O-Fe structural unit failed to reveal resonance-enhanced Raman modes attributable to the Fe-O-Fe symmetric stretch using 488.0-nm excitation.[29] It is possible that this vibrational feature might have been observed in some of these complexes with excitation in the near-ultraviolet region.

Conclusion

Comparisons of structural, magnetic, and vibrational spectroscopic properties of a number of μ-oxo-bridged binuclear iron complexes are given in Table V. As has been discussed previously,[34,47] the Fe-O distances fall within a narrow range whereas the Fe-O-Fe angles (and, therefore, Fe-Fe separations) are much more variable. Furthermore, these complexes show a high degree of antiferromagnetic interaction, which appears to be a consequence of Fe-O σ bonding and is relatively unrelated to bond angle. The Fe-O-Fe vibrations, on the other hand, do appear to correlate with bond angle as has been delineated by Wing and Callahan[40] for oxo-bridged complexes of molybdenum. The general trend of ν_{as}(Fe-O-Fe) to decrease with decreasing bond angle and of ν_s(Fe-O-Fe) to increase with decreasing bond angle is borne out by the iron complexes in Table V. The $^{16}O \rightarrow {}^{18}O$ frequency shifts of 5-18 cm^{-1} for ν_s(Fe-O-Fe) and 40-60 cm^{-1} for ν_{as}(Fe-O-Fe) are also within the ranges expected for these bridged structures.[40]

The singly bridged μ-oxo dimers have long been considered as good models for the electronic and magnetic properties of binuclear iron proteins such as hemerythrin and ribonucleotide reductase. The work reported here indicates that these complexes are also appropriate models for the resonance Raman spectroscopic properties of these binuclear iron proteins. Although the iron complex in hemerythrin contains two carboxylate bridges in addition to a μ-oxo bridge,[10-12] its spectroscopic and magnetic characteristics appear to be dominated by the Fe-O-Fe component. This is further supported by work on the recently described binuclear iron complex $[Fe_2O(CH_3COO)_2(HB(pz)_3)_2]$,[45] in which the irons share three bridging groups, a μ-oxo and two bidentate carboxylates, as in hemerythrin. The vibrational spectroscopic values of the triply bridged complex (Table V) are in the range expected for an Fe-O-Fe species with a bridging angle of 124°.

Acknowledgment. The Nicolet R3m/E X-ray diffractometer and crystallographic computer system at Colorado State University were purchased with funds provided by a National Science Foundation grant (CHE 81-03011). Research at the Oregon Graduate Center was generously supported by a grant from the National Institutes of Health (GM 18865). The authors thank Joann Sanders-Loehr and Andrew K. Shiemke for helpful disscussions and critical reading of the manuscript and Stephen J. Lippard for communicating results prior to publication.

Registry No. $[Fe_2O(phen)_4(H_2O)_2]Cl_4$, 92282-00-3; $[Fe_2O(phen)_4(H_2O)_2](NO_3)_4 \cdot 5H_2O$, 92282-02-5; $[Fe_2O(phen)_4(H_2O)_2](ClO_4)_4$, 92217-00-0; $Fe(phen)_3(ClO_4)_3$, 14634-90-3; ^{18}O, 14797-71-8.

Supplementary Material Available: Tables of anisotropic thermal parameters, calculated coordinates and U's for hydrogen atoms, metric parameters for unconstrained nitrate groups, site occupancy factors, and structure factors (38 pages). Ordering information is given on any current masthead page.

