J. Am. Chem. Soc. **1986**, *108*, 5495-5503

ports,[19,20] from $1/k_{obsd} = 1/k_i + \{(K_i/k_i)/[I]\}\{1 + [S]/K_m\}$. Extrapolation of $1/k_{obsd}$ to $[S] = 0$ by linear least squares gives $(K_i/k_i)/[I]$ since $1/k_i$ is negligible in our experiments.

In experiments with trypsin, an excess of >20-fold in enzyme over NPN was used. Liberation of 4-nitrophenol was first order. Division of k_{obsd} by the enzyme concentration yielded k_i/K_i.

Stoichiometry. These measurements were conducted at the pH optimum for each enzyme in the buffer systems used for kinetic studies and are summarized in Tables IV and V for MPN and NPN, respectively. Aliquots of the methanolic stock solutions of the inhibitors were injected into preequilibrated buffer solutions followed by the injection of the enzymes from stock solutions. Release of 4-nitrophenol, monitored at 400 nm, leveled off within 20 min with NPN and within 15–23 h with MPN. Remaining enzyme activities were measured after these times by the addition of the appropriate reagents to the reaction mixture.

Enzyme-active-site molarities of stock enzyme solutions and inhibited enzyme solutions were determined according to Bender et al.[21] for chymotrypsin, elastase, and subtilisin. To 940 μL of a buffer solution was added 10 μL of a stock solution of 4-nitrophenyl acetate (stock solution, 70 mM; final concentration after enzyme addition, 0.7 mM). The absorbance was recorded for several minutes to determine the nonenzymic rate. A 50-μL aliquot enzyme stock solution was then added and the absorbance monitored through the burst phase and into the steady-state reaction. Active-site molarities were calculated both from the burst amplitude and the enzyme-dependent part of the steady-state rate, the average values being taken. Experiments were done in duplicate or triplicate.

The active-site molarity for trypsin was determined[22] from the burst phase of the hydrolysis of 4-nitrophenyl 4′-guanidinobenzoate hydrochloride (Sigma Chemical Co.).

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Oxygen Transfer Involving Non-Heme Iron. The Reaction of (EDTA)Fe^{III} with *m*-Chloroperbenzoic Acid

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Abstract: Oxygen transfer from percarboxylic acids to (ethylenediaminetetraacetato)iron(III) ((EDTA)Fe^{III}) has been investigated (solvent CH_3OH; *T* 30 °C), using 2,4,6-tri-*tert*-butylphenol (TBPH) as a trapping reagent for the reactive iron–oxo intermediate formed upon oxygen transfer. In the presence of TBPH the percarboxylic acid peroxo bond undergoes 100% heterolytic cleavage during oxygen transfer to (EDTA)Fe^{III}, as demonstrated with phenylperacetic acid. This requires the reaction to involve the transfer of an oxene or oxygen atom to the iron(III) moiety of the (EDTA)Fe^{III} catalyst to form what may be formally written as (EDTA)Fe^{V}O. Since the so-constituted oxidant oxidized $PhCH_2COH$ by 1e$^-$ transfer to provide $(PhCH_2)_2$ at a rate greater than the oxidation of carboxylate ligand, the electron deficiency of the oxidant must reside at the oxygen to a greater extent than on iron. The structure of the oxidant is, therefore, best represented as something between (EDTA)Fe^{V}O and one in which the iron(III) species stabilizes the oxygen atom by d-orbital overlap ((EDTA)Fe^{III}O) species. The kinetics of the reaction of a percarboxylic acid with (EDTA)Fe^{III} were studied by using *m*-chloroperbenzoic acid (MCPBA). The reaction was monitored by following the appearance of 2,4,6-tri-*tert*-butylphenoxyl radical (TBP$^\bullet$). Oxygen transfer was shown to be rate limiting from the first-order dependence upon [MCPBA] and zero-order dependence upon [TBPH]. At constant [MCPBA] and [TBPH], the pseudo-first-order rate constants, k_{obsd}, for the appearance of TBP$^\bullet$ increases linearly with increase in [(EDTA)Fe^{III}] and reaches a limiting value at high (EDTA)Fe^{III} concentrations. Oxidation of TBPH to TBP$^\bullet$ is shown to compete with methanol solvent oxidation to formaldehyde and the oxidative coupling of MCPBA with TBPH to provide a peroxidic component, OXO. The percentage yields of TBP$^\bullet$, CH_2O, and OXO are independent of the concentration of (EDTA)Fe^{III}, provided the concentrations of MCPBA and TBPH are kept constant. However, increasing the initial concentration of MCPBA increases the concentration of OXO, and, correspondingly, the yield of the other two products decreases. Similarly, the yield of phenoxyl radical increases with increase in [TBPH]. The initial addition of formaldehyde retards the rate of the oxidation reactions. A kinetically competent series of reactions which allow the calculation of experimental values of k_{obsd} and the yields of products have been arrived at by computer simulation (Scheme III). Comparison of the second-order rate constants (in methanol) for oxygen transfer from MCPBA to (tetraphenylporphyrinato)iron(III) chloride ((TPP)Fe^{III}Cl) and to (EDTA)Fe^{III} establishes the former to be but 45-fold a better acceptor.

Iron complexes, both heme and non-heme, play important roles as catalysts in biochemical oxidation reactions at the level of ligand–Fe(III) + 2e– + O_2. Among the (protoporphyrin IX)–Fe(III) enzymes are the peroxidases,[1] which carry out 1e– oxidations when charged by hydroperoxide, and cytochrome P-450 enzymes,[2] which perform substrate oxygen chemistry when charged by ordered combination with 1e–, O_2, and 1e–. Non-heme iron plays an important but, as yet, poorly understood role in the mechanism of the pterin-requiring mammalian phenylalanine hydroxylase[3] and in a class of α-ketoglutarate-requiring enzymes (prolyl, lysyl, etc. and hydroxylases[4]) which perform oxygen insertions into C–H bonds (much as in the case of some cytochrome P-450 reactions).

Studies from this laboratory have recently been directed to the oxygen-transfer chemistry of (*meso*-tetraphenylporphinato)metal(III) chlorides ((TPP)M^{III}Cl).[5] The second-order rate

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constants (k_{YOOH}) for oxygen transfer to (TPP)Cr^{III}Cl,[5d] (TPP)Fe^{III}Cl,[5e] (TPP)Mn^{III}Cl,[5f] (TPP)Mn^{III}(ImH)Cl,[5g] and (TPP)Co^{III}Cl[5h] by hydroperoxides and percarboxylic acids (YOOH) have been determined. With (TPP)Cr^{III}Cl, YO–OH bond scission was found to be heterolytic with both percarboxylic acids and alkyl hydroperoxides. This was shown to be so by the finding that phenylacetic acid is the product when YOOH is phenylperacetic acid and from the observation that both percarboxylic acids and alkyl hydroperoxides fit to the same linear-free energy plot of log k_{YOOH} vs. the pK_a of the YOH leaving groups ($\beta_{lg} = -0.35$). In the reaction of percarboxylic acids and the most acidic alkyl hydroperoxides with (TPP)Fe^{III}Cl, (TPP)Mn^{III}(ImH)Cl, and (TPP)Co^{III}Cl linear plots of log k_{YOOH} vs. pK_a of YOH were also obtained (for Fe^{III}, $\beta_{lg} = -0.35$); however, for all three metallo(III)porphyrins a break in slope to a much smaller value of $-\beta_{lg}$ was observed at a value of pK_a of YOH between 9 and 10. The change in slope of the linear free-energy plots was proposed to be due to a change of mechanism of YO–OH bond breaking from heterolytic for percarboxylic acids and the most acidic alkyl hydroperoxides to homolytic for the weakly acidic alkyl hydroperoxides and hydrogen peroxide. Thus, with (TPP)Fe^{III}Cl, heterolysis of the YO–OH bond with percarboxylic acids was established, while homolytic YO–OH scission of the alkyl hydroperoxides was supported by the finding that the products of their reaction are those expected from the homolytic cleavage. The role of the porphyrin ligand in the determination of the modes of YOH bond cleavage is of considerable interest. It has been shown that the products of electrolytic oxidation of (TPP)Fe^{III}OH are the iron(IV)–oxo porphyrin and the iron(IV)–oxo tetraphenylporphyrin π-cation radical.[5i,j] Presumably, the same species is formed on reaction with percarboxylic acids (eq 1). Homolytic

$$(\mathrm{TPP})\mathrm{Fe^{III}X} + \mathrm{RCO_3H} \rightarrow {}^{+\bullet}(\mathrm{TPP})\mathrm{Fe^{IV}O} + \mathrm{RCO_2H} \quad (1)$$

oxygen–oxygen bond scission with alkyl hydroperoxides and hydrogen peroxides should produce, as an immediate product, the iron(IV)–oxo tetraphenylporphyrin (eq 2).

$$(\mathrm{TPP})\mathrm{Fe^{III}X} + \mathrm{ROOH} \rightarrow (\mathrm{TPP})\mathrm{Fe^{IV}O} + \mathrm{RO^\bullet} + \mathrm{H^+} \quad (2)$$

$$(\mathrm{TPP})\mathrm{Fe^{IV}O} + \mathrm{RO^\bullet} + \mathrm{H^+} \rightarrow {}^{+\bullet}(\mathrm{TPP})\mathrm{Fe^{IV}O} + \mathrm{ROH}$$

An important question may be posed. Does the porphyrin ligand participate in the mechanism of YO–OH bond scission in a manner which determines the importance of heterolysis vs. homolysis or is this change of mechanism a property of the central metal ion? Walling[6] has previously established that the reaction of (ethylenediaminetetraacetato)iron(III) ((EDTA)Fe^{III}) with H_2O_2 involves homolysis of the HO–OH bond in aqueous medium. In this investigation we have studied the mechanism of the reaction of (EDTA)Fe^{III} with percarboxylic acids in methanol solvent. The reaction has been followed by using 2,4,6-tri-*tert*-butylphenol which, along with methanol solvent, serves as a trap for the intermediate (EDTA)$(FeO)^{5+}$ species. The present study establishes that the reaction of (EDTA)Fe^{III} with percarboxylic acids involves RCO_2–OH bond heterolysis.

