CPBA	33 ± 3	32 ± 4
3	Fe(TPFPP)Cl + *m*-CPBA	4 ± 1	65 ± 5
4	Fe(TPFPP)OH + *m*-CPBA[d]	2 ± 1	42 ± 5

[a] See Experimental Section for detailed experimental procedures. [b] All reactions were run at least in triplicate, and the data reported represent the average of these reactions. [c] Based on the amounts of *m*-CPBA used. [d] The reaction of Fe(TPFPP)OH with *m*-CPBA affords the formation of $(TPFPP)Fe^{IV}$═O under the reaction conditions.[10]

catalyzed by Fe(TPFPP)X complexes. For comparison, the labeled water experiment was performed with an in situ generated oxoiron(IV) porphyrin cation radical complex $[(TPFPP)^{+\bullet}Fe^{IV}$═O] as well.[4,16] As the results are shown in Table 2, the ^{18}O percentages in the cyclohexanol product formed in the hydroxylation of cyclohexane by Fe(TPFPP)(CF_3SO_3) and *m*-CPBA and by the in situ generated $[(TPFPP)^{+\bullet}Fe^{IV}$═O] complex were similar (entries 1 and 2), demonstrating that **2** was formed as a hydroxylating intermediate in the catalytic hydroxylation of cyclohexane by Fe(TPFPP)(CF_3SO_3) and *m*-CPBA. Also, the observation that only a trace amount of ^{18}O was incorporated from $H_2{}^{18}O$ into the cyclohexanol product formed in the hydroxylation of cyclohexane by *m*-CPBA catalyzed by Fe(TPFPP)Cl and Fe(TPFPP)OH[17] complexes (Table 2, entries 3 and 4) leads us to conclude that the reactive species generated in this reaction should be **1a**, since **1a** cannot exchange its oxygen with labeled water in the course of the oxygen atom transfer from **1a** to alkanes.[16]

Then, how are two distinct hydroxylating intermediates such as **1a** and **2** formed depending on the anionic axial ligands of the iron(III) porphyrin complexes? At this moment, we presume that the axial ligands may affect the oxidizing power and lifetime

Scheme 5



of **1a**. If the oxidizing power of **1a** is high enough to activate the C−H bonds of alkanes and the lifetime of **1a** is long enough to transfer its oxygen to alkanes prior to the O−O bond cleavage of **1a**, then **1a** becomes the hydroxylating intermediate (Scheme 5, pathway B). If the oxidizing power of **1a** is weak and/or the lifetime of **1a** is short, **1a** cannot effect the hydroxylation of alkanes. In this case, O−O bond cleavage of **1a** takes place and **2** becomes the reactive species (Scheme 5, pathway A). Detailed studies to understand the effect of the anionic axial ligands on the reactivities of **1a** and **2** are actively in progress in this laboratory.[18,19]

In conclusion, we have obtained evidence that an acylperoxoiron(III) porphyrin complex is a viable reactive intermediate capable of activating the energetically difficult C−H bonds of alkanes to yield the corresponding alcohol products in iron porphyrin-catalyzed hydroxylation of alkanes by *m*-CPBA. We also proposed that both **1a** and **2** are involved as reactive intermediates in alkane hydroxylation reactions, depending on the reaction conditions such as the nature of the anionic axial ligands bound to iron(III) porphyrin complexes. The observation that two different electrophilic oxidants effect the hydroxylation of alkanes in iron porphyrin models is relevant to the recent proposal of Newcomb, Coon, Vaz, and co-workers for cytochrome P-450 reactions.[5] Finally, we are currently investigating the following questions: (1) how is the oxygen atom of (Porp)-Fe^{III}−OOR inserted into the C−H bond of alkanes?[5,7,20] and (2) what are the reactivity differences between oxoiron(IV) porphyrin cation radical and oxidant-iron(III) porphyrin intermediates?

Experimental Section

Materials. Dichloromethane (anhydrous) and acetonitrile (anhydrous) were obtained from Aldrich Chemical Co. and purified by distillation over CaH_2 prior to use. All reagents purchased from Aldrich Chemical Co. were the best available purity and used without further purification unless otherwise indicated. *m*-CPBA purchased from Aldrich Chemical Co. was purified by washing with phosphate buffer (pH 7.4) followed by water and then dried under reduced pressure. All iron(III) porphyrin complexes were obtained from Mid-Century Chemicals and used without further purification.

Instrumentation. UV−vis spectra were recorded on a Hewlett-Packard 8453 spectrophotometer equipped with *Optostat*^{DN} variable-temperature liquid-nitrogen cryostat (Oxford Instruments). Product analyses for alkane hydroxylation reactions were performed on either

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(16) Fujii, H. *Chem. Lett.* **1994**, 1491−1494.