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Iron Porphyrin Models of Peroxidase Enzyme Intermediates: Oxidation of Deuteroferriheme by C_6H_5IO and $C_6H_5I(OAc)_2$

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Received October 28, 1983

Treatment of the iron(III) complex of deuteroporphyrin IX, deuteroferriheme, with iodosobenzene or (diacetoxyiodo)benzene (commonly called iodobenzene diacetate) yields an oxidized form of the iron porphyrin which is spectrally identical to that obtained from heme oxidation by peroxo substrates and chlorite ion and which mimics the catalytic activity of reaction intermediates derived from hemoprotein peroxidase enzymes. Two moles of iron porphyrin is stoichiometrically equivalent to 1 mol of oxidant, suggesting the heme-derived "intermediate state" to consist of one or more one-electron oxidation products of heme iron(III). Stopped-flow spectrophotometric determination of the rate of intermediate formation shows a first-order dependence on both *monomeric* heme and oxidant, the second-order rate constant for oxidation by iodobenzene diacetate being about twice that obtained with iodosobenzene. This is tentatively attributed to a statistical factor associated with O-atom donation of C_6H_5I-bound oxygen to the iron(III) center. Regeneration of free heme from "intermediate state" is dependent on the nature and concentration of oxidant and is suggested to involve catalytic turnover of oxidant analogous to heme-catalyzed decomposition of H_2O_2.

Introduction

Numerous studies of the peroxidase-like catalytic activity of iron(III) porphyrins (hemes) have focused on the oxidative formation and reactivity of intermediate species that appear to be functional analogues of intermediates generated in hemoprotein enzyme systems.[1-11] Such studies are somewhat complicated by the tendency of the protein-free hemes to aggregate in aqueous solution,[12-14] since it is the nonaggregated

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or monomeric form of the iron porphyrin that is believed to be dominant in terms of reactivity with substrate oxidant.[2] Since deuteroferriheme (dfh), the iron(III) complex of deuteroporphyrin IX, undergoes dimerization to a lesser degree than some structurally related complexes,[14] this species has found widespread use as a catalytic model. Of particular interest has been the stoichiometry and kinetics of dfh oxidation by peroxides and other oxygen-containing substrates, the peroxidatic reactivity of the resulting intermediate species (the "intermediate state"), and more recently, the relevance of intermediate formation to heme-catalyzed chlorination reactions of chlorite ion.[15]

The reaction of heme with substituted peroxobenzoic acids has been shown to display the stoichiometric ratio [monomeric heme iron(III)]:[peroxo acid] = 2:1,[4] implying an equivalence of 1 mol of heme to 1 equiv of oxidant. Based in part on the widely accepted notion that hemoprotein enzymes such as catalase and selected peroxidases undergo two-electron oxidations to form catalytically active reaction intermediates believed to contain iron-bound oxygen (denoted as compound I species)[16,17] and, in part, on the known tendency of iron(III) porphyrins to form oxo-bridged dinuclear complexes,[18,19] the peroxo acid–dfh reaction was proposed to proceed via an initial two-electron oxidation of monomeric heme Fe(III) followed by reaction of the product (depicted formally as "FeO") with a second heme Fe(III) unit, possibly involving formation of a "dimeric heme" entity.[4] Consistent with the peroxo acid–heme stoichiometry are results obtained through a study of heme oxidation by oxyhalide species ClO_2^- and OCl^-.[9] The molar equivalence Fe(III):ClO_2^- = 4:1, observed for the reaction of dfh with (four-electron oxidant) chlorite ion, has been interpreted in terms of successive two-electron oxidations by ClO_2^- and OCl^-, respectively, each occurring through O atom transfer to separate heme Fe(III) centers followed by comproportionation of each "FeO" species with a free heme Fe(III). This formally corresponds to one-electron oxidation of four monomeric heme Fe(III) molecules. Whether the oxidized "intermediate state" consists of a single species or an equilibrium mixture has not been demonstrated, although formation of an oxo-bridged dinuclear complex has been suggested in which each iron center is formally denoted as Fe(IV), implying the same oxidation state at each metal center.[9] An alternative view of intermediate aggregation to a "mixed-oxidation-state dimer" also has been suggested.[11] It is of particular interest that the optical spectrum of the solution of "intermediate state" is independent of whether the oxidant used in its formation is peroxo acid or ClO_2^- and that kinetic parameters describing the peroxidatic oxidation of selected species, such as I^- and various phenols, are the same whether the intermediate state is generated from ClO_2^- or H_2O_2.[5,9]