Experimental Section

Materials. The sodium salt of (ethylenediaminetetraacetato)iron(III) was prepared from an equimolar solution of ferric ammonium sulfate and the disodium salt of ethylenediaminetetraacetic acid as described in the literature.[7] The purity of the complex was checked by its characteristic absorption maximum in the UV region (λ_{max} 258 nm; ϵ_{max} 9000 M^{-1} cm^{-1}).[8] *m*-Chloroperbenzoic acid (Aldrich Chemicals) was determined, by iodometric titration (vide infra), to be 80% pure and was used as received. Phenylperacetic acid was synthesized from phenacetyl chloride and alkaline hydrogen peroxide.[9,10] The peracid was standardized iodometrically by adding a known aliquot of peracid to a previously buffered 0.1 M sodium iodide solution in 95% ethanol followed by spectrophotometric determination of the concentration of triiodide (λ 358 nm; ϵ_{358} 2.5 × 10^4 M^{-1} cm^{-1}).[11] 2,4,6-Tri-*tert*-butylphenol (TBPH) (Aldrich Chemicals) was recrystallized several times from 95% ethanol until the solution in ethanol was colorless. Anhydrous methanol (Mallinckrodt, AR) was used as received.

Kinetic Studies. All reactions were carried out under argon in anhydrous methanol in Thunberg cuvettes. In a typical reaction, a mixture of (ethylenediaminetetraacetato)iron(III) ((EDTA)Fe^{III}) complex and a methanolic solution of 2,4,6-tri-*tert*-butylphenol (TBPH) was taken in the cuvette compartment of a Thunberg and about 0.30–0.40 mL of a methanolic solution of *m*-chloroperbenzoic acid was taken in the bulb compartment. After degassing of both Thunberg compartments with methanol saturated argon for nearly 1 h, the oxidation was initiated by mixing well the solutions from the top and bottom compartments. The Thunberg was transferred to a Perkin-Elmer Model 553 recording spectrophotometer thermostated at 30 ± 0.2 °C and the appearance of phenoxyl radical ($TBP^\bullet$) monitored at 400 nm. Reactions were generally carried out under the pseudo-first-order conditions of [TBPH] ≫ [MCPBA] ≫ [(EDTA)Fe^{III}]. Each reported rate constant is an average of at least two different determinations. Each kinetic trace was analyzed as a combination of sequential pseudo-first-order and zero-order reactions with the help of software written for this purpose using a Hewlett-Packard Model 9825A computer.

Determination of the mode of cleavage of the percarboxylic acid peroxo bond was carried out as follows: 0.20 mL of a methanolic solution of (EDTA)Fe^{III} and 0.05 mL of phenylperacetic acid (PPAA) were mixed under N_2 in a closed vial capped with a gas-tight rubber septum containing 0.5 mL of a methanolic solution 0.2 M in TBPH. The final concentrations of reactants are (EDTA)Fe^{III} = 1.22 × 10^{-4} M to 3.80 × 10^{-3} M and PPAA = 3.60 × 10^{-3} M. At higher concentrations of (EDTA)Fe^{III}, the reaction solution was incubated for 1 h, while in the case of lower concentrations of (EDTA)Fe^{III}, the reaction mixture was allowed to stand for 10 h to make sure that the reaction had gone to completion. To the spent reaction solution there was then added 0.5 mL of a freshly prepared ethereal solution of diazomethane and the concentration of methyl phenylacetate determined by GC with a Varian Model 3700 using a Varian WCOT capillary column (vitreous silica, 18 m, 50 QC2/BPI - 0.25). Each sample was analyzed at least 3 times and each value determined was an average of two experiments.

Epoxidation of cyclohexene in the presence of (EDTA)Fe^{III} was carried out with phenylperacetic acid under N_2 and the formation of cyclohexene epoxide was followed by GC as described above. The reaction was carried out under the pseudo-first-order conditions of [cyclohexene] ≫ [phenylperacetic acid] > [(EDTA)Fe^{III}].

Results

In the present study we have examined the reaction of *m*-chloroperbenzoic acid with (ethylenediaminetetraacetato)iron(III) complex ((EDTA)Fe^{III}) in absolute methanol (30 °C, under oxygen-free argon) in the presence of 2,4,6-tri-*tert*-butylphenol (TBPH). Reactions were followed spectrophotometrically at the λ_{max} of $TBP^\bullet$ (λ 400 nm; ε 1200 M^{-1} cm^{-1}). In the absence of the metal catalyst, the *m*-chloroperbenzoic acid (MCPBA) oxidation of TBPH to phenoxyl radical ($TBP^\bullet$ at 400 nm) is very slow. The second-order rate constant that may be calculated from the reaction of MCPBA (1.5 × 10^{-3} M) with TBPH (0.1 M) is 2 × 10^{-4} M^{-1} s^{-1}. (EDTA)Fe^{III} serves as a catalyst for the MCPBA oxidation of TBPH to the phenoxyl radical $TBP^\bullet$. However, (EDTA)Fe^{III} is not as an effective catalyst as is (TPP)Fe^{III}Cl,[5e] so that at catalyst concentration of 1.5 × 10^{-4} M the catalytic reaction must compete with the slow and direct oxidation of TBPH by MCPBA. The latter accounts for only a few percent of the $TBP^\bullet$ formed and may, thus, be ignored. In the presence

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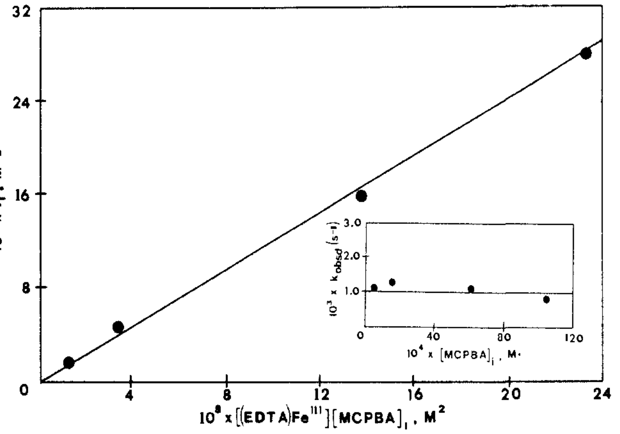

Figure 1. A plot of the initial rate (v_i) for the formation of TBP• vs. $[(EDTA)Fe^{III}][MCPBA]_i$ at constant $[(EDTA)Fe^{III}] = 2.25 \times 10^{-5}$ M and [TBPH] = 9.50×10^{-2} M. Insert: A plot of the pseudo-first-order rate constants for the formation of TBP• (k_{obsd}) vs. $[MCPBA]_i$ at $[(EDTA)Fe^{III}] = 2.25 \times 10^{-5}$ M and [TBPH] = 9.50×10^{-2} M.

of $(EDTA)Fe^{III}$ and MCPBA the methanol solvent is also oxidized to formaldehyde. Analysis for the concentration of TBP• was carried out at 630 nm (ϵ_{630} 200 M^{-1} cm^{-1} in methanol) and the formaldehyde concentration determined by the method of Nash.[12] Because we wished to avoid solvent oxidation, solvents other than methanol were investigated. The $(EDTA)Fe^{III}$ complex was found to be insoluble in acetonitrile, benzonitrile, and dichloromethane (solvents commonly used for oxidation reactions).

Investigation of the kinetics of the oxygen transfer from MCPBA to $(EDTA)Fe^{III}$ were followed by observing the appearance of TBP• while methodically changing the concentrations of MCPBA, TBPH, and $(EDTA)Fe^{III}$. The plots of A_{400} vs. time were found to be biphasic. An initial first-order reaction occurs to about 90% completion in the appearance of TBP•, and this is followed by a very slow and continual formation of the radical. As will be explained further on in the article, the first-order component relates to oxygen transfer from MCPBA to $(EDTA)Fe^{III}$ while the zero-order component arises from the decomposition of a peroxidic component formed during the reaction. All the plots of A_{400} vs. time were analyzed as combinations of sequential pseudo-first-order and zero-order processes. Kinetic analysis is restricted to the major pseudo-first-order reaction.

The kinetic results may be considered in terms of eq 3 (where v_i represents initial rates). To establish the reaction order for

$$v_i = k[MCPBA][(EDTA)Fe^{III}][TBPH] \qquad (3)$$

MCPBA the concentration of this agent was varied from 5.0×10^{-4} M to 1.05×10^{-2} M while $[(EDTA)Fe^{III}]_i$ and $[TBPH]_i$ were held constant at 2.25×10^{-5} M and 9.5×10^{-2} M, respectively. An apparent second-order rate constant for the oxidation of TBPH was determined as the slope of a plot of v_i vs. $[MCPBA]_i \times [(EDTA)Fe^{III}]_i$ divided by $[TBPH]_i$ (see Figure 1). At a constant $[(EDTA)Fe^{III}] = 2.22 \times 10^{-5}$ M, the appearance of TBP• follows the first-order rate law and the calculated first-order rate constant is independent of the initial concentration of MCPBA (see insert to Figure 1). Further, when disappearnce of MCPBA was followed by an iodometric procedure (see Experimental Section), it was found to follow the first-order rate law. These findings show that the oxidation of TBPH is first order in MCPBA.