(17) A reviewer suggested to investigate the ^{18}O-labeled water experiment with Fe(TPFPP)OH, since a small amount of ^{18}O-incorporation from $H_2{}^{18}O$ into cyclohexanol observed in Fe(TPFPP)Cl-catalyzed hydroxylation of cyclohexane by *m*-CPBA might be the result of the absence of a hydroxo ligand trans to the iron−oxo group (i.e., "redox tautomerism").[15d] The result of only a trace amount of ^{18}O-incorporation into the cyclohexanol product obtained in the Fe(TPFPP)OH reaction (Table 2, entry 4) suggests that the small amount of ^{18}O-incorporation observed in the Fe(TPFPP)Cl reaction was not due to the axial ligand effect on the oxygen exchange between an iron−oxo and labeled water.

(18) (a) Gross, Z.; Nimri, S. *Inorg. Chem*. **1994**, *33*, 1731−1732. (b) Gross, Z. *J. Biol. Inorg. Chem*. **1996**, *1*, 368−371. (c) Czarnecki, K.; Nimri, S.; Gross, Z.; Proniewicz, L. M.; Kincaid, J. R. *J. Am. Chem. Soc*. **1996**, *118*, 2929−2935.

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(20) (a) Harris, N.; Cohen, S.; Filatov, M.; Ogliaro, F.; Shaik, S. *Angew. Chem., Int. Ed.* **2000**, *39*, 2003−2007. (b) Groves, J. T. *J. Chem. Educ*. **1985**, *62*, 928−931.

a Hewlett-Packard 5890 II Plus gas chromatograph interfaced with Hewlett-Packard model 5989B mass spectrometer or a Donam Systems 6200 gas chromatograph equipped with a FID detector using 30-m capillary column (Hewlett-Packard, HP-1 and HP-5).

Reaction Conditions. Since the hydroxylation reactions were not affected by molecular oxygen, all of the reactions presented in this study were performed in air. *m*-CPBA (1.2×10^{-3} mmol, diluted in 20 μL of CH_3CN) was added to a reaction solution containing an iron(III) porphyrin complex (1×10^{-3} mmol) and alkane (0.3 mmol) in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:1) at -40 °C. The reaction mixture was stirred for 30 min at -40 °C, and then PPh_3 (2.4×10^{-2} mmol, diluted in 0.1 mL of CH_2Cl_2) was added to quench the reaction. The resulting solution was directly analyzed by GC and GC/MS, and product yields were determined by comparison against standard curves (decane was used as an internal standard).

UV−vis spectroscopic studies were carried out as follows: in a typical reaction, a reaction solution containing an iron(III) porphyrin complex in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:1) was cooled to -40 °C in a 0.1-cm UV cell. *m*-CPBA (1.2 equiv, diluted in 50 μL of CH_3CN) was injected to the UV cell in one portion, and spectral changes were directly monitored by UV−vis spectroscopy (see Figure captions for detailed reaction conditions).

^{18}O-Labeled Water Experiments. The ^{16}O and ^{18}O compositions in cyclohexanol were determined by the relative abundance of mass peaks at $m/z = 57$ for ^{16}O and $m/z = 59$ for ^{18}O.

Stoichiometric hydroxylation of cyclohexane by $(TPFPP)^{+\bullet}Fe^{IV}{=}O$ in the presence of $H_2{}^{18}O$ was performed as follows: a mixture of cyclohexane (0.15 mmol) and $H_2{}^{18}O$ (5 μL, 95% ^{18}O enriched, Aldrich Chemical Co.) in a solvent mixture (0.2 mL) of CH_2Cl_2 and CH_3CN (1:2) was added to a reaction solution containing $(TPFPP)^{+\bullet}Fe^{IV}{=}O$, which was prepared by reacting $Fe(TPFPP)(CF_3SO_3)$ (2×10^{-3} mmol) with 3 equiv of *m*-CPBA in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:6) at -40 °C. The reaction mixture was stirred for 30 min at -40 °C and then directly analyzed by GC/MS.

Catalytic hydroxylation of cyclohexane by Fe(TPFPP)X and *m*-CPBA in the presence of $H_2{}^{18}O$ was conducted as follows: *m*-CPBA (6×10^{-3} mmol, diluted in 20 μL of CH_3CN) was added to the reaction solutions containing Fe(TPFPP)X (2×10^{-3} mmol), cyclohexane (0.15 mmol), and $H_2{}^{18}O$ (5 μL, 95% ^{18}O enriched) in a solvent mixture (0.5 mL) of CH_2Cl_2 and CH_3CN (1:6) at -40 °C. The reaction mixtures were stirred for 30 min at -40 °C, and then PPh_3 (0.06 mmol, diluted in 0.1 mL of CH_2Cl_2) was added to quench the reaction. The resulting solution was directly analyzed by GC/MS.

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