Acylperoxo−Iron(III) Porphyrin Complexes: A New Entry of Potent Oxidants for the Alkene Epoxidation

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Received August 8, 1994. Revised Manuscript Received February 7, 1995[⊗]

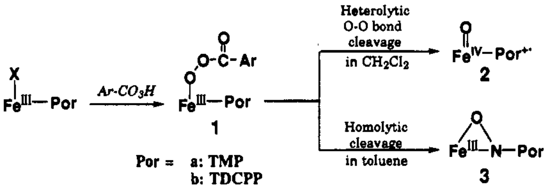
Abstract: Competitive epoxidation of norbornylene and α-methylstyrene by peracids in the presence of iron porphyrins has been carried out in methylene chloride and toluene at −78 °C. When (TMP)Fe^{III}(RCO$_2$) (TMP = 5,10,15,20-tetramesitylporphyrin) is used as a catalyst *in methylene chloride*, selectivity of norbornylene oxide over α-methylstyrene oxide is almost identical even though a variety of peracids are used, since O=Fe^{IV}TMP π-cation radical **2a** is the common oxidant in the reactions. On the other hand, the selectivity in the epoxidations catalyzed by (TDCPP)Fe^{III}(X) (TDCPP: 5,10,15,20-tetrakis(2,6-dichlorophenyl)porphyrin) is found to be dependent on the structure of peracids. The latter type of the results is also obtained for the reactions catalyzed both by (TMP)Fe^{III}(X) and by (TDCPP)Fe^{III}(X) *in toluene*. The dependence of the selectivity in the epoxidation on the structure of peracids is attributed to the alteration of the oxidant from **2** to peracid−Fe(III) complexes **1**. The direct involvement of **1** in the epoxidation has been further confirmed by spectroscopic studies of the reactions. Under the catalytic epoxidation conditions at low temperature, the participation of **1** and **2** as the active species is controlled either by electronic structure of iron porphyrin complexes (push−pull effect) or by alteration of the solvent.

Introduction

In biological oxidations by cytochromes P-450, peroxidases, and catalases, high valent oxo−iron porphyrin complexes, formally two-electron oxidized from the ferric state, have been widely proposed as the reactive intermediates.[1] These enzymes are believed to react with hydrogen peroxide (or O$_2$, 2e$^-$, and 2H$^+$) to form hydroperoxo−iron(III) porphyrin complexes, and the following heterolytic O−O bond cleavage affords oxo-ferryl porphyrin π-cation radicals **2** or their equivalent. In fact, **2** is called "compound I" and is observable in many peroxidase and catalase reactions.[1d,2]

Synthetic iron porphyrins have been widely used as model catalysts for oxidation of olefins and saturated hydrocarbons to understand the details of the enzymatic oxidation reaction mechanisms.[1c,3] While a wide variety of biological oxidation reactions catalyzed by heme enzymes are mimicked by these heme models,[1c,3] the active species responsible for these reactions are still obscure in many instances. Among them, extensive mechanistic studies have been made for the reactions of ferric porphyrins with peracids. For example, in the reaction of 5,10,15,20-tetramesitylporphinatoiron(III) [(TMP)Fe^{III}(X), X = HO$^-$ or RCO$_2^-$] and peracid *in methylene chloride* at low temperature, the formation of an acylperoxoiron(III) porphyrin complex [(TMP)Fe^{III}(RCO$_3$)**1a**][4] followed by the heterolytic O−O bond cleavage to give the oxo-ferryl porphyrin π-cation radical [(TMP$^{+\bullet}$)Fe^{IV}=O **2a**] has been directly observed[5,6ac] (Scheme 1). On the other hand, (TMP)Fe^{III} *N*-oxide **3a** is formed in the same reaction *in toluene* due to the homolytic O−O bond cleavage of **1a**.[6bc,7] While recent studies on the reactivity of **2** and **3** have provided evidence that **2** is the only species able to oxidize alkanes and alkenes,[6c,7] we have suggested that peracid−iron(III) porphyrin complexes **1** are also potent reactive species for the epoxidation on the basis of competitive epoxidation of norbornylene and α-methylstyrene by *m*CPBA in the presence of a catalytic amount of iron porphyrin in methylene chloride and toluene.[8]

Scheme 1



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[⊗] Abstract published in *Advance ACS Abstracts*, June 15, 1995.

(1) (a) White, R. E.; Coon, M. J. *Annu. Rev. Biochem.* **1980**, *50*, 315−356. (b) Ortiz de Montellano, P. R. In *Cytochrome P-450*; Ortiz de Montellano, P. R., Ed.; Plenum Press: New York, 1986; pp 217−271. (c) Watanabe, Y.; Groves, J. T. In *The Enzymes*; Sigman, D. S., Ed.; Academic Press: San Diego, 1992; Vol. 20, pp 405−452. (d) *Peroxidases in Chemistry and Biology*; Everse, J., Everse, K. E., Grisham, M. B., Eds.; CRC Press: Boca Raton, FL, 1991; Vols. 1 and 2.

(2) (a) Dolphin, D.; Forman, A.; Borg, D. C.; Fajer, J.; Felton, R. H. *Proc. Natl. Acad. Sci. U.S.A.* **1971**, *68*, 614−618. (b) DiNello, R. K.; Dolphin, D. H. *J. Biol. Chem.* **1981**, *256*, 6903−6912. (c) La Mar, G. N.; de Ropp, J. S.; Smith, K. M.; Langry, K. C. *J. Biol. Chem.* **1981**, *256*, 237−243. (d) Schultz, C. E.; Devanry, P. W.; Winkler, H.; Debrunner, P. G.; Doan, N.; Chiang, R.; Rutter, R.; Hager, L. P. *FEBS Lett.* **1979**, *103*, 102−105. (e) Hashimoto, S.; Mizutani, Y.; Tatsuno, Y.; Kitagawa, T. *J. Am. Chem. Soc.* **1991**, *113*, 6542−6549. (f) Schultz, C. E.; Rutter, R.; Saga, J. T.; Debrunner, P. G.; Hager, L. P. *Biochemistry* **1984**, *23*, 4743−4754.

(3) (a) Groves, J. T.; Nemo, T. E.; Myers, R. S. *J. Am. Chem. Soc.* **1979**, *101*, 1032−1033. (b) Watanabe Y.; Ishimura, Y. *J. Am. Chem. Soc.* **1989**, *111*, 401−411 and 8047−8049. (c) Ostovic, D.; Bruice, T. C. *Acc. Chem. Res.* **1992**, *25*, 314−320. (d) Meunier, B. *Chem. Rev.* **1992**, *92*, 1411−1456. (e) Mansuy, D. In *Bioorganic Catalysis*; Reedijk, J., Ed.; Marcel Dekker: New York, 1993; pp 395−424.

(4) In order to specify the porphyrin ligands used in this study, **a** and **b** are used to represent TMP and TDCPP, respectively.