The oxidation reaction was also studied as a function of the concentration of TBPH and $(EDTA)Fe^{III}$. The concentration of TBPH was varied from 0.025 M to 0.38 M while the initial concentrations of MCPBA and $(EDTA)Fe^{III}$ were kept constant. Under these conditions the rate of oxidation of TBPH was found to be independent of its concentration (Table I), thereby satisfying a kinetic criterion for its acting as a trap for the iron–oxo reactive intermediate formed on reaction of $(EDTA)Fe^{III}$ with MCPBA.

Table I. Effect of TBPH Concentration on the Pseudo-First-Order Rate Constant for TBP• Formation, [MCPBA] = 1.5×10^{-3} M[a]

$(EDTA)Fe^{III}$, M	TBPH, M	$k_{obsd} \times 10^4$, s^{-1}
2.22×10^{-5}	0.095	13.3
2.22×10^{-5}	0.025	15.7
2.22×10^{-5}	0.050	16.9
2.22×10^{-5}	0.200	15.3
2.22×10^{-5}	0.38	12.5
1.48×10^{-4}	0.025	31.4
1.50×10^{-4}	0.095	34.0
1.48×10^{-4}	0.380	30.0

[a] Solvent CH_3OH; *t* 30 ± 0.1 °C; λ 400 nm.

Table II. Effect of Formaldehyde Concentration on the Pseudo-First-Order Rate Constant for TBP• Formation When $[TBPH]_i = 0.095$ M, $[MCPBA]_i = 1.50 \times 10^{-3}$ M, and $[(EDTA)Fe^{III}]_i = 2.25 \times 10^{-5}$ M

$[CH_2O]_i$, M	$k_{obsd} \times 10^4$, s^{-1}
1.73×10^{-3}	3.90[a,b]
1.75×10^{-3}	2.10[b]
7.33×10^{-4}	5.64

[a] Followed by monitoring the disappearance of [MCPBA] at various time intervals. [b] $[CH_2O]$ formed = 4.30×10^{-4} M; [TBP•] = 3.40×10^{-4} M; [OXO] = 1.50×10^{-4} M.

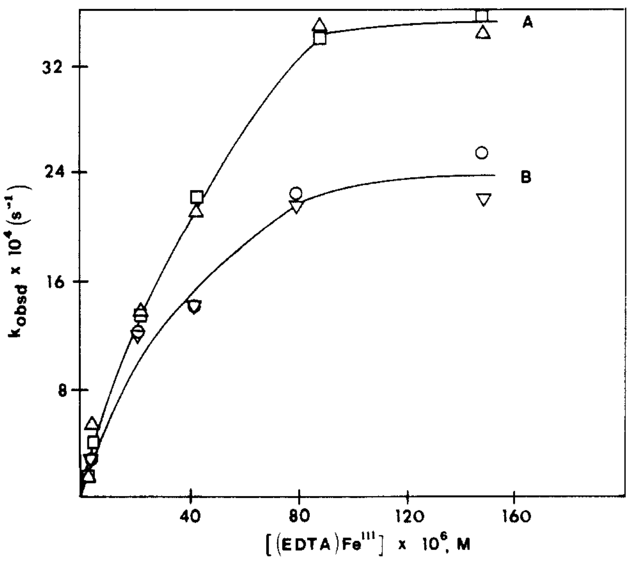

Figure 2. A plot of the pseudo-first-order rate constant, k_{obsd}, for the formation of TBP• vs. $[(EDTA)Fe^{III}]$ at $[TBPH]_i = 9.5 \times 10^{-2}$ M. Line A, $[MCPBA]_i = 1.50 \times 10^{-3}$ M (△). Line B, $[MCPBA]_i = 8.00 \times 10^{-4}$ M (▽). The (□, ○) points represent k_{obsd} values simulated via Scheme III.

The dependence of reaction rate upon the concentration of $(EDTA)Fe^{III}$, in the range 1.0×10^{-6} M–1.50×10^{-4} M, was determined while holding the initial concentrations of MCPBA and TBPH constant. The dependence of k_{obsd} upon $[(EDTA)Fe^{III}]_i$ at $[MCPBA]_i = 1.5 \times 10^{-3}$ and 8×10^{-4} M was determined. Plots of the pseudo-first-order rate constants (k_{obsd}), determined by computer-fitting of the time course for TBP• appearance, vs. $[(EDTA)Fe^{III}]_i$ is shown in Figure 2. Inspection of Figure 2 shows that k_{obsd} increases with increase in $[(EDTA)Fe^{III}]_i$ becoming independent of catalyst at its higher concentrations.

Formaldehyde retards the reaction. Thus, addition of formaldehyde at the time of initiation of the reaction retards the rate of formation of TBP•. Product analysis reveals that at the highest concentration of added formaldehyde, the formaldehyde formed at completion of reaction plus the small amount of TBP• is less than the amount of MCPBA consumed (Table II). Presumably the imbalance in the stoichiometry is due to oxidation of about 33% formaldehyde to formic acid. Such imbalance in stoichiometry is not observed, unless formaldehyde is added (to >1.7 × 10^{-3} M) at initiation of the reactions.

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Table III. Effect of $(EDTA)Fe^{III}$ on the Yield of Products in Oxidation of TBPH (0.095 M) by MCPBA, Catalyzed by $(EDTA)Fe^{III}$

					yield, %			
$(EDTA)Fe^{III}$, M	MCPBA, M	CH_2O,[a] M	$TBP^\bullet$,[b] M	OXO[c]	$TBP^\bullet$	CH_2O	OXO	total
1.09×10^{-6}	1.50×10^{-3}	9.80×10^{-4}	5.10×10^{-4}	2.04×10^{-4}	16.7	64.0	13.6	94.3
4.20×10^{-6}	1.50×10^{-3}	1.05×10^{-3}	6.00×10^{-4}	0.96×10^{-4}	20.1	70.2	6.4	96.7
2.20×10^{-5}	1.50×10^{-3}	9.86×10^{-4}	6.23×10^{-4}	1.20×10^{-4}	21.0	66.2	8.0	95.2
4.40×10^{-5}	1.50×10^{-3}	9.50×10^{-4}	6.90×10^{-4}	1.17×10^{-4}	22.0	66.1	7.7	95.8
8.90×10^{-5}	1.50×10^{-3}	1.08×10^{-3}	4.60×10^{-4}	0.76×10^{-4}	15.4	72.0	5.1	92.5
1.48×10^{-4}	1.50×10^{-3}	9.64×10^{-4}	6.80×10^{-4}	1.46×10^{-4}	22.6	64.3	10.6	97.5
4.20×10^{-6}	8.02×10^{-4}	5.69×10^{-4}	3.0×10^{-4}	0.33×10^{-4}	18.8	67.7	4.4	91.0
2.27×10^{-5}	8.00×10^{-4}	5.79×10^{-4}	3.35×10^{-4}	0.37×10^{-4}	20.9	72.0	4.6	97.5
4.25×10^{-5}	8.10×10^{-4}	4.10×10^{-4}	4.15×10^{-4}	1.70×10^{-4}	25.9	51.2	21.5	98.0
8.04×10^{-5}	8.06×10^{-4}	3.60×10^{-4}	3.90×10^{-4}	2.98×10^{-4}	24.3	45.0	37.2	106.0
1.50×10^{-4}	8.07×10^{-4}	3.98×10^{-4}	5.35×10^{-4}	1.61×10^{-4}	33.2	49.3	19.9	102.0

[a] Estimated by the method of Nash. [b] Estimated from the absorbance changes at 630 nm. [c] Estimated iodometrically (see Experimental Section).

Table IV. Effect of [MCPBA] on the Percentage Yield of Products When $[(EDTA)Fe^{III}] = \sim 2.25 \times 10^{-5}$ M and [TBPH] = 0.095 M

				yield, %			
MCPBA, M	CH_2O, M	$TBP^\bullet$, M	OXO	$TBP^\bullet$	CH_2O	OXO	total
5.10×10^{-4}	3.27×10^{-4}	2.60×10^{-4}	0.55×10^{-4}	25.5	63.8	10.7	100.0
8.00×10^{-4}	5.79×10^{-4}	3.35×10^{-4}	0.37×10^{-4}	20.9	72.0	4.6	97.5
1.50×10^{-3}	9.86×10^{-4}	6.23×10^{-4}	1.20×10^{-4}	21.0	66.2	8.0	95.2
6.06×10^{-3}	2.87×10^{-3}	1.80×10^{-3}	9.20×10^{-4}	15.7	47.3	15.2	78.2
1.05×10^{-2}	4.60×10^{-3}	2.64×10^{-3}	3.90×10^{-3}	13.0	43.8	37.1	93.9

Table V. Effect of [TBPH] on the Yield of Products at $[MCPBA] = 1.5 \times 10^{-3}$ M

					yield, %			
$(EDTA)Fe^{III}$, M	TBPH, M	CH_2O, M	$TBP^\bullet$, M	OXO, M	$TBP^\bullet$	CH_2O	OXO	total
2.25×10^{-5}	0	1.03×10^{-3}	0	0	0	68.6	0	a
2.25×10^{-5}	0.025	1.07×10^{-3}	1.85×10^{-4}	2.20×10^{-4}	6.3	72.2	14.9	93.0
1.48×10^{-4}	0.025	1.17×10^{-3}	1.90×10^{-4}	9.60×10^{-6}	6.3	77.3	0.64	84.0
2.22×10^{-5}	0.050	9.28×10^{-4}	3.75×10^{-4}	2.51×10^{-4}	12.5	61.9	16.8	91.2
2.25×10^{-5}	0.095	9.86×10^{-4}	6.23×10^{-4}	1.20×10^{-4}	21.0	66.2	8.0	95.2
2.26×10^{-5}	0.200	7.50×10^{-4}	1.05×10^{-3}	2.00×10^{-4}	34.8	53.0	13.0	101.0
2.20×10^{-5}	0.380	7.00×10^{-4}	1.36×10^{-3}	0.95×10^{-4}	45.3	46.6	6.30	98.2
1.51×10^{-4}	0.380	4.83×10^{-4}	1.41×10^{-3}	4.06×10^{-4}	47.0	32.2	27.1	106.0

[a] The reaction was arbitrarily followed for 90 min, at which time 70% of MCPBA had disappeared from solution. Therefore, formaldehyde is formed in 100% yield.

