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Iron-oxidation-state-dependent O-O bond cleavage of *meta*-chloroperbenzoic acid to form an iron(IV)-oxo complex

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Abstract

The mechanism of formation of $[\text{Fe}^{\text{IV}}(\text{O})(\text{N4Py})]^{2+}$ (**2**, N4Py = *N,N*-bis(2-pyridylmethyl)-*N*-bis(2-pyridyl)methylamine) from the reaction of $[\text{Fe}^{\text{II}}(\text{N4Py})(\text{CH}_3\text{CN})]^{2+}$ (**1**) with *m*-chloroperbenzoic acid (mCPBA) in CH_2Cl_2 at -30°C has been studied on the basis of the visible spectral changes observed and the reaction stoichiometry. It is shown that the conversion of **1** to **2** in 90% yield requires 1.5 equiv peracid and takes place in two successive one-electron steps via an $[\text{Fe}^{\text{III}}(\text{N4Py})\text{OH}]^{2+}$ (**3**) intermediate. The first oxidation step uses 0.5 equiv peracid and produces 0.5 equiv 3-chlorobenzoic acid, while the second step uses 1 equiv peracid and affords byproducts derived from chlorophenyl radical. We conclude that the $\text{Fe}^{\text{II}}(\text{N4Py})$ center promotes O-O bond heterolysis, while the $\text{Fe}^{\text{III}}(\text{N4Py})$ center favors O-O bond homolysis, so the nature of O-O bond cleavage is dependent on the iron oxidation state.

Keywords

Oxoiron(IV) complexes; Non-heme ligands; O-O bond lysis; Iron oxidation state

Introduction

High valent iron-oxo intermediates are considered to be the active species in the catalytic cycles of mononuclear non-heme iron enzymes that activate dioxygen.¹ Within the last four years, such species have been identified in three 2-oxoglutarate dependent monoiron enzymes, namely TauD,² prolyl 4-hydroxylase,³ and the halogenase CytC3,⁴ and characterized as having a high-spin iron(IV) center with a terminal Fe=O unit. In biomimetic studies, a number of mononuclear non-heme iron (IV)-oxo complexes bearing tetradentate and pentadentate ligands have been reported and extensively characterized by a variety of spectroscopic techniques.⁵ Typically, these oxoiron(IV) complexes were synthesized by reaction of respective iron(II) precursors with oxygen atom donors like iodosobenzene or peracids.⁵

The reactions of peracids with iron(III) centers have been studied in detail in the case of porphyrin complexes.⁶ Depending on the solvent, the acylperoxoiron(III) intermediate can undergo O-O bond homolysis or heterolysis, with the more polar solvent favoring the latter.⁶ The recent availability of non-heme oxoiron(IV) complexes provides the opportunity to investigate the reactions of peracids with non-heme iron(II) centers. For example, $[\text{Fe}^{\text{IV}}(\text{O})(\text{TPA})(\text{CH}_3\text{CN})]^{2+}$ (TPA = tris(2-pyridylmethylamine) is formed in quantitative yield from

Dedicated to Professor Edward I. Solomon on the occasion of his 60th birthday

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the reaction of $[\text{Fe}^{\text{II}}(\text{TPA})](\text{OTf})_2$ with one equivalent of peracetic acid in CH_3CN ,^{5c} presumably deriving from the heterolysis of the peracid O-O bond as required by the reaction stoichiometry. In this paper we focus on the formation of $[\text{Fe}^{\text{IV}}(\text{O})(\text{N4Py})]^{2+}$ (**2**, N4Py = *N,N*-bis(2-pyridylmethyl)-*N*-bis(2-pyridyl)methylamine) from the reaction of $[\text{Fe}^{\text{II}}(\text{N4Py})(\text{CH}_3\text{CN})]^{2+}$ (**1**) with *m*-chloroperbenzoic acid (mCPBA) in CH_3CN and CH_2Cl_2 . Insights into the formation of the oxoferryl species derive from the different visible spectral changes observed, as well as the stoichiometry of the reaction. We find that how the O-O bond of the peracid is cleaved depends on the iron oxidation state; an iron(II) center promotes heterolysis, while an iron(III) center favors homolysis.

Experimental

A) Materials

All reagents were purchased from Aldrich. Solvents were purified according to published procedures.⁷ The commercially available 85% *m*-chloroperbenzoic acid was purified by washing with a phosphate buffer of pH 7.5, and drying the residue under reduced pressure. $[\text{Fe}^{\text{II}}(\text{N4Py})(\text{CH}_3\text{CN})](\text{CF}_3\text{SO}_3)_2$ ⁸ and $[\text{Fe}^{\text{II}}(\text{TPA})(\text{CF}_3\text{SO}_3)_2]$ ^{5c} were made according to published methods.

