Kinetic Studies of the Formation of Iron (III) Ethylenediaminetetraacetate-Hydrogen Peroxide Complex
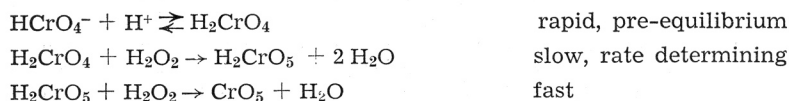
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The formation of a red-purple iron (III) ethylenediaminetetra-acetate mono hydrogen peroxide species obeys the kinetic expression rate $= k$ [Fe(EDTA) (OH)$_2^{3-}$] [H$_2$O$_2$] over the range pH 9.0—11.0. The Arrhenius equation, $k = 1.9 \times 10^7$ exp (—6,700/RT) holds and at 25^0, $k = 2.5 \times 10^2$ M^{-1} sec^{-1}. An enhanced rate above pH $= 11.0$ may be associated with enhanced reactivity of [Fe(EDTA) (OH)$_3$]$^{4-}$ or HO$_2^-$. A brief comparison is made of the results with data for peroxidase and catalase reactions with hydrogen peroxide.

INTRODUCTION

We have previously examined the kinetics of formation of peroxy species of chromium (VI), vanadium (V) and titanium (IV) in acid media[1]. These rapid reactions which involved replacement of oxy by peroxy groups are first-order in transition metal ion concentration and first-order in hydrogen peroxide concentration and are usually acid-catalysed, involving, we believe, protonated oxy-ions as effective reactants, e. g.,

HCrO$_4^-$ + H$^+$ ⇌ H$_2$CrO$_4$ rapid, pre-equilibrium

H$_2$CrO$_4$ + H$_2$O$_2$ → H$_2$CrO$_5$ + 2 H$_2$O   slow, rate determining

H$_2$CrO$_5$ + H$_2$O$_2$ → CrO$_5$ + H$_2$O   fast

We now turn our attention to the peroxy compounds of metal chelates, where the major portion of the coordination sphere is occupied by a firmly attached multidentate ligand and a water or hydroxy group is replaced by the entering hydrogen peroxide. Since an increasing amount of data is becoming available concerning the water exchange rate of metal aqua and coordinated ions[2] we can attempt to relate the water exchange and hydrogen peroxide entry rates. Present trends in this area are towards identifying the role of these peroxy complexes in the catalysed decomposition of hydrogen peroxide, a large variety of metal chelates** having been studied, including the biological important iron (III) enzymes, catalase and peroxidases.[5]

In this paper we study the formation of a red-purple peroxy species of the iron (III)-ethylenediaminetetraacetate (EDTA) complex in alkaline solution.

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** Of recent interest in this context are Copper (II) complexes (See Ref. 3) and Nickel (II) complexes (See Ref. 4).

Materials

A stock solution of the iron (III) EDTA complex was prepared from $Fe(ClO_4)_3 \cdot$
$\cdot 6 H_2O$ (G. F. Smith Chemical Co.) and the disodium salt of EDTA (Fisher). Concentrations of iron (III)[6] and the EDTA complex[7] were determined spectrophotometrically. An excess of EDTA was used to ensure complete complex formation. Both sodium stannate-stabilized and non-stabilized hydrogen peroxide (Fisher) were used with similar results. Sodium hydroxide and perchloric acid solutions were used to obtain the appropriate pH and ionic strength. The concentration of hydrogen peroxide was determined with standard cerium (IV), immediately after the completion of a run.

Equilibria Measurements

A Cary 14 was used to characterise the species spectrally. The method employed for the measurements was essentially that described by Ringbom, Siitonen and Saxen[8] and later used by Mader[9]. The absorbancy at 520 mμ was measured at room temperature (23^0 C) of a series of solutions (at various pH values) containing different concentrations of iron (III)-EDTA and H_2O_2. The ionic strength was maintained at 0.1 M using sodium perchlorate and the pH was adjusted after all components had been added, to prevent precipitation of ferric hydroxide. The equilibrium constant K was calculated on the basis of the expression (1)[8]

