Significant Electronic Effect of Porphyrin Ligand on the Reactivities of High-Valent Iron(IV) Oxo Porphyrin Cation Radical Complexes

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High-valent iron(IV) oxo porphyrin cation radical complexes containing a series of substituents at the meso position of the porphyrin ring (i.e., electron-donating and -withdrawing substituents on phenyl groups) were prepared and used in oxygen atom transfer reactions to elucidate the electronic effect of porphyrin ligands on the reactivities of iron porphyrin complexes. The reactions that we studied with the in situ generated high-valent iron oxo porphyrins were (1) the relative reactivities of the intermediates toward oxygen atom transfer and ROOH disproportionation (ROOH = hydrogen peroxide and *tert*-butyl hydroperoxide), (2) the mechanism of heterolytic versus homolytic O−O bond cleavage of hydroperoxides, (3) the dependence of oxidizing power of the intermediates on the electronic nature of porphyrin ligands, and (4) the relative rates between oxygen atom transfer and oxygen exchange with labeled $H_2{}^{18}O$. We found from these reactivity studies that (1) a high-valent iron oxo porphyrin complex containing electron-donating substituents reacts fast with ROOH in a competitive reaction performed with a mixture of olefin and ROOH, whereas a high-valent iron oxo porphyrin containing electron-withdrawing substituents transfers its oxygen atom to olefin to give an epoxide product at a fast rate, (2) the O−O bond of hydroperoxides is homolytically cleaved by iron porphyrin complexes in aprotic solvent, (3) a high-valent iron oxo complex of electron-deficient porphyrin ligand is a more powerful oxidizing species than that of electron-rich porphyrin ligand in alkane hydroxylation reactions, and (4) the presence of electron-donating substituents on a porphyrin ligand gives a relatively high ^{18}O incorporation from labeled $H_2{}^{18}O$ into an oxygenated product when a mixture of olefin and $H_2{}^{18}O$ is added to a reaction solution containing a high-valent iron oxo intermediate, whereas only a small amount of ^{18}O incorporation is observed with iron porphyrin complexes containing electron-withdrawing substituents. These results clearly demonstrate that the electronic nature of iron porphyrin complexes is an important factor in determining the reactivities of iron porphyrin complexes in oxygen atom transfer reactions.

Introduction

Elucidation of the mechanisms of dioxygen activation and oxygen atom transfer reactions by monooxygenase enzymes and their model complexes has been the major goal of biological, bioinorganic, and oxidation chemistry in the past decade.[1] Because high-valent iron(IV) oxo porphyrin cation radical intermediates, commonly called compounds I, play a key role in a variety of oxidation reactions by heme-containing enzymes such as peroxidases, catalases, and cytochrome P-450 monooxygenases, the preparation, characterization, and reactivities of such intermediates have been intensively studied with synthetic iron(III) porphyrin complexes.[2−6] Groves et al. were the first to prepare and characterize a high-valent iron(IV) oxo porphyrin cation radical complex, $(TMP)^{+\bullet}Fe^{IV}{=}O$ (TMP = *meso*-tetramesitylporphyrin).[2] Since then, a number of high-valent iron(IV) oxo porphyrin cation radical complexes have been prepared at low temperature and well characterized with a variety of spectroscopic methods such as UV−vis, EPR, Mossbauer, EXAFS, NMR, resonance Raman, and magnetic circular dichroism.[3] Although the intermediacy of high-valent iron oxo species has been widely proposed in the catalytic oxygenation of hydrocarbons by iron porphyrin complexes, direct reactivity studies with in situ generated high-valent iron(IV) oxo porphyrin cation radical complexes have been less

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(1) (a) Sono, M.; Roach, M. P.; Coulter, E. D.; Dawson, J. H. *Chem. Rev.* **1996**, *96*, 2841−2887. (b) Traylor, T. G.; Traylor, P. S. In *Active Oxygen in Biochemistry*; Valentine, J. S., Foote, C. S., Greenberg, A., Liebman, J. F., Eds.; Blackie Academic & Professional, Chapman & Hall: London, 1995; pp 84−187. (c) Montanari, F., Casella, L., Eds. *Metalloporphyrins Catalyzed Oxidations*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1994. (d) Arasasingham, R. D.; Bruice, T. C. In *The Activation of Dioxygen and Homogeneous Catalytic Oxidation*; Barton, D. H. R., Martell, A. E., Sawyer, D. T., Eds.; Plenum Press: New York, 1993; pp 147−169. (e) Meunier, B. *Chem. Rev.* **1992**, *92*, 1411−1456. (f) Ortiz de Montellano, P. R., Ed. *Cytochrome P-450*: *Structure, Mechanism, and Biochemistry*; Plenum Press: New York, 1986.

(2) Groves, J. T.; Haushalter, R. C.; Nakamura, M.; Nemo, T. E.; Evans, B. J. *J. Am. Chem. Soc.* **1981**, *103*, 2884−2886.

(3) (a) Jones, R.; Jayaraj, K.; Gold, A.; Kirk, M. L. *Inorg. Chem.* **1998**, *37*, 2742−2843. (b) Fujii, H.; Yoshimura, T.; Kamada, H. *Inorg. Chem.* **1997**, *36*, 6142−6143. (c) Czarrnecki, K.; Nimri, S.; Gross, Z.; Proniewicz, L. M.; Kincaid, J. R. *J. Am. Chem. Soc.* **1996**, *118*, 2929−2935. (d) Fujii, H.; Yoshimura, T.; Kamada, H. *Inorg. Chem.* **1996**, *35*, 2373−2377. (e) Fujii, H. *Chem. Lett.* **1994**, 1491−1494. (f) Ochsenbein, P.; Mandon, D.; Fischer, J.; Weiss, R.; Austin, R.; Jayaraj, K.; Gold, A.; Terner, J.; Bill, E.; Muther, M.; Trautwein, A. X. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1437−1439. (g) Mandon, D.; Weiss, R.; Jayaraj, K.; Gold, A.; Terner, J.; Bill, E.; Trautwein, A. X. *Inorg. Chem.* **1992**, *31*, 4404−4409. (h) Yamaguchi, K.; Watanabe, Y.; Morishima, I. *J. Chem. Soc., Chem. Commun.* **1992**, 1721−1723.

(4) (a) Gross, Z.; Nimri, S. *J. Am. Chem. Soc.* **1995**, *117*, 8021−8022. (b) Tsuchiya, S. *J. Chem. Soc., Chem. Commun.* **1991**, 716−717. (c) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1986**, *108*, 507−508.

(5) (a) Gross, Z.; Nimri, S.; Barzilay, C. M.; Simkhovich, L. *J. Biol. Inorg. Chem.* **1997**, *2*, 492−506. (b) Gross, Z. *J. Biol. Inorg. Chem.* **1996**, *1*, 368−371. (c) Gross, Z.; Nimri, S.; Simkhovich, L. *J. Mol. Catal. A*: *Chem.* **1996**, *113*, 231−238. (d) Gross, Z.; Nimri, S. *Inorg. Chem.* **1994**, *33*, 1731−1732.

