Fenton's Reagent. III. Addition of Hydroxyl Radicals to Acetylenes and Redox Reactions of Vinyl Radicals[1]

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Abstract: Competitive kinetic and product studies show that hydroxyl radicals, generated from Fe^{2+}–H_2O_2, add readily to acetylene. The intermediate β-hydroxyvinyl radicals are reduced by Fe^{2+} to give acetaldehyde as the major product. In the presence of Cu^{2+} the radicals are oxidized to yield glycolaldehyde, but Fe^{3+} gives no oxidation. A number of acetylene derivatives show similar fast addition followed by reduction, but oxidation by Cu^{2+} is less important or not observed with sterically hindered vinyl radicals. Dimethyl acetylenedicarboxylate gives a small yield of tetramethyl furantetracarboxylate as one product of the reaction.

In previous papers,[3,4] we have shown that under suitable conditions (slow addition of H_2O_2 to Fe^{2+}–substrate solutions) the stoichiometry of the ferrous ion–hydrogen peroxide reaction in the presence of an organic substrate is consistent with the equation

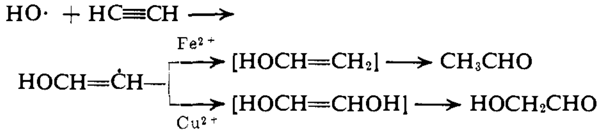
$$R = 2ar(1 - R) + b \qquad (1)$$

where $R = \Delta[Fe^{2+}]/2\Delta[H_2O_2]$, the ratio of moles of Fe^{2+} oxidized to mole of H_2O_2 reacted or reciprocal of the kinetic chain length, $r = [Fe^{2+}]/2[RH]$, and a and b are ratios of rate constants from which we may determine the relative rates of hydroxyl radical with substrate and Fe^{2+} and the fate of the radicals produced: oxidation by Fe^{3+} (or added Cu^{2+}), dimerization, or reduction by Fe^{2+}.[5] Hydroxyl radical reactions with acetylenes have received little attention,[6] and this paper describes application of our techniques to several examples.

Acetylene. Addition of H_2O_2 to a Fe^{2+} solution saturated with acetylene gave $R = 0.44$, only a small difference in stoichiometry from that observed with Fe^{2+} alone ($R = 1$). Addition of Cu^{2+} produces a striking change. R is close to zero and the oxidation becomes a very long chain process. Product analyses show a comparable change in reaction path, the major products changing from acetaldehyde to glycolaldehyde, Figure 1.

Both kinetics and products are consistent with a rapid addition of hydroxyl radicals to acetylene, followed by reduction and oxidation of the intermediate vinyl radical by Fe^{2+} and Cu^{2+}, respectively.[7] If so, the reaction is interesting as the first case among the systems which we have examined in which the same radical is both oxidized and reduced, and, since the two products appear in equal yield at a Cu^{2+}/Fe^{2+} ratio of 2, we estimate that the rate constant for the oxidation is about half that for reduction.[8] In order to see whether oxidation could also be effected by ferric ion, a series of experiments was run in the presence of up to 0.02 M added Fe^{3+}. No drop in acetaldehyde yield (or presence of glycolaldehyde) was detected. In the case of simple alkyl radicals we have concluded[3] that Fe^{3+} oxidation fails because of the unfavorable equilibrium

$$Fe^{3+} + R\cdot \rightleftharpoons Fe^{2+} + R^+ \qquad (3)$$


(2)

$$HO\cdot + HC{\equiv}CH \longrightarrow HOCH{=}\dot{C}H\text{—}\left\{\begin{array}{l}\xrightarrow{Fe^{2+}} [HOCH{=}CH_2] \longrightarrow CH_3CHO \\ \xrightarrow[Cu^{2+}]{} [HOCH{=}CHOH] \longrightarrow HOCH_2CHO\end{array}\right. \qquad (2)$$

Applying the same test[3] to vinyl radicals, 2-buten-2-yl triflate (trifluoromethanesulfonate) was added to a $Fe(ClO_4)_2$–$HClO_4$ solution containing acrylonitrile under N_2. Rapid precipitation of polyacrylonitrile occurred, although none was observed in the absence of Fe^{2+}. Since this triflate ester is considered to solvolyze to the corresponding vinyl cation[9] and the polymerization observed is a good test for free radicals, we conclude that the same situation obtains here: oxidation by Fe^{3+} fails because of the reversibility of reaction 3.