(5) (a) Groves, J. T.; Haushalter, R. C.; Nakamura, M.; Nemo, T. E.; Evans, B. J. *J. Am. Chem. Soc.* **1981**, *103*, 2884−2886. (b) Penner-Hahn, J. E.; Eble, K. S.; McMurry, T. J.; Renner, M.; Balch, A. L.; Groves, J. T.; Dawson, J. H.; Hodgson, K. O. *J. Am. Chem. Soc.* **1986**, *108*, 7819−7825.

(6) (a) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1986**, *108*, 7834−7836. (b) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1986**, *108*, 7836−7837. (c) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1988**, *110*, 8443−8452.

(7) Tsurumaki, H.; Watanabe, Y.; Morishima, I. *J. Am. Chem. Soc.* **1993**, *115*, 11784−11788.

In this paper, we discuss the reactions of (TMP)Fe^{III}(X) and 5,10,15,20-tetrakis(2,6-dichlorophenyl)porphinatoiron(III) [(TDCPP)Fe^{III}(X)] with a series of peracids both in methylene chloride and in toluene to demonstrate the direct participation of the peracid–iron(III) porphyrin complexes in epoxidation reactions.

Experimental Section

Materials. CH_2Cl_2 was distilled from CaH_2 before use. Toluene was treated with H_2SO_4, distilled from CaH_2, and stored under Ar atmosphere with molecular sieves (4A).[9] *m*-Chloroperoxybenzoic acid (*m*CPBA) was purchased from Tokyo Kasei. Other peroxycarboxylic acids were prepared by a literature method.[10] All peroxycarboxylic acids were purified by washing either with phosphate buffer or with sodium bicarbonate saturated aqueous solution. Pentafluoroiodosylbenzene (F_5PhIO) was prepared as described before.[11] Iodosylbenzene (PhIO) was purchased from Tokyo Kasei and used without further purification. $TMPH_2$ (5,10,15,20-tetramesitylporphyrin) and $TDCPPH_2$ [5,10,15,20-tetrakis(2,6-dichlorophenyl)porphyrin] were prepared by a method reported.[12] Iron was inserted into the porphyrins to form iron(III) porphyrin chloride complexes, (Por)Fe^{III}(Cl), by literature procedures.[13] Hydroxo–iron(III) complexes, (Por)Fe^{III}(OH), were prepared as described.[14] Reaction of (Por)Fe^{III}(OH) and an excess amount of *m*-chlorobenzoic acid in benzene or toluene was carried out at room temperature for the preparation of (Por)Fe^{III}(*m*CBA) (*m*CBA: *m*-chlorobenzoate). After the filtration of unsolved *m*-chlorobenzoic acid, (Por)Fe^{III}(*m*CBA) was purified by SiO_2 column chromatography. Norbornylene and α-methylstyrene were purchased from Tokyo Kasei and used without further purification.

Instrumental. Absorption spectra were recorded on a Hitachi 330 spectrophotometer. Low-temperature absorption spectra were obtained by using a DN 1704 variable-temperature liquid-nitrogen cryostat (Oxford Instruments). GLC analyses were performed on a Shimadzu GC-14A with a Shimadzu CBP1 (25m) capillary column. EPR spectra were obtained with a JEOL PE-2X spectrometer.

UV–vis Measurements. In a typical reaction, a methylene chloride solution of (Por)Fe^{III}(OH) (1.0×10^{-5} M) was cooled to −80 °C in a UV-cuvette. Peroxycarboxylic acid (2–3 equiv) was introduced to the cuvette, and spectral changes according to the reaction were directly monitored by UV–vis spectroscopy.

Iodometric Titration. A methylene chloride solution of (TDCPP)Fe^{III}(*m*CBA) (4 mL, 1.5×10^{-5} M) was precooled to −78 °C in a dry ice–acetone bath, and 3 equiv of *m*CPBA was added to the resulting solution. Time dependent consumption of the oxidizing equivalent either in the absence or presence of olefin (10 equiv) was determined by the introduction of an excess amount of tetra-*n*-butylammonium iodide (*n*Bu_4NI). The formation of I_3^- was determined by UV–vis spectroscopy at 363 nm.

Competitive Epoxidation. A methylene chloride solution (1 mL) containing a 1:1 mixture of norbornylene and α-methylstyrene (300 μmol each) was cooled to −78 °C in the presence of a catalytic amount of either (TDCPP)Fe^{III}(*m*CBA) or (TMP)Fe^{III}(*m*CBA) (1 μmol). The oxidation was initiated by adding peroxycarboxylic acid (30 μmol) and took place for 3 h at −78 °C under Ar atmosphere. The reaction was terminated by adding *n*Bu_4NI to prevent possible oxidation of olefins at higher temperature. The reaction products were determined by GLC. Naphthalene was used as an internal standard. The same reactions also took place in toluene at −78 °C. Similar competitive oxidations by PhIO and F_5PhIO (30 μmol) in the presence of (Por)Fe^{III}(Cl) were examined in CH_2Cl_2 at −40 °C.

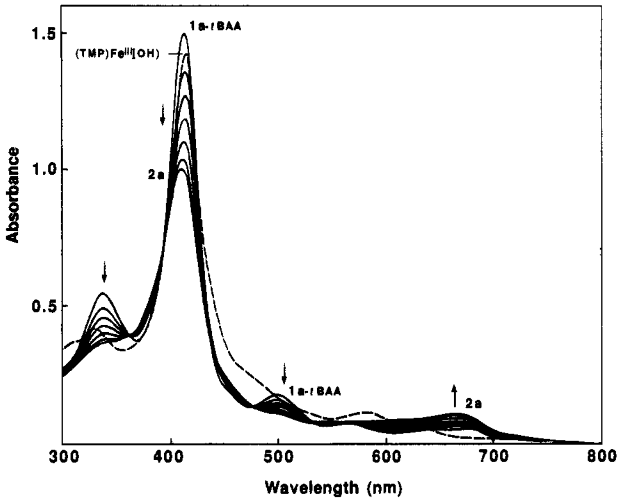

Figure 1. UV–vis spectral changes in the reaction of 1.0×10^{-5} M of (TMP)Fe^{III}(OH) (− − −) and *t*-$BuCH_2CO_3H$ (*t*BPAA) in CH_2Cl_2 at −80 °C. The spectrum of **1a** was recorded immediate after the addition of *t*BPAA, and the following spectral changes were recorded at 30 min intervals.

Preparation of EPR Sample of (TMP)Fe^{III}(*m*CPBA), 1a-*m*CPBA. A toluene solution of (TMP)Fe^{III}(OH) (1 mM) in EPR tubes was cooled to −78 °C. After the addition of 2 equiv of *m*CPBA, the resulting solution was immediately frozen by liquid N_2 for EPR measurement.

Preparation of (TDCPP$^{\bullet+}$)Fe^{IV}=O, 2b. A methylene chloride solution of (TDCPP)Fe^{III}(OH) (2.2×10^{-5} M) in the presence of 9 equiv of *m*-chlorobenzoic acid in UV-cuvette was cooled to −80 − −90 °C. *p*-Nitroperoxybenzoic acid (*p*NPBA, 1.8 equiv) was added to the resulting solution, and the reaction was directly observed by UV–vis spectroscopy.