(6) Fujii, H. *J. Am. Chem. Soc.* **1993**, *115*, 4641−4648.

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investigated. Several high-valent iron oxo porphyrin complexes have been prepared and directly used in olefin epoxidations,[4−6] and we have shown recently that a high-valent iron(IV) oxo porphyrin cation radical complex with highly electron-withdrawing substituents on the porphyrin ligand is an efficient oxygenating agent in olefin epoxidations and alkane hydroxylations.[7]

It has been observed in iron porphyrin-catalyzed oxygenation reactions that the electronic nature of porphyrin ligands bound to iron is an important factor in determining the reactivities of iron porphyrin complexes and electron-withdrawing substituents on porphyrin ligands generally increase the catalytic activity of iron porphyrin complexes.[8,9] Fujii prepared a series of high-valent iron(IV) oxo porphyrin cation radical complexes and studied the effects of the electron-withdrawing peripheral substituents on the electronic structures and the reactivities of the intermediates.[6] It was concluded by the study that the reactivity of the oxygen atom of the high-valent iron oxo complexes depends on the redox potential of the porphyrin macrocycles. Also, Gross et al. recently reported an elegant result of a remarkable axial ligand effect on the reactivity of a high-valent iron(IV) oxo porphyrin cation radical in olefin epoxidation and ethylbenzene hydroxylation reactions.[5] Here, we studied the substituent effects of porphyrin ligand on the reactivities of high-valent iron oxo intermediates by preparing a variety of high-valent iron(IV) oxo porphyrin cation radical complexes containing a series of substituents at the meso position of the porphyrin ring (i.e., electron-donating and -withdrawing substituents on phenyl groups) and using these intermediates directly in oxygen atom transfer reactions. The results obtained from this study clearly indicate that the electronic nature of the porphyrin ligands drastically changes the reactivities of the high-valent iron(IV) oxo porphyrin cation radical complexes. We also discussed the mechanism of heterolytic versus homolytic O−O bond cleavages of hydroperoxides by iron(III) porphyrin complexes.

Results and Discussion

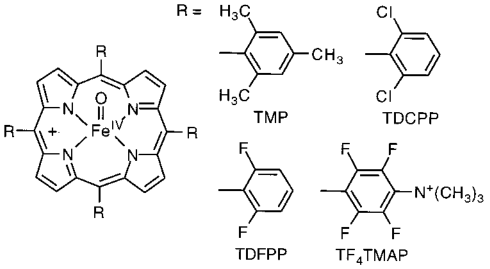
Preparation and Characterization of High-Valent Iron(IV) Oxo Porphyrin Cation Radical Complexes. The iron(III) porphyrin complexes used in this study were Fe(TMP)(CF_3SO_3) (TMP = *meso*-tetramesitylporphyrin), Fe(TDCPP)(CF_3SO_3) (TDCPP = *meso*-tetrakis(2,6-dichlorophenyl)porphyrin), Fe(TDFPP)(CF_3SO_3) (TDFPP = *meso*-tetrakis(2,6-difluorophenyl)porphyrin), and Fe(TF_4TMAP)(CF_3SO_3)$_5$ (TF_4TMAP = *meso*-tetrakis(2,3,5,6-tetrafluoro-*N*,*N*,*N*-trimethyl-4-anilinium yl)porphyrin). High-valent iron(IV) oxo porphyrin cation radicals (i.e., (TMP)$^{+\bullet}$Fe^{IV}=O, (TDCPP)$^{+\bullet}$Fe^{IV}=O, (TDFPP)$^{+\bullet}$Fe^{IV}=O, and (TF_4TMAP)$^{+\bullet}$Fe^{IV}=O; see Chart 1 for structures) were prepared by reacting the triflate iron(III) porphyrins[10] with 1.2 equiv of *m*-chloroperoxybenzoic acid (MCPBA) at low temperature and found to be stable enough for studying reactivities under the reaction conditions. The formation of the high-valent iron oxo intermediates was unequivocally identified by taking low-temperature UV−vis spectra (Table 1).[3e−h,4−6]

Table 1. UV−Vis Spectra of High-Valent Iron(IV) Oxo Porphyrin Cation Radicals[a]

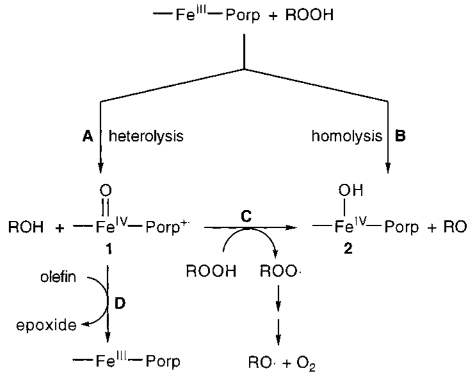
iron porphyrins	λ_{max} (nm)	ref
(TMP)$^{+\bullet}$Fe^{IV}=O	405, 661	3e
(TDCPP)$^{+\bullet}$Fe^{IV}=O	392, 679	3e
(TDFPP)$^{+\bullet}$Fe^{IV}=O[a]	390, 660	*b*
(TF_4TMAP)$^{+\bullet}$Fe^{IV}=O[a]	389, 652	*b*

[a] In CH_3CN/CH_2Cl_2 (1:1) at −45 °C. [b] This work.

Chart 1



Scheme 1



Competition between Olefin Substrate and ROOH for Reaction with High-Valent Iron(IV) Oxo Porphyrin Cation Radical Complexes. The reactions of hydroperoxides with iron porphyrins have been proposed to involve both heterolytic[11,12] and homolytic[13,14] O−O bond cleavages of hydroperoxides (Scheme 1, pathways A and B), and one of the frequently used mechanistic tools to differentiate the types of O−O bond cleavages is to investigate product distributions formed in the epoxidation of olefins by iron porphyrin complexes and hydro-

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(7) (a) Lee, Y. J.; Goh, Y. M.; Han, S.-Y.; Kim, C.; Nam, W. *Chem. Lett.* **1998**, 837−838. (b) Nam, W.; Goh, Y. M.; Lee, Y. J.; Lim, M. H.; Kim, C. *Inorg. Chem.*, submitted for publication.

(8) (a) Dolphin, D.; Traylor, T. G.; Xie, L. Y. *Acc. Chem. Res.* **1997**, *30*, 251−259 and references therein. (b) Traylor, T. G.; Miksztal, A. R. *J. Am. Chem. Soc.* **1989**, *111*, 7443−7448. (c) Nappa, M. J.; Tolman, C. A. *Inorg. Chem.* **1985**, *24*, 4711−4719.

(9) Vangberg, T.; Ghosh, A. *J. Am. Chem. Soc.* **1998**, *120*, 6227−6230 and references therein.

