

Isolation of an Oxomanganese(v) Porphyrin Intermediate in the Reaction of a Manganese(III) Porphyrin Complex and H₂O₂ in Aqueous Solution

Wonwoo Nam,^{*,[a]} Inwoo Kim,^[a] Mi Hee Lim,^[a] Hye Jin Choi,^[a] Je Seung Lee,^[b] and Ho G. Jang^[b]

Abstract: The reaction of [Mn(TF₄TMAP)](CF₃SO₃)₅ (TF₄TMAP = *meso*-tetrakis(2,3,5,6-tetrafluoro-*N,N,N*-trimethyl-4-aniliniumyl)porphinato dianion) with H₂O₂ (2 equiv) at pH 10.5 and 0 °C yielded an oxomanganese(v) porphyrin complex **1** in aqueous solution, whereas an oxomanganese(IV) porphyrin complex **2** was generated in the reactions of *tert*-alkyl hydroperoxides such as *tert*-butyl hydroperoxide and 2-methyl-1-phenyl-2-propyl hydroperoxide. Complex **1** was capable of epoxidizing olefins and exchanging its oxygen with H₂¹⁸O, whereas **2** did not epoxidize olefins. From the reactions of [Mn(TF₄TMAP)]⁵⁺ with various ox-

dants in the pH range 3–11, the O–O bond cleavage of hydroperoxides was found to be sensitive to the hydroperoxide substituent and the pH of the reaction solution. Whereas the O–O bond of hydroperoxides containing an electron-donating *tert*-alkyl group is cleaved homolytically, an electron-withdrawing substituent such as an acyl group in *m*-chloroperoxybenzoic acid (*m*-CPBA) facilitates O–O bond heterolysis. The mechanism of the O–O bond

cleavage of H₂O₂ depends on the pH of the reaction solution: O–O bond homolysis prevails at low pH and O–O bond heterolysis becomes a predominant pathway at high pH. The effect of pH on ¹⁸O incorporation from H₂¹⁸O into oxygenated products was examined over a wide pH range, by carrying out the epoxidation of carbamazepine (CBZ) with [Mn(TF₄TMAP)]⁵⁺ and KHSO₅ in buffered H₂¹⁸O solutions. A high proportion of ¹⁸O was incorporated into the CBZ-10,11-oxide product at all pH values but this proportion was not affected significantly by the pH of the reaction solution.

Keywords: enzyme mimetics • epoxidation • heme proteins • O–O activation • porphyrinoids

Introduction

An important objective in research aimed at understanding biological oxygenation reactions by heme-containing monooxygenase enzymes is to elucidate the nature of the reactive intermediates and the mechanism of formation of high-valent metal oxo porphyrin intermediates.^[1–2] Model studies using synthetic iron(III) porphyrin complexes have been fruitful in affording a mechanistic insight into the enzymatic reactions and developing biomimetic oxygenation reactions.^[3] Some high-valent oxoiron(IV) porphyrin cation radicals have been isolated and characterized, and the reactivities of the oxoiron(IV) porphyrins in a variety of oxygenation reactions have

been investigated.^[4] As a result of intensive studies of the formation of high-valent oxoiron(IV) porphyrin intermediates in the reactions of iron(III) porphyrin complexes and hydroperoxides, O–O bond heterolysis and homolysis have been proposed.^[5]

Although synthetic manganese(III) porphyrin complexes have shown promise as versatile catalysts in the oxygenation of hydrocarbons,^[6] only recently has the key oxomanganese(v) porphyrin intermediate been isolated and well characterized spectroscopically.^[7] Groves and co-workers generated an oxomanganese(v) porphyrin complex in the reaction of a water-soluble manganese(III) *meso*-tetrakis(*N*-methyl-2-pyridyl)porphyrin [Mn^{III}TM-2-PyP] with artificial oxidants such as *m*-chloroperoxybenzoic acid (*m*-CPBA), HSO₅[–] (oxone), and OCl[–] at room temperature in aqueous solution.^[7b] An analogous oxomanganese(v) complex with a corrole ligand was also synthesized and characterized by Gross and co-workers, and the catalytic activity of the oxomanganese(v) corrole intermediate was investigated in oxygenation reactions.^[8] Thus elucidation of the chemistry of the long-sought high-valent oxomanganese(v) intermediates began by isolation and characterization of the oxomanganese(v) complexes of porphyrin and corrole ligands.^[9]

[a] Prof. Dr. W. Nam, I. Kim, M. H. Lim, H. J. Choi
Department of Chemistry and Division of Molecular Life Sciences,
Ewha Womans University
Seoul 120-750 (Korea)
Fax: (+82) 2-3277-2384
E-mail: wwnam@ewha.ac.kr

[b] J. S. Lee, Prof. Dr. H. G. Jang
Department of Chemistry, Korea University
Seoul 136-701 (Korea)

Supporting information for this article is available on the WWW under <http://www.wiley-vch.de/home/chemistry/> or from the author.

