

An EPR Spectroscopic Study of the Radicals Formed in the Electro-oxidation (Kolbe Reaction) of 2-Hydroximinopropanoic and 2-Hydroximinohexanoic Acid

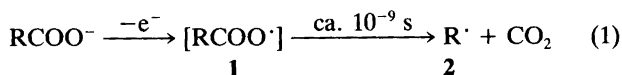
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Electro-oxidation of 2-hydroximinopropanoic and 2-hydroximinohexanoic acid, dissolved in H₂O or phosphate buffers gives rise to free radicals detectable by EPR spectroscopy in the pH range 5–12. It is suggested that the primary radicals CH₃C[=NO(H)] and CH₃(CH₂)₃C[=NO(H)] formed in the anodic oxidation of the carboxylates are trapped by their parent compounds by addition to their C=N bonds followed by dehydration and cyclization to form 3-carboxylato-3,4-dimethyl-2,3-dihydro-1,2,5-oxadiazol-2-yl and 3,4-dibutyl-3-carboxylato-2,3-dihydro-1,2,5-oxadiazol-2-yl.

It is generally accepted that radicals are involved in the anodic oxidation of carboxylate ions, i.e., the Kolbe reaction,¹ as shown in eqns. (1) and (2). The radicals can be



trapped and converted into diamagnetic products by addition of electroinactive compounds containing multiple bonds.² The major side-reactions that divert the reaction from the radical pathway is the oxidation of the radical to a carbocation [eqn. (3)].

Only recently has it been possible to trap a radical from a Kolbe electrolysis in the form of a detectable paramagnetic species, namely addition of the trifluoromethyl radical from the anodic oxidation of trifluoroacetic acid [eqn. (1), R = CF₃] to a perfluorinated olefin [(CF₃)₂CF]₂C=CFCF₃, to give the stable radical $\dot{\text{C}}[\text{CF}(\text{CF}_3)_2]_3$ which was detectable by EPR spectroscopy.³ Here both the trapping molecule and the resulting radical are resistant to the high potential needed for the discharge of carboxylates, often > 2.2 V vs. NHE.⁴

No other observations of **2** by the use of EPR spectroscopy seem to have been reported, either directly or in the form of aminoxyl radicals formed in the addition to spin traps of the nitroso or nitron type added to the electrolysis solution. Presumably, this is due to oxidation of the spin trap and/or the trapped radical under the usually very strongly oxidizing conditions near the anode.

Characteristically enough, the so-called photo-Kolbe reaction, in which oxidation of adsorbed acetate ions is induced by light quanta impinging upon a titanium dioxide surface, does lend itself to detection of the methyl radicals by trapping with α -phenyl-*N-tert*-butylnitron.⁵ In this case, no strong, uniform electric field is set up at the interface and trapped radicals can thus escape and be detected by EPR spectroscopy.

As mentioned above, the application of the spin-trapping technique in electrochemistry is limited to a potential window between -2.4 and 1.8 V, a range in which one can find systems where both trap and aminoxyl radicals are electroinactive.^{6,7} Clearly this conflicts with the conditions prevailing during most Kolbe electrolyses where the potential is > 2.2 V vs. NHE. One approach to avoid this restriction would be to find a carboxylate which is relatively easy to oxidize. Such cases are known, the most prominent being oxalate ion which is oxidized already at 0.2 V vs. SCE.⁸ A carboxylic acid containing an α -keto function or a group derived from it might thus be a good choice; it is known that α -keto carboxylates undergo Kolbe coupling in high yield.⁹

From these considerations, it was eventually found that α -hydroximino carboxylates fulfil the requirements above. They are oxidizable at relatively low potentials and give rise to radicals that are detectable by EPR spectroscopy. From what follows, it is seen that the α -hydroximino carboxylate acts as a 'self-trapping' agent for the radical formed in its anodic decarboxylation. The radical first formed is assumed to cyclize to an 2,3-dihydro-1,2,5-oxadiazole-type radical which is the EPR-active species.

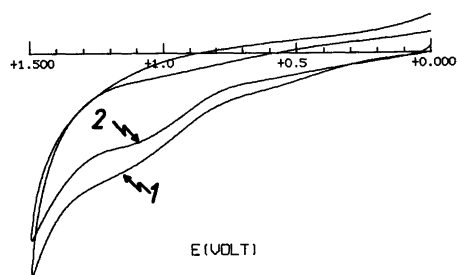


Fig. 1. Cyclic voltammetry of a solution of 2-hydroximinopropanoic acid (3 mM) in water–ammonium hexafluorophosphate (0.05 M). Curve 1, pH 6, curve 2, pH 10, scan rate 50 mV s^{-1} . Reference electrode, Ag/AgCl.