(10) The formation of a green intermediate was not observed when chloride iron(III) porphyrin complexes such as Fe(TDCPP)Cl and Fe(TDFPP)Cl were reacted with MCPBA at −45 °C. However, the reactions of the triflate iron(III) porphyrins with MCPBA resulted in the generation of high-valent iron(IV) oxo porphyrin cation radicals. See refs 3e and 6.

(11) (a) Traylor, T. G.; Xu, F. *J. Am. Chem. Soc.* **1987**, *109*, 6201−6202. (b) Traylor, T. G.; Ciccone, J. P. *J. Am. Chem. Soc.* **1989**, *111*, 8413−8420.

(12) (a) Traylor, T. G.; Kim, C.; Fann, W.-P.; Perrin, C. L. *Tetrahedron* **1998**, *54*, 7977−7986. (b) Traylor, T. G.; Kim, C.; Richards, J. L.; Xu, F.; Perrin, C. L. *J. Am. Chem. Soc.* **1995**, *117*, 3468−3474. (c) Traylor, T. G.; Tsuchiya, S.; Byun, Y.-S.; Kim, C. *J. Am. Chem. Soc.* **1993**, *115*, 2775−2781. (d) Traylor, T. G.; Fann, W.-P.; Bandyopadhyay, D. *J. Am. Chem. Soc.* **1989**, *111*, 8009−8010.

(13) (a) Bruice, T. C. *Acc. Chem. Res.* **1991**, *24*, 243−249. (b) Almarsson, O.; Bruice, T. C. *J. Am. Chem. Soc.* **1995**, *117*, 4533−4544. (c) Arasasingham, R. D.; Cornman, C. R.; Balch, A. L. *J. Am. Chem. Soc.* **1989**, *111*, 7800−7805.

(14) (a) Minisci, F.; Fontana, F.; Araneo, S.; Recupero, F.; Banfi, S.; Quici, S. *J. Am. Chem. Soc.* **1995**, *117*, 226−232. (b) He, G.-X.; Bruice, T. C. *J. Am. Chem. Soc.* **1991**, *113*, 2747−2753. (c) Labeque, R.; Marnett, L. J. *J. Am. Chem. Soc.* **1989**, *111*, 6621−6627. (d) Balasubramanian, P. N.; Lindsay Smith, J. R.; Davies, M. J.; Kaaret, T. W.; Bruice, T. C. *J. Am. Chem. Soc.* **1989**, *111*, 1477−1483.

peroxides.[12,14] A high yield of epoxide products with stereospecificity is the indication of the formation of a high-valent iron(IV) oxo porphyrin cation radical, **1**, via heterolytic O−O bond cleavage of hydroperoxides (Scheme 1, pathway A),[12] whereas the generation of a ferryl-oxo complex, **2**, via the homolytic O−O bond cleavage of hydroperoxides (Scheme 1, pathway B) affords a low yield of epoxide products with a loss of stereospecificity in the epoxidation of olefins.[14,15] In most cases, the reactions of iron porphyrins with hydroperoxides showed product distributions of homolytic O−O bond cleavages (i.e., a low yield of epoxide product and a nonstereoselectivity); therefore, the major pathway of the hydroperoxide reactions has been considered to be the homolytic O−O bond cleavage (Scheme 1, pathway B). However, Traylor et al. proposed that the reactions of iron porphyrin complexes with hydroperoxides initially proceed by heterolytic O−O bond cleavages (Scheme 1, pathway A) but that subsequent side reaction between **1** and ROOH takes place fast (Scheme 1, pathway C), giving the product distributions identical to the homolytic O−O bond cleavages.[11] They further suggested that the ratio of the rate of epoxidation process (Scheme 1, pathway D) to that of ROOH disproportionation (Scheme 1, pathway C) changes dramatically with the electronic nature of iron porphyrin complexes.[12b] Iron porphyrin complexes with electron-withdrawing substituents on the porphyrin ring favor oxygen atom transfer from **1** to olefin (Scheme 1, pathway D); therefore, high yields of epoxide products can be achieved with electron-deficient iron porphyrin complexes when the epoxidation of olefins is carried out with hydroperoxides such as H_2O_2 and *tert*-butyl hydroperoxide (*t*-BuOOH).[12] In contrast, iron porphyrin complexes containing electron-donating substituents have the tendency to react with ROOH fast (Scheme 1, pathway C), resulting in either no formation of epoxide product or a loss of epoxide stereochemistry.[12] Because they suggested the mechanism on the basis of kinetic studies only, we decided to examine the influence of the electronic nature of iron porphyrins on the reactivity change of high-valent iron oxo intermediates (i.e., oxygen atom transfer vs ROOH disproportionation) by performing direct reactivity studies with the in situ generated high-valent iron oxo intermediates of electron-rich and -deficient porphyrins.

We first tested the epoxidation of cyclohexene with the high-valent iron oxo porphyrins such as $(\mathrm{TMP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$, $(\mathrm{TDCPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$, $(\mathrm{TDFPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$, and $(\mathrm{TF_4TMAP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$ and found that high yields of cyclohexene oxide were formed in the reactions (Table 2, entries 1, 4, 7, and 10). We then tested the effect of ROOH (i.e., H_2O_2 and *t*-BuOOH) on the epoxidation of cyclohexene by adding a mixture of cyclohexene and ROOH to the reaction solutions containing the high-valent iron oxo porphyrins to understand the relative rates of oxygen atom transfer (Scheme 1, pathway D) and ROOH disproportionation (Scheme 1, pathway C). We found that the yield of cyclohexene oxide formed was dramatically decreased in the case of $(\mathrm{TMP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$ (Table 2, entries 2 and 3), indicating that a high-valent iron(IV) oxo containing electron-donating substituents on the porphyrin ligand reacts faster with ROOH (Scheme 1, pathway C) than with cyclohexene (Scheme 1, pathway D). In contrast, the presence of ROOH did not affect the yields of cyclohexene oxide formed in the reactions of the high-valent iron oxo porphyrin complexes containing electron-withdrawing substituents such as $(\mathrm{TDCPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$ (Table 2, entries 5 and 6), $(\mathrm{TDFPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$ (Table 2, entries 8 and 9), and $(\mathrm{TF_4TMAP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$ (Table 2, entries 11 and 12),[16] demonstrating that the rate of oxygen atom transfer from these complexes to cyclohexene (Scheme 1, pathway D) is faster than that of the reaction with ROOH (Scheme 1, pathway C).