The following results support oxidation of TBPH and methanol to occur in reactions which compete with each other for an iron–oxo species which is formed in the rate-controlling step. The yield of both $TBP^\bullet$ and formaldehyde at various concentrations of $(EDTA)Fe^{III}$ is given in Table III, when $[MCPBA]_i$ equals 1.50×10^{-3} M and 8×10^{-4} M and when $[TBPH]_i$ is constant at 9.5×10^{-2} M. It can be seen from the data of Table III, when taking into account that one MCPBA is consumed per two $TBP^\bullet$ formed and one MCPBA is used per formation of one formaldehyde, that the yields of $TBP^\bullet$ and formaldehyde in each experiment leave about 10% of the $[MCPBA]_i$ unaccounted for. When all $TBP^\bullet$ has been formed, there is found, invariably, a peroxidic component that by iodometric titration (Experimental Section) accounts for the mixxing 10% of $[MCPBA]_i$ (Table III). When $[MCPBA]_i$ is 1.50×10^{-3} M the percentage yield of $TBP^\bullet$ is around 20%, whereas that of formaldehyde is around 65%—implying that the ratio of both products is always a constant for the entire range of concentrations of $(EDTA)Fe^{III}$ employed. However, when $[MCPBA]_i$ is lowered from 1.50×10^{-3} M to 8.0×10^{-4} M, there is some change in the ratio of these products. There is a marginal increase in the precentage yield of $TBP^\bullet$ as the concentration of the metal catalyst is increased, whereas the percentage yield of formaldehyde drops to a correspondingly lower value.

The kinetics for the oxidation of TBPH by MCPBA was studied as a function of $[MCPBA]_i$ while the catalyst and TBPH concentrations were maintained constant. The percentage yield of both $TBP^\bullet$ and CH_2O decreases with increase in $[MCPBA]_i$, the ratio of both remaining constant (Table IV). Also, the peroxidic component present at completion of reaction increases with increase in the initial concentration of MCPBA.

Finally, the percentage yields and the ratios of $TBP^\bullet$ and CH_2O depends on the concentration of TBPH. At $[(EDTA)Fe^{III}]_i$ equals 2.25×10^{-5} M and 1.5×10^{-4} M the percentage yield of $TBP^\bullet$ and formaldehyde remains almost constant, provided $[MCPBA]_i$ and $[TBPH]_i$ are kept constant (Table V). In the absence of TBPH, formaldehyde is the only product. As the concentration of TBPH is increased from 0 to 0.38 M, the percentage yield of $TBP^\bullet$ increases from 0 to 50 while the percentage yield of formaldehyde decreases from 100% to 50%. The upper concentration of TBPH that may be used is limited to about 0.38 M by its solubility in methanol.

The stability of $(EDTA)Fe^{III}$ to percarboxylic acid oxidation was studied with both MCPBA and perlauric acid (PLA). Use of PLA has an advantage in that it is an aliphatic peracid with no significant absorbance at 258 nm—the only absorption maximum for $(EDTA)Fe^{III}$. Reactions with PLA were studied in the absence of TBPH and at $[(EDTA)Fe^{III}]_i = 2.22 \times 10^{-5}$ M and $[PLA]_i = 1.50 \times 10^{-3}$ M. TBPH could not be used due to its strong aromatic absorbance masking the entire UV region. The rate of reaction of MCPBA is greater than that of PLA with $(EDTA)Fe^{III}$. This is to be expected from past experience[5d-h] and the greater acidity of *m*-chlorobenzoic acid when compared to that of phenylacetic acid. After the reaction was over, the percentage yield of formaldehyde was estimated to be ~75%. The 25% imbalance in the percentage yield of formaldehyde based on peracid reacted may be attributed to formaldehyde oxidation. The concentration of the catalyst $(EDTA)Fe^{III}$ was determined from its absorbance at 258 nm. It was found that nearly 80% of the catalyst remains as $(EDTA)Fe^{III}$, suggesting that the metal catalyst is rather stable even in the absence of TBPH.

The stability of $(EDTA)Fe^{III}$ to peracid oxidation in the presence of TBPH was also examined. The oxidation of TBPH (0.1 M) by MCPBA (1.5×10^{-3} M) in the presence of $(EDTA)Fe^{III}$ at 2.27×10^{-5} M was carried to completion. An

Table VI. Percentage Yield of Methyl Phenylacetate Obtained by Reaction of Phenylacetic Acid Product with Diazomethane in Oxidation of TBPH by Phenylperacetic Acid Catalyzed by (EDTA)Fe^{III}

(EDTA)Fe^{III}, M	PPAA, M	TBPH, M	$[PPAA]_{injected}$, μmol	methyl phenylacetate formed	yield, %
3.80×10^{-3}	3.60×10^{-3}	0	2.18×10^{-3}	1.45×10^{-3}	66.5[a]
3.80×10^{-3}	3.60×10^{-3}	0	1.09×10^{-3}	0.68×10^{-3}	62.3[a]
5.72×10^{-3}	3.60×10^{-3}	0	2.1×10^{-3}	1.39×10^{-3}	63.8[a]
5.72×10^{-3}	3.60×10^{-3}	0	1.09×10^{-3}	0.69×10^{-3}	63.3[a]
4.88×10^{-3}	4.07×10^{-3}	0.2	1.74×10^{-3}	1.62×10^{-3}	92.8
9.76×10^{-4}	4.07×10^{-3}	0.2	1.74×10^{-3}	1.89×10^{-3}	108.0
4.88×10^{-4}	4.07×10^{-3}	0.2	1.74×10^{-3}	1.01×10^{-3}	109.0
1.22×10^{-4}	4.07×10^{-3}	0.2	1.74×10^{-3}	1.69×10^{-3}	97.1

[a] Nearly 4% of bibenzyl has been detected under the same GC conditions; our attempts to determine the other possible products corresponding to nearly 20% of the peracid reaction were unsuccessful.

aliquot of the spent reaction mixture was removed, and to this was added an additional shot of (EDTA)Fe^{III}. The lack of formation of additional TBP• established that all MCPBA had been consumed, even though the spent reaction solution is active toward I^- due to the presence of the peroxidic component. To another aliquot of the spent reaction mixture there was added a shot of MCPBA, and this resulted in the formation of additional TBP•. The rate constants obtained for TBP• formation in the initial reaction and in the following reaction on addition of the shot of MCPBA were found to be comparable (1.50×10^{-3} s^{-1} vs. 1.84×10^{-4} s^{-1}), providing one takes into account the retarding effect upon rate of the formaldehyde generated in the first reaction. Thus, in an independent experiment initiated with [CH_2O] equal to that formed in the first reaction, it was found that the rate of TBP• formation was decreased 8-fold. This shows that little or no catalyst is oxidized under the expreimental conditions of these kinetic studies.