Results and discussion

A. Electrochemistry of 2-hydroximinopropanoic acid. The electrochemical oxidation of 2-hydroximinopropanoic acid (Pt anode) in water, 0.05 M in ammonium hexafluorophosphate, was briefly investigated by cyclic voltammetry. Fig. 1 shows that oxidation takes place around 0.3 V (vs. Ag/AgCl) both at pH 6 and at pH 10 and that there is an indication of a peak around 1.1 V in both cases. We ascribe this peak to oxidation of the carboxylate, which must be by

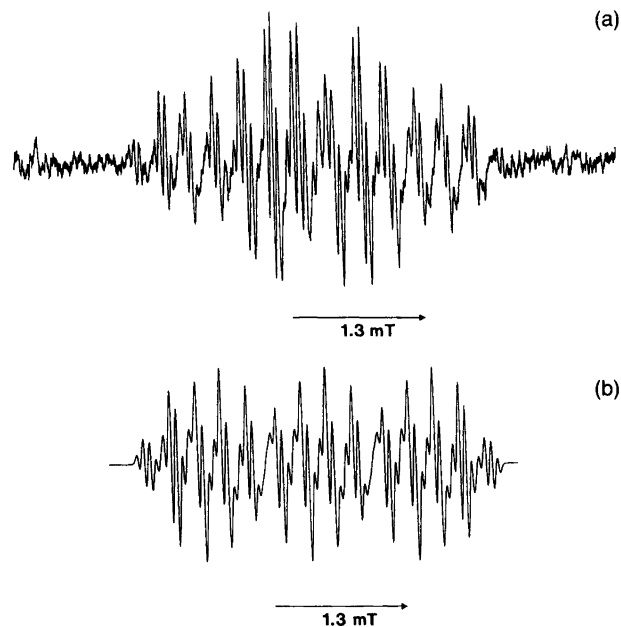


Fig. 2. (a) EPR spectrum of the radicals formed during *in situ* anodic oxidation of 2-hydroximinopropanoic acid dissolved in H_2O , pH 9.0. The potential between the platinum grid in the EPR cell and the reference electrode was 2.5 V. Microwave power: 5 mW, 100 kHz modulation: 0.025 mT; (b) simulated EPR spectrum corresponding to the experimental spectrum [Fig. 2(a)] obtained with 2-hydroximinopropanoic acid. The isotropic spectrum was constructed by use of the following parameters: $a_{\text{N1}} = 1.04 \text{ mT}$, $a_{\text{N2}} = 0.24 \text{ mT}$, $a_{\text{H1}} = 0.26 \text{ mT}$ (quartet 1:3:3:1), $a_{\text{H2}} = 0.06 \text{ mT}$ (quartet 1:3:3:1), linewidth: 0.035 mT.

far the predominant species in both solutions. We have not been able to find any measured $\text{p}K$ value of an α -hydroximinic acid, but its first $\text{p}K$ must be similar to that of an α -keto acid, ≈ 2.5 .¹⁰ The $\text{p}K$ of the hydroximinic group must be larger than that of a simple, uncharged oxime (2-hydroximinobutane has $\text{p}K \approx 12.5$)¹⁰ because of the acid-weakening effect of the carboxylate function.

B. EPR spectroscopic experiments. Electro-oxidation *in situ* in the EPR cavity of a solution of 2-hydroximinopropanoic acid in H_2O (20 mM), or in phosphate buffer, with pH adjusted by NaOH or HCl, gave rise to a radical, the EPR spectrum of which is shown in Fig. 2(a). The anode was a platinum grid ($40 \times 5 \times 0.5 \text{ mm}$, mesh 52) situated in a flat aqueous solution cuvette, the cathode a 3 M KCl–calomel electrode. The anode potential was measured by use of a third electrode (calomel) situated close to the anode.

The following experimental observations were recorded.

1. The radical was observed in the pH range between 4.7 and at least 12.5 with a relatively sharp maximum at 10.6, as seen from Fig. 3 which gives the relative amplitude of the radical signal plotted against the pH of the reaction mixture.

2. The radical appeared about 1 min after the application of the potential, and persisted at approximately the same level as long as electrolysis was performed. The radical disappeared almost immediately when the electrolysis was discontinued.