The present study of heme oxidation by (diacetoxyiodo)-benzene (commonly called iodobenzene diacetate) and iodosobenzene was undertaken in an effort to further explore the nature of the heme-derived intermediate state and was prompted, in part, by reports of the use of iodosobenzene and derivatives as oxygen donors in reactions of cytochrome P-450.[20,21] Additional studies of iodosobenzene interaction with selected metalloporphyrin systems also have been reported.[21-25]

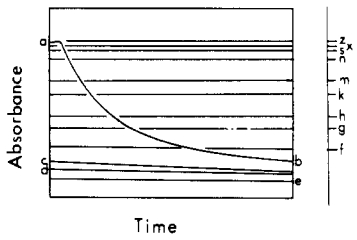

Figure 1. Stopped-flow trace for reaction of dfh with C_6H_5IO ($[dfh]_0 = 9 \times 10^{-6}$ M; $[C_6H_5IO]_0 = 5 \times 10^{-6}$ M; pH 7.13; μ = 0.1 M; λ = 384 nm; T = 25 °C): (a) mixing at t_0; (b) completion of first scan, t = 0.1 s; (c) start of second scan; (d) start of third scan; (e) A_∞; (f) t = 20 s; (g) t = 40 s; (h) t = 1 min; (k) t = 2 min; (m) t = 3 min; (n) t = 6 min; (s) t = 9 min; (x) t = 12 min; (z) t = 30 min. ΔA_{max} for a–e = 0.6A.

Experimental Section

Deuteroferriheme (dfh) was prepared from triply recrystallized hemin (Nutritional Biochemicals Corp.) via the resorcinol melt method and characterized as the pyridine ferrohemochrome,[26] spectrophotometric analysis of which revealed purity in excess of 99% ($\epsilon = 2.4 \times 10^4$ M^{-1} cm^{-1} at λ = 544 nm). Iodobenzene diacetate of 98% purity was obtained from Aldrich.

Iodosobenzene was prepared as described by Saltzman and Sharefkin.[27] An 8.05-g (0.025-mol) sample of $C_6H_5I(OAc)_2$ was placed in a 150-mL three-neck flask and stirred with 40 mL of 3 N NaOH for 5 min. The reaction mixture was allowed to stand for 45 min, following which 25 mL of H_2O was added with vigorous stirring. The solid product was collected by filtration, washed with H_2O, and dried over anhydrous $CaSO_4$; yield 4.2 g (76% theory). Iodometric analysis showed 98% purity.

Reactant solutions were prepared with use of deionized water that was subsequently passed through a Barnstead mixed-bed ion-exchange column (conductivity <0.01 ppm measured as NaCl). Buffer components Na_2CO_3, $NaHCO_3$, Na_2HPO_4, and KH_2PO_4 were of analytical reagent grade. Buffered solutions of heme contained 70 mM total buffer and were adjusted to an ionic strength of μ = 0.2 M. Unbuffered solutions of C_6H_5IO and $C_6H_5I(OAc)_2$ were prepared by dilution of the respective aqueous stock solutions, and oxidant concentrations were determined by iodometric analysis. All oxidant solutions were prepared shortly before their use in kinetic studies. Although disproportionation of iodosobenzene occurs upon steam distillation,[28] heme–oxidant reactions were studied at 25 °C and corresponding stopped-flow traces were reproducible, indicating no significant alteration of C_6H_5IO concentration in oxidant solutions during the time frame of studies described below.