The association of (EDTA)Fe^{III} species was investigated by spectral and electrochemical methods. The absorbance of (EDTA)Fe^{III} (1.10×10^{-6} M–1.50×10^{-4} M) at 258 nm in methanol was found to vary in a linear fashion with its concentration. By this criterion (Beer's law), (EDTA)Fe^{III} remains monomeric at the concentrations employed in this study. Also, a cyclic voltammetric examination of a methanol (EDTA)Fe^{III} solution was carried out at the highest concentration of metal catalyst used (1.50×10^{-4} M) in these oxidation studies ($\mu = 0.10$ with $NaClO_4$; with a glassy carbon electrode). We observed that the metal catalyst has a single, reversible reduction wave at −200 mV (SCE) with a peak separation of 80 mV. Therefore, by this criterion the catalyst is also monomeric.[8]

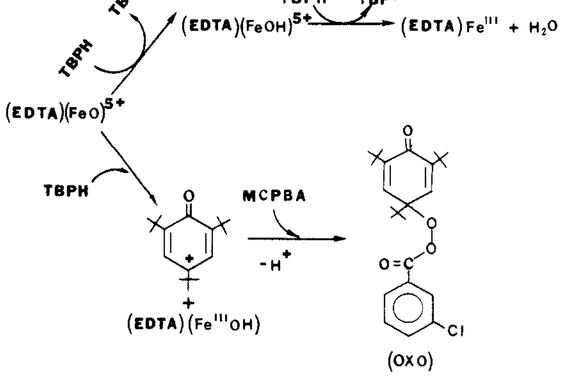
Homolytic vs. heterolytic cleavage of the O–O bond of peracid was investigated with phenylperacetic acid (PPAA) as the oxidant. Heterolytic O–O bond scission would result in the formation of phenylacetic acid which can be trapped with diazomethane and estimated as methyl phenylacetate by GC analysis. The results are summarized in Table VI. From Table VI: (i) About 65% of methyl phenylacetate was formed when near-equimolar concentrations of both (EDTA)Fe^{III} and PPAA in the absence of TBPH were used, and there was also shown to be present (Experimental Section) approximately 4% of bibenzyl. (ii) With $[TBPH]_i = 50 \times [PPAA]_i = [(EDTA)Fe^{III}]$, there was formed 92 ± 1% of methyl phenylacetate. (iii) Under the conditions used for the kinetic studies ($((EDTA)[Fe^{III}]_i = 9.76 \times 10^{-4}$ M to 1.22×10^{-4} M, $[PPAA]_i = 4.07 \times 10^{-3}$ M, $[TBPH]_i = 0.2$ M) the percentage yield of methyl ester of phenylacetic acid reached 100%. These results show that in the presence of TBPH the "peroxo" bond is quantitatively cleaved via a heterolytic mechanism to give phenylacetate anion. The ~30% decarboxylation in the absence of the TBPH trap may be attributed to oxidation of the phenylacetic acid product by the iron–oxo species.

Epoxidation of Cyclohexene. The appearance of cyclohexene epoxide in methanol from cyclohexene (1.0 M) by epoxidation with phenylperacetic acid (4.3×10^{-3} M) in the presence of (EDTA)Fe^{III} (7.70×10^{-4} M) is associated with a pseudo-first-order rate constant of 7.60×10^{-4} s^{-1}. In the absence of catalyst, the pseudo-first-order rate constant is 5.0×10^{-4} s^{-1}. Comparison of these constants shows that epoxide formation is 1.5 times faster in the presence of catalyst. In the absence of catalyst the formation of epoxide is 100% based upon $[PPAA]_i$; however, in the presence of catalyst the percentage yield of epoxide is but 63%, and there is also formed 40% yield of formaldehyde. In parallel first-order reactions, as is the case for epoxide and formaldehyde formation, both products appear at the same rate which is equal to the rate of disappearance of starting material and to the sum of the pseudo-first-order rate constants for the formation of each product. With this information and the percentage yields of epoxide and formaldehyde there may be calculated as 4.6×10^{-4} s^{-1} the true pseudo-first-order rate constant for epoxide formation. Thus, catalysis of phenylperacetic acid epoxidation of cyclohexene by (EDTA)Fe^{III}, if it should occur, cannot be seen over the uncatalyzed reaction in methanol.

Discussion

In this study we have determined the kinetics for the reaction of *m*-chloroperbenzoic acid with (EDTA)Fe^{III} using solvent methanol and 2,4,6-tri-*tert*-butylphenol (TBPH) as a substrate (30 °C; solvent methanol). Experiments establish that the (EDTA)Fe^{III} catalyst is stable under all the experimental conditions of this study. By spectral and electrochemical criteria there can be discerned none but monomeric catalyst at $[(EDTA)Fe^{III}]_i$ used in the kinetic investigations. The reactions were monitored spectrophotometrically at 400 nm by following the formation of 2,4,6-tri-*tert*-butylphenoxyl radical (TBP•).

Reactions were found to be biphasic. Under the conditions ($[TBPH]_i > [MCPBA]_i = 1.5 \times 10^{-3}$ M) at which most of the kinetic studies have been carried out, the major portion of TBP• formation (≥90%) occurs via first-order kinetics, followed by a much slower zero-order formation of TBP• which continues long after consumption of all MCPBA. The latter slow formation of TBP• is due to the breakdown of a peroxidic product which is produced in about 10% yield based upon the initial concentration of MCPBA. With increase in $[MCPBA]_i$, with $[TBPH]_i$ always in excess, the yield of this peroxidic component increases (Table IV). From experiments which involved the addition of the various components of the reaction at completion of MCPBA consumption (see Results) it may be concluded that the peroxidic component is formed on condensation of MCPBA and TBPH. Our presumption of this reaction is included in eq 4. The proposed structure of the peroxidic component (OXO) has precedence in the known formation of like products in the reaction of base-



(4)

catalyzed oxygenations[13] by TBPH. Frostin-Rio and co-workers[14] have reported the formation of similar peroxidic compounds from TBPH during its oxidation by molecular oxygen catalyzed by ligated metal species. They postulate a metal peroxo complex as intermediate. In eq 4, the iron–oxo intermediate oxidizes TBPH by two parallel reaction paths: (i) two single-electron-transfer reactions resulting in the formation of two TBP$^\bullet$ radials and (ii) hydride-equivalent transfer from TBPH to the iron–oxo species to form a carbocation species which then undergoes nucleophilic attack by MCPBA (eq 4) to yield OXO. From a knowledge of the concentrations of TBP$^\bullet$ and OXO at completion of the pseudo-first-order component of the reaction one can state that the ratio of the rate constants for the formation of TBP$^\bullet$/OXO is 2/1 at $[\mathrm{TBPH}]_i \gg [\mathrm{MCPBA}]_i = 1.5 \times 10^{-3}$ M.

The rate constants for the initial and major portion of the reaction involving the first-order appearance of TBP$^\bullet$ and the slower and minor zero-order appearance of TBP$^\bullet$ from decomposition of OXO were separated by computer-fitting of the appropriate equations for consecutive first- and zero-order reactions to the experimentally determined absorbances of TBP$^\bullet$ at 400 nm. Since $[\mathrm{CH_3OH}] \gg [\mathrm{TBPH}]$ the major oxidation product is formaldehyde. The catalytic turnover of decomposition of MCPBA by (EDTA)Fe$^{\mathrm{III}}$ in the presence of TBPH is characterized by the following: (i) The pseudo-first-order rate constant for formation of TBP$^\bullet$ is independent of [TBPH]. (ii) TBP$^\bullet$ formation is also independent of [MCPBA]. (iii) At low (EDTA)Fe$^{\mathrm{III}}$, k_{obsd} shows a linear dependence on [(EDTA)Fe$^{\mathrm{III}}$], becoming independent at high concentration of catalyst. (iv) The ratio of the prroducts formaldehyde/TBP$^\bullet$ depends upon the initial concentrations of TBPH. These results are in accord with the formation of a complex of MCPBA with (EDTA)Fe$^{\mathrm{III}}$ and rate-limiting decomposition of this complex to provide an iron–oxo EDTA species, $(\mathrm{EDTA})(\mathrm{FeO})^{5+}$, which reacts with both TBPH and CH$_3$OH in non-rate-determining steps.

The findings that the reaction of (EDTA)Fe$^{\mathrm{III}}$ with phenylperacetic acid provides phenylacetic acid (identified as its methyl ester with diazomethane) in 65% yield but that this reaction in the presence of TBPH gives the carboxylic acid in 100% yield establish that the reaction of MCPBA with (EDTA)Fe$^{\mathrm{III}}$ to provide $(\mathrm{EDTA})(\mathrm{FeO})^{5+}$ occurs by a two-electron heterolytic cleavage of the PhCH$_2$CO$_2$–OH bond. If $(\mathrm{EDTA})(\mathrm{FeO})^{5+}$ is not trapped by TBPH, it can react with carboxylic acid (eq 5). It is known that the radical species PhCH$_2$CO$_2^\bullet$ formed on 1e-oxidation of phenylacetic acid has essentially no lifetime, decomposing to CO$_2$ and PhCH$_2^\bullet$.[15] The small amount of bibenzyl product obtained in the absence of TBPH (eq 5d) would then be due to coupling of PhCH$_2^\bullet$ obtained from the reaction of eq 5b.

$$(\mathrm{EDTA})\mathrm{Fe^{III}} + \mathrm{PhCH_2CO_3H} \rightarrow (\mathrm{EDTA})(\mathrm{FeO})^{5+} + \mathrm{PhCH_2CO_2H} \quad (5a)$$

$$(\mathrm{EDTA})(\mathrm{FeO})^{5+} + 2\mathrm{PhCH_2CO_2H} \rightarrow (\mathrm{EDTA})\mathrm{Fe^{III}} + 2\mathrm{PhCH_2}^\bullet + 2\mathrm{CO_2} \quad (5b)$$

$$(\mathrm{EDTA})(\mathrm{FeO})^{5+} + 2\mathrm{TBPH} \rightarrow (\mathrm{EDTA})\mathrm{Fe^{III}} + 2\mathrm{TBP}^\bullet + \mathrm{H_2O} \quad (5c)$$

$$2\mathrm{PhCH_2}^\bullet \rightarrow \mathrm{PhCH_2CH_2Ph} \quad (5d)$$

There are two principal means to analyze the kinetics for complex reactions which involve catalyst turnover. The method of choice has been dependent upon the change in the values of the reciprocal of the initial rate as a function of the reciprocal of the concentrations of reactants, inhibitors, etc. This methodology[16] has been developed to a high degree of sophistication by individuals as Cleland. It receives a great deal of attention from the biochemical community, because it provides a means of computation which does not require the real time solution of complex differential equations. It is now possible, with the advent of modern computer technology and the development of software based on Gear integration,[17] to fit the time course for disappearance of reactants and appearance of products, etc., to completion of reaction. The latter procedure has been employed in recent studies from this laboratory,[18] and it has been used in the present investigation. A number of possible reaction schemes have been examined to explain the results of the present study. The first sequence of reactions to be considered is shown in Scheme I. [a] Units are moles and seconds.