B) Instrumentation

Low temperature UV-vis spectra were recorded on an HP 8453A diode array spectrometer equipped with a USP-203 cryostat from Unisoku Scientific Instruments, Japan. Electrospray ionization mass spectral experiments were carried out on a Bruker BioTOF II mass spectrometer using the following conditions: spray chamber voltage = 4000 V; gas carrier temperature = 200 °C. Samples for ESI-MS analysis were prepared in a 1:1 $\text{CH}_3\text{CN}/\text{H}_2\text{O}$ mixture. Product analyses were performed on a Perkin-Elmer Sigma 3 gas chromatograph (AT-1701 column, 30 m) with a flame ionization detector. GC mass spectral analyses were performed on a HP 5898 GC (DB-5 column, 60 m) with a Finnigan MAT 95 mass detector or a HP 6890 GC (HP-5 column, 30 m) with an Agilent 5973 mass detector. A 4 % NH_3/CH_4 mix was used as the ionization gas for chemical ionization analyses.

Results

The reaction of $[\text{Fe}^{\text{II}}(\text{TPA})](\text{OTf})_2$ with 1 equiv mCPBA in CH_3CN affords $[\text{Fe}^{\text{IV}}(\text{O})(\text{TPA})(\text{CH}_3\text{CN})]^{2+}$ quantitatively (eqn 1).^{5c} The reaction stoichiometry and the appearance of an isosbestic point at 590 nm in the course of the reaction clearly indicated the clean conversion of the iron(II) precursor to the oxoiron(IV) complex.^{5c} A similar result was obtained in the reaction of $[\text{Fe}^{\text{II}}(\text{N4Py})(\text{CH}_3\text{CN})](\text{OTf})_2$ with mCPBA, but 5–6 equiv mCPBA were necessary to obtain **2** in quantitative yield at 25 °C, as indicated by the appearance of its characteristic near-IR band at 696 nm ($\epsilon = 400 \text{ M}^{-1}\text{cm}^{-1}$). As shown in Fig 1, the conversion of **1** to **2** shows isosbestic points at 335 and 578 nm, indicating that, as for the Fe(TPA) complex, the reaction proceeds from **1** to **2** without accumulation of an intermediate (eqn 1). The excess peracid required to oxidize the N4Py complex can be ascribed to the kinetic inertness of the $[\text{Fe}^{\text{II}}(\text{N4Py})(\text{CH}_3\text{CN})]^{2+}$ complex in this solvent, as dissociation of the CH_3CN ligand to make a coordination site available is very likely an important first step.

In contrast, when the reaction was carried out in CH_2Cl_2 , **2** could be generated in 90% yield from **1** by the addition of only 1.5 equiv mCPBA at -30 °C. Spectral changes more complex than found in CH_3CN solution were observed in the course of oxidation and are shown in Fig 2. The reaction involved the initial disappearance of the bands of **1** at 380 and 455 nm along

with the appearance of a new band at 305 nm. However **2** did not form until after the complete disappearance of **1**, and it developed at the expense of the 305 nm band. The progress of the reaction when monitored at 696 nm was thus biphasic, exhibiting a brief initial lag phase followed by first-order growth of the product chromophore (Fig 2 inset). On the other hand, the absorbance at 305 nm increased during the lag phase and decayed concomitantly with the growth of the 696-nm band (Fig 2 inset). This behavior is very similar to that observed previously in the electrochemical oxidation of **1** to **2**, which occurred by two successive one-electron steps via $[\text{Fe}^{\text{III}}(\text{OH})(\text{N4Py})]^{2+}$ (**3**) (eqn 2).⁹