Spectrophotometric measurements were performed at 25 °C on Perkin-Elmer Model 552 and Gilford Model 250 UV–visible spectrophotometers and pH measurements on a Corning Model 130 digital pH meter. A Durrum-Gibson D-110 stopped-flow spectrophotometer was used in conjunction with a Tektronix oscilloscope for stoichiometric studies. An initial reference absorbance was obtained with a solution

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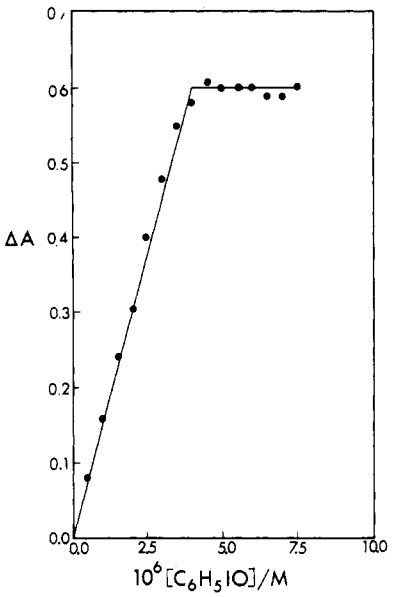

Figure 2. Stopped-flow spectrophotometric titration of dfh with C_6H_5IO (pH 7.13; λ = 384 nm; μ = 0.1 *M*; *T* = 25 °C; $[dfh]_0 = 9 \times 10^{-6}$ M; $[dfh]/[C_6H_5IO] = 2.2/1.0$).

resulting from the stopped-flow mixing of a buffered heme solution with an equal volume of H_2O. The maximum decrease in optical density, ΔA_{max}, at 384 nm corresponding to the oxidation of heme to "intermediate state" was then measured for a series of reactions in which solutions, each containing a fixed initial concentration of heme, were mixed with equal volumes of solutions containing different amounts of C_6H_5IO or $C_6H_5I(OAc)_2$. Such reaction solutions contained 35 mM total buffer and μ = 0.1 M. A similar experimental technique was employed in kinetic studies wherein absorbance changes were followed as a function of time.

Point spectra of heme and its "intermediate state" were obtained at pH 7.13 by subtracting ΔA_{max} from the heme absorbance at 5-nm intervals between 250 and 420 nm. Continuous spectra also were obtained at pH 7.74 on solutions prepared by rapidly mixing 10 μM heme with equal volumes of 10 μM C_6H_5IO and 10 μM $C_6H_5I(OAc)_2$, respectively. The heme spectrum was determined on a solution 5 μM in dfh. In each case, spectra were scanned from 250 to 400 nm with use of buffered solutions as references.

Results and Discussion

Treatment of deuteroferriheme with iodosobenzene or iodobenzene diacetate produces a decrease in absorption in the Soret band region of the heme spectrum similar to the effect of peroxides and species such as ClO_2^- and OCl^-, which are presumed to serve as oxygen atom donors in the oxidation of the iron(III) porphyrin to its peroxidatically active "intermediate state". A typical stopped-flow trace showing the time dependence of absorbance in the dfh–C_6H_5IO system is shown in Figure 1. After relatively rapid attainment of a minimum level of optical density, A_{min}, a slower increase in absorbance is observed eventually leading to essentially complete restoration of the initial heme absorbance, A_0. The rate of the regeneration process is found to increase with increasing initial concentrations of C_6H_5IO.

The maximum decrease in optical density ($\Delta A_{max} = A_0 - A_{min}$) corresponds to maximum conversion of heme to its "intermediate state" under the conditions of the given stopped-flow experiment. When this reaction is sufficiently fast to approach completion before subsequent reactions involving heme or the resulting intermediate species (e.g., heme regeneration) can occur, the molar equivalency of heme to oxidant may be determined through a stopped-flow "titration" in which ΔA_{max} is measured as a function of oxidant concentration for a given initial concentration of heme (Figure 2). The equivalence point corresponds to the intersection of the line of positive slope, obtained with oxidant concentrations