Scheme I[a]

$$\text{(a) } (\mathrm{EDTA})\mathrm{Fe^{III}} + \mathrm{MCPBA} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \underset{\text{“precursor complex”}}{(\mathrm{EDTA})\mathrm{Fe^{III}}\text{–}\mathrm{MCPBA}} \qquad k_1/k_{-1} = 1.0 \times 10^4/1.0 \times 10^3$$

$$\text{(b) } (\mathrm{EDTA})\mathrm{Fe^{III}MCPBA} \xrightarrow[\text{r.d.s.}]{k_2} (\mathrm{EDTA})(\mathrm{FeO})^{5+} + \mathrm{MCBA} \qquad k_2 = 6.0$$

$$\text{(c) } (\mathrm{EDTA})(\mathrm{FeO})^{5+} + \mathrm{TBPH} \xrightarrow{k_3} (\mathrm{EDTA})(\mathrm{FeOH})^{5+} + \mathrm{TBP}^\bullet \qquad k_3 = 1.0 \times 10^4$$

$$\text{(d) } (\mathrm{EDTA})(\mathrm{FeOH})^{5+} + \mathrm{TBPH} \xrightarrow{k_4} (\mathrm{EDTA})\mathrm{Fe^{III}} + \mathrm{TBP}^\bullet + \mathrm{H_2O} \qquad k_4 = 1.0 \times 10^4$$

$$\text{(e) } (\mathrm{EDTA})(\mathrm{FeO})^{5+} + \mathrm{CH_3OH} \xrightarrow{k_5} (\mathrm{EDTA})\mathrm{Fe^{III}} + \mathrm{CH_2O} + \mathrm{H_2O} \qquad k_5 = 90.0$$

$$\text{(f) } (\mathrm{EDTA})(\mathrm{FeO})^{5+} + \mathrm{TBPH} + \mathrm{MCPBA} \xrightarrow{k_6} (\mathrm{EDTA})\mathrm{Fe^{III}} + \mathrm{OXO} \qquad k_6 = 5.0 \times 10^6$$

$$\text{(g) } (\mathrm{EDTA})\mathrm{Fe^{III}} + \mathrm{CH_2O} \underset{k_{-7}}{\overset{k_7}{\rightleftharpoons}} (\mathrm{EDTA})\mathrm{Fe^{III}CH_2O} \qquad k_7/k_{-7} = 100/10$$

The constants K_1 ($= k_1/k_{-1}$) and k_2 were determined by iteration using the entirety of the kinetic data of this study. The absolute values of k_1 and k_{-1} are not of importance as long as they are large enough to assure that $k_{-1} \gg k_2 \ll k_1$, so that a preequilibrium conditions is in effect. The ratio k_1/k_{-1} is important to the fitting of the data. Also, the absolute values of k_7 and k_{-7} are not important but their ratio provides the equilibrium constant (K_7) for complexing of formaldehyde or, more likely, its hydrate to (EDTA)Fe$^{\mathrm{III}}$. Since the reaction steps which follow the rate-limiting step (k_2) are rapid (viz., the oxidation of TBPH to yield TBP$^\bullet$, the formation of CH$_2$O from methanol and the formation of the peroxidic component (OXO)), the only constraints upon k_3, k_4, k_5, and k_6 are that they not be rate-determining and that their ratios be such that the correct yields of the various products are predicted. Suitable numerical values were chosen by the method of iteration. This scheme accommodates the following experimental observations: (i) By use of the constants listed with Scheme I, simulations show that the rate of appearance of TBP$^\bullet$ follows the first-order rate law. (ii) The pseudo-first-order rate constants (k_{obsd}) for appearance of TBP$^\bullet$ reaches a limiting value on increase in $[(\mathrm{EDTA})\mathrm{Fe^{III}}]_i$, suggesting formation of a precursor complex between (EDTA)Fe$^{\mathrm{III}}$ and MCPBA. (iii) A peroxidic component is formed by reaction of MCPBA with TBPH, and the product does not react with (EDTA)Fe$^{\mathrm{III}}$. (iv) Formaldehyde has a retarding effect on k_{obsd}.

Fitting of the simulated time curves for appearance of TBP$^\bullet$ to the first-order rate law allows the calculation of what should

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Table VII. Effect of the Initial Concentration of $\mathrm{(EDTA)Fe^{III}}$ on the Yield of Various Products for the Oxidation of TBPH by MCPBA at $[\mathrm{TBPH}]_i = 9.5 \times 10^{-2}$ M

$\mathrm{(EDTA)Fe^{III}}$, M	MCPBA, M	$\mathrm{TBP^{\bullet}}$, M × 10^4		$\mathrm{CH_2O}$, M × 10^4		OXO × 10^4, M	
		calcd	obsd	calcd	obsd	calcd	obsd
1.50×10^{-4}	1.50×10^{-3}	6.16	6.75	9.03	9.76	1.07	1.34
8.90×10^{-5}	1.50×10^{-3}	5.93	4.20	9.47	10.8	1.04	0.76
4.40×10^{-5}	1.50×10^{-3}	6.16	6.90	9.50	8.90	1.08	3.15
2.25×10^{-5}	1.50×10^{-3}	6.16	6.23	9.62	9.71	1.08	1.18
4.20×10^{-6}	1.50×10^{-3}	5.97	6.00	9.43	10.60	0.70	0.41
1.10×10^{-6}	1.50×10^{-3}	5.70	5.25	9.00	8.20	1.08	3.76
1.50×10^{-4}	8.07×10^{-4}	4.10	5.35	3.80	3.98	0.93	2.22
8.04×10^{-5}	8.06×10^{-4}	4.10	3.90	3.89	3.60	0.93	2.98
4.25×10^{-5}	8.10×10^{-4}	4.10	4.15	4.00	4.10	0.94	1.74
2.25×10^{-5}	8.00×10^{-4}	3.51	3.35	5.45	5.79	0.33	0.37
4.20×10^{-6}	8.00×10^{-4}	3.46	3.05	5.45	5.40	0.34	0.35
4.20×10^{-6}	6.00×10^{-3}	15.9	14.7	25.5	28.3	11.3	11.0

be the experimentally determined pseudo-first-order rate constants (k_{obsd}) for $\mathrm{TBP^{\bullet}}$ appearance. The simulated values of k_{obsd} for the formation of $\mathrm{TBP^{\bullet}}$ are independent of the initial [MCPBA], as is found experimentally. However, when $[\mathrm{(EDTA)Fe^{III}}]_i$ is changed by the computer and the computed plots of $\mathrm{TBP^{\bullet}}$ formed with time are fitted to the first-order equation, it is found that the computed values of k_{obsd} are larger than those obtained experimentally. In order to force a fit of Scheme I to the experimental data, it is required that k_2 decreases with increase in $[\mathrm{(EDTA)Fe^{III}}]_i$. This result would be in accord with the consumption of $\mathrm{(EDTA)Fe^{III}}$ by its reaction with $\mathrm{(EDTA)(FeO)^{5+}}$ at high $[\mathrm{(EDTA)Fe^{III}}]_i$. Such a situation would mirror that reported by Walling[6b] for the reaction of $\mathrm{H_2O_2}$ with $\mathrm{(EDTA)Fe^{III}}$ where disappearance of catalyst was attributed to its reaction with $\mathrm{HO^{\bullet}}$. With the present system, however, we find that the catalyst is quite stable. The difference between the experimental conditions of Walling and associates and ourselves is that in our case both TBPH and $\mathrm{CH_3OH}$ solvent serve as very effective traps for oxygen radicals and $\mathrm{(EDTA)(FeO)^{5+}}$, whereas the Walling experiments were carried out in $\mathrm{H_2O}$ and the $\mathrm{(EDTA)Fe^{III}}$ served along with $\mathrm{H_2O_2}$ as the only oxidizable substrates. The destruction of catalyst cannot account for our experimental results is shown by simulation. The reaction of eq h when added to those of Scheme I provides Scheme II. [a] Units are moles and seconds. The constants listed with Scheme II are best as determined by iteration. By the same means as previously described it was found that k_2 must again be adjusted downward with increase in $[\mathrm{(EDTA)Fe^{III}}]$ in order to reproduce the experimental time courses of $\mathrm{TBP^{\bullet}}$ appearance. It would appear as though the only remaining assumption is that the activity coefficient of $\mathrm{(EDTA)Fe^{III}}$ decreases over the 100-fold change in concentration used in this study. An explanation based upon reversible binding of a minor product of the reaction appears unlikely because at high $[\mathrm{(EDTA)Fe^{III}}]$ there are fewer turnovers of the catalyst. At high $\mathrm{(EDTA)Fe^{III}}$ concentration, the formation of a μ-oxo dimeric iron species like $\mathrm{(EDTA)(Fe\text{–}O\text{–}Fe)(EDTA)^{8+}}$ due to a comproportionation reaction of $\mathrm{(EDTA)(FeO)^{5+}}$ with $\mathrm{(EDTA)Fe^{III}}$ seems also unlikely because when the concentration of TBPH is changed at high $\mathrm{(EDTA)Fe^{III}}$ concentrations, the zero-order dependence on TBPH remains unchanged (see Table I). Though, by both spectral and electrochemical techniques (see Results), there could not be obtained evidence of association of $\mathrm{(EDTA)Fe^{III}}$, the ability to simulate the collected body of kinetic experiments requires some sort of association. (Association through bridging by solvent molecules or a formaldehyde hydrate could preclude spectral or electrochemical detection.) Addition of eq h′ to Scheme I provides Scheme III. [a] Units are moles and seconds. The rate constants presented with Scheme III were obtained by iteration employing the complete body of experimental data. It should be noted that the destruction of $\mathrm{(EDTA)Fe^{III}}$ need not be assumed. The resistance of $\mathrm{(EDTA)Fe^{III}}$ to oxidation under