Table 2. Reactivity Comparisons of Various High-Valent Iron(IV) Oxo Porphyrin Cation Radicals in the Epoxidation of Cyclohexene Performed in the Absence and Presence of ROOH[a,b]

Competition between Olefin and ROOH

entry	iron porphyrins	reactions	yield (%) cyclohexene oxide[c]
1	$(\mathrm{TMP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$	cyclohexene	75
2		cyclohexene + H_2O_2	21
3		cyclohexene + *t*-BuOOH	17
4	$(\mathrm{TDCPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$	cyclohexene	98
5		cyclohexene + H_2O_2	98
6		cyclohexene + *t*-BuOOH	98
7	$(\mathrm{TDFPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$	cyclohexene	92
8		cyclohexene + H_2O_2	83
9		cyclohexene + *t*-BuOOH	96
10	$(\mathrm{TF_4TMAP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$	cyclohexene	60
11		cyclohexene + H_2O_2	130[d]
12		cyclohexene + *t*-BuOOH	60

Control Reactions

entry	iron porphyrins	oxidants	yield (%) cyclohexene oxide[e]
13	$\mathrm{Fe(TMP)(CF_3SO_3)}$	H_2O_2	0
14		*t*-BuOOH	0
15	$\mathrm{Fe(TDCPP)(CF_3SO_3)}$	H_2O_2	2
16		*t*-BuOOH	0
17	$\mathrm{Fe(TDFPP)(CF_3SO_3)}$	H_2O_2	0.7
18		*t*-BuOOH	0
19	$\mathrm{Fe(TF_4TMAP)(CF_3SO_3)_5}$	H_2O_2	18
20		*t*-BuOOH	3

[a] See Experimental Section for detailed experimental procedures. [b] All reactions were run at least in duplicate, and the data represent the average of these reactions. [c] Based on the amount of MCPBA (2.4×10^{-3} mmol) used. [d] Some of cyclohexene oxide was formed by the reaction of $\mathrm{Fe(TF_4TMAP)(CF_3SO_3)_5}$ and H_2O_2. See entry 19. [e] Based on the amount of oxidants (0.01 mmol) added.

The relative reactivity of alkane was also studied with the high-valent iron oxo complexes of electron-deficient porphyrin ligands (i.e., $(\mathrm{TDCPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$, $(\mathrm{TDFPP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$, and $(\mathrm{TF_4TMAP})^{+\bullet}\mathrm{Fe^{IV}{=}O}$). We first confirmed that these high-valent iron oxo complexes yield high amounts of cyclohexanol product in the hydroxylation of cyclohexane (see Table 3). Then, we added a mixture of cyclohexane and ROOH (i.e., H_2O_2 and *t*-BuOOH) to the reaction solutions containing the high-valent iron oxo intermediates and found no formation of cyclohexanol product, demonstrating that the reactivity of ROOH is greater than that of cyclohexane toward the high-valent iron oxo complexes. Therefore, the relative reactivities of substrates for reaction with high-valent iron oxo porphyrin cation radicals can now be summarized as follows: Electron-rich iron porphyrin complex, cyclohexene < H_2O_2, *t*-BuOOH; electron-deficient iron porphyrin complex: cyclohexane < H_2O_2, *t*-BuOOH < cyclohexene.

On the basis of the results of the direct reactivity studies performed with the in situ generated high-valent iron oxo porphyrin complexes, it is now clear that the reaction pathway (Scheme 1, pathways C and D) of iron porphyrin complexes depends significantly on the electronic nature of porphyrin

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(15) Groves, J. T.; Gross, Z.; Stern, M. K. *Inorg. Chem.* **1994**, *33*, 5065−5072.

(16) We confirmed, by carrying out control reactions (see Table 2, control reactions), that the cyclohexene oxide product was formed by the reactions of high-valent iron oxo porphyrin complexes and not by the reactions of iron(III) porphyrin complexes with hydroperoxides.

Table 3. Hydroxylation of Cyclohexane by High-Valent Iron(IV) Oxo Porphyrin Cation Radicals[a,b]

	iron porphyrins (yield (%) of cyclohexanol)[c,d]			
time (min)	$(TMP)^{+\bullet}$-$Fe^{IV}{=}O$	$(TDCPP)^{+\bullet}$-$Fe^{IV}{=}O$	$(TDFPP)^{+\bullet}$-$Fe^{IV}{=}O$	$(TF_4TMAP)^{+\bullet}$-$Fe^{IV}{=}O$
5	trace[e]	2	4	32
20	trace[e]	7	10	30
60	trace[e]	27	31	34
150	trace[e]	40	34	37
300	*f*	45	32	*f*

[a] See Experimental Section for detailed experimental procedures. All reactions were run at least in duplicate, and the data represent the average of these reactions. [b] Because the hydroxylation reactions were not affected by molecular oxygen, all the reactions were performed in air. [c] Based on the amount of MCPBA (1.2×10^{-3} mmol) used. [d] A small amount (10% based on oxidant) of cyclohexene oxide was also formed as a result of the presence of cyclohexene impurity (0.2 mol %) in cyclohexane. [e] Less than 3% of cyclohexanol was formed. [f] Not determined.

ligands bound to iron. High-valent iron oxo intermediates with electron-rich porphyrins react fast with ROOH (i.e., catalase and peroxidase type of chemistry; one-electron oxidation of ROOH), whereas high-valent iron oxo intermediates with electron-deficient porphyrins have the tendency to react fast with olefin (i.e., cytochrome P-450 type of chemistry; oxygen atom transfer), as Traylor et al. suggested previously.[12b] Moreover, these results inform us that when a high-valent iron oxo porphyrin intermediate is formed as an oxygenating species in the iron porphyrin-catalyzed oxygenations of organic substrates by hydroperoxides, an electron-deficient iron porphyrin complex should be used as a catalyst to achieve a high yield of oxygenated products by avoiding the facile reaction between iron oxo intermediate and ROOH.[7b,12b,17]

Heterolytic versus Homolytic O−O Bond Cleavage of Hydroperoxides. Traylor et al. suggested that the reactions of iron porphyrin complexes with ROOH *invariably* generate high-valent iron oxo porphyrin cation radicals via heterolytic O−O bond cleavage of hydroperoxides (Scheme 1, pathway A) and that the failure to obtain efficiently catalyzed epoxidations was a result of the fast side reaction between a high-valent iron oxo intermediate and ROOH (Scheme 1, pathway C).[11,12] However, Marnett et al. and Bruice et al. presented evidence that the major pathway of hydroperoxide O−O bond cleavages is homolysis in aprotic solvents (Scheme 1, pathway B).[14b,c] It has been also reported by Ortiz de Motellano et al. that there are competitive heterolytic and homolytic O−O bond cleavages of alkyl hydroperoxides by sperm whale myoglobin and its mutants.[18] Although we have shown above that there is indeed a facile reaction between a high-valent iron oxo intermediate of electron-rich porphyrin ligand (i.e., $(TMP)^{+\bullet}Fe^{IV}{=}O$) and ROOH, this result does not support a mechanism in which hydroperoxide O−O bonds are invariably cleaved heterolytically by iron porphyrin complexes, as Traylor et al. proposed. Therefore, we decided to clarify the mechanism of the O−O bond cleavage of H_2O_2 by iron porphyrin complexes in aprotic solvent.