Since the oxomanganese(v) porphyrin complexes are generated by heterolytic O–O cleavage of hydroperoxides by manganese(III) porphyrin complexes, an understanding of the mechanism of hydroperoxide O–O bond cleavage is crucial in designing better catalysts in manganese(III) porphyrin complex catalyzed oxygenation reactions. Although the mechanism of O–O bond cleavage of peracids such as *m*-CPBA has been well established,^[10] the exact nature of O–O bond cleavage of biologically relevant hydroperoxides such as hydrogen peroxide (H₂O₂) and alkyl hydroperoxides (ROOH) has been less clearly understood. In the present study, we report the isolation of an oxomanganese(v) porphyrin intermediate in the reaction of a biologically important oxidant, H₂O₂, in buffered aqueous solution. The oxomanganese(v) porphyrin complex was demonstrated to be a reactive epoxidizing intermediate in the catalytic epoxidation of olefins by H₂O₂. Some mechanistic aspects such as the pH dependence of the O–O bond cleavage of various hydroperoxides by the manganese(III) porphyrin complex and the oxygen exchange between the oxomanganese(v) porphyrin intermediate and ¹⁸O-labeled water, H₂¹⁸O, are discussed.

Results and Discussion

Addition of H₂O₂ (2 equiv) to a reaction solution containing [Mn(TF₄TMAP)](CF₃SO₃)₅ ((TF₄TMAP = *meso*-tetraakis-(2,3,5,6-tetrafluoro-*N,N,N*-trimethyl-4-aniliniumyl)porphinato dianion; see Supporting Information, Figure S1) at pH 10.5 and 0 °C caused immediate generation of a new species **1** with a strong and sharp Soret band at 427 nm (Figure 1).^[11] The formation of **1** was also observed in the reactions of [Mn(TF₄TMAP)]⁵⁺ with other oxidants such as *m*-CPBA, KHSO₅, NaOCl, and iodosylbenzene (PhIO) under identical reaction conditions.^[7a, b] Interestingly, when *tert*-alkyl hydroperoxides such as *tert*-butyl hydroperoxide (*t*BuOOH) and 2-methyl-1-phenyl-2-propyl hydroperoxide (MPPH)^[12] were used as terminal oxidants, the formation of another inter-

mediate **2** with a broad and weak Soret band at 417 nm was observed at pH 10.5 and 0 °C (Figure 1).^[7b, 13] While the X-band EPR of **2** showed a strong and broad resonance at $g_{\perp} \approx 4$ and a weak signal at $g_{\parallel} \approx 2$ (see Supporting Information, Figure S2), **1** was EPR-silent.^[7b] On the basis of the UV/Vis and EPR spectral features of **1** and **2**, we suggest that **1**, generated in the reactions of H₂O₂ and other single oxygen atom donors, is an oxomanganese(v) porphyrin complex and **2**, formed in the reactions of *tert*-alkyl hydroperoxides, is an oxomanganese(IV) porphyrin complex (*vide infra*).

The reactivity of the intermediates **1** and **2** was then examined in olefin epoxidation reactions, by generating the intermediates and using them directly in reactivity studies. When an olefin substrate such as carbamazepine (CBZ)^[7d, 14] was added to a reaction solution containing **1** generated in the reaction of [Mn(TF₄TMAP)]⁵⁺ with a stoichiometric amount of H₂O₂, the intermediate **1** reverted to the starting manganese(III) porphyrin complex with clear isosbestic points at 394, 442, and 555 nm and with a half-life of 47 s (Figure 2).^[15] HPLC analysis of the resulting solution revealed that a good