Scheme II[a]

(a) $\mathrm{(EDTA)Fe^{III} + MCPBA \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} (EDTA)Fe^{III}\text{–}MCPBA}$
$k_1/k_{-1} = 1.0 \times 10^4/1.0 \times 10^3$

(b) $\mathrm{(EDTA)Fe^{III}MCPBA \xrightarrow{k_2} (EDTA)(FeO)^{5+} + MCBA}$ $k_2 = 6.0$

(c) $\mathrm{(EDTA)(FeO)^{5+} + TBPH \xrightarrow{k_3} (EDTA)(FeOH)^{5+} + TBP^{\bullet}}$ $k_3 = 5.0 \times 10^3$

(d) $\mathrm{(EDTA)(FeOH)^{5+} + TBPH \xrightarrow{k_4} (EDTA)Fe^{III} + TBP^{\bullet} + H_2O}$ $k_4 = 5.0 \times 10^2$

(e) $\mathrm{(EDTA)(FeO)^{5+} + CH_3OH \xrightarrow{k_5} (EDTA)Fe^{III} + CH_2O + H_2O}$ $k_5 = 50.0$

(f) $\mathrm{(EDTA)(FeO)^{5+} + MCPBA + TBPH \xrightarrow{k_6} (EDTA)Fe^{III} + OXO}$ $k_6 = 2.5 \times 10^6$

(g) $\mathrm{(EDTA)Fe^{III} + CH_2O \underset{k_{-7}}{\overset{k_7}{\rightleftharpoons}} (EDTA)Fe^{III}CH_2O}$
$k_7/k_{-7} = 1.0 \times 10^2/10.0$

(h) $\mathrm{(EDTA)(FeO)^{5+} + (EDTA)Fe^{III} \xrightarrow{k_8} (EDTA)Fe^{III}}$ + deactivated product $k_8 = 4.0 \times 10^5$

Scheme III[a]

(a) $\mathrm{(EDTA)Fe^{III} + MCPBA \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} (EDTA)Fe^{III}\text{–}MCPBA}$
$k_1/k_{-1} = 1.20 \pm 0.2 \times 10^4/1.0 \times 10^3$

(b) $\mathrm{(EDTA)Fe^{III}MCPBA \xrightarrow{k_2} (EDTA)(FeO)^{5+} + MCBA}$ $k_2 = 6.2 \pm 0.20$

(c) $\mathrm{(EDTA)(FeO)^{5+} + TBPH \xrightarrow{k_3} (EDTA)(FeOH)^{5+} + TBP^{\bullet}}$ $k_3 = 5.5 \pm 0.5 \times 10^3$

(d) $\mathrm{(EDTA)(FeOH)^{5+} + TBPH \xrightarrow{k_4} (EDTA)Fe^{III} + TBP^{\bullet} + H_2O}$ $k_4 = 5.0 \times 10^2$

(e) $\mathrm{(EDTA)(FeO)^{5+} + CH_3OH \xrightarrow{k_5} (EDTA)Fe^{III} + CH_2O + H_2O}$ $k_5 = 48 \pm 3$

(f) $\mathrm{(EDTA)(FeO)^{5+} + TBPH + MCPBA \xrightarrow{k_6} (EDTA)Fe^{III} + OXO}$ $k_6 = 4.5 \pm 2.0 \times 10^6$

(g) $\mathrm{(EDTA)Fe^{III} + CH_2O \underset{k_{-7}}{\overset{k_7}{\rightleftharpoons}} (EDTA)Fe^{III}CH_2O}$
$k_7/k_{-7} = 2.0 \times 10^4/10.0$

(h′) $\mathrm{(EDTA)Fe^{III} + (EDTA)Fe^{III} \underset{k_{-8}}{\overset{k_8}{\rightleftharpoons}} ((EDTA)Fe^{III})_2}$
$k_8/k_{-8} = 1.0 \times 10^5/9.0 \pm 2.0$

Table VIII. Effect of the Initial Concentration of TBPH on the Yield of Various Products for the Oxidation of TBPH by MCPBA (1.50×10^{-3} M)

$(EDTA)Fe^{III}$, M	TBPH, M	$[TBP^\bullet] \times 10^4$, M calcd	obsd	$[CH_2O] \times 10^4$, M calcd	obsd	OXO $\times 10^4$, M calcd	obsd
2.25×10^{-5}	0.025	1.90	1.85	11.3	10.7	1.21	2.20
2.25×10^{-5}	0.050	3.25	3.75	9.27	9.28	1.96	2.50
2.25×10^{-5}	0.20	9.42	10.5	6.96	7.50	1.60	2.00
2.25×10^{-5}	0.38	13.9	13.6	5.96	7.00	0.98	0.95
1.50×10^{-4}	0.025	2.17	1.90	12.2	11.7	0.39	0.09
1.50×10^{-4}	0.38	12.3	14.1	4.41	4.83	2.00	4.06

Table IX. Effect of the Initial Concentration of MCPBA on the Yield of Various Products for the Oxidation of TBPH by MCPBA at $[(EDTA)Fe^{III}]_i = 2.25 \times 10^{-5}$ M and $[TBPH]_i = 9.5 \times 10^{-2}$ M

MCPBA, M	$TBP^\bullet$, M $\times 10^4$ calcd	obsd	CH_2O, M $\times 10^4$ calcd	obsd	OXO, M $\times 10^4$ calcd	obsd
5.10×10^{-4}	2.32	2.70	3.58	3.10	1.37	0.74
8.00×10^{-4}	3.51	3.35	5.45	5.79	0.33	0.37
1.50×10^{-3}	6.16	6.23	9.62	9.71	1.08	1.18
6.00×10^{-3}	17.5	18.8	28.0	28.7	11.30	9.21
1.05×10^{-2}	24.3	26.4	39.4	46.0	26.0	45.4

Table X. Effect of the Initial Concentration of MCPBA on the Rate Constant k_1 for the Rate of Appearance of $TBP^\bullet$ at $[(EDTA)Fe^{III}]_i = 2.25 \times 10^{-5}$ M and $[TBPH]_i = 9.5 \times 10^{-2}$ M and at Constant $k_2 = 8.0$ s^{-1} and $k_{-8} = 10.0$ M^{-1} s^{-1}

MCPBA, M	k_1	$10^3 \times k_{obsd}$, s^{-1} calcd	obsd
5.10×10^{-4}	1.10×10^4	1.17	1.09
8.00×10^{-4}	1.10×10^4	1.23	1.19
1.50×10^{-3}	1.40×10^4	1.35	1.33
6.00×10^{-3}	1.40×10^4	0.87	0.89
1.05×10^{-2}	1.50×10^4	0.75	0.80

Table XI. Effect of the Initial Concentration of TBPH on the Rate Constant k_1 for the Rate of Appearance of $TBP^\bullet$ at $[(EDTA)Fe^{III}]_i = 2.25 \times 10^{-5}$ M and $[MCPBA]_i = 1.50 \times 10^{-3}$ M and at Constant $k_2 = 8.0$ s^{-1} and $k_{-8} = 10$ M^{-1} s^{-1}

TBPH, M	k_1	$10^3 \times k_{obsd}$, s^{-1} calcd	obsd
0.025	1.4×10^4	1.35	1.57
0.05	1.5×10^4	1.47	1.69
0.20	1.5×10^4	1.59	1.53
0.38	1.2×10^4	1.23	1.25

the experimental conditions has been affirmed (see Results). The reactions of Scheme III with associated constants seems to explain the observed kinetic details and the percentage yields of products. The yield of the various products, $TBP^\bullet$, CH_2O, and the OXO calculated on the basis of Scheme III and the corresponding experimentally observed product yields, are given in Tables VII, VIII, and IX. From these tables the agreement between the computed values and the observed yields is reasonably good. At the same time, the required changes in the rate constants (k_1, k_2, and k_{-8}) required to fit k_{obsd} for the appearance of $TBP^\bullet$ may be examined under various reaction conditions: (i) Change in $[MCPBA]_i$ at constant [TBPH) and $[(EDTA)Fe^{III}]$ is given in Table X. As $[MCPBA]_i$ is increased (20-fold), there is but a marginal increase (($1.3 \pm 0.2) \times 10^4$ M^{-1} s^{-1}) in the value of k_1, while k_2 and k_{-8} are constant, and there is good agreement between computed and experimentally determined values of k_{obsd}. (ii) The influence of change in $[TBPH]_i$ at constant $[MCPBA]_i$ and $[(EDTA)Fe^{III}]_i$ upon the computed and experimentally observed values of k_{obsd} is given in Table XI. The best values of k_1, k_2 and k_{-8} for the fitting of the experimental data are almost constant, and the agreement between the computed and experimental k_{obsd} is within experimental error. (iii) Fitting of the experimental results for changing $[(EDTA)Fe^{III}]_i$, at constant $[MCPBA]_i$ and $[TBPH]_i$, requires (Table XII) only a small change in k_1 (($1.3 \pm 0.2) \times 10^4$ M^{-1} s^{-1}), while k_{-8} has been changed for only two cases and is virtually constant and k_2 averages to 7.0 ± 2.0 s^{-1}. The computer calculated values of k_{obsd} agree reasonably well with the experimentally observed values. (iv) The diminution in k_{obsd} for appearance of $TBP^\bullet$ brought about by addition of formaldehyde may be simulated (as shown in Table XIII) by using the rate constants $k_1 = 1.1 \pm 0.1 \times 10^4$ M^{-1} s^{-1}, $k_2 = 6.0$ s^{-1}, and $k_{-8} = 10$ s^{-1}, and the corresponding calculated product yields are given in Table XIV.