We have shown above that the rate of oxygen transfer from $(TDCPP)^{+\bullet}Fe^{IV}{=}O$ and $(TDFPP)^{+\bullet}Fe^{IV}{=}O$ to cyclohexene is faster than that of the reactions with ROOH, resulting in a high yield of cyclohexene oxide product (Table 2, entries 5, 6, 8, and 9). We also showed that the reactions of the iron(III) porphyrins with H_2O_2 did not yield the cyclohexene oxide product under the identical reaction conditions (Table 2, control reactions, entries 15−18). If the latter reactions generated high-valent iron oxo intermediates by heterolytic O−O bond cleavages, then the formation of cyclohexene oxide should be observed. However, this was not the case, suggesting that the reactions of the iron(III) porphyrins with hydroperoxides did not form the high-valent iron oxo intermediates. However, because the lack of formation of cyclohexene oxide might be due to the fact that H_2O_2 remained intact under the reaction conditions (e.g., low-temperature reaction), we performed control experiments with H_2O_2 to verify that oxidants were actually used up in the reactions.[19] As shown in eq 1, the

$$\mathrm{Fe(TDFPP)^+} + \text{cyclohexene} \xrightarrow[-45\ ^\circ\mathrm{C}/1\ \mathrm{h}]{\mathrm{H_2O_2}} \underset{1.5\%}{\text{cyclohexene oxide}} \tag{1}$$

epoxidation of cyclohexene by $Fe(TDFPP)^+$ and H_2O_2 gave a trace amount of cyclohexene oxide on the basis of the H_2O_2 added. We also studied the cyclohexene epoxidation by H_2O_2 in the presence of $Fe(TF_4TMAP)^{5+}$ and found a high yield of cyclohexene oxide formation (eq 2).[7a] We then added $Fe(TF_4TMAP)^{5+}$ to the reaction solution of $Fe(TDFPP)^+$ and H_2O_2 to determine whether H_2O_2 remained in the reaction solution. If H_2O_2 was still alive in the reaction solution of $Fe(TDFPP)^+$ and H_2O_2, then a good amount of cyclohexene oxide should be formed by the addition of $Fe(TF_4TMAP)^{5+}$. As shown in eq 3,

$$\mathrm{Fe(TF_4TMAP)^{5+}} + \text{cyclohexene} \xrightarrow[-45\ ^\circ\mathrm{C}/1\ \mathrm{h}]{\mathrm{H_2O_2}} \underset{45\%}{\text{cyclohexene oxide}} \tag{2}$$

$$\mathrm{Fe(TDFPP)^+} + \text{cyclohexene} \xrightarrow[-45\ ^\circ\mathrm{C}/1\ \mathrm{h}]{\mathrm{H_2O_2}} \xrightarrow[-45\ ^\circ\mathrm{C}/1\ \mathrm{h}]{\mathrm{Fe(TF_4TMAP)^{5+}}} \underset{2.5\%}{\text{cyclohexene oxide}} \tag{3}$$

the amount of cyclohexene oxide formed after adding $Fe(TF_4TMAP)^{5+}$ to the reaction solution of $Fe(TDFPP)^+$ and H_2O_2 was not increased, indicating that H_2O_2 was no longer present in the reaction solution. On the basis of these results, we are able to conclude unambiguously that the hydroperoxide O−O bond is cleaved homolytically by the iron porphyrin complex (i.e., $Fe(TDFPP)^+$ and $Fe(TDCPP)^+$) in aprotic solvent. However, it should be noted here that iron porphyrin complexes do not cleave the hydroperoxide O−O bond homolytically in all cases. Heterolytic O−O bond cleavages of H_2O_2 and *tert*-butyl hydroperoxide by iron porphyrin complexes have been well evidenced in protic solvent systems.[12,20] We also showed that a highly electron-deficient iron porphyrin complex is capable of cleaving the HO−OH bond heterolytically in the hydroxylation of alkanes by H_2O_2 in aprotic solvent.[7b] Moreover, the importance of the nature of the axial ligand bound to iron has been reported for the heterolytic and homolytic O−O bond cleavages.[14c,18] As a conclusion, there are several factors (i.e., solvent effect, electronic effect of porphyrin ligand, axial ligand effect, and general acid−base properties) that determine the types of

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(17) Robert, A.; Loock, B.; Momenteau, M.; Meunier, B. *Inorg. Chem.* **1991**, *30*, 706−711.

(18) Allentoff, A. J.; Bolton, J. L.; Wilks, A.; Thompson, J. A.; Oritz de Montellano, P. R. *J. Am. Chem. Soc.* **1992**, *114*, 9744−9749.

(19) Because the reaction of $Fe(TF_4TMAP)^{5+}$ and *t*-BuOOH did not yield the cyclohexene oxide product in the epoxidation of cyclohexene, we did not perform the identical control reactions with *t*-BuOOH to determine whether *t*-BuOOH remained in the reaction solution.

(20) Yang, S. J.; Nam, W. *Inorg. Chem.* **1998**, *37*, 606−607.

O−O bond cleavages of hydroperoxides by iron porphyrin complexes, and it is highly possible to control the hydroperoxide O−O bond cleavage from homolysis to heterolysis by varying those factors.[21]

Alkane Hydroxylation by the High-Valent Iron(IV) Oxo Porphyrin Cation Radical Complexes. We investigated the effect of the electronic nature of porphyrin ligands on the oxidizing power of high-valent iron oxo complexes by attempting the hydroxylation of cyclohexane with the in situ generated high-valent iron oxo porphyrin cation radical intermediates. As the results show in Table 3, a high-valent iron oxo intermediate containing electron-donating substituents (i.e., $(TMP)^{+\bullet}Fe^{IV}{=}O$) is inefficient to activate the C−H bond of cyclohexane to give cyclohexanol at low temperature, whereas the iron complexes of electronegatively substituted porphyrin ligands such as $(TDCPP)^{+\bullet}Fe^{IV}{=}O$, $(TDFPP)^{+\bullet}Fe^{IV}{=}O$, and $(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$ hydroxylate cyclohexane to give cyclohexanol with a good yield. Moreover, $(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$, which is the most electron-deficient iron porphyrin complex among the tested iron porphyrins, hydroxylates cyclohexane at a rapid rate. These results clearly indicate that the oxidizing power of high-valent iron oxo porphyrin complexes is sensitive to the electronic nature of porphyrin ligands and that iron complexes with electron-deficient porphyrin ligands are more powerful oxidants than those with electron-rich porphyrins in the oxygenation of organic substrates.[6,8]

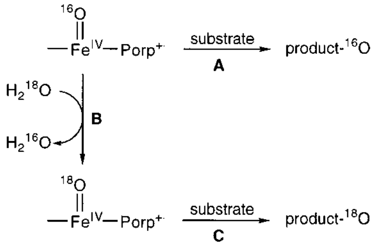
Competition between Oxygen Transfer and Oxygen Exchange. Isotopically labeled water ($H_2{}^{18}O$) experiments have been frequently conducted to obtain indirect evidence for the intermediacy of high-valent metal oxo complexes in the catalytic oxygenation reactions of organic substrates by metal complexes.[22,23] When labeled ^{18}O was found to be incorporated from $H_2{}^{18}O$ into oxygenated products, the oxygenating species was suggested to be a high-valent metal oxo complex because it has been generally accepted that the oxygen of high-valent metal oxo complexes exchanges invariably fast with labeled water.[22] However, Groves et al. and we have shown recently that the rate of oxygen exchange between high-valent iron oxo porphyrin complexes and $H_2{}^{18}O$ is actually slower than that of oxygen transfer from the intermediates to olefin substrates in the catalytic epoxidation of olefins.[24,25] In this study, we report the results of ^{18}O-labeled water experiments performed directly with the in situ generated high-valent iron oxo porphyrin complexes to understand the electronic effect of porphyrin ligand on the degree of ^{18}O exchange when the oxygenation of organic substrates by the intermediates is carried out in the presence of $H_2{}^{18}O$.