3. Fig. 4 shows the relative radical concentration plotted against the anode potential, recorded at pH 10.6. The radical begins to appear at about +0.3 V. There is an almost linear increase of the radical concentration from this value to about +0.8 V. Above this value, the curve flattens and reaches a plateau level at about +1 V. At pH values lower than 10.6, somewhat higher anode potentials had to be applied to reach the limiting value of the signal amplitude.

4. An EPR spectrum identical with that of Fig. 2(a) was obtained in the electrolysis of 2-hydroximinopropanoic acid dissolved in D_2O with pD adjusted to about 10.

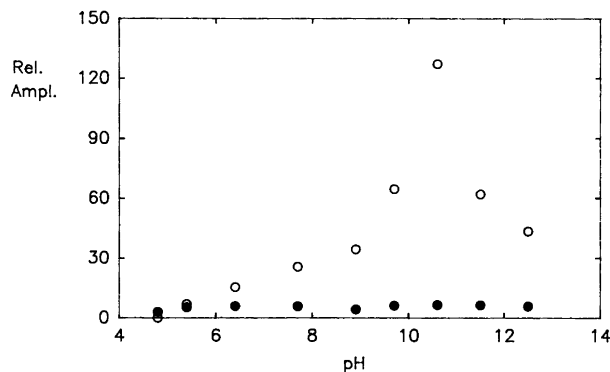


Fig. 3. The yield of radicals **6** (○), and the iminoxyl radical $\text{CH}_3\text{C}(\text{=NO}^\cdot)\text{COO}(\text{H})$ (●) in relative units plotted against the pH of the solution. Potential: 2.0 V.

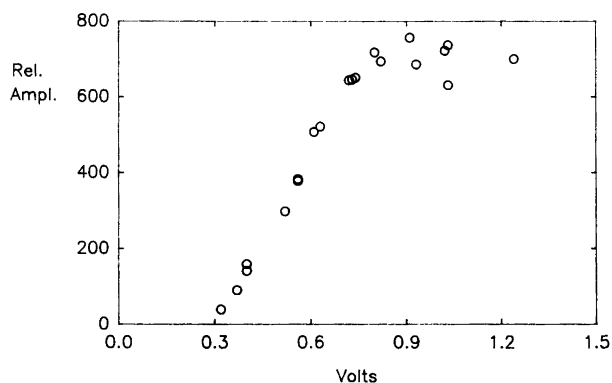


Fig. 4. The yield of radical 6 in relative units plotted against the potential between the platinum grid and the reference electrode, pH 10.6.

5. No radical was detected when the polarity of the electrodes was reversed.

6. No radical could be detected when a solution of 2-hydroximinopropanoic acid in H₂O at pH 10.5 was irradiated *in situ* with UV light after the addition of a small amount of H₂O₂ indicating that hydroxyl radicals were not involved in the formation of the radical.

7. Anodic oxidation of a solution of ethyl 2-hydroximinopropanoate, i.e. CH₃C(=NOH)COOC₂H₅ (20 mM) in 0.1 M NaClO₄, containing 10% ethanol, gave rise to the corresponding iminoxyl radical: $a_N = 3.17$ mT, $a_H = 0.13$ mT (quartet 1:3:3:1). No trace of the radical species of Fig. 2(a) could be detected.

8. Fig. 5(a) shows the EPR spectrum obtained in the anodic oxidation of a solution of 2-hydroximinohexanoic acid (20 mM) in phosphate buffer at pH 10.5 and an anodic potential of +2.0 V.

C. The EPR spectra: radicals derived from 2-hydroximinopropanoic acid. The spectrum of Fig. 2(a) exhibits 14 main groups, each split into a number of lines. An analysis of the spectrum by simulation indicated a relatively satisfactory fit to a system with an interaction between the unpaired electron and two non-equivalent ¹⁴N nuclei, with $a_{N1} = 1.04$ mT and $a_{N2} = 0.24$ mT, together with two sets of three equivalent hydrogen nuclei, $a_{H1} = 0.26$ mT and $a_{H2} = 0.06$ mT [Fig. 2(b)] (linewidth 0.035 mT). The *g*-value was found to be 2.0061.

Distortion of the line groups in the center of the 14 groups constituting the spectrum [Fig. 2(a)], originates from a superposition of the $M_I = 0$ component of the spectrum of an iminoxyl radical derived from the parent substance. This radical [CH₃C(=NO[•])COO⁻, $a_N \approx 3.0$ mT] is formed in a low concentration by oxidation at the anode.