Further insight into the formation of **2** was obtained from reactions of **1** with various amounts of mCPBA in CH_2Cl_2 at -30°C , the results of which are summarized in Fig 3. Introduction of up to 0.5 equiv mCPBA caused the decrease of the characteristic absorptions of the starting complex at 380 and 455 nm and the appearance of the band at 305 nm. An isosbestic point (Fig 4) was observed at 350 nm. ESI-MS analysis of the 305-nm species showed the most prominent ion to have an m/z value of 589.21 and an isotope distribution pattern consistent with the composition $\{[\text{Fe}^{\text{III}}(\text{OH})(\text{N4Py})](\text{CF}_3\text{SO}_3)\}^+$ (Fig 4 inset). This species has an absorption spectrum ($\lambda_{\text{max}} = 305$ nm, shoulder) identical to that of the electrochemically generated one-electron oxidized product of **1** and is thus identified to be **3**.⁹ The subsequent reaction of **3** with another equivalent of mCPBA gave rise to **2** in 90% yield (Figure 5). These observations thus support a reaction sequence in which **1** is first oxidized to **3**, which in turn is converted to **2** (eqn 2). Addition of mCPBA in excess of 1.5 equiv resulted in a decreased yield of **2** (Fig 3) and the generation of a new species with $\lambda_{\text{max}} = 564$ nm. The new species very likely arises from the hydroxylation of bound 3-chlorobenzoate to form the corresponding salicylate complex, as reported previously for the reaction of $[\text{Fe}^{\text{II}}(\text{TPA})(\text{NCCH}_3)_2]^{2+}$ with 3 equiv mCPBA at -40°C .¹⁰

The conversion of **1** to **2** requires 1.5 equiv mCPBA with half an equivalent needed to convert **1** to **3** and a full equivalent needed to convert **3** to **2**. Both steps represent one-electron oxidations, but the different peracid stoichiometries suggest that the peracid must undergo heterolytic O-O bond cleavage in the first step and homolytic O-O bond cleavage in the second step. This notion was corroborated by gas chromatographic analysis of the peracid-derived products in the reaction of **1** with 1.5 equiv of mCPBA at -30°C in CH_2Cl_2 . Observed were 0.45 equiv 3-chlorobenzoic acid, 0.27 equiv chlorobenzene, 0.15 equiv 1,3-dichlorobenzene, and 0.18 equiv 3-chlorophenol. The 0.45 equiv 3-chlorobenzoic acid reasonably matches the peracid stoichiometry for the oxidation of **1** to **3**. We speculate that the first step of the **1**-to-**2** conversion is in fact the oxidation of 0.5 equiv **1** to 0.5 equiv **2**, but the **2** that is formed reacts rapidly with residual **1** to form **3**. This comproportionation is greatly facilitated in CH_2Cl_2 by the partial dissociation of the CH_3CN ligand of **1**, which converts low-spin six-coordinate **1** to a high-spin five-coordinate derivative that can rapidly react with **2**. In contrast, the dissociation of CH_3CN from **1** is significantly inhibited in CH_3CN by a mass action effect, so formation of **3** is not observed in CH_3CN .

The remaining observed products are formed from the chlorophenyl radical that derives from O-O bond homolysis of mCPBA upon binding to **3** in the second step (eqn 3).

The chlorophenyl radical could abstract hydrogen or chlorine atoms from the CH_2Cl_2 solvent or react with O_2 to form the observed products. Although these byproducts represent only 67% of the 0.9 equiv chlorophenyl radical that was expected to be formed, the amounts observed are sufficient to establish that O-O bond homolysis of mCPBA does occur in the oxidation of **3** to **2**.

The reactions of **1** and **3** with mCPBA both afford **2**. These observations lead to the interesting conclusion that the $\text{Fe}^{\text{II}}(\text{N4Py})$ center promotes O-O bond heterolysis, while the $\text{Fe}^{\text{III}}(\text{N4Py})$ center favors O-O bond homolysis. Such a difference in the O-O bond cleavage mode has been noted previously by Foster and Caradonna in their investigation of the reactions of non-heme diiron(II) and diiron(III) complexes with ROOH.¹¹ We note also that the recently reported first example of an oxoiron(V) complex was generated from the reaction of its iron(III) precursor with mCPBA in butyronitrile at -60°C in two one-electron oxidation steps,¹² like what we observed for the conversion of **1** to **2** in CH_2Cl_2 . It will thus be of great interest to refine our understanding of the roles the oxidation and spin states of the iron center play in determining the mode of peroxo O-O bond lysis.