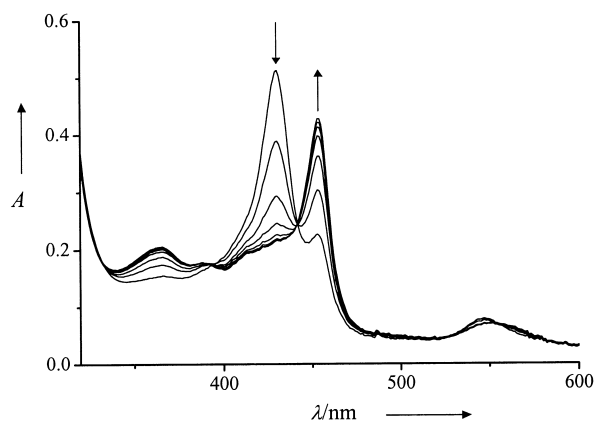


Figure 2. UV/Vis spectral changes upon addition of CBZ (2.1 mM, dissolved in 0.1 mL CH₃CN) into a 0.1 cm UV cuvette containing a solution of **1** generated in the reaction of [Mn(TF₄TMAP)]⁵⁺ (7×10^{-2} mM) and H₂O₂ (7×10^{-2} mM) in a solvent mixture of 50 mM borate buffer (0.5 mL, pH 10.5) and CH₃CN (0.05 mL) at 0 °C. Scan interval: 45 s (first scan was immediately after the addition of CBZ).

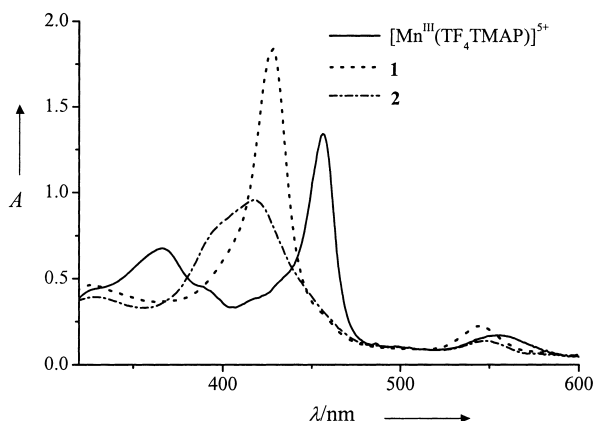
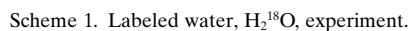
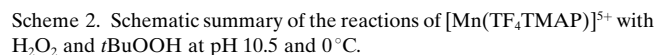


Figure 1. UV/Vis spectra of [Mn(TF₄TMAP)]⁵⁺, **1**, and **2**. Reaction conditions: ROOH (4×10^{-2} mM, dissolved in 0.05 mL H₂O) was injected into a 1 cm UV cuvette containing a reaction solution of [Mn(TF₄TMAP)]⁵⁺ (2×10^{-2} mM) in 50 mM borate buffer (3 mL, pH 10.5) at 0 °C.

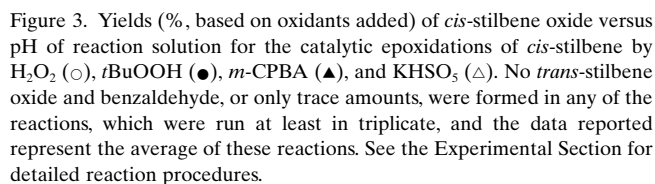
yield ($55 \pm 10\%$ based on the amount of **1** formed) of CBZ-10,11-oxide was obtained, demonstrating that **1** is capable of oxidizing the olefin to give the epoxide product. Furthermore, when a stoichiometric amount of H₂O₂ was added to a reaction solution containing [Mn(TF₄TMAP)]⁵⁺ and CBZ, **1** was formed immediately upon addition of H₂O₂ to the reaction mixture and then decayed back to the starting [Mn^{III}(TF₄TMAP)]⁵⁺ complex (see Supporting Information, Figure S3). HPLC analysis of the reaction mixture revealed a yield of $60 \pm 10\%$ CBZ-10,11-oxide (based on the amount of H₂O₂ added). Significantly, when the latter reaction was performed with H₂¹⁶O₂ in buffered ¹⁸O-labeled water (H₂¹⁸O) solution,^[16] 45% of the oxygen in the CBZ-10,11-oxide product came from the labeled water (Scheme 1)^[7d, 14a, 14b, 17] These results demonstrate that **1** is generated as a reactive species in the catalytic epoxidation of olefins by [Mn^{III}(TF₄TMAP)]⁵⁺ and H₂O₂ and that the oxygen atom