$$K = [FeEDTA-H_2O_2] / [FeEDTA] [HO_2^-] \quad \text{or}$$

$$(1)$$

$$K = \frac{[FeEDTA-H_2O_2] \{[H^+] + K_{H_2O_2}\}}{[FeEDTA] K_{H_2O_2} \{[H_2O_2] - [FeEDTA-H_2O_2]\}}$$

where $[H_2O_2]$ = total peroxide added, $[FeEDTA-H_2O_2]$ = concentration of the colored peroxy species which is the only contributor to the optical density at 520 mμ ($\varepsilon = 530$ cm.$^{-1}$ M^{-1}), and $K_{H_2O_2} = 2.2 \times 10^{-12}$, $[FeEDTA]$ represent the concentration of all Fe (III)-EDTA species present. Charges of the complex species have been omitted for clarity. The values of K are accurate to $\pm 8^0/0$. The spectra of completely formed peroxy species have been taken at pH = 11—12. The complex obeys Beer's law in the range of concentrations used, $9 \times 10^{-6} - 1.7 \times 10^{-4}$ M. At lower pH (8.0—9.5) the high H_2O_2 concentrations, needed to ensure complete complex formation, promote a subsequent appearance of a yellow color that interferes with spectral measurements, but not with the kinetic measurements of the red species. At high pH ($\geqslant 12.5$) a yellow solution appears which then becomes turbid, probably due to decomposition to ferric hydroxide. By working quickly however it was possible to measure the spectra of the peroxy species from pH = 8.5 to 12.0. An additional excess of EDTA had very small effect on the absorbancy.

Kinetic Runs

The formation of the red violet iron EDTA-H_2O_2 species was studied at 520 mμ, using a glass-lucite stopped-flow apparatus. The concentrations of iron EDTA were $6.4—8.6 \times 10^{-5}$ M, with excess EDTA $6.1 \times 10^{-5} - 4.0 \times 10^{-5}$ M. Hydrogen peroxide was always present in large excess, ensuring pseudo first-order conditions, but its concentration range was limited at the lower end by requirements for completion of reaction and at higher concentrations with sufficiently long half-lives (t$_{1/2}$ $\geqslant$ 5 msec). High H_2O_2 concentrations produced oxygen bubbles in the observation chamber which prevented measurements. In the majority of the kinetic runs, peroxy formation was substantially complete, but in the two runs at pH = 9.5 and 9.0, the extent of formation was $\sim$90 and $\sim$80^0/0 respectively, so that k_{obs} ($= 0.93/t_{1/2}$) probably includes a small contribution from the back reaction. Excellent traces and first-order kinetics were shown.

Attempts were made to follow the rates of formation of $[Fe(EDTA) (OH)]^{2-}$ from $[Fe(EDTA)]^-$ and of $[Fe(EDTA) (OH_2)]^{3-}$ from $[Fe(EDTA) (OH)]^{2-}$ by reacting a solution of $[Fe(EDTA)]^-$ at pH = 6—7 with an alkaline solution so as to obtain a final pH of $\sim$8.5 or $\sim$10.0, using phenolphthalein or thymolphthalein as indicators. There was no indication of any slow processes in the production of the hydroxy species, indicator color adjustment being complete in the time of mixing. In the

event that a coordinated carboxylate (rather than an aqua species) was being replaced by hydroxide ion a measurable rate may have resulted.

A rapid hydroxylation is however inconclusive in distinguishing between the two possibilities.

RESULTS AND DISCUSSION

Iron (III) ethylenediaminetetraacetate complex forms hydroxy species in alkaline solution, $[Fe(EDTA)OH]^{2-}$ $pK = 7.5$, $[Fe(EDTA)(OH_2)]^{3-}$ $pK = 9.5$ and $[Fe(EDTA)(OH)_3]^{4-}$ $pK \approx 12.5^{10}$. At the low concentrations of complex used, binuclear species are unimportant[11]. In most our kinetic studies, the major species in solution is the dihydroxy complex.

Our results, where they overlap, are in substantial agreement with previous workers. The red-violet peroxy species has a maximum at 520 mμ[12], $\varepsilon = 530$, slightly lower than the value reported by Mader[9] ($\varepsilon = 547$). The position of the absorption maximum is identical from pH — 8.5 to 12.0 and so if in this range there exists different peroxy species with respect to the number of hydroxy groups (which is the case with ferric-EDTA itself) they appear to have identical spectral characteristics.

TABLE I

Formation Constants (Expression (1)) for Iron Ethylenediaminetetraacetate Peroxy Species at 23⁰, I = 0.1 M

[Fe^{III} complex] μM	pH	10^{-3} K M^{-1}
75	8.5	9.4
75	9.0	9.9
75	10.0	9.8
75	11.0	8.3
86	11.0	7.8
170	11.0	7.2
340	11.0	7.8
75	11.5	7.1

The constancy of K (Table I) on the basis of expression (1) indicates[8] that H₂O is being replaced by HO_2^{2-} or that O_2^{2-} is taking the place of OH⁻ in the coordination sphere of iron(III). The magnitude of K (9.8×10^3) is naturally sensitive to the chosen value of $K_{H_2O_2}$: For our conditions, $K_{H_2O_2} = 2.2 \times 10^{-12}$ appears reasonable[13,14]. The values for K previously reported are 3.6×10^3 at 22⁰ (conditions unspecified)[8] and 7.1×10^3 at 25⁰ (I = 0.38)[9]. The latter value would be modified to 1.3×10^4 if our value for $K_{H_2O_2}$ was used. Our constant shows a small trend toward decreasing values with increase in pH which, if real, possibly means a small direct participation of H₂O₂ in the reaction.