Table 4. Percentages of ^{18}O Incorporated from $H_2{}^{18}O$ into Cyclohexene Oxide Product[a,b]

	cyclohexene oxide	
iron porphyrins	^{18}O (%)	yield (%)[c]
$(TMP)^{+\bullet}Fe^{IV}{=}O$	32 ± 5	70
$(TDCPP)^{+\bullet}Fe^{IV}{=}O$	15 ± 3	82
$(TDFPP)^{+\bullet}Fe^{IV}{=}O$	4 ± 1	70
$(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$	2 ± 1	58

[a] See Experimental Section for detailed experimental procedures. [b] All reactions were run at least in duplicate, and the data represent the average of these reactions. [c] Based on the amount of MCPBA (1.2×10^{-3} mmol) added.

Scheme 2



As shown in Table 4, the amount of ^{18}O incorporated into the oxide product depends significantly on the electronic nature of the porphyrin ligands bound to iron, and the general trend appears to be that the presence of electron-donating groups on the porphyrin resulted in high ^{18}O incorporation, whereas electron-withdrawing groups gave no or small amounts of ^{18}O incorporation into the oxide product. Because it has been shown previously[24,25] that the reaction of the intermediates with olefin (Scheme 2, pathway A) is competing with isotopically labeled water that leads to oxygen exchange (Scheme 2, pathway B), two possible explanations may be considered. One is that the rate of the oxygen transfer from the intermediate to cyclohexene (Scheme 2, pathway A) increases when electron-withdrawing groups are present on the porphyrin ligand, resulting in giving no or small amounts of ^{18}O incorporation into the oxide product. Another explanation is that the rate of oxygen exchange with labeled water (Scheme 2, pathway B) is decreased when electron-withdrawing groups are present on the porphyrin ligand. We prefer the former explanation on the basis of the results that show that high-valent iron oxo intermediates of electronegatively substituted porphyrin ligands transfer their oxygen atoms in a fast rate, as shown in the cyclohexane hydroxylation reactions. Nonetheless, we believe that there should be some (or significant) electronic effect of iron porphyrin complexes on the rate of oxygen exchange with labeled water, but this phenomenon cannot be interpreted with the present results at this moment.

We also measured the extent of ^{18}O incorporation into the alcohol products in the hydroxylation of various alkanes by $(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$. Interestingly, the extent of ^{18}O incorporation from $H_2{}^{18}O$ into the products was found to depend on the C−H bond energies of alkanes (Table 5). As the C−H bond strength increases, the amount of ^{18}O incorporated into the alcohol product increases. An explanation for this result is that the oxygen transfer from the intermediate to alkane (Scheme 2, pathway A) competes with the oxygen exchange between the intermediate and labeled water (Scheme 2, pathway B) and that an alkane with a strong C−H bond gives more time for the high-valent iron oxo porphyrin complex to exchange its oxygen with labeled water, resulting in a high level of ^{18}O incorporation into the alcohol product (e.g., 74% ^{18}O incorporation with C_6D_{12}).[25]

As a conclusion of the ^{18}O-labeled water experiments, high-valent iron oxo porphyrin complexes exchange their oxygen atoms with labeled water, and the extent of ^{18}O incorporation depends on the electronic nature of iron porphyrin complexes.

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(21) Nam, W.; Choi, H. J.; Lee, H. J.; Han, H. J.; Kim, C., unpublished results.

(22) Nam, W.; Valentine, J. S. *J. Am. Chem. Soc.* **1993**, *115*, 1772−1778 and references therein.

(23) (a) Bernadou, J.; Meunier, B. *Chem. Commun.* **1998**, 2167−2173. (b) Balahura, R. J.; Sorokin, A.; Bernadou, J.; Meunier, B. *Inorg. Chem.* **1997**, *36*, 3488−3492. (c) Song, R.; Sorokin, A.; Bernadou, J.; Meunier, B. *J. Org. Chem.* **1997**, *62*, 673−678. (d) Pitie, M.; Bernadou, J.; Meunier, B. *J. Am. Chem. Soc.* **1995**, *117*, 2935−2936. (e) Bernadou, J.; Fabiano, A.-S.; Robert, A.; Meunier, B. *J. Am. Chem. Soc.* **1994**, *116*, 9375−9376.

(24) Groves, J. T.; Lee, J.; Marla, S. S. *J. Am. Chem. Soc.* **1997**, *119*, 6269−6273.

(25) Lee, K. A.; Nam, W. *J. Am. Chem. Soc.* **1997**, *119*, 1916−1922.

Table 5. Percentages of ^{18}O Incorporated from $H_2{}^{18}O$ into Alcohol Products in the Hydroxylation of Alkanes by $(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$[a,b]

substrate	product[c]	^{18}O (%)	C−H bond energy (kcal/mol)
cis-1,2-dimethylcyclohexane	*cis*-1,2-dimethylcyclohexanol	34 ± 3	∼96[d]
cyclooctane	cyclooctanol	39 ± 3	95.7[e]
cyclohexane	cyclohexanol	55 ± 4	99.3[e]
hexane	2-hexanol	63 ± 5	99.9[f]
	3-hexanol	65 ± 5	99.9[f]
cyclohexane-d_{12}	cyclohexanol-d_{12}	74 ± 5	100.6[g]

[a] See Experimental Section for detailed experimental procedures. [b] All reactions were run at least in duplicate, and the data represent the average of these reactions. [c] See ref 7b for the yields of alcohol products formed in the hydroxylation of alkanes by $(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$. [d] The *tertiary* C−H bond energy of $(CH_3)_3C-H$ is roughly equal to the cyclooctane C−H bond energy. See ref 27. [e] Data obtained from ref 27. [f] Secondary C−H bond energy of $(CH_3)_2CH_2$. See ref 28. [g] The C−D bond energy of C_6D_{12} is 1.3 kcal/mol higher than the C−H bond energy of C_6H_{12}.