As we have observed formation of another intermediate **2** in the reactions of *tert*-alkyl hydroperoxides such as *t*BuOOH and MPPH, the reactivity of **2** was also examined in the CBZ epoxidation. When CBZ was added to a reaction solution containing **2** generated in the reaction of *t*BuOOH, the UV/Vis spectrum of the reaction solution did not change for 2 h, and HPLC analysis of the reaction mixture did not show the formation of CBZ-10,11-oxide. In addition, when *t*BuOOH was used as a terminal oxidant in the catalytic epoxidation of CBZ by [Mn(TF₄TMAP)]⁵⁺, the intermediate **2** formed upon the addition of *t*BuOOH to the [Mn(TF₄TMAP)]⁵⁺ solution did not show any UV/Vis spectral changes, and HPLC analysis of the resulting solution revealed no CBZ-10,11-oxide product formation. These results demonstrate that **2** does not oxidize olefins under our reaction conditions. The unreactivity of an oxomanganese(IV) porphyrin complex [oxoMn^{IV}TM-2-PyP] toward olefin epoxidation in aqueous solution has also been reported by Groves and co-workers.^[7b] Scheme 2 summarizes the above results: the UV/Vis and EPR spectral features and reactivities of **1** and **2** clearly indicate that **1**, generated in the H₂O₂ reaction, is an oxomanganese(V) porphyrin complex (pathway **A**) and **2**, formed in the reactions of *tert*-alkyl hydroperoxides such as *t*BuOOH and MPPH, is an oxomanganese(IV) porphyrin complex (pathway **B**). The complex **1** epoxidizes olefins (pathway **C**) and readily exchanges its oxygen with H₂¹⁸O (pathway **E**), where-



The pH dependence of $[\text{Mn}(\text{TF}_4\text{TMAP})]^{5+}$ reactions with various oxidants has been investigated for the catalytic epoxidation of *cis*-stilbene in the pH range 3–11 at room temperature.^[12c, 20] Whereas the *cis*-stilbene oxide yields were high and independent of pH in the reactions of *m*-CPBA and KHSO_5 , the oxide product yields in the H_2O_2 reaction varied depending on the pH of the buffer solution (Figure 3). In the



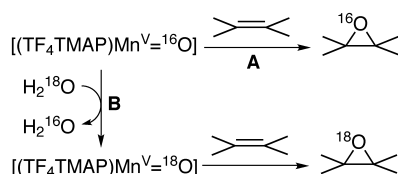
Since the oxide yields in the KHSO_5 reaction were high and independent of pH, we have examined the effect of pH on the

extent of incorporation of ^{18}O from H_2^{18}O into oxygenated products over a wide pH range,^[17a] by epoxidation of CBZ with $[\text{Mn}(\text{TF}_4\text{TMAP})]^{5+}$ and KHSO_5 in buffered H_2^{18}O solutions. Some of the oxygen in the CBZ-10,11-oxide was derived from ^{18}O -labeled water (Table 1), indicating the involvement of **1** as a common reactive species over the entire pH range. In addition, the amounts of ^{18}O incorporated into the oxide product did not differ greatly at different pH values, implying that the oxygen exchange between **1** and H_2^{18}O (Scheme 3, pathway **B**) may not be affected significantly by the pH of the reaction solution. However, the oxygen exchange between **1** and H_2^{18}O (Scheme 3, pathway **B**) is competing with the oxygen transfer from **1** to organic substrate (Scheme 3, pathway **A**).^[7d, 17b] Therefore, another factor that may influence the degree of ^{18}O incorporation in H_2^{18}O experiments is the effect of pH on the rate of oxygen transfer from **1** to olefins (Scheme 3, pathway **A**). Consequently, to elucidate the effect of pH on the oxygen exchange between **1** and H_2^{18}O , the effect of pH on the rate of oxygen transfer from **1** to olefins should be determined as well; this is under active investigation in this laboratory.