Results

Reactions of Peracids with (TMP)Fe^{III}(OH) and (TDCPP)Fe^{III}(OH) in Methylene Chloride. Reactions of (TMP)Fe^{III}(OH) and peracids in methylene chloride at −80 °C have been examined by UV–vis spectroscopy. For example, the reaction of (TMP)Fe^{III}(OH) and *t*-$BuCH_2CO_3H$ (*t*BPAA) readily formed (TMP)Fe^{III}(*t*BPAA) **1a-*t*BPAA** and the following isosbestic conversion of **1a-*t*BPAA** gave (TMP$^{\bullet+}$)Fe^{IV}=O **2a**. The spectral changes according to these sequential processes are shown in Figure 1. Very similar results were also observed when *t*BPAA was replaced by the other peroxyacids employed in this study. On the other hand, when the reactions of (TDCPP)Fe^{III}(OH) with peroxyacids were performed under the same conditions, different results were obtained. Upon addition of *m*CPBA to (TDCPP)Fe^{III}(OH) at −80 °C, instantaneous conversion of the UV–vis spectrum to that for typical ferric high spin was observed (Figure 2). Though the (TDCPP)Fe^{III}(*m*CPBA) **1b-*m*CPBA** is the most likely description of the product, the corresponding (TDCPP)Fe^{III}(*m*CBA) could be an alternative candidate, since these two complexes are known to exhibit similar UV–vis spectra.[6c] Fortunately, these two complexes can be readily distinguished by iodometric titration of the reaction product. The production of **1b-*m*CPBA** implies the presence of oxidizing equivalent of the peracid used, while formation of the carboxylic acid complex indicates the loss of the oxidizing equivalent, since the carboxylic acid complex is expected to be the reduced product of **1b-*m*CPBA** as shown in Scheme 2. Especially, that polyhalogenated iron–porphyrin complexes are known as very efficient oxidation catalysts

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(8) Watanabe, Y.; Yamaguchi, K.; Morishima, I.; Takehira, K.; Shimizu, M.; Hayakawa, T.; Orita, H. *Inorg. Chem.* **1991**, *30*, 2581–2582.

(9) Treatment of toluene with H_2SO_4 is highly recommended to eliminate impurities.

(10) Silbert, L. S.; Siegel, E.; Swern, D. *J. Org. Chem.* **1962**, *27*, 1336–1342.

(11) Scmeiser, M.; Dahman, K.; Sartori, P. *Chem. Ber.* **1967**, *100*, 1633–1637.

(12) Lindsey, L. S.; Wagner, R. W. *J. Org. Chem.* **1989**, *54*, 828–836.

(13) Kobayashi, H.; Higuchi, T.; Kaizu, Y.; Osada, H.; Aoki, M. *Bull. Chem. Soc. Jpn.* **1975**, *48*, 3137–3141.

(14) (a) Cheng, R.-J.; Latos-Grazynski, L.; Balch, A. L. *Inorg. Chem.* **1982**, *21*, 2412–2418. (b) Arasasingham, R. D.; Balch, A. L. Latos-Grazynski, L. *J. Am. Chem. Soc.* **1987**, *109*, 5846–5847.

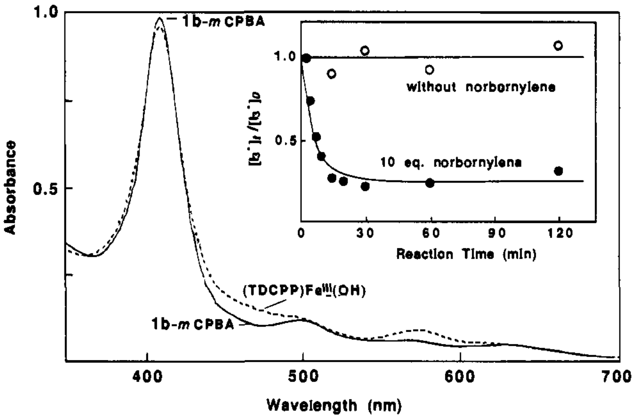
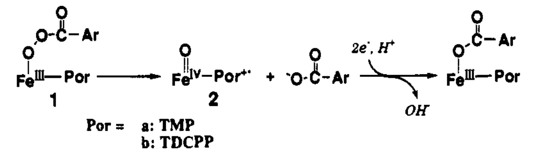


Figure 2. (A) UV−vis spectral change upon the addition of 3 equiv *m*CPBA to (TDCPP)Fe^{III}(OH) (− − −, 1.0 × 10^{-5} M) in CH$_2$Cl$_2$ at −80 °C. Inset: Plots of [I$_3^-$]/[I$_3^-$]$_0$ vs time in the mixture of (TDCPP)Fe^{III}(*m*CBA) and *m*CPBA without norbornylene (○) and with 10 equiv of norbornylene (●).

Scheme 2



implies the high valent oxo species of these porphyrins are less stable than that of the (TMP)Fe derivatives.[15]

Thus, we have examined time dependent consumption of the oxidizing equivalent of *m*CPBA in the presence of (TDCPP)Fe^{III}(OH). For more than 2 h no consumption of the oxidizing equivalent of *m*CPBA was observed when an oxidizable substrate was absent (Figure 2, *inset*). UV−vis spectral change and the formation of the stoichiometric amount of I$_3^-$ are the clear evidence for the formation of **1b-*m*CPBA** as a stable species under the reaction conditions. The same reaction was carried out in the presence of 10 equiv moles of norbornylene. As shown in Figure 2 (*inset*), most of the oxidizing equivalent was consumed in 30 min, though *m*CPBA itself is not able to react with norbornylene under the conditions without (TDCPP)Fe^{III}(OH). These observations are indicative of the active species responsible for the oxidation of norbornylene to be different from (TDCPP$^{+\bullet}$)Fe^{IV}=O **2b** in this particular case. Since **1b-*m*CPBA** is the only species observed as a stable species in the reaction of (TDCPP)Fe^{III}(OH) and *m*CPBA in methylene chloride at −80 °C, **1b-*m*CPBA** is the most attractive candidate for the active species.

Reactions of (TMP)Fe^{III}(OH) and (TDCPP)Fe^{III}(OH) with *m*CPBA in Toluene. When the reaction of (TMP)Fe^{III}(OH) with 3 equiv of *m*CPBA was carried out in toluene at −30 °C, (TMP)Fe^{III} *N*-oxide **3a** via the transient formation of **1a-*m*CPBA** was observed, consistent with previous observation (Figure 3, *inset*).[6b,c,7] By lowering the temperature to −80 °C, we were able to terminate the conversion of **1a-*m*CPBA** to **3a**, i.e., **1a-*m*CPBA** was obtained as a stable intermediate at −80 °C (Figure 3). Likewise the EPR spectrum of **1** in methylene chloride,[16] the EPR spectrum of **1a-*m*CPBA** exhibited a characteristic absorption of ferric high spin complexes at g = 5.5 at 77 K.