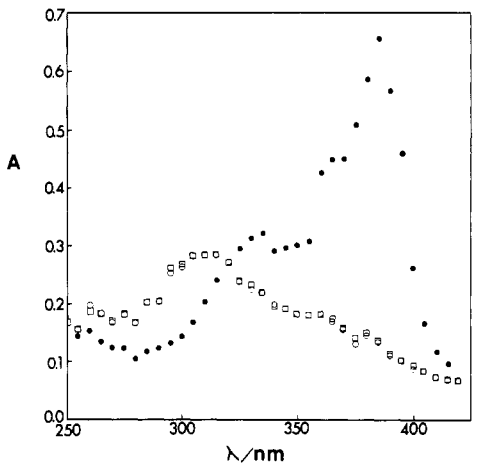

Figure 3. Absorption spectra from stopped-flow spectrophotometric studies (pH 7.13; μ = 0.1 M; *T* = 25 °C): (●) 6×10^{-6} M dfh + H_2O; (○) 6×10^{-6} M dfh + 6×10^{-6} M C_6H_5IO; (□) 6×10^{-6} M dfh + 6×10^{-6} M *m*-chloroperoxobenzoic acid.

below that of stoichiometric equivalence, with the horizontal that defines ΔA_{max} for oxidant sufficient for complete conversion of heme to intermediate(s). The observed molar ratio [heme Fe(III)]:$[C_6H_5IO]$ = 2.2:1 is consistent with results of previous studies with substituted peroxobenzoic acids and chlorite ion at pH 7–7.5, which show a ratio of 1 mol of heme Fe(III) to one oxidizing equivalent of oxidant. A similar result is obtained with iodobenzene diacetate; $[Fe(III)]/[C_6H_5I(OAc)_2]$ = 2.2:1.

At concentrations of iodosobenzene greater than twice the stoichiometric equivalence of heme, ΔA_{max} decreases with increasing concentration of oxidant. This may be due to enhancement of oxidant-dependent heme regeneration to the degree that this reaction is no longer negligible compared to that of intermediate formation, the result being a steady-state concentration of intermediate lower than that corresponding to stoichiometric conversion. It has been shown that lower the stoichiometric steady-state concentrations of the heme-derived intermediate(s) arise via oxidation by H_2O_2 due to the catalase-like decomposition of oxidant.[1,2,4] Also, in the dfh–chlorite system, the *apparent* heme–ClO_2^- equivalence ratio decreases with increasing alkalinity in the region pH 8–10, an effect attributed to an increase in the *relative* rate of regeneration resulting from decreasing rates of intermediate formation with increasing pH.

In Figure 3 are shown point spectra of solutions containing 6 μM heme, 6 μM heme + 6 μM *m*-chloroperoxybenzoic acid, and 6 μM heme + 6 μM iodosobenzene. Within experimental error, spectra of the corresponding intermediate states are superimposable. As noted earlier, previous studies have shown virtually identical spectra of solutions derived from heme oxidation by *m*-chloroperoxybenzoic acid and ClO_2^- and comparable kinetic parameters for the peroxidatic activity of intermediate originating from the reaction of heme with ClO_2^- and with H_2O_2. Continuous scanning of solutions prepared by rapidly mixing dfh separately with C_6H_5IO and $C_6H_5I(OAc)_2$ also produce comparable spectra. It is evident that the same "intermediate state" is obtained through heme oxidation by a variety of oxidants that now include iodosobenzene and iodobenzene diacetate.[29]

As expected, the rate of formation of intermediate state is dependent upon the nature of the oxidant, and Tables I and

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Table I. Rates of Formation of Intermediate State from Deuteroferriheme and Iodosobenzene[a]