Two typical kinetic oscilloscope traces are shown in Fig. 1. These demontrate, together with the data in Table II, the insensitivity to pH from 9 to 11 of a second-order rate constant k_2 for which:

$$\frac{d}{dt}[Fe(EDTA) — H_2O_2] = k_2 [Fe(EDTA)(OH)_2^{3-}] [H_2O_2]$$

with $k_2 = 1.9 \times 10^7$ exp (—6,700/RT) and at 25⁰, $k_2 = 2.5 \times 10^2$ M^{-1} sec.⁻¹ The rate law does not, of course, distinguish between a replacement mechanism controlled by a water exchange process[2] and a simple bimolecular reaction
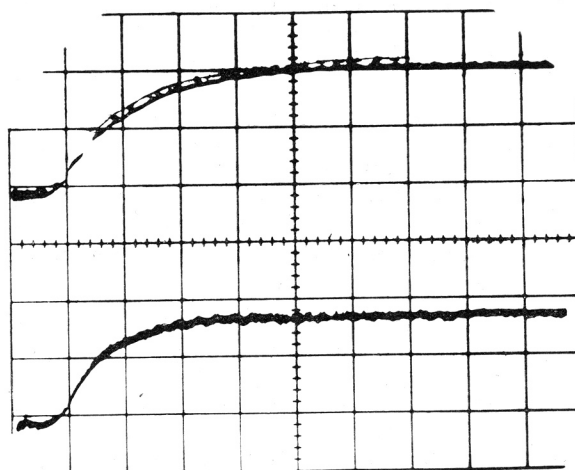
Fig. 1. Stopped-flow trace showing formation of red-violet [FeEDTA—H₂O₂] complex from [FeEDTA(OH)₂]³⁻. [FeEDTA] = 6.4 × 10⁻⁵ M, [H₂O₂] = 0.09 M, I = 0.1 M, t = 23° C. Upper curve at pH = 11.5, lower at pH = 10. Each major division represents 0.05 sec. Increasing optical density is represented upwards.

TABLE II

Kinetic Data for the Formation of Iron (III) Ethylenediaminetetraacetate Peroxy Species, I = 0·1 M

Temp. °C	pH	$[H_2O_2]_t{}^a$ mM	$t_{1/2}$ sec.	$10^{-2} k_{obs}/[H_2O_2]^b$ M^{-1} sec.⁻¹
23	9.0	203	0.018	1.9
23	9.5	144	0.020	2.4
23	10.0	123	0.026	2.2
23	10.0	101ᶜ	0.036	2.0
23	10.0	101ᵈ	0.037	1.9
23	10.0	101	0.034	2.1
23	11.0	96	0.031	2.8
23	11.0	56	0.061	2.4
23	11.0	20	0.20	2.2
23	11.0	6	0.58	2.5
23	11.5	90	0.025	5.2
23	12.0	80	0.027	10.3
23	12.0	40	0.058	9.6
23	12.0	21	0.12	9.2
14.5	11.0	60	0.072	1.6
6.5	11.0	60	0.097	1.2
1.0	11.0	60	0.12	1.0

ᵃTotal hydrogen peroxide used. ᵇFree [H₂O₂]. ᶜIron (III) complexes 1.3 × 10⁻⁴ M. ᵈExcess [EDTA] = 3.2 × 10⁻⁴ M.

between [Fe(EDTA) (OH)₂]³⁻ and H₂O₂. Certainly the second order rate constant is not an unreasonable value for the water exchange for iron (III) coordinated water should this be present in the complex or alternatively for possible carboxylate-iron (III) bond breakage prior to H₂O₂ attack. On the other hand a coordination number exceeding six is present in *solid* structures of Fe(III)-EDTA complexes and so a direct S_N2 reaction, unusual in replacement

reactions generally, may be plausible here. We consider the equivalent process (in terms of the composition of the transition state) between $[Fe(EDTA)(OH)]^{2-}$ and HO_2^- unlikely in view of the constancy of a computed k_2 at $pH = 9.0$, where the monohydroxy species dominates. It appears that H_2O_2 reacts equally easily with the mono- and di-hydroxy iron (III) chelate.

At pH above 11.0 there is an increase of rate which may be associated with increasing amounts and reactivity of the HO_2^- species. Alternatively the reaction of $[Fe(EDTA)(OH_3)]^{4-}$, which appears at these alkalinities, with H_2O_2 or HO_2^- may play a role in the enhanced rates. The low enthalpy of activation (6.1 kcal. mole⁻¹) and the highly negative entropy of activation (— 28 e. u.) are characteristic of the formation of peroxy compounds so far studied[1].