3-Hexyne. Oxidation of a two-phase system containing excess 3-hexyne to maintain saturation of the aqueous layer gave only short kinetic chains ($R = 0.83$) and 3-hexanone as the major and only identified product again indicating vinyl radical reduction. In this case, added Cu^{2+} had little effect ($R = 0.63$) and produced no change in products.

Propargyl Alcohol. In order to investigate our oxidations in more detail, attention was shifted to more water-soluble acetylene derivatives so that Fe^{2+}/substrate ratios could be examined over a greater range. At a 5:1 ratio of propargyl alcohol:Fe^{2+}, a short chain oxidation occurs, $R = 0.39$, presumably because of some attack on propargylic C–H bonds to yield ox-

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[3] C. Walling and S. Kato, *J. Amer. Chem. Soc.*, **93**, 4275 (1971).

[4] C. Walling and G. El-Taliawi, *ibid.*, **95**, 844 (1973).

[5] Reduction or dimerization of all radicals gave, respectively, intercepts of 1 and 0.5, and any oxidation leads to lower values. At high substrate/Fe^{2+} ratios, a value of $R > 0.5$ for a single experimental point indicates reduction of at least some of the radicals present.

[6] (a) P. G. Clay, G. R. A. Johnson, and J. Weiss, *J. Phys. Chem.*, **63**, 862 (1969), have examined the radiolysis of aqueous acetylene solutions and conclude that hydroxyl radicals add readily to the acetylenic bond; (b) M. Fiti, *Rev. Roum. Chim.*, **19**, 377 (1965), has examined the pulse radiolysis of aqueous Fe^{2+}–acetylene systems.

[7] The difference from $R = 1$ in the case of Fe^{2+} alone could well represent some chain oxidation of acetaldehyde as formed since yields are not quantitative and decrease slightly in a series of experiments in which the amount of added H_2O_2 was systematically increased.

[8] The reduction of the hydroxyvinyl radical by Fe^{2+} has also been deduced by Fiti[6b] from radiolysis results. For a discussion of the analogous oxidation of phenyl radicals by Cu^{2+}, *cf.* A. H. Lewin and T. Cohen, *J. Org. Chem.*, **32**, 3844 (1967).

[9] P. J. Stang and R. Summerville, *J. Amer. Chem. Soc.*, **91**, 4600 (1969).

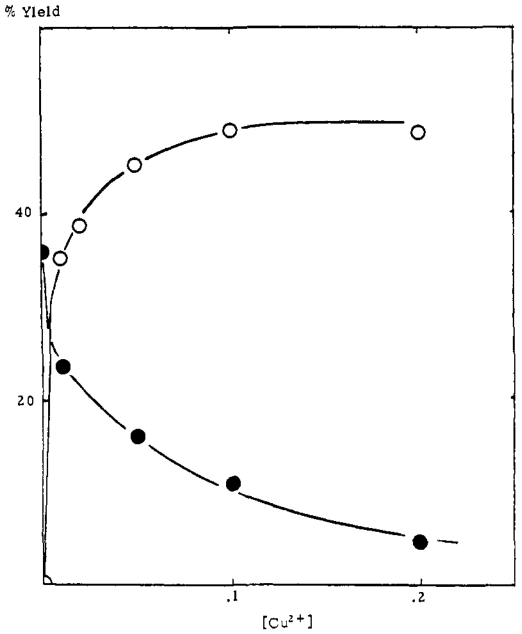
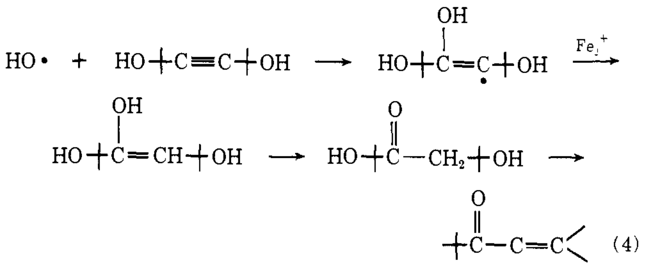


Figure 1. Effect of Cu^{2+} on products from acetylene–Fenton's reagent: ●, acetaldehyde; ○, glycolaldehyde.

idizable radicals. (If essentially all hydroxyl radicals attack substrate, as would be expected at this ratio, the value corresponds to 39% addition and 61% C–H attack.) Addition of Cu^{2+} gave a very long chain reaction, $R = 0.09$, evidently with rapid oxidation of the vinyl radicals produced by addition. Product studies confirm these conclusions. In the presence of Cu^{2+} dihydroxyacetone (detected as its dinitrophenylhydrazone) was a major product, but none could be detected with iron alone. Its formation incidently tells nothing about the point of hydroxyl radical addition since both possible modes lead to the same enol intermediate.