pH	$10^6 \times$ [dfh], M	$10^{-6} \times k_2$, M^{-1} s^{-1} [b]	α[c]	$10^{-7} \times k_m$, M^{-1} s^{-1} [d]	$10^{-7} \times k_m$(av), M^{-1} s^{-1}
7.13	3.0	14.9	0.45	3.3	2.7
	6.0	8.9	0.34	2.6	
	9.0	6.4	0.29	2.2	
7.29	3.0	12.3	0.39	3.2	2.7
	6.0	7.4	0.30	2.5	
	9.0	5.8	0.25	2.3	
7.53	3.0	7.5	0.31	2.4	2.5
	6.0	7.3	0.30	2.4	
	9.0	5.3	0.20	2.7	
7.75	3.0	5.9	0.26	2.3	2.5
	6.0	4.7	0.19	2.5	
	9.0	4.2	0.16	2.6	
7.97	3.0	4.7	0.20	2.3	2.6
	6.0	4.3	0.15	2.7	
	9.0	3.3	0.12	2.8	
8.63	3.0	2.5	0.10	2.5	2.6
	5.0	2.1	0.080	2.6	
	7.0	1.8	0.068	2.6	
	9.0	1.5	0.060	2.5	
8.78	3.0	1.7	0.086	2.0	2.4
	5.0	2.1	0.068	3.1	
	7.0	1.0	0.057	1.8	
	9.0	1.5	0.057	2.5	
9.18	3.0	1.4	0.055	2.5	2.6
	5.0	1.1	0.043	2.6	
	7.0	1.1	0.037	3.0	
	9.0	0.79	0.032	2.5	
9.62	3.0	0.81	0.034	2.4	2.6
	5.0	0.54	0.026	2.1	
	7.0	0.62	0.022	2.8	
	9.0	0.59	0.020	3.0	

[a] Conditions: $T = 25$ °C; $\mu = 0.1$ M; 2-20-fold molar excess $[C_6H_5IO]_0$ over [monomeric dfh]. [b] $k_2 = d[dfh]/([dfh][dt \times [C_6H_5IO])$. [c] $\alpha = [dfh]_m/[dfh]_0$, where $[dfh]_m$ denotes [monomeric dfh] and $[dfh]_0$ denotes stoichiometric dfh (=[monomeric dfh] + $\frac{1}{2}$[dimeric dfh]). [d] $k_m = k_2/\alpha$.

Table II. Rates of Formation of Intermediate State from Deuteroferriheme and Iodosobenzene Diacetate[d]

pH	$10^6 \times$ [dfh], M	$10^6 \times [C_6H_5I(OAc)_2]$, M	$10^{-7}k_2$, M^{-1} s^{-1} [a]	α[b]	$10^{-7}k_m$, M^{-1} s^{-1} [c]	$10^{-7} \times k_m$(av), M^{-1} s^{-1}
7.07	3.0	3.5	2.4	0.47	5.1	5.5
	5.0	5.5	2.0	0.39	5.1	
	7.0	7.5	2.1	0.34	6.2	
	9.0	10.0	1.7	0.31	5.5	
7.28	3.0	3.5	2.7	0.39	6.9	6.8
	5.0	5.5	2.4	0.32	7.5	
	7.0	7.5	1.9	0.28	6.8	
	9.0	10.0	1.5	0.25	6.0	
7.51	3.0	3.5	2.0	0.32	6.3	7.0
	5.0	5.5	1.8	0.26	6.9	
	7.0	9.0	1.6	0.22	7.3	
	9.0	10.5	1.5	0.20	7.5	
7.74	3.0	4.5	1.5	0.26	5.8	5.7
	5.0	5.5	1.2	0.21	5.7	
	7.0	9.0	1.0	0.18	5.6	

[a] $k_2 = 1/(a-b) \ln [b(a-x)/(a(b-x))]$, where a and b represent initial concentrations of $C_6H_5I(OAc)_2$ and dfh and x = reaction variable. [b] Values calculated from data of ref 12. [c] $k_m = k_2/\alpha$. [d] Conditions: $T = 25$ °C; $\mu = 1.0$ M.

II show data for dfh oxidation by C_6H_5IO and $C_6H_5I(OAc)_2$, respectively. Under the experimental conditions employed, reactions were found to be first order each in heme and oxidant. Second-order rate constants were determined by a second-order treatment in the case of $C_6H_5I(OAc)_2$ and under pseudo-first-order conditions of excess oxidant in the case of C_6H_5IO. In both cases, the second-order rate constant, k_2, is seen to vary with stoichiometric dfh concentration but in a manner that reflects a first-order dependence on *heme monomer*. Thus, division of k_2 by α, defined as the fraction of heme present in monomeric form,[30] yields the dfh concentration-independent second-order rate constant k_m.