Peroxidase and catalase are hemo-proteins containing, like also hemoglobin and myoglobin, the same reactive group, iron (III) protoporphyrin. Peroxidase has one heme group and catalase four heme groups per molecule. The kinetics of their reactions with peroxides have been studied by Chance and his colleagues by rapid flow methods[5].

The formation of the peroxidase or catalase 1 : 1 adducts with hydrogen peroxide (which probably also involves replacement of iron (III) coordinated aqua or hydroxy groups) are also second-order and as in our reactions are fairly indepedent of pH over a wide range, pH 4—11. They occur however with several orders of magnitude higher second-order rate constants (9×10^6 and 5×10^6 M^{-1} sec.⁻¹) than the corresponding reaction of $[Fe(EDTA)(OH)_2]^{3-}$, 2.5×10^2 M^{-1} sec.⁻¹ This presumably reflects an enhanced lability of coordinated water or hydroxy group in the former case caused by the strong in-plane coordination of the fused porphyrin ring to the iron (III). This would be similar to the effect of coordinated hydroxide on the rates of reaction of iron (III). With a variety of ligands $Fe(OH)^{2+}$ reacts with formation rate constants of the order 10^4 M^{-1} sec.⁻¹, whereas the corresponding reactions with the fully aquated iron (III) ion proceed much more slowly ($k \sim 10$ M^{-1} sec.⁻¹)[2].

REFERENCES

1. P. M o o r e, S. F. A. K e t t l e, and R. G. W i l k i n s, *Inorg. Chem.* **5** (1966) 466. M. O r h a n o v i ć and R. G. W i l k i n s, *J. Am. Chem. Soc.* **89** (1967) 278.
2. M. E i g e n and R. G. W i l k i n s, *The Kinetics and Mechanism of Formation of Metal Complexes* in *Mechanisms of Inorganic Reactions, Advances in Chemistry Series* 49, American Chemical Society, Washington, 1965.
3. H. S i g e l and H. E r l e n m e y e r, *Helv. Chim. Acta* **49** (1966) 1266.
4. R. Z e l l and H. S i g e l, *Helv. Chim. Acta* **49** (1966) 870.
5. B. C h a n c e, *Enzyme Kinetics in the Transient State* in *Investigation of Rates and Mechanisms of Reactions* Part II, S. L. F r i e s, E. S. L e w i s, and A. W e i s s b e r g e r, Eds., Interscience Publ., New York, 1963.
6. W. L. R e y n o l d s, N. L i u, and G. M i c k u s, *J. Am. Chem. Soc.* **83** (1961) 1078.
7. R. B a s t i n, R. W e b e r l i n g, and F. P a h l a, *Anal. Chem.* **28** (1956) 459.
8. A. R i n g b o m, S. S i i t o n e n, and B. S a x e n, *Anal. Chim. Acta* **16** (1957) 541.
9. P. M. M a d e r, *J. Am. Chem. Soc.* **82** (1960) 2956.
10. G. S c h w a r z e n b a c h and J. H e l l e r, *Helv. Chim. Acta* **34** (1951) 576.
11. R. L. G u s t a f s o n and A. E. M a r t e l l, *J. Phys. Chem.* **67** (1963) 576.
12. Z. P. K a c h a n o v a and. A. P. P u r m a l, *Zhur. fiz. khim.* **38** (1964) 1342.

13. M. G. E v a n s and N. U r i, *Trans. Faraday Soc.* **45** (1949) 224.
14. K. Y. S a l n i s, K. P. M i s h c h e n k o, and I. E. F l i s, *Zhur. neorg. khim.* **2** (1957) 1985.

IZVOD

Kinetičke studije stvaranja Fe (III) etilendiamin-tetraacetat-hidrogen peroksid kompleksa

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Stvaranje purpurno crvene Fe (III) etilenediamin-tetraacetat mono hidrogenper-oksid kompleksne vrste slijedi kinetički izraz brzine $= k [Fe(EDTA)(OH)_2^{3-}] [H_2O_2]$ u području pH od 9,0—11,0. Arrheniusova jednadžba, $k = 1,9 \times 10^7 \exp (- 6.700/RT)$ vrijedi i kod 25^0 C $k = 2,5 \times 10^2$ M^{-1} sek^{-1}. Povećana brzina reakcije iznad $pH = 11,0$ mogla bi se pripisati povećanoj reaktivnosti $[Fe(EDTA)(OH)_3]^{4-}$ ili HO_2^-. Rezultati su ukratko uspoređeni s podacima reakcija peroksidaze i katalaze s vodikovim peroksidom.

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