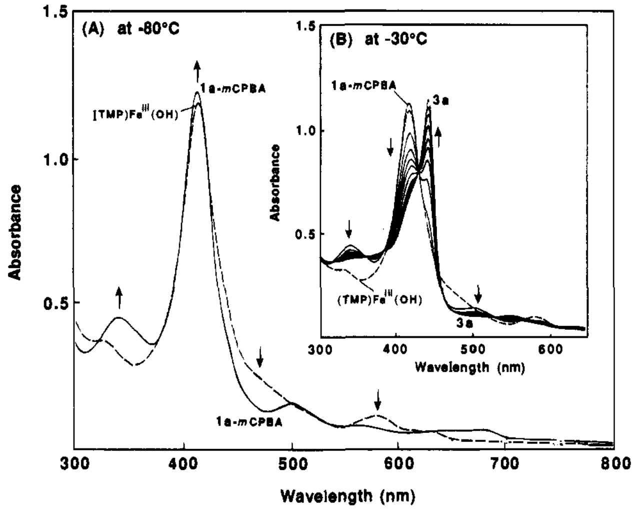


Figure 3. (A) Spectral changes in the reaction of 1.2 × 10^{-5} M of (TMP)Fe^{III}(OH) (− − −) and *m*CPBA in toluene at −80 °C. (B) Time-dependent spectral changes of 1.2 × 10^{-5} M of (TMP)Fe^{III}(OH) (− − −) and *m*CPBA in toluene at −30 °C.

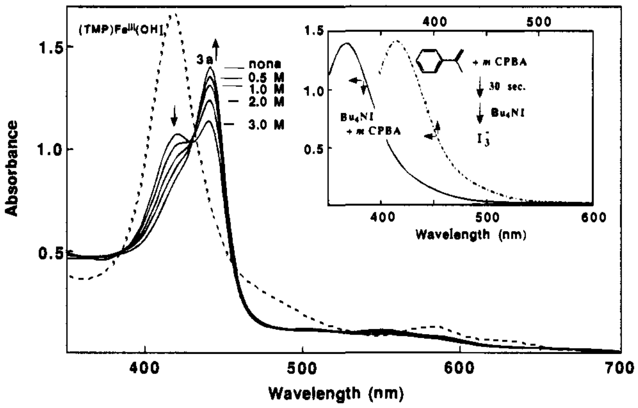


Figure 4. Spectral changes in the reactions of 1.5 × 10^{-5} M of (TMP)Fe^{III}(OH) (− − −) and *m*CPBA in toluene at 0 °C in the absence and presence of a various concentration of α-methylstyrene. The spectra were recorded 30 s after the introduction of *m*CPBA. Inset, (—) visible spectrum of I$_3^-$ formed by direct reaction of *m*CPBA (4.5 × 10^{-5}M) and Bu$_4$NI at 0 °C in toluene and (− • − • −) visible spectrum of I$_3^-$ formed after the reaction of α-methylstyrene (3.0 M) and *m*CPBA (4.5 × 10^{-5} M) for 30 s.

Though *N*-oxides of (TMP)Fe^{III} and (TDCPP)Fe^{III} (**3a,b**) do not react with olefin even at 0 °C, the formation of **3a** and **3b** was diminished when α-methylstyrene was present. More importantly, the amount of the *N*-oxide formed was dependent on the concentration of the olefin in the solution (Figure 4). In order to confirm whether or not the suppression of the *N*-oxide formation was caused by the direct reaction of *m*CPBA with olefin, the same reaction in the absence of (TMP)Fe^{III}(OH) took place over 30 s at 0 °C, while it takes only a few seconds for complete formation of **3** under the same conditions. Iodometric titration of the reaction mixture of *m*CPBA and α-methylstyrene (2.0 M) indicates no consumption of oxidizing equivalent (Figure 4, *inset*). These results indicate the *N*-oxide formation is inhibited by the competitive reaction of an intermediate with α-methylstyrene. Since **1** is the sole intermediate formed in the course of the *N*-oxide formation as depicted in Figure 3, we conclude that **1** could directly react with olefin. In order to gain further insight into the possible involvement of **1** in the epoxidation of olefins, we have examined competitive epoxi-

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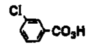
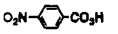
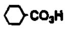
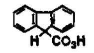
[15] (a) Traylor, P. S.; Dolphin, D.; Traylor, T. G. *J. Chem. Soc., Chem. Commun.* **1984**, 279−280. (b) Depoorte, B.; Ricci, M.; Bortolini, O.; Meunier, B. *J. Mol. Catal.* **1985**, *31*, 221−224. (c) Traylor, T. G.; Nakano, T.; Dunlap, B. E.; Traylor, P. S.; Dolphin, D. *J. Am. Chem. Soc.* **1986**, *108*, 2783−2784. (d) Robert, A.; Munier, B.; *New. J. Chem.* **1988**, *12*, 885−896. (e) Battioni, P.; Renaud, J. P.; Bartoli, J. F.; Reina-Artiles, M; Fort, M.; Mansuy, D. *J. Am. Chem. Soc.* **1988**, *110*, 8462−8470. (f) Tsuchiya, S.; Senô, M. *Chem. Lett.* **1989**, 263−266. (g) Traylor, T. G.; Miksztal, A. R. *J. Am. Chem. Soc.* **1989**, *111*, 7443−7448.

Table 1. Competitive Epoxidation of Norbornylene and α-Methylstyrene with Peracids Catalyzed by (TMP)Fe^{III}(*m*CBA) and (TDCPP)Fe^{III}(*m*CBA) in CH_2Cl_2[a]

Oxidant	norbornylene oxide (*exo/endo*) : α-methylstyrene oxide (turnover number[b)] and yield[c)])		
	(TMP)Fe	(TDCPP)Fe	none[d)]
	100 (89/11) : 8 ± 1.5 (28; 93%)	100 (91/9) : 78 ± 10 (26; 87%)	100 (94/6) : 19 ± 0.8 (93%)
	100 (84/16) : 7 ± 0.8 (28; 92%)	100 (87/13) : 82 ± 1.8 (27; 91%)	100 (92/8) : 19 ±1.7 (89%)
	100 (93/7) : 15 ± 1.5 (8.9; 29%)	100 (91/9) : 33 ± 1.9 (17; 55%)	100 (95/95) : 22 ± 2.1 (84%)
$Me_3CCH_2CO_3H$	100 (93/7) : 6 ± 0.8 (23; 76%)	100 (91/9) :41 ± 2.6 (12; 40%)	100 (94/6) : 22 ± 0.3 (86%)
$PhCH(Et)CO_3H$	100 (93/7) : 6 ± 0.4 (28; 92%)	100 (91/9) : 65 ± 0.9 (22; 72%)	100 (95/5) : 18 ± 0.5 (87%)
	100 (91/9) : 6 ± 0.5 (29; 97%)	100 (92/8) : 62 ± 0.5 (24; 81%)	100 (90/10) : 20 ± 3.6 (83%)

[a] The reactions took place for 3 h at −78 °C (*see Experimental Section*). [b] Epoxides (mol)/catalyst (mol). [c] Yields in parentheses were based on peracids. [d] Oxidations by peracids at 25 °C.

dation of less sterically hindered and hindered olefins by employing various type of peroxycarboxylic acids.