As Groves et al. and we have suggested previously,[24,25] the intermediacy of high-valent iron oxo complexes can be anticipated with confidence when ^{18}O incorporation from $H_2{}^{18}O$ into oxygenated products is observed in the catalytic oxygenation of hydrocarbons by oxidants such as H_2O_2 and peroxyacids.[26] Moreover, on the basis of the result of the cyclohexene epoxidation by $(TF_4TMAP)^{+\bullet}Fe^{IV}{=}O$ carried out in the presence of $H_2{}^{18}O$ (see Table 4), we cannot exclude the possibility of a high-valent iron oxo intermediate when no ^{18}O incorporation is observed in $H_2{}^{18}O$ experiments, because some metal oxo complexes may transfer oxygen atoms to organic substrates too fast to exchange their oxygen with labeled water.

Conclusion

We have provided evidence, by using in situ generated high-valent iron oxo complexes of electron-rich and -deficient porphyrin ligands directly in oxygen atom transfer reactions, that the electronic nature of porphyrin ligands bound to iron is an important factor in determining the reactivities of iron porphyrin complexes. These results inform us that we can select iron porphyrin catalysts to obtain desired reaction pathways. For example, when hydroperoxides are used as oxidant, a highly electron-deficient iron porphyrin complex is an appropriate catalyst to increase the yield of oxygenated products (i.e., cytochrome P-450 type of chemistry). In contrast, an electron-rich iron porphyrin complex would be a better catalyst to increase the rate of ROOH disproportionation (i.e., catalase and peroxidase type of chemistry). Another example is to use an electron-deficient iron porphyrin complex as a catalyst in oxidation reactions such as the remarkably difficult hydroxylation of unactivated C−H bonds of alkanes,[8] because the intermediate of the electron-deficient iron porphyrin complex is a more efficient oxidant than that of an electron-rich iron porphyrin.

The present results also provide some useful information relevant to biological systems. Heme enzymes such as peroxidase, catalase, and cytochrome P-450 monooxygenase have a common prosthetic group, protoporphyrin IX, but different axial ligands. It has been emphasized recently that the role of the proximal axial ligand bound to iron is to regulate the reactivities of compounds I of heme-based enzymes (e.g., oxygen atom transfer with cysteinate axial ligand in cytochrome P-450 and one-electron oxidation of substrate with histidine axial ligand in peroxidase) by influencing the electrophilicity of the compounds I and/or by influencing the energy barrier for oxygen atom transfer pathways.[5b,29,30] As the heme-based enzymes control their specific functions with proximal axial ligands, the reactivities of high-valent iron oxo porphyrin intermediates can be regulated by the electronic nature of the porphyrin ligand in biomimetic model systems.

Experimental Section

Materials. Acetonitrile (anhydrous) and dichloromethane (anhydrous) were obtained from Aldrich Chemical Co. and were used without further purification. All chemicals obtained from Aldrich were the best available purity and were used without further purification unless otherwise indicated. $H_2{}^{18}O$ (95% ^{18}O enrichment) and MCPBA (65%) were purchased from Aldrich. Purity of MCPBA was determined by iodometric analysis.[31] H_2O_2 (30% aqueous) and *t*-BuOOH (70% aqueous) were purchased from Fluka and Sigma, respectively. $Fe(TF_4TMAP)(CF_3SO_3)_5$,[32] Fe(TDFPP)Cl,[33] Fe(TDCPP)Cl,[3g] and Fe(TMP)Cl[3g] were obtained from Mid-Century Chemicals. $Fe(TDFPP)(CF_3SO_3)$, $Fe(TDCPP)(CF_3SO_3)$, and $Fe(TMP)(CF_3SO_3)$ were prepared by stirring equimolar amounts of the chloride iron(III) porphyrins with $Ag(CF_3SO_3)$ and filtering through a 0.45-μM filter. The resulting solution was used immediately for further studies.

Instrumentation. Product analyses were performed on either a Hewlett-Packard 5890 II Plus gas chromatograph interfaced with a Hewlett-Packard 5989B mass spectrometer or a Donam Systems 6200 gas chromatograph equipped with a FID detector using a 30-m capillary column (Hewlett-Packard, HP-1, HP-5, and Ultra 2). UV−vis spectra were recorded on a Hewlett-Packard 8453 spectrophotometer equipped with *Optostat*^{DN} variable-temperature liquid-nitrogen cryostat (Oxford Instruments).

Preparation of High-Valent Iron(IV) Oxo Porphyrin Cation Radicals. In general, the reactions of triflate iron(III) porphyrin complexes with 1.2 equiv of MCPBA in a solvent mixture of CH_3CN/CH_2Cl_2 (1:1) at −45 °C produced green solutions. The formation and stability of the high-valent iron oxo intermediates were confirmed by taking low-temperature UV−vis spectra of the green solutions. The spectra showed new absorption bands around 550−700 nm and a Soret band with decreased intensity, characteristic of porphyrin cation radical complexes.

Competition between Organic Substrates and ROOH Studied with High-Valent Iron Oxo Porphyrins. Substrate [cyclohexene (0.2 mmol) or a mixture of cyclohexene (0.2 mmol) and ROOH (ROOH = H_2O_2 or *t*-BuOOH, 0.01 mmol), dissolved in a solvent mixture (0.2 mL) of CH_3CN/CH_2Cl_2 (1:1)] was added to a reaction solution containing a high-valent iron oxo porphyrin (2.0×10^{-3} mmol), prepared in situ by reacting with 1.2 equiv of MCPBA (2.4×10^{-3} mmol) in a solvent mixture (1.0 mL) of CH_3CN/CH_2Cl_2 (1:1) at −45 °C. The reaction mixture was stirred for 10 min, and then PPh_3 (0.2

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(26) These oxidants do not exchange their oxygen atoms with labeled water, but iodosylbenzene exchanges its oxygen with labeled water prior to the formation of the high-valent metal oxo intermediate; see ref 22.

(27) (a) Mayer, J. M. *Acc. Chem. Res.* **1998**, *31*, 441−450. (b) Cook, G. K.; Mayer, J. M. *J. Am. Chem. Soc.* **1995**, *117*, 7139−7156.

(28) Castelhano, A. L.; Griller, D. *J. Am. Chem. Soc.* **1982**, *104*, 3655−3659.

(29) (a) Poulos, T. L. *J. Biol. Inorg. Chem.* **1996**, *1*, 356−359. (b) Goodin, D. B. *J. Biol. Inorg. Chem.* **1996**, *1*, 360−363. (c) Rietjens, I. M. C. M.; Osman, A. M.; Veeger, C.; Zakharieva, O.; Antony, J.; Grodzicki, M.; Trautwein, A. X. *J. Biol. Inorg. Chem.* **1996**, *1*, 372−376. (d) Weiss, R.; Mandon, D.; Wolter, T.; Trautwein, A. X.; Muther, M.; Bill, E.; Gold, A.; Jayaraj, K.; Terner, J. *J. Biol. Inorg. Chem.* **1996**, *1*, 377−383.