Table 1. ^{18}O [%]^[a] incorporated from H_2^{18}O into CBZ-10,11-oxide in the catalytic epoxidation of CBZ by $[\text{Mn}(\text{TF}_4\text{TMAP})]^{5+}$ and KHSO_5 at different pH values.^[b]

pH	3	5	7	9	10.5
^{18}O incorporated [%] ^[a]	26 ± 4	28 ± 4	37 ± 5	36 ± 5	35 ± 5
CBZ converted to CBZ-10,11-oxide [%]	45	60	50	50	50

[a] Calculated on the basis of the mass balance of oxygen derived from H_2^{18}O . [b] All reactions were run at least in duplicate, and the data reported represent the average of these reactions. See the Experimental Section for detailed reaction procedures. It had been demonstrated previously that oxygen exchange between KHSO_5 and H_2^{18}O , and between CBZ-10,11-oxide- ^{16}O and H_2^{18}O , did not occur.^[7d, 14a, 14b]



Scheme 3. Competition between oxygen exchange and oxygen transfer for the reaction of **1**.

Experimental Section

Materials: $[\text{Mn}(\text{TF}_4\text{TMAP})](\text{CF}_3\text{SO}_3)_3$ was purchased from Mid-Century Chemicals. All chemicals obtained from Aldrich Chemical Co. were of the highest purity available and were used without further purification unless otherwise indicated. H_2O_2 (30% aqueous), $t\text{BuOOH}$ (70% aqueous), $m\text{-CPBA}$, and KHSO_5 (oxone) were purchased from Aldrich. $m\text{-CPBA}$ was purified by washing with phosphate buffer (pH 7.4) followed by water and then dried under reduced pressure. PhIO was prepared from iodobenzene diacetate by a literature method.^[23] H_2^{18}O (95% ^{18}O -enriched) and H_2^{16}O (90% ^{18}O -enriched, 2% solution in H_2^{16}O) were obtained from Aldrich and ICON Isotopes, respectively. CBZ-10,11-oxide was prepared by a literature method.^[14a] Water used in all the experiments was distilled and deionized (Millipore, Milli-Q).

Instrumentation: Product analyses were performed on a Dionex Summit HPLC System equipped with a variable-wavelength UVD-170S detector. Products were separated on a Waters Symmetry C_{18} reverse-phase column

(4.6 mm × 250 mm), and detected at 215 and 254 nm. Low-temperature UV/Vis spectra were recorded on a Hewlett Packard 8453 spectrophotometer equipped with an Optostat variable-temperature liquid-nitrogen cryostat (Oxford Instruments). EPR spectra were obtained on a JEOL JES-FA200 spectrometer.

Catalytic epoxidation of *cis*-stilbene: In a typical reaction, oxidant (2 mm H_2O_2 , 2 mm $m\text{-CPBA}$, 2 mm KHSO_5 , and 4 mm $t\text{BuOOH}$) was added to a reaction solution containing $[\text{Mn}(\text{TF}_4\text{TMAP})]^{5+}$ (4×10^{-2} mm) and *cis*-stilbene (6 mm) in a solvent mixture (5 mL) of buffered H_2O (2.5 mL)/ CH_3OH (1.0 mL)/ CH_3CN (1.5 mL) to make the reaction mixture homogeneous. Reactions were performed at pH 3–4 in formate buffer (0.1 M), at pH 5–6 in acetate buffer (0.1 M), at pH 7–9 in phosphate buffer (0.1 M), and at pH 10–11 in borate buffer (0.05 M), and the pH of the reaction solutions was adjusted by adding either HCl (3 N) or NaOH (3 N) solutions whenever necessary. The reaction mixture was stirred in air for 1 h (H_2O_2 , $m\text{-CPBA}$, and KHSO_5) or 4 h ($t\text{BuOOH}$) at 25 °C, and then analyzed by HPLC. Products were separated on a Waters Symmetry C_{18} reverse-phase column (4.6 mm × 250 mm), and product yields were determined by comparison with standard curves of known authentic samples.

H_2^{18}O experiments with CBZ: Reactions were run in buffered ^{18}O -labeled water solutions (0.15 mL, 85% ^{18}O -enriched) containing $[\text{Mn}(\text{TF}_4\text{TMAP})]^{5+}$ (7×10^{-2} mm) and CBZ (3.6×10^{-1} mm). Oxone (0.7 mm in 0.1 M pH 3 formate buffer, 1 mm in 0.1 M pH 5 acetate buffer and pH 7 phosphate buffer, 1.6 mm in 0.1 M pH 9 phosphate buffer, 2 mm in 0.1 M pH 10.5 borate buffer) was added to the reaction solution, which was stirred for 40 min at room temperature, then taken to dryness in a Speed-Vac. After addition of CH_3CN (0.1 mL) to the residue, followed by filtration, the filtrate was analyzed by the electronic impact method at 70 eV with a VG70-VSEQ mass spectrometer (VG Analytical). ^{16}O and ^{18}O compositions in CBZ-10,11-oxide were determined from the relative abundances of mass peaks at m/z 252 (^{16}O) and 254 (^{18}O).^[7d, 14]