While we have mostly employed (TMP)Fe^{III}(OH) and (TDCPP)Fe^{III}(OH) in the spectroscopic measurements to demonstrate the formation of **1**, (TMP)Fe^{III}(*m*CBA) and (TDCPP)Fe^{III}(*m*CBA) are exclusively used in catalytic reactions, since (Por)Fe^{III}(OH) is completely converted to (Por)Fe^{III}(*m*CBA) after single turnover of the oxidation by *m*CPBA.

Competitive Epoxidation of Norbornylene and α-Methylstyrene Catalyzed by (TMP)Fe^{III}(*m*CBA) and (TDCPP)Fe^{III}(*m*CBA) in Methylene Chloride. Competitive epoxidation of norbornylene and α-methylstyrene (1:1, 300 equiv each with respect to the catalyst) in the presence of a catalytic amount of (TMP)Fe^{III}(*m*CBA) took place in methylene chloride at −78 °C. The reaction was initiated by adding peroxycarboxylic acids.

As summarized in Table 1, the ratios of the oxidation products, norbornylene oxide and α-methylstyrene oxide, are almost identical even though different types of substituents are introduced to the peroxycarboxylic acid. The only exception is cyclohexaneperoxycarboxylic acid. In addition, the reactions of (TMP)Fe^{III}(*m*CBA) with these peroxycarboxylic acids readily afford **2a** at −78 °C in the absence of olefins, as shown in Figure 1. These results indicate the formation of the common active species responsible for the epoxidation, i.e., **2a**, thus the selectivity is independent of the structure of peroxycarboxylic acids used. The result with cyclohexaneperoxycarboxylic acid is discussed later.

We have also examined the competitive epoxidation catalyzed by (TDCPP)Fe^{III}(*m*CBA) under the same conditions; remarkable changes in the shape selectivity were obtained. As listed in Table 1, the selectivity is *varied by changing peroxycarboxylic acids*. These observations demonstrate the active species is different from **2b**, consistent with the spectroscopic observations shown in Figure 2.

Preparation and Reaction of ($TDCPP^{+\bullet}$)Fe^{IV}=O 2b. According to the push−pull effect[6c,16−18] on the formation of **2**, electron-withdrawing substituents on peracids as well as acids in the solution encourage the O−O bond cleavage of acylperoxoiron(III) porphyrin complexes.[6c] Thus, we were able to prepare **2b** by the reaction of (TDCPP)Fe^{III}(*m*CB) and *p*-nitroperbenzoic acid (*p*NPBA) in the presence of *m*-chlorobenzoic acid at −80 °C in methylene chloride as reported before.[19]

Table 2. Comparison of the Selectivity of Norbornylene Oxide over α-Methylstyrene Oxide under Catalytic and Single Turnover Conditions

	Selectivity (norbornylene oxide: α-methylstyrene oxide)[a)]	
	(TMP)Fe	(TDCPP)Fe
Fe^{III}Por + *p*-NO_2PBA[b)]	100 : 7[c)]	100:82[c)]
O=$Fe^{IV}Por^{+\bullet}$ (2)[d)]	100 : 8	100:31

[a] Selectivity for catalytic reactions is determined by GLC, while that for single turnover reaction is calculated based on the UV−vis spectral changes in the reactions of each olefin with **2**. [b] Catalytic oxidations at −78 °C with 30 equiv amounts of *p*-NO_2PB. [c] Data taken from Table 1. [d] Stoichiometric reactions of the olefins with **2** (*see Experimental for the preparation of* **2b**).

After the complete formation of **2b** in a UV-cuvette, either norbornylene or α-methylstyrene was introduced to the resulting solution at −80 °C. On the basis of the spectral changes due to the reaction of **2b** with olefin, the relative reactivity of norbornylene to α-methylstyrene was calculated to be 100:31 (Table 2). A selectivity of 100:8 with **2a** was also obtained in a similar manner. Since the reaction was carried out stoichiometrically (single turnover), the observed ratio is the intrinsic value for the competitive epoxidation by **2b**. The different selectivity observed under catalytic conditions, (TDCPP)Fe^{III}(*m*CB)/30 equiv of *p*NPBA, listed in Table 1 is discussed later along with the result for cyclohexaneperoxycarboxylic acid.

Competitive Epoxidation Catalyzed by (TMP)Fe^{III}(*m*CBA) and (TDCPP)Fe^{III}(*m*CBA) in Toluene. The competitive epoxidation of norbornylene and α-methylstyrene was also carried out in toluene at −78 °C. The results are summarized in Table 3. The reactions catalyzed both by (TMP)Fe^{III}(*m*CBA) and by (TDCPP)Fe^{III}(*m*CBA) show selectivity dependent on the structure of the peracids. These results are very similar to those observed by (TDCPP)Fe^{III}(*m*CBA)/peracid systems in methylene chloride.

Competitive Epoxidation with Iodosylarenes. Iron porphyrin catalyzed competitive epoxidations were examined by employing iodosylbenzene (PhIO) and pentafluoroiodosylbenezene (F_5PhIO) as oxidants. As listed in Table 4, the competitive oxidations by F_5PhIO exhibit similar selectivity obtained with **2**. The reaction of (TMP)Fe^{III}(Cl) and F_5PhIO in methylene chloride at −40 °C was directly monitored by UV−vis spectroscopy, and the formation of **2a** was observed. On the

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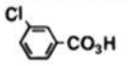
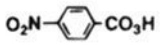
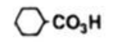
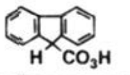
(16) Yamaguchi, K.; Watanabe, Y.; Morishima, I. *J. Am. Chem. Soc.* **1993**, *115*, 4058−4065.

(17) (a) Dawson, J. H.; Holm, R. H.; Trudell, J. R.; Barth, G.; Linder, R. E.; Bunnenberg, E.; Djerassi, C.; Tang, S. C. *J. Am. Chem. Soc.* **1976**, *98*, 3707−3709. (b) Murthy, M. R. N.; Reid, T. J., III; Sicignano, A.; Tanaka, N.; Rossmann, M. G. *J. Mol. Biol.* **1981**, *152*, 465−499. (c) Poulos, T. L.; Finzel, B. C.; Gunsalus, I. C.; Wagner, G. C.; Kraut, J. *J. Biol. Chem.* **1985**, *260*, 16122−16130. (d) Poulos, Y. L.; Finzel, B. C.; Howard, A. J. *Biochemistry* **1986**, *25*, 5314−5322. (e) Poulos, Y. L.; Howard, A. J. *Biochemistry* **1987**, *26*, 8165−8174. (f) Thanabal, V.; de Ropp, J. S.; La Mar, G. N. *J. Am. Chem. Soc.* **1988**, *110*, 3027−3035. (g) Dawson J. H. *Science* **1988**, *240*, 433−439.