Data are consistent, therefore, with the suggestion that heme oxidation occurs via O-atom transfer to the iron center of the monomeric form of the metal porphyrin as depicted in Scheme I, where $XO_n^{m\pm}$ denotes the oxidant, Fe(III) depicts monomeric dfh, and "FeO", the initially formed two-electron-oxidation product without commitment as to the location of specific oxidation sites in the molecule. Analogous hemoprotein intermediates have been suggested to be Fe(IV)–cation radical species.[31] It also should be noted that an iron(III) porphyrin–π-cation radical has been proposed as the product of *one-electron* oxidation of ferric porphyrins.[32]

Scheme I

$$Fe(III) + XO_n^{m\pm} \rightleftharpoons Fe^{III}{\cdot}XO_n^{m\pm} \rightarrow \text{"FeO"} + XO_{n-1}^{m\pm} \quad (1)$$

$$\text{"FeO"} + Fe(III) \rightleftharpoons \underset{\text{(intermediate state)}}{Fe^{IV}OFe^{IV}} \quad (2)$$

$$\text{intermediate state} \xrightarrow{XO_n^{m\pm}} 2Fe(III) + \text{substrate reaction products} \quad (3)$$

The [Fe(III)][[oxidant] ratio is proposed to result from reaction of a second Fe(III) species with the initially formed two-electron-oxidation product. This is depicted in (2) as a comproportionation reaction wherein Fe^{IV}_2O denotes a possible aggregated form of the intermediate state. Whether this should be regarded as a species actually containing Fe(IV) or one in which the oxidation site lies elsewhere is unresolved. Fe(IV) porphyrins have been proposed as products of one-electron electrochemical oxidations of ferric porphyrins,[33] whereas an Fe(III) porphyrin–cation radical species has been suggested from reactivity correlations in dfh–peroxobenzoic acid systems.[11,34] Equation 3 denotes an oxidant-dependent pathway for heme regeneration of which little is known mechanistically. It may involve a catalase-like decomposition of substrate oxidant that proceeds at a rate specific for each $XO_n^{m\pm}$ species formally similar to the oxidative decomposition of H_2O_2, in which case, decomposition products will be $XO_{n-1}^{m\pm} + O_2$. It is possible that heme regeneration occurs through more than one pathway.

Scheme I also acknowledges possible reversibility of (2), and in accord with observed saturation kinetics in previous studies of heme oxidation, "FeO" is presumed to arise from the decomposition of a reversibly formed heme–oxidant complex.[1-3,10] Direct complexation of $C_6H_5IO(OAc)$ and C_6H_5IO to porphyrin-bound metal centers has been considered in a variety of studies of metal complex–iodosobenzene oxidizing systems.[20,21,23,25]

(30) The term α, defined as [monomeric dfh]/([monomeric dfh] + $\frac{1}{2}$[dimeric dfh]), is derived from spectral studies and is pH and dfh concentration dependent.[12] It should also be noted that studies of the monomer–dimer interconversion by relaxation methods suggest aggregation equilibria to be attained rapidly relative to the rate of oxidation of dfh monomer.

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Since stopped-flow titrations show the heme Fe(III):oxidant ratio to be the same for both oxidants (2.2:1), it is clear that only one oxygen of a $C_6H_5I(OAc)_2$ molecule is used in intermediate formation. The respective k_m terms, therefore, indicate the reactivity of iodobenzene diacetate toward monomeric dfh to be about twice that of iodosobenzene. It seems likely that this may reflect a statistical factor arising from the diacetate having two equivalent oxygen atoms for potential donation to the heme iron center. If such is the case, there appears to be little discrimination between the substrates with respect to attack of heme Fe(III) at C_6H_5I-bound oxygen.