The conversion of CBZ and the yield of CBZ-10,11-oxide were determined by carrying out the reactions in buffered H_2^{16}O solutions under identical conditions. The reaction mixture was analyzed directly by HPLC. CBZ and its oxide derivative were separated on a Waters Symmetry C_{18} column; the detection was made at 215 nm.

Acknowledgement

This work was supported by the Korea Science and Engineering Foundation (R03–2001–00028), Ewha Womans University (2000), CCSR at Ewha Womans University, and the Korea Research Foundation (DP0270). I.K. and J.S.L. hold a Research Fellowship (Brain Korea 21 Program).

- [1] a) B. Meunier, J. Bernadou, *Struct. Bonding* **2000**, 97, 1–35; b) D. L. Wertz, J. S. Valentine, *Struct. Bonding* **2000**, 97, 37–60; c) M. Newcomb, P. H. Toy, *Acc. Chem. Res.* **2000**, 33, 449–455; d) D. Schröder, S. Shaik, H. Schwarz, *Acc. Chem. Res.* **2000**, 33, 139–145; e) M. Sono, M. P. Roach, E. D. Coulter, J. H. Dawson, *Chem. Rev.* **1996**, 96, 2841–2887; f) P. R. Ortiz de Montellano, *Cytochrome P450: Structure, Mechanism, and Biochemistry*, 2nd ed., Plenum Press, New York, **1995**.
- [2] a) R. Davydov, T. M. Makris, V. Kofman, D. E. Werst, S. G. Sligar, B. M. Hoffman, *J. Am. Chem. Soc.* **2001**, 123, 1403–1415; b) I. Schlichting, J. Berendzen, K. Chu, A. M. Stock, S. A. Maves, D. E. Benson, R. M. Sweet, D. Ringe, G. A. Petsko, S. G. Sligar, *Science* **2000**, 287, 1615–1622; c) M. Newcomb, R. Shen, S.-Y. Choi, P. H. Toy, P. F. Hollenberg, A. D. N. Vaz, M. J. Coon, *J. Am. Chem. Soc.* **2000**, 122, 2677–2686.
- [3] a) J. L. McLain, J. Lee, J. T. Groves, in *Biomimetic Oxidations Catalyzed by Transition Metal Complexes* (Ed.: B. Meunier), Imperial College Press, London, **2000**, pp. 91–169; b) Y. Watanabe in *The Porphyrin Handbook, Vol. 4* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), Academic Press, San Diego, **2000**, pp. 97–117; c) J. P. Collman, A. S. Chien, T. A. Eberspacher, J. I. Brauman, *J. Am. Chem. Soc.* **2000**, 122, 11098–11100; d) W. Nam, M. H. Lim, H. J. Lee, C. Kim, *J. Am. Chem. Soc.* **2000**, 122, 6641–6647.