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References

1. (a) Solomon EI, Brunold TC, Davis MI, Kemsley JN, Lee S-K, Lehnert N, Neese F, Skulan AJ, Yang Y-S, Zhou J. *Chem Rev* 2000;100:235. [PubMed: 11749238] (b) Costas M, Mehn MP, Jensen MP, Que L Jr. *Chem Rev* 2004;104:939. [PubMed: 14871146] (c) Abu-Omar MM, Loaiza A, Hontzeas N. *Chem Rev* 2005;105:2227. [PubMed: 15941213]
2. (a) Bollinger JM Jr, Price JC, Hoffart LM, Barr EW, Krebs C. *Eur J Inorg Chem* 2005;4245. (b) Krebs C, Price JC, Baldwin J, Saleh L, Green MT, Bollinger JM Jr. *Inorg Chem* 2005;44:742. [PubMed: 15859243]
3. Hoffart LM, Barr EW, Guyer RB, Bollinger JM Jr, Krebs C. *Proc Natl Acad Sci USA* 2006;103:14738. [PubMed: 17003127]
4. Galonic DP, Barr EW, Walsh CT, Bollinger JM Jr, Krebs C. *Nat Chem Biol* 2007;3:113. [PubMed: 17220900]
5. (a) Grapperhaus CA, Mienert B, Bill E, Weyhermüller T, Wieghardt K. *Inorg Chem* 2000;39:5306. [PubMed: 11187471] (b) Rohde JU, In JH, Lim MH, Brennessel WW, Bukowski MR, Stubna A, Münck E, Nam W, Que L Jr. *Science* 2003;299:1037. [PubMed: 12586936] (c) Lim MH, Rohde JU, Stubna A, Bukowski MR, Costas M, Ho RYN, Münck E, Nam W, Que L Jr. *Proc Natl Acad Sci USA* 2003;100:3665. [PubMed: 12644707] (d) Kaizer J, Klinker EJ, Oh NY, Rohde JU, Song WJ, Stubna A, Kim J, Münck E, Nam W, Que L Jr. *J Am Chem Soc* 2004;126:472. [PubMed: 14719937] (e) Balland V, Charlot MF, Banse F, Girerd JJ, Mattioli TA, Bill E, Bartoli JF, Battioni P, Mansuy D. *Eur J Inorg Chem* 2004;301. (f) Jensen MP, Costas M, Ho RYN, Kaizer J, Mairata i Payeras A, Münck E, Que L Jr, Rohde J-U, Stubna A. *J Am Chem Soc* 2005;127:10512. [PubMed: 16045338] (g) Bukowski MR, Koehntop KD, Stubna A, Bominaar EL, Halfen JA, Münck E, Nam W, Que L Jr. *Science* 2005;310:1000. [PubMed: 16254150] (h) Decker A, Rohde JU, Que L Jr, Solomon EI. *J Am Chem Soc* 2004;126:5378. [PubMed: 15113207] (i) Shan X, Que L Jr. *J Inorg Biochem* 2006;100:421. [PubMed: 16530841]
6. Groves JT, Watanabe Y. *J Am Chem Soc* 1988;110:8443.
7. Armarego, WLF.; Perrin, DD. *Purification of Laboratory Chemicals*. Pergamon Press; 1997.
8. Rohde J-U, Torelli S, Shan X, Lim MH, Klinker EJ, Kaizer J, Chen K, Nam W, Que L Jr. *J Am Chem Soc* 2004;126:16750. [PubMed: 15612713]
9. Collins MJ, Ray K, Que L Jr. *Inorg Chem* 2006;45:8009. [PubMed: 16999397]
10. Oh NY, Seo MS, Lim MH, Consugar MB, Park MJ, Rohde JU, Han J, Kim KM, Kim J, Que L Jr, Nam W. *Chem Commun* 2005:5644.
11. Foster TL, Caradonna JP. *J Am Chem Soc* 2003;125:3678. [PubMed: 12656580]

12. Tiago de Oliveira F, Chanda A, Banerjee D, Shan X, Mondal S, Que L Jr, Bominaar EL, Münck E, Collins TJ. Science 2007;315:835. [PubMed: 17185561]

Figure 1. Spectral changes associated with the reaction of 0.25 mM solution of **1** with 6 equiv of mCPBA in CH_3CN at 25 °C. The inset shows the corresponding time course of the reaction monitored at 696 nm.

Figure 2. Spectral changes associated with the reaction of 0.3 mM solution of **1** with 1.5 equiv of mCPBA in CH_2Cl_2 at -30°C . The inset shows the corresponding time course of the reaction monitored at 696 nm and 305 nm.

Figure 3
. Yields of **2** obtained after addition of different amounts of mCPBA to solutions of **1** in CH_2Cl_2 at -30°C .

Figure 4. Spectral changes associated with the reaction of 0.3 mM **1** in CH_2Cl_2 with 0.5 equiv mCPBA at -30°C . Inset: Isotope distribution pattern of the most prominent ion in the ESI-MS spectrum of the product solution.

Figure 5. Spectral changes associated with the formation of **2** by reaction of **3** with 1 equiv of mCPBA in CH_2Cl_2 at -30°C . The inset shows the corresponding time course of the reaction monitored at 696 nm and 305 nm.