As shown in Table I, the rate of intermediate formation from heme and C_6H_5IO is independent of $[H^+]$ in the region pH 7.1–9.6. This contrasts with the oxidation of dfh by ClO_2^-, wherein rates diminish with increasing alkalinity in the same region, and by H_2O_2, in which a first-order dependence on OH^- is observed. In the dfh–ClO_2^- system, the observed pH dependence may be due to the importance of chlorous acid as an oxidizing substrate; however, this remains speculative. The hydroxide ion dependence of heme oxidation by H_2O_2 has been attributed to HO_2^- serving as the active form of the oxidant, and rate enhancement in the H_2O_2–dfh system observed in phosphate buffers has been suggested to be due to $H_2PO_4^-$ facilitating decomposition of a heme–HO_2^- complex to the "FeO" structure.[2] Similar acid–base ionization is not possible in iodosobenzene, and the absence of a pH effect here offers additional indirect support for the contention that intermediate formation from dfh and H_2O_2 does indeed proceed via attack of heme by oxidant conjugate base, i.e., perhydroxyl anion.[2]

Acknowledgment. This research was supported by The Robert A. Welch Foundation (Grant P-162).

Registry No. Iodosobenzene, 536-80-1; iodobenzene diacetate, 29733-61-7; dfh, 21007-21-6.

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Oxidative Electrochemistry of Iron Thiocarbonyl Porphyrins

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Received August 24, 1983

The oxidative electrochemistry of thiocarbonyl(5,10,15,20-tetraphenylporphinato)iron(II), (TPP)FeCS, was studied in 1,2-dichloroethane solution at a Pt-button electrode. Results from detailed voltammetric and combined electronic, IR, and EPR spectroelectrochemical experiments indicated that (TPP)FeCS can be oxidized in two chemically reversible, one-electron transfers. This is in marked contrast with the analogous carbon monoxide Fe(II) porphyrin derivative that loses CO concomitantly with the removal of the first electron. The product of the first oxidation is a thiocarbonyl Fe(III) porphyrin whereas the second oxidation step occurs at the periphery of the porphyrin ring, producing a thiocarbonyl Fe(III) porphyrin radical. Addition of nitrogenous bases to solution generated the monoadduct (TPP)FeCS[nitrogenous base]. This adduct was also oxidized in two discrete, one-electron transfers. The product of the first oxidation, $\{(TPP)Fe^{III}CS$-[nitrogenous base]$\}^+$, was stable for hours. The product of the second oxidation, however, readily underwent nucleophilic attack by uncomplexed nitrogenous base present in solution. The electronic effects generated by the ligand trans to the thiocarbonyl moiety are discussed in the context of their influence on the spectral, electrochemical, and thermodynamic properties of the thiocarbonyliron porphyrin.

Introduction

Synthetic iron porphyrin complexes possessing an iron–carbon bond have received considerable attention recently. The impetus has been provided by the discovery of cytochrome P-450 complexes possessing this bonding moiety.[2] These complexes were formed during the metabolic reduction of polyhalogenated compounds. Such compounds have found widespread use as industrial solvents and as toxic components in fungicide and insecticide formulations. A detailed knowledge of the redox stability of the iron–carbon bond is essential for a complete understanding of this particular aspect of the biochemistry of cytochrome P-450.

Three approaches for preparing synthetic Fe porphyrin compounds with an Fe–C bond have been developed: (1) the direct reaction of Fe porphyrins with isocyanides; (2) the reaction of Fe(I) porphyrins with alkyl halides to form (σ-alkyl)porphyrins; (3) the reaction of either Fe(III) or Fe(II) porphyrins with polyhalogenated compounds under reducing conditions to form iron carbene complexes. The first two schemes have been known for sometime.[3,4] Lexa and co-workers[5] have investigated the electroreduction of the (σ-alkyl)porphyrins in detail. Elliott and Marrese[6] have exploited the second reaction sequence and demonstrated its utility in electrocatalysis. The third reaction scheme has been extensively explored by Mansuy and co-workers.[7]

A particularly intriguing carbene ligand is thiocarbonyl. Relatively few complexes of this type are known, due to the instability of C≡S. The synthetic routes to these complexes have involved either the reduction of thiophosgene or the

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0020-1669/84/1323-3563$01.50/0