- [4] a) Y. Watanabe, H. Fujii, *Struct. Bonding* **2000**, 97, 61–89; b) F. Ogliaro, S. Cohen, M. Filatov, N. Harris, S. Shaik, *Angew. Chem.* **2000**, 112, 4009–4013; *Angew. Chem. Int. Ed.* **2000**, 39, 3851–3855; c) A. Gold, R. Weiss, *J. Porphyrins Phthalocyanines* **2000**, 4, 344–349; d) Y. M. Goh, W. Nam, *Inorg. Chem.* **1999**, 38, 914–920; e) Y. Goto, Y. Watanabe, S. Fukuzumi, J. P. Jones, J. P. Dinnocenzo, *J. Am. Chem. Soc.* **1998**, 120, 10762–10763; f) Z. Gross, S. Nimri, *J. Am. Chem. Soc.* **1995**, 117, 8021–8022; g) J. T. Groves, R. C. Haushalter, M. Nakamura, T. E. Nemo, B. J. Evans, *J. Am. Chem. Soc.* **1981**, 103, 2884–2886.
- [5] a) W. Nam, H. J. Han, S.-Y. Oh, Y. J. Lee, M.-H. Choi, S.-Y. Han, C. Kim, S. K. Woo, W. Shin, *J. Am. Chem. Soc.* **2000**, 122, 8677–8684, and references therein; b) T. G. Traylor, P. S. Traylor in *Active Oxygen in Biochemistry* (Eds.: J. S. Valentine, C. S. Foote, A. Greenberg, J. F. Liebman), Blackie Academic and Professional/ Chapman and Hall, London, **1995**, pp. 84–187; c) O. Almarsson, T. C. Bruice, *J. Am. Chem. Soc.* **1995**, 117, 4533–4544.
- [6] a) R. A. Sheldon, *Metalloporphyrins in Catalytic Oxidations*, Marcel Dekker, New York, **1994**; b) D. Mansuy, *Coord. Chem. Rev.* **1993**, 125, 129–142; c) B. Meunier, *Chem. Rev.* **1992**, 92, 1411–1456.
- [7] a) N. Jin, J. L. Bourassa, S. C. Tizio, J. T. Groves, *Angew. Chem.* **2000**, 112, 4007–4009; *Angew. Chem. Int. Ed.* **2000**, 39, 3849–3851; b) N. Jin, J. T. Groves, *J. Am. Chem. Soc.* **1999**, 121, 2923–2924; c) F.-C. Chen, S.-H. Cheng, C.-H. Yu, M.-H. Liu, Y. O. Su, *J. Electroanal. Chem.* **1999**, 474, 52–59; d) J. T. Groves, J. Lee, S. S. Marla, *J. Am. Chem. Soc.* **1997**, 119, 6269–6273; e) N. W. J. Kamp, J. R. Lindsay Smith, *J. Mol. Catal. A: Chem.* **1996**, 113, 131–145.
- [8] a) Z. Gross, G. Golubkov, L. Simkhovich, *Angew. Chem. Int. Ed.* **2000**, 39, 4045–4047; b) Z. Gross, *J. Biol. Inorg. Chem.* **2001**, 6, 733–738.
- [9] a) A. Ghosh, E. Gonzalez, *Isr. J. Chem.* **2000**, 40, 1–8; b) S. P. de Visser, F. Ogliaro, Z. Gross, S. Shaik, *Chem. Eur. J.* **2001**, 7, 4954–4960; c) R. Weiss, V. Bulach, A. Gold, J. Turner, A. X. Trautwein, *J. Biol. Inorg. Chem.* **2001**, 6, 831–845.
- [10] a) J. T. Groves, Y. Watanabe, *Inorg. Chem.* **1986**, 25, 4808–4810; b) P. N. Balasubramanian, A. Sinha, T. C. Bruice, *J. Am. Chem. Soc.* **1987**, 109, 1456–1462; c) R. D. Arasasingham, S. Jeon, T. C. Bruice, *J. Am. Chem. Soc.* **1992**, 114, 2536–2544.
- [11] The stability of the intermediate **1** depends on the pH values of the reaction solution, in which **1** is relatively stable at high pH (> pH 10); as the pH of the reaction solution decreases, either **1** decays fast (pH ≈ 9) or the formation of **1** is not detectable (pH < 8). The pH dependence of the stability of an oxomanganese(v) porphyrin complex [(TM-2-PyP)Mn^V=O] has been reported previously: see ref. [7e].
- [12] a) P. A. MacFaul, D. D. M. Wayner, K. U. Ingold, *Acc. Chem. Res.* **1998**, 31, 159–162; b) P. A. MacFaul, K. U. Ingold, D. D. M. Wayner, L. Que, Jr., *J. Am. Chem. Soc.* **1997**, 119, 10594–10598; c) W. Nam, H. J. Choi, H. J. Han, S. H. Cho, H. J. Lee, S.-Y. Han, *Chem. Commun.* **1999**, 387–388.