(30) Another important role of the proximal axial ligand that has been suggested is to assist O−O bond heterolysis by the "push" effect: (a) Yamaguchi, K. Y.; Watanabe, Y.; Morishima, I. *J. Am. Chem. Soc.* **1993**, *115*, 4058−4065 and references therein. (b) Dawson, J. H. *Science* **1988**, *240*, 433−439.

(31) Mair, R. D.; Graupner, A. J. *Anal. Chem.* **1964**, *36*, 194−204.

(32) La, T.; Miskelly, G. M.; Bau, R. *Inorg. Chem.* **1997**, *36*, 5321−5328.

(33) Nanthakumar, A.; Goff, H. M. *J. Am. Chem. Soc.* **1990**, *112*, 4047−4049.

mmol, diluted in 0.2 mL of CH_2Cl_2) was added to quench the reaction. The reaction solution was warmed to room temperature and analyzed by GC with known authentic samples. For the relative reactivity of cyclohexane, all reaction procedures were the same as described above except that cyclohexane (0.2 mmol) was used as a substrate.

Control reactions were performed by adding a solution of ROOH (0.01 mmol in 0.2 mL of CH_3CN/CH_2Cl_2 (1:1)) to a reaction solution containing a triflate iron(III) porphyrin complex (0.002 mmol) and cyclohexene (0.2 mmol) in a solvent mixture (1.0 mL) of CH_3CN/CH_2Cl_2 (1:1) at −45 °C. The reaction mixture was stirred for 10 min, and then PPh_3 (0.2 mmol diluted in 0.2 mL of CH_2Cl_2) was added. Subsequently, the reaction solution was warmed to room temperature and analyzed by GC.

Epoxidation of Cyclohexene by H_2O_2 in the Presence of Iron(III) Porphyrin Complexes for the O−O Bond Cleavage Experiments. H_2O_2 (0.01 mmol, diluted in 0.2 mL of CH_3CN/CH_2Cl_2 (1:1)) was added to a reaction solution containing an iron porphyrin complex (2.0×10^{-3} mmol, Fe(TDFPP)(CF_3SO_3) or Fe(TF_4TMAP)(CF_3SO_3)$_5$) and cyclohexene (0.2 mmol) in a solvent mixture (1.0 mL) of CH_3CN/CH_2Cl_2 (1:1) at −45 °C. The reaction solution was stirred for 1 h at −45 °C, and PPh_3 was added (0.2 mmol diluted in 0.2 mL of CH_2Cl_2) to quench the reaction. The reaction solution was warmed to room temperature and analyzed by GC.

For the reaction of the addition of Fe(TF_4TMAP)$^{5+}$ to the reaction solution of Fe(TDFPP)$^+$ and H_2O_2, H_2O_2 (0.01 mmol, diluted in 0.2 mL of CH_3CN) was added to a reaction solution containing Fe(TDFPP)$^+$ (2.0×10^{-3} mmol) and cyclohexene (0.2 mmol) in a solvent mixture (1.0 mL) of CH_3CN/CH_2Cl_2 (1:1) at −45 °C. Then, the reaction solution was stirred for 1 h at −45 °C. Subsequently, Fe(TF_4TMAP)$^{5+}$ (2.0×10^{-3} mmol, diluted in 0.2 mL of CH_3CN/CH_2Cl_2 (1:1)) was added to the reaction solution, and the resulting solution was stirred for 1 h. The mixture was then assayed for the formation of cyclohexene oxide by GC.

Hydroxylation of Cyclohexane with Various High-Valent Iron(IV) Oxo Porphyrin Cation Radicals. Cyclohexane (0.1 mmol in 0.2 mL of CH_3CN/CH_2Cl_2 (1:1)) was added to a reaction solution containing a high-valent iron oxo porphyrin (1.0×10^{-3} mmol) in a solvent mixture (0.5 mL) of CH_3CN/CH_2Cl_2 (1:1) at −45 °C. After the reaction solution was stirred for the given time interval, PPh_3 (0.01 mmol diluted in 0.1 mL of CH_2Cl_2) was added to quench the reaction, and the resulting solution was analyzed by GC.

Epoxidation of Cyclohexene by High-Valent Iron(IV) Oxo Porphyrin Cation Radicals in the Presence of Labeled $H_2{}^{18}O$. A mixture of cyclohexene (0.01 mmol) and $H_2{}^{18}O$ (5 μL, 0.26 mmol, 95% ^{18}O enriched) in a solvent mixture (0.2 mL) of CH_3CN/CH_2Cl_2 (4:1) was added to a solution (1.0 mL of CH_3CN/CH_2Cl_2 (4:1)) containing a high-valent iron oxo porphyrin complex (1.0×10^{-3} mmol) prepared in situ by reacting a triflate iron(III) porphyrin complex with 1.2 equiv of MCPBA at −45 °C. The reaction mixture was stirred for 20 min, and then PPh_3 (0.01 mmol diluted in 0.1 mL of CH_2Cl_2) was added to the reaction solution. The reaction solution was analyzed by GC−MS. ^{16}O and ^{18}O compositions in cyclohexene oxide were determined by the relative abundances of mass peaks at $m/z = 83$ for ^{16}O and 85 for ^{18}O.

Hydroxylation of Alkanes by (TF_4TMAP)$^{+\bullet}$Fe^{IV}=O in the Presence of Labeled $H_2{}^{18}O$. A mixture of alkane (0.2 mmol) and $H_2{}^{18}O$ (5 μL, 0.26 mmol, 95% ^{18}O enriched) in 0.2 mL of CH_3CN/CH_2Cl_2 (3:1) was added to a solution (CH_3CN, 0.5 mL) containing (TF_4TMAP)$^{+\bullet}$-Fe^{IV}=O (2.0×10^{-3} mmol) prepared in situ by reacting Fe(TF_4TMAP)-(CF_3SO_3)$_5$ with 1.2 equiv of MCPBA at −40 °C. The reaction mixture was stirred for 10 min at −40 °C and analyzed directly by GC−MS. ^{16}O and ^{18}O compositions in alcohol products were analyzed by the relative abundances of the following mass peaks: $m/z = 71$ (^{16}O) and 73 (^{18}O), 85 (^{16}O) and 87 (^{18}O) for *cis*-1,2-dimethylcyclohexanol; $m/z = 57$ (^{16}O) and 59 (^{18}O) for cyclooctanol; $m/z = 57$ (^{16}O) and 59 (^{18}O) for cyclohexanol; $m/z = 45$ (^{16}O) and 47 (^{18}O), 87 (^{16}O) and 89 (^{18}O) for 2-hexanol; $m/z = 59$ (^{16}O) and 61 (^{18}O), 73 (^{16}O) and 75 (^{18}O) for 3-hexanol; $m/z = 61$ (^{16}O) and 63 (^{18}O) for cyclohexanol-d_{12}.

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