(18) (a) Traylor, T. G.; Lee, W. A.; Stynes, D. V. *J. Am. Chem. Soc.* **1984**, *106*, 755−764. (b) Traylor, T. G.; Popovitz-Biro, R. *J. Am. Chem. Soc.* **1988**, *110*, 239−243. (c) Traylor, T. G.; Xu, F. *J. Am. Chem. Soc.* **1990**, *112*, 178−186. (d) Lee, W. A.; Bruice, T. C. *J. Am. Chem. Soc.* **1985**, *107*, 513−514. (e) Zipplies, M. F.; Lee, W. A.; Bruice, T. C. *J. Am. Chem. Soc.* **1986**, *108*, 4433−4445. (f) Yuan, L.-C.; Bruice, T. C. *J. Am. Chem. Soc.* **1986**, *108*, 1643−1650. (g) Bruice, T. C.; Balasubramanian, P. N.; Lee, R. W.; Lindsay Smith, J. R. *J. Am. Chem. Soc.* **1988**, *110*, 7890−7892. (h) Panicucci, R.; Bruice, T. C. *J. Am. Chem. Soc.* **1990**, *112*, 6063−6071. (i) Gopinath, E.; Bruice, T. C. *J. Am. Chem. Soc.* **1991**, *113*, 4653−4665. (j) Groves, J. T.; Watanabe, Y. *Inorg. Chem.* **1986**, *25*, 4808−4810. (k) Labeque, R.; Marnett, L. J. *J. Am. Chem. Soc.* **1989**, *111*, 6621−6627. (l) Higuchi, T.; Uzu, S.; Hirobe, M. *J. Am. Chem. Soc.* **1990**, *112*, 7051−7053. (m) Robert, A.; Loock, B.; Momenteau, M.; Meunier, B. *Inorg. Chem.* **1991**, *30*, 706−711.

(19) Yamaguchi, K.; Watanabe, Y.; Morishima, I. *J. Chem. Soc., Chem. Commun.* **1992**, 1721−1723.

Table 3. Competitive Epoxidation of Norbornylene and α-Methylstyrene with Peracids Catalyzed by (TMP)Fe^{III}(*m*CBA) and (TDCPP)Fe^{III}(*m*CBA) in Toluene[a]

Oxidant	norbornylene oxide (*exo*/*endo*) : α-methylstyrene oxide (turnover number[b] and yield[c])		
	(TMP)Fe	(TDCPP)Fe	none[d]
	100 (93/7) : 37 ± 1.5 (15; 51%)	100 (92/8) : 64 ± 2.1 (9; 30%)	100 (95/5) : 23 ± 1.2 (81%)
	100 (94/6) : 14 ±1.5 (12; 39%)	100 (92/8) : 36 ± 3.1 (12; 40%)	100 (93/7) : 22 ± 0.6 (82%)
	100 (96/4) : 20 ± 0.8 (24; 81%)	100 (94/6) : 51 ± 0.9 (11; 35%)	100 (93/7) : 26 ± 0.8 (75%)
$Me_3CCH_2CO_3H$	100 (87/13) : 15 ± 3.9 (24, 79%)	100 (91/9) : 60 ± 5.4 (8; 27%)	100 (91/9) : 24 ± 1.7 (78%)
$PhCH(Et)CO_3H$	100 (95/5) : 18 ± 4.4 (14; 45%)	100 (93/7) : 60 ± 1.2 (13; 43%)	100 (94/6) : 24 ± 1.5 (74%)
	100 (88/12) : 29 ± 2.1 (12; 40%)	100 (91/9) : 42 ± 4.9 (10; 34%)	100 (88/12) : 26 ± 0.4 (69%)

[a] The reactions were carried out at −78 °C for 3 h. [b] Epoxides (mol)/catalyst (mol). [c] Yield (%) in parentheses were peracids. [d] Oxidations by peracids at 25 °C.

Table 4. Competitive Epoxidation of Norbornylene and α-Methylstyrene with PhIO and F_5PhIO Catalyzed by (Por)Fe^{III}(Cl) in CH_2Cl_2 at −40 °C[a]

oxidant	selectivity (norbornylene oxide and α-methylstyrene oxide)	
	(TMP)Fe	(TDCPP)Fe
F_5Ph·IO	100:8 ± 0.4	100:28 ± 0.9
Ph·IO	100:28 ± 2.6	100:75 ± 1.3
2	100:8[b]	100:31[b]

[a] The reactions took place for 3 h with 30 equiv of PhIO (or F_5PhIO). [b] Data from Table 2.

other hand, remarkable changes in the shape selectivity of the olefin epoxidation were obtained when the same reaction was carried out with PhIO. Attempt to observe intermediates in the reaction of iron porphyrin and PhIO was not successful in methylene chloride.[20]

Discussion

Oxo-ferryl porphyrin π-cation radicals **2** or their equivalent, so called compound I, plays the key role in many types of oxidative metabolisms by heme enzymes such as peroxidases, catalases, and P-450s. An anionic fifth ligand and distal amino acid residues around the heme vicinity are considered to encourage the heterolytic O−O bond cleavage of a putative hydroperoxo−iron(III) complex to afford compound I.[17] Likewise with the biological systems, we have shown that the rate of the heterolytic O−O bond cleavage of (TPP)Fe^{III}(RCO_3)[21] is controlled by changing substituents both on *meso*-phenyl groups of TPP and on peracids.[6a,c,16] For example, introduction of electron-donating groups on the phenyl groups at the *meso* positions enhances the rate of the cleavage reaction, whereas electron-donating substituents on peracids suppress the heterolysis.

Because of these "push−pull" effects, the reaction of (TDCPP)Fe^{III}(X) and *m*CPBA gives (TDCPP)Fe^{III}(*m*CPBA) **1b-*m*CPBA** as a relatively stable intermediate at −80 °C in methylene chloride, while the same reaction with electron-rich (TMP)Fe^{III}(X) readily affords ($TMP^{+\bullet}$)Fe^{IV}=O **2a** via transient formation of **1a-*m*CPBA** (Figures 1 and 2). Iodometric titration of **1b-*m*CPBA** indicates that the adduct is stable for more than 2 h at −80 °C as shown in Figure 2 (*inset*). Thus, the consumption of oxidizing equivalent by norbornylene with concomitant formation of epoxide in 30 min (Figure 2, inset) should not be attributed to the reaction of ($TDCPP^{+\bullet}$)Fe^{IV}=O **2b** with norbornylene, but it is rather suggestive of the direct epoxidation by **1b-*m*CPBA**. Sterically hindered (TTPPP)Fe^{III}-(OH)[22] is also known to yield (TTPPP)Fe^{III}(*m*CPBA) in the reaction with *m*CPBA as a stable complex at −78 °C.[23] Moreover, (TMP)Mn^{III}(RCO_3) has been reported to be stable species in acetonitrile at low temperature.[24]

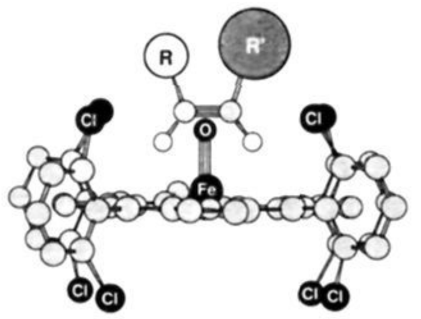


Figure 5. Side-on approach of *cis*-olefin to a metal−oxo complex in the oxygen transfer. All protons bound to the porphyrin are eliminated for simplicity.