- [13] a) J. T. Groves, M. K. Stern, *J. Am. Chem. Soc.* **1988**, 110, 8628–8638; b) R. D. Arasasingham, G.-X. He, T. C. Bruice, *J. Am. Chem. Soc.* **1993**, 115, 7985–7991; c) K. Ayougou, E. Bill, J. M. Charnock, C. D. Garner, D. Mandon, A. X. Trautwein, R. Weiss, H. Winkler, *Angew. Chem.* **1995**, 107, 370–373; *Angew. Chem. Int. Ed. Engl.* **1995**, 34, 343–346.
- [14] Carbamazepine (5-*H*-dibenzo[*b,f*]azepine-5-carboxamide) is a moderately water-soluble olefin often used as a substrate in reactions in aqueous solution: a) J. Bernadou, A.-S. Fabiano, A. Robert, B. Meunier, *J. Am. Chem. Soc.* **1994**, 116, 9375–9376; b) S. J. Yang, W. Nam, *Inorg. Chem.* **1998**, 37, 606–607; c) K. Wietzerbin, J. G. Muller, R. A. Jameton, G. Pratviel, J. Bernadou, B. Meunier, C. J. Burrows, *Inorg. Chem.* **1999**, 38, 4123–4127; d) T. J. Hubin, J. M. McCormick, S. R. Collinson, M. Buchalova, C. M. Perkins, N. W. Alcock, P. K. Kahol, A. Raghunathan, D. H. Busch, *J. Am. Chem. Soc.* **2000**, 122, 2512–2522.
- [15] In the absence of an olefin substrate, the intermediate **1** decayed slowly to the starting manganese(III) porphyrin complex with a half-life of 450 s (data not shown).
- [16] Into a reaction solution of [Mn(TF₄TMAP)]⁵⁺ (7×10^{-2} mM) and CBZ (5×10^{-1} mM) in 0.1 M pH 10.5 borate buffer (0.25 mL, 85% ¹⁸O-enriched), H₂O₂ (1 mM) was added in five portions (0.2 mM each) at 30 min intervals, at 0 °C. The conversion of CBZ was 80% and the yield of CBZ-10,11-oxide was 40% based on H₂O₂ added. Detailed experimental procedures for the determination of the epoxide yield and the percentage of ¹⁸O in the epoxide product are described in the Experimental Section.
- [17] a) J. Bernadou, B. Meunier, *Chem. Commun.* **1998**, 2167–2173; b) K. A. Lee, W. Nam, *J. Am. Chem. Soc.* **1997**, 119, 1916–1922; c) M. Pitie, J. Bernadou, B. Meunier, *J. Am. Chem. Soc.* **1995**, 117, 2935–2936.
- [18] All the experimental procedures were as described in [16] except that ¹⁸O-labeled H₂¹⁸O₂ was used as an oxidant.
- [19] a) P. N. Balasubramanian, E. S. Schmidt, T. C. Bruice, *J. Am. Chem. Soc.* **1987**, 109, 7865–7873; b) T. G. Traylor, F. Xu, *J. Am. Chem. Soc.* **1987**, 109, 6201–6202; c) A. Robert, B. Looock, M. Momenteau, B. Meunier, *Inorg. Chem.* **1991**, 30, 706–711; d) N. N. Gerasimchuk, A. Gerges, T. Clifford, A. Danby, K. Bowman-James, *Inorg. Chem.* **1999**, 38, 5633–5636, and references therein.
- [20] *cis*-Stilbene has been often used as a mechanistic probe in studies of the mechanism of O–O bond cleavage of hydroperoxides by metal complexes: a) G.-X. He, T. C. Bruice, *J. Am. Chem. Soc.* **1991**, 113, 2747–2753; b) A. J. Castellino, T. C. Bruice, *J. Am. Chem. Soc.* **1988**, 110, 158–162.
- [21] The pH-dependent activity of manganese and iron microperoxidases 8 has been observed in the catalytic oxidation of organic substrates by H₂O₂: J.-L. Primus, M. G. Boersma, D. Mandon, S. Boeren, C. Veeger, R. Weiss, I. M. C. M. Rietjens, *J. Biol. Inorg. Chem.* **1999**, 4, 274–283.
- [22] We do not know why homolysis takes place at low pH and heterolysis predominates at high pH in manganese(III) porphyrin-mediated O–O bond cleavage of H₂O₂ and why the pH-dependent patterns of HO–OH bond cleavage by manganese(III) and iron(III) porphyrin complexes are mutual opposites. More detailed mechanistic studies are needed to elucidate the effect of pH on the O–O bond cleavage mechanism in manganese and iron porphyrin systems.
- [23] H. Saltzman, J. G. Sharefkin, *Organic Syntheses, Collection Vol. V*, Wiley, New York, **1973**, p. 658.

Received: October 31, 2001 [F3646]