The radicals derived from 2-hydroximinohexanoic acid. Simulation of the spectrum of Fig. 5(a) gave rise to a system with an interaction between the unpaired electron and two non-equivalent ¹⁴N nuclei, $a_{N1} = 0.82$ mT and $a_{N2} = 0.52$ mT, and two equivalent hydrogen nuclei, $a_H = 0.21$ mT (linewidth 0.085 mT), Fig. 5(b).

Formation and structure of the radicals. The formation of the radicals of Figs. 2(a) and 5(a) must be associated with the carboxylic group of the parent substances, since no species of the actual type were observed from ethyl 2-hydroximinopropanoate. The pH dependence of the signal amplitude is also consistent with a carboxylic group being involved in the reaction. The signal appeared at a pH value somewhat above the pK_a value of the free acid, and increased with increasing pH. The sharp maximum at pH 10.6 seems to indicate that the formation of the radical is base-catalyzed, and/or involves dissociation of the hydroximino group of the parent compound. A pK_a value of the parent compound of 2.5–3 infers that the radical should appear at a pH value below 3, and not first at pH \approx 5 (Fig. 3). This finding might be connected with a higher pK_a value of the radical than of the parent acid, and/or with destruction of the radical at pH lower than 5. It is also reasonable to assume that the radical is destroyed at high pH values by attack of OH⁻ ions. This means that the profile of the intensity versus pH is more dependent on the stability of the radical than on the dissociation state of the carboxylic group.

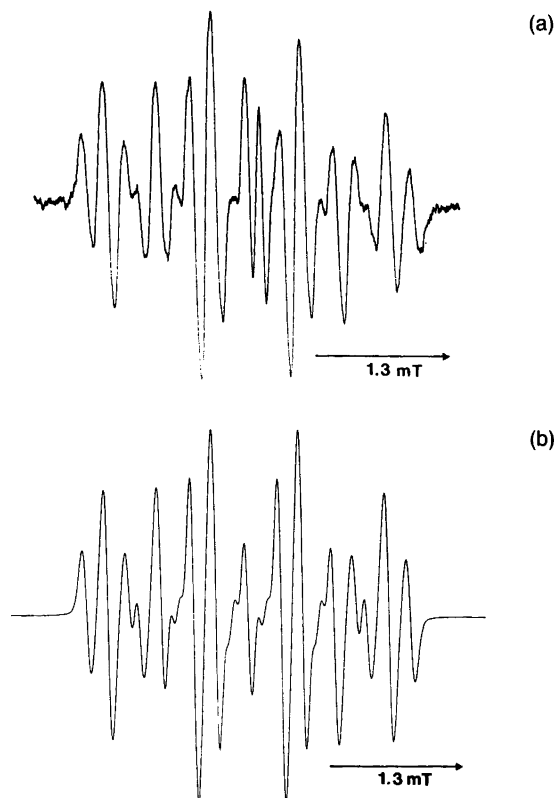


Fig. 5. (a) The EPR spectrum of the radical 8 obtained by anodic oxidation of 2-hydroximinohexanoic acid (20 mM) in phosphate buffer of pH 10.5. Potential: 2.0 V; (b) simulated EPR spectrum of the radicals obtained with 2-hydroximinohexanoic acid [Fig. 5(a)]. The parameters used were: $a_{N1} = 0.82$ mT, $a_{N2} = 0.52$ mT, and $a_H = 0.21$ mT (triplet 1:2:1), linewidth: 0.085 mT.

ca. 3.0 mM. The pH value was adjusted by addition of aqueous sodium hydroxide solution.

Electron spin resonance measurements. The EPR spectra were recorded with a Varian E-9 spectrometer and a Varian Electrolytic Cell Accessory V-4556. The voltage source was a variable dc power supply equipped with voltage and current meters. The potential of the anode relative to the reference electrode (3 M KCl-calomel) was measured by use of a Hewlett-Packard 34703A DCV meter. The microwave power was between 2 and 5 mW, and the 100 kHz modulation amplitude was between 0.025 and 0.05 mT. Hyperfine splitting constants were measured by comparison with the splitting of Fremy's radical ($a_N = 1.30$ mT). The g -value of the radicals was estimated by means of the superposition spectra obtained from a solution containing both the radicals of this series and Fremy's radical. The g -value was calculated from the formula $g = 0.7145 (\nu/H)$ where ν is the microwave frequency and H (gauss) is the magnetic field, assuming the g -value of Fremy's radical to be equal to 2.0054.¹⁵ The microwave frequency was measured with a cavity wavemeter.

The spectral simulation was performed by use of the data program constructed by Oehler and Janzen.¹⁶

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