If (Por)Fe^{III}(RCO_3) **1** is able to oxidize olefins, we could differentiate two active species, **1** and **2**, on the basis of steric effect of peracids on the reactivity with olefins. When **2** is the oxidant, the reactivity of **2** toward olefins is independent of the structure of the peracids used. In the reactions of (TMP)Fe^{III}-(X) with the peroxycarboxylic acids listed in Table 1, we have observed the formation of **2a** at −78 °C in methylene chloride. Thus, the selectivity of norbornylene oxide versus α-methylstyrene oxide is constant except for cyclohexaneperoxycarboxylic acid. Further, favorable epoxidation of *cis*-olefin by **2a** is in good agreement with the perpendicular approach of olefin to the O=Fe moiety of **2a** as pointed out by Groves (Figure 5).[25] Thus, norbornylene approaches the active site of porphyrin more easily than α-methylstyrene when **2** is the active species. While the visualization of the transition state in the epoxidation by **2** has been further demonstrated by recent crystal structure of an adduct of styrene oxide and (TDCPP)Ru^{II}(CO),[26] Bruice et al. suggested that the olefin could reach to the oxo-oxygen from the top of the porphyrin plane when one uses crowded iron−porphyrin complexes.[27,28]

On the other hand, we have proposed the involvement of **1b** in the epoxidation when (TDCPP)Fe^{III}(X) is used at low temperature.[8] Figure 6 illustrates idealized structures of **1b-*m*CPBA** and **1b-*t*BPAA**. Recent studies on the olefin epoxidation by **2** show the crucial roles of bulky substituents at the porphyrin periphery.[25,29] Therefore, asymmetric epoxidation of prochiral olefins have been achieved with chiral iron porphy-

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(20) As reported before, the reaction of (TMP)Fe^{III}(Cl) and PhIO *in CH_2Cl_2−MeOH* gave (TMP)$Fe^{IV}$$(OMe)_2$, which did not react with olefin at −40 °C. Groves, J. T.; Quinn, R.; McMurry, T. J.; Nakamura, M.; Lang, G.; Boso, B. *J. Am. Chem. Soc.* **1985**, *107*, 354−360.

(21) TPP: 5,10,15,20-tetraphenylporphyrin.

(22) TTPPP: 5,10,15,20-tetrakis(2,4,6-triphenylphenyl)porphyrin.

(23) Groves, J. T.; Watanabe, Y. *Inorg. Chem.* **1987**, *26*, 785−786.

(24) Groves, J. T.; Watanabe, Y.; McMurry, T. J. *J. Am. Chem. Soc.* **1983**, *105*, 4489−4490.

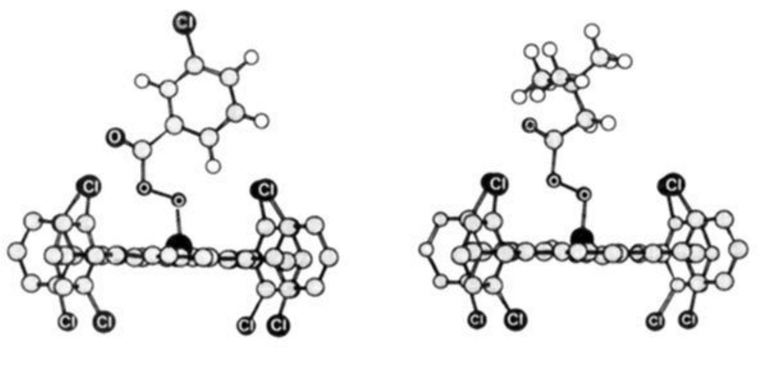
(25) Groves, J. T.; Nemo, T. E. *J. Am. Chem. Soc.* **1983**, *105*, 5786−5791.

(26) Groves, J. T.; Han, Y.; Van, Engen, D. *J. Chem. Soc., Chem. Commun.* **1990**, 436−437.

(27) Though the perpendicular approach of olefin to the O=Fe moiety is proposed as an idealized pathway,[26] steric hindrance around the heme perifery would perturb the transition state structure as shown in refs 26 and 28.

(28) Ostovic, D.; Bruice, T. C. *J. Am. Chem. Soc.* **1989**, *111*, 6511−6517.

(29) For example: Suslick, K. S. In *Activation and Functionalization of Alkenes*; Hill, C. L., Ed.; John Wiley & Sons: New York, 1989; pp 219−241.



1b-*m*CPBA **1b-*t*BPAA**

Figure 6. Idealized structures of peracid−Fe(III) porphyrin complexes. All protons bound to the porphyrins are eliminated for simplicity.

rins.[30] These results suggest that the structure of the peracid in **1b** may also affect the interaction of the oxidant with substrates. Apparently, the epoxidations catalyzed by (TDCPP)Fe^{III} shown in Table 1 are such cases. Though the peroxycarboxylic acids themselves are not able to epoxidize these olefins under the conditions at −78 °C, the selectivity of norbornylene oxide over α-methylstyrene oxide by these peroxycarboxylic acids at room temperature in methylene chloride is almost constant (100:19 ∼ 100:22, Table 1). Accordingly, relatively preferable oxidation of α-methylstyrene over norbornylene by **1b** suggests that the approach of olefin to **1b** is highly restricted by steric hindrance of the reaction site as expected from the structures illustrated in Figure 6.

Due to the "push−pull" effect on the heterolytic O−O bond cleavage in **1**, peroxybenzoic acids having electron-withdrawing groups accelerate the heterolysis.[6a,c,18f,g] Thus, we have examined the reaction of *p*NPBA with (TDCPP)Fe^{III}(*m*CBA) and obtained (TDCPP$^{+\bullet}$)Fe^{IV}=O **2b** in methylene chloride at −80 °C as reported before,[19] though the production of **2b** proceeded much slower than that of (TMP)Fe derivatives.[31] As listed in Table 2, stoichiometric reaction (single turnover) of **2b** with norbornylene proceeds three times faster than that with α-methylstyrene (100:31). The different selectivity between **2b** itself and catalytic epoxidation (Table 1, run 2) indicates that *the rate of the direct reaction of olefins with **1b** is much greater than that for the formation of **2b***. Similar consideration explains the selectivity observed for the (TMP)Fe^{III}(*m*CBA)/cyclohexaneperoxycarboxylic acid system, in which case both rate are expected to be comparative.

Replacement of methylene chloride to toluene in the reactions of *m*CPBA with (TMP)Fe^{III}(X) and (TDCPP)Fe^{III}(X) (X = HO$^-$ and RCO$_3^-$) is known to allow the formation of the corresponding *N*-oxides (**3**) due to the homolysis of the O−O bond in **1**.[6b,c] As demonstrated in Figure 3, **1** is observable as a stable intermediate by lowering the reaction temperature to −80 °C. While **3** is not able to oxidize olefins even at room temperature, we have found that the *N*-oxide formation is competitively inhibited by olefin (Figure 4) with concomitant formation of epoxide at 0 °C.[6c] On the basis of these observations, we have proposed the direct epoxidation of olefin by **1** in toluene at 0 °C or below[8] and now examined the competitive epoxidation of norbornylene and α-methylstyrene by a series of peroxycarboxylic acids catalyzed by (TMP)Fe^{III}(*m*CBA) and (TDCPP)-Fe^{III}(*m*CBA) in toluene at −78 °C to compare the selectivity with that observed in CH_2Cl_2. As expected, the selectivity of norbornylene oxide over α-methylstyrene oxide is dependent on the structure of peroxycarboxylic acids used (Table 3). Therefore, we conclude that **1** is the active species in the epoxidation of olefin catalyzed by (TMP)Fe^{III}(*m*CBA) and (TDCPP)Fe^{III}(*m*CBA) in toluene below 0 °C.