Our previous studies establishes that oxygen transfer from percarboxylic acids to (tetraphenylporphinato)metal(III) salts (metal(III) = Fe^{III}, Mn^{III}, Cr^{III}, and Co^{III}) involves heterolytic O–O bond scission. For oxygen transfer from weakly acidic alkyl hydroperoxides to (tetraphenylporphinato)metal(III) salts (Fe^{III}, Mn^{III}, and Co^{III}) homolytic O–O bond breaking is involved.[5e,f,g,h] In the present study we have shown that the oxygen transfer from

Table XII. Effect of Initial Concentration of $(EDTA)Fe^{III}$ on the Rate Constants k_1, k_2, and k_{-8} for the Rate of Appearance of $TBP^\bullet$ at $[TBPH]_i = 9.50 \times 10^{-2}$ M

$(EDTA)Fe^{III}$, M	MCPBA, M	k_1	k_2	k_{-8}	$10^3 \times k_{obsd}$, s^{-1} calcd	obsd
1.50×10^{-4}	1.50×10^{-3}	1.10×10^4	6.0	10.0	3.54	3.40
8.90×10^{-5}	1.50×10^{-3}	1.40×10^4	6.5	10.0	3.38	3.50
4.40×10^{-5}	1.50×10^{-3}	1.40×10^4	7.0	10.0	2.19	2.12
2.25×10^{-5}	1.50×10^{-3}	1.40×10^4	8.0	10.0	1.35	1.33
4.20×10^{-6}	1.50×10^{-3}	1.50×10^4	9.0	15.0	0.37	0.53
1.10×10^{-6}	1.50×10^{-3}	1.50×10^4	10.0	15.0	0.14	0.15
1.50×10^{-4}	8.07×10^{-4}	1.0×10^4	5.0	7.0	2.55	2.00
8.04×10^{-5}	8.06×10^{-4}	1.0×10^4	6.0	10.0	2.25	2.15
4.25×10^{-5}	8.10×10^{-4}	1.0×10^4	6.0	10.0	1.42	1.42
2.25×10^{-5}	8.00×10^{-4}	1.1×10^4	8.0	10.0	1.23	1.19
4.20×10^{-6}	8.00×10^{-4}	1.4×10^4	6.5	10.0	0.28	0.27
4.20×10^{-6}	6.02×10^{-3}	1.0×10^4	6.0	10.0	0.12	0.11

Table XIII. Effect of the Initial Concentration of Formaldehyde on the Rate Constant k_1 for the Appearance of TBP• at $[(EDTA)Fe^{III}]_i = 2.25 \times 10^{-5}$ M, $[MCPBA]_i = 1.50 \times 10^{-3}$ M, and $[TBPH]_i = 9.50 \times 10^{-2}$ M

$[CH_2O]_i$, M × 10^4	k_1	k_2	k_{-8}	$10^3 \times k_{obsd}$, s^{-1}	
				calcd	obsd
7.30	1.3 × 10^4	6.0	10.0	0.56	0.56
17.0	1.0 × 10^4	6.0	10.0	0.29	0.21
17.3	1.2 × 10^4	6.0	10.0	0.36	0.39[a]

[a] Followed by monitoring the disappearance of [MCPBA].

Table XIV. Effect of the Initial Concentration of Formaldehyde on the Yield of Various Products for the Oxidation of TBPH by MCPBA at $[(EDTA)Fe^{III}]_i = 2.25 \times 10^{-5}$ M, $[MCPBA]_i = 1.50 \times 10^{-3}$ M, and $[TBPH]_i = 9.50 \times 10^{-2}$ M

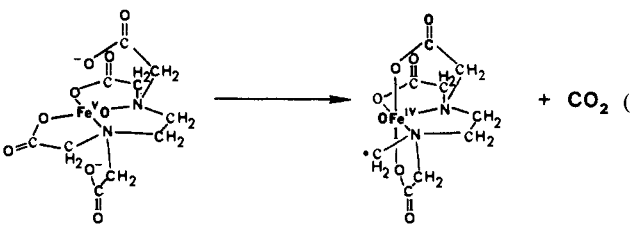
$[CH_2O]_i$, M × 10^4	[TBP•] × 10^4, M		$[CH_2O]$ × 10^4, M		OXO × 10^4, M	
	calcd	obsd	calcd	obsd	calcd	obsd
7.30	4.74	4.60	10.2	9.20	1.05	1.13
17.0	4.38	3.40	9.30	4.30[a]	1.04	1.50

[a] The remaining ~5.0 × 10^{-4} M in formaldehyde is likely to be further oxidized to formic acid (33%).

percarboxylic acids to $(EDTA)Fe^{III}$ involves heterolytic O–O bond breaking. Walling[6b] has previously shown that the oxygen transfer from hydrogen peroxide to $(EDTA)Fe^{III}$ involves homolytic O–O bond cleavage in aqueous medium.

In methanol solvent employing TBPH as a trap for the iron–oxo species, the second-order rate constant for oxygen transfer from MCPBA to $(TPP)Fe^{III}(CH_3OH)Cl$[5e] exceeds that for oxygen transfer from MCPBA to $(EDTA)Fe^{III}$ by about 45-fold. The extensively π-conjugated porphyrin ligand, as compared to EDTA, provides the greatest electron density to the iron(III), increasing its softness and nucleophilicity. Though $(TPP)Fe^{III}(CH_3OH)Cl$ is more reactive than $(EDTA)Fe^{III}$ toward MCPBA, oxidation of CH_3OH solvent (in competition with TBPH oxidation) by the generated iron–oxo porphyrin species does not occur, whereas it does in the case of the iron–oxo EDTA species. This may be taken to indicate that the harder iron center imparts a greater reactivity and lesser selectivity to the iron–oxo EDTA species.

It is surprising to us, even in the presence of both TBPH and CH_3OH solvent as traps, that oxygen transfer to the $(EDTA)Fe^{III}$ catalyst does not result in its destruction by oxidative decarboxylation of the carboxylate ligand groups (eq 6). This suggests



(6)

to us that the structure $(EDTA)(Fe^{V}O)^{5+}$ is inadequate and that considerable electron deficiency must reside on the oxygen atom. Sawyer[19] and associates have proposed that, in general, oxygen transfer to ferric ion does not expand the oxidation state of the latter and that the iron(III) stabilizes the oxygen atom by d-orbital overlap. If such were the case, the structure of the iron–oxo intermediate species of this study would be $(EDTA)(Fe^{III}O)^{5+}$. Two-electron oxidation of iron(III) tetraphenylporphyrin salts $((Porph)Fe^{III}X)$ provides an iron(III) tetraphenylporphyrin dication $((Porph)Fe^{III}X^{2+})$ when the ligand X^- is weakly basic such as ClO_4^- and Cl^- and an iron(IV) tetraphenylporphyrin π-cation radical $((^{\bullet}Porph)Fe^{IV}(OCH_3)^+)$ when X^- is a strongly basic oxyanion as HO^- and CH_3O^-.[5i,j] Oxygen atom transfer to ligated iron(III) is equivalent to the addition of HO^- to ligated iron(III) followed by 2e– oxidation. The analogy supports the iron(IV)–oxo porphyrin π-cation radical as the product of oxygen transfer to iron(III) porphyrins. An imidazole-ligated iron(IV)–oxo porphyrin π-cation radical represents the reactive species (compound I) of the peroxidase enzymes.[20] The nature of the iron–oxo species formed upon oxygen atom transfer to iron(III) would appear to be dependent upon the nature of the ligands.

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Radical Cation Chain Oxygenation of Dienes by Triplet Oxygen

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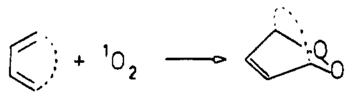
Abstract: Alkylated 1,3-dienes are shown to oxygenate to endoperoxides by a cation radical chain mechanism. Steric slowing of Diels–Alder dimerization appears to be necessary; 1,3-cyclohexadiene (**21**) gave only dimer under conditions where its 1-isopropyl-4-methyl derivative, **17**, gave a 96% yield of ascaridole (**18**). The cation radical chain conditions tolerate more steric crowding than does the singlet oxygen reaction, as 4,4′-bihomoadamantenyl (**11**) gave an 84% yield of its endoperoxide **16** while singlet oxygen gave a mixture of several products. Oxygenation products were not observed from biadamantylideneethane (**5**), which is sterically prohibited from assuming an s-cis conformation.

The characteristic reaction of s-cis 1,3-dienes with singlet oxygen is Diels–Alder 1,4-cycloaddition to give the unsaturated six-membered ring endoperoxide, as shown in eq 1.[1] Barton and co-workers[2] showed that a variety of Lewis acids catalyze endoperoxide formation from dienes and triplet oxygen, both in the



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