Very recently, Nam and Valentine[32] have studied the incorporation of labeled water oxygen ($H_2{}^{18}O$) in the Fe porphyrin-catalyzed epoxidation of cyclohexene by *m*CPBA. While high valent oxo complexes are generally supposed to exchange oxygen atom with water in the reaction mixture, they showed that no ^{18}O enrichment in the product was given by the introduction of electron-withdrawing groups to the porphyrin ring. Apparently, the alteration of the active species from **2** to **1** explains these observations. These authors also examined the epoxidation by PhIO in the presence of aluminum(III) porphyrin.[33] Though aluminum(III) porphyrin does not produce high valent oxo complexes, epoxide formation was observed. These results imply metalloporphyrin complexes can catalyze the epoxidation by the pathways that do not involve high valent oxo intermediates. On the basis of these observations, they proposed PhIO−metalloporphyrin complexes as the reactive intermediate.

In order to verify the active species in the epoxidation of olefin by PhIO in the presence of iron porphyrins, we have examined the competitive epoxidation. Since (Por)Fe(Cl) are commonly used catalysts in olefin epoxidation with PhIO, we have examined the oxidations catalyzed by (TMP)Fe^{III}(Cl) and (TDCPP)Fe^{III}(Cl) in these particular cases. If **2a** and **2b** are the active species, we should obtain the selectivity of norbornylene oxide/α-methylstyrene oxide being 100:8 and 100:28, respectively. As depicted in Table 4, the expected selectivity is observed only when F_5PhIO is employed. Therefore, the active species for the epoxidation of olefin by PhIO in the presence of (TMP)Fe^{III}(Cl) or (TDCPP)Fe^{III}(Cl) in methylene chloride is not **2** but possibly PhIO−Fe porphyrin complexes (**4**) under the reaction conditions. Similar (TPP)Mn^{IV}−iodosylbenzene complexes have been shown to oxidize alkanes.[34] Likewise the difference between *m*CPBA and *p*NPBA, the use of perfluorinated-PhIO (F_5PhIO) could accelerate the O−I bond cleavage in **4** to form **2** because of better leaving ability (pull effect). In fact, the reaction of F_5PhIO and (TMP)Fe^{III}(Cl) gives **2a**, while PhIO fails to yield **2a** in methylene chloride at −40 °C.[20]

Conclusion

We have demonstrated herein that the active species responsible for the epoxidation of olefin catalyzed by iron porphyrins is not always the oxo-ferryl intermediate; i.e., peracid−Fe(III) complexes **1** are also able to oxidize olefins. Further, we have shown that the competitive epoxidation is a good indicator to

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(30) (a) Groves, J. T.; Myers, R. S. *J. Am. Chem. Soc.* **1983**, *105*, 5791−5796. (b) Groves, J. T.; Viski, P. *J. Am. Chem. Soc.* **1989**, *111*, 8537−8538. (c) Mansuy, D.; Battioni, P.; Renaud, J.-P.; Guerin, P. *J. Chem. Soc. Chem. Commun.* **1985**, 155−156. (d) O'Malley, S.; Kodadek, T. *J. Am. Chem. Soc.* **1989**, *111*, 9116−9117. (e) Naruta, Y.; Tani, F.; Ishihara, N.; Maruyama, K. *J. Am. Chem. Soc.* **1991**, *113*, 6865−6872. (f) Maillard, P.; Guerquin-Kern, J. L.; Momenteau, M. *Tetrahedron Lett.* **1991**, *32*, 4901−4904. (g) Weber, L.; Imiolczyk, I.; Haufe, G.; Rehorek, D.; Hennig, H. *J. Chem. Soc., Chem. Commun.* **1992**, 301−303. (h) Ohkubo, K.; Sagawa, T.; Ishida, H. *Inorg. Chem.* **1992**, *31*, 2682−2688. (i) Konishi, K.; Oda, K.; Nishida, K.; Aida, T.; Inoue, S. *J. Am. Chem. Soc.* **1992**, *114*, 1313−1317. (j) Collman, J. P.; Lee, V. J.; Zhang, X.; Ibers, J. A.; Brauman, J. I. *J. Am. Chem. Soc.* **1993**, *115*, 3834−3835.

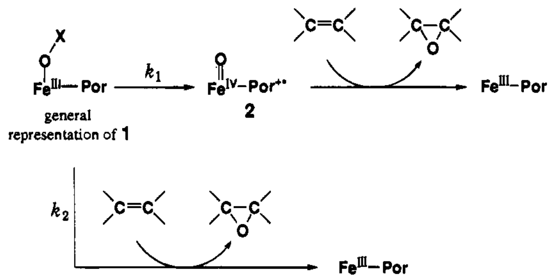
(31) (a) Instead of *p*NPBA, *m*CPBA can be used to prepare **3b** if Fe^{III}-TPCPP(ClO_4) is the starting material,[25b] since the ligand exchange reaction of Fe^{III}TPCPP(ClO_4) with *m*CPBA yields $HClO_4$ to make the reaction solution acidic. As we have reported before, concentration of acid is also an important factor to encourage the heterolytic O−O bond cleavage.[5a,c] (b) Fujii, H. *J. Am. Chem. Soc.* **1993**, *115*, 4641−4648.

(32) Nam, W.; Valentine, J. S. *J. Am. Chem. Soc.* **1993**, *115*, 1772−1778.

(33) Nam, W.; Valentine, J. S. *J. Am. Chem. Soc.* **1990**, *112*, 4977−4979.

(34) (a) Smegal, J. A.; Schardt, B. C.; Hill, C. L. *J. Am. Chem. Soc.* **1983**, *105*, 3510−3515. (b) Smegal, J. A.; Hill, C. L. *J. Am. Chem. Soc.* **1983**, *105*, 3515−3521.

Scheme 3



discriminate the active species in iron porphyrin catalyzed epoxidation, and the structure of oxidants plays a crucial role for the stereoselectivity in olefin epoxidation reactions by oxidant-iron−porphyrin complexes, while the selectivity in the epoxidation by the corresponding oxo-ferryl porphyrin π-cation radicals is independent of the oxidants. Under the catalytic epoxidation conditions, the participation of these two oxidants is controlled by the electronic structure of iron porphyrin complexes (push−pull effect) as well as the polarity of the solvent. While we have carried out most of reactions at −78 °C to ensure the formation of **1**, involvement of **1** in the epoxidation at higher temperature is dependent on the relative rates of k_1 and k_2 shown in Scheme 3.

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