2,5-Dihydroxy-2,5-dimethyl-3-hexyne. Oxidation of this substrate by Fe^{2+}–H_2O_2 alone again gave little chain reaction, $R = 0.79$, at 1:1 Fe^{2+}:substrate ratio and yielded as the major product 2,5-dimethyl-2-hydroxyhex-4-en-3-one, presumably *via* reduction of the intermediate vinyl radical followed by dehydration in the acid medium. Addition of Cu^{2+} here had little effect on chain length ($R = 0.68$) or product. Since the addition of hydroxyl radicals to acetylenes followed by vinyl radical reduction is kinetically equivalent to hydroxyl radical reactions leading to carbonyl conjugated radicals,[4] acetylenes should act as hydroxyl radical traps and inhibit the oxidation of substrates such as methanol. This was investigated using the same kinetic treatment as before (eq 8 in our preceding paper[4]) with results shown in Figure 2. The good linear plot yields the ratio for addition to the acetylene and attack on methanol, $k_{3k}/k_{3i} = 3.38$, showing the rapidity of hydroxyl radical addition. Added Fe^{3+} had no effect on the stoichiometry, so here there is no complication due to hydroxymethyl radical addition to the acetylene.[4]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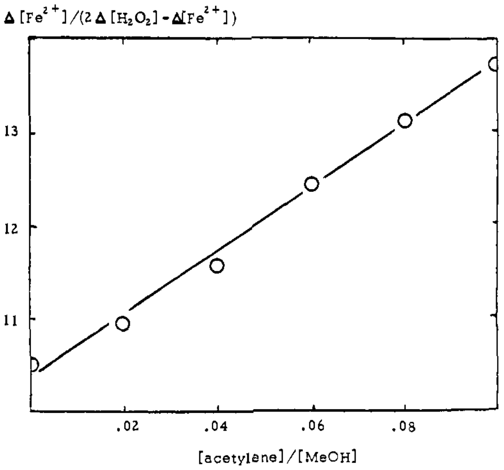
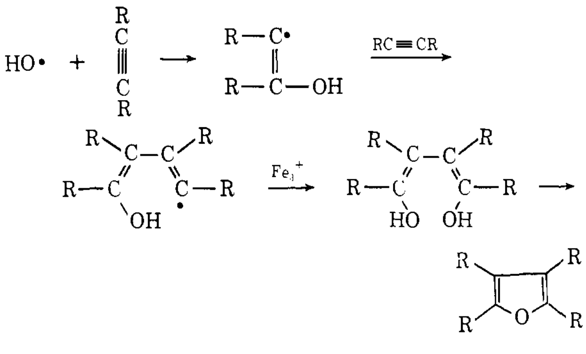


Figure 2. Plot of dimethyldihydroxyhexyne–methanol data, eq 8 ref 4.

3-Hydroxy-3-methyl-1-butyne. A plot of eq 1 with this substrate gave a line of very small slope and an intercept of 0.9, again indicating predominantly reduction of the intermediate radicals. Addition of Cu^{2+} increases the chain length moderately, but the effect appears to level out near a Cu^{2+}/Fe^{2+} ratio of 1 (higher ratios were not examined because of analytical difficulties). Such a phenomenon suggests two intermediate radicals, only one of which is oxidized by Cu^{2+}, and qualitative tests on reaction mixtures indicated both an α,β-unsaturated aldehyde [presumably β-methylcrotonaldehyde, formed as in (4)] and traces of a methyl ketone as would be formed by some nonterminal addition to the triple bond.

Dimethyl Acetylenedicarboxylate. Although this substrate was too insoluble to investigate over a concentration range (the acid, while soluble, yields highly colored, unstable reaction mixtures) at a 2:1 Fe^{2+}:substrate ratio, it gave $R \cong 0.5$, increasing slightly with added Fe^{3+}, implying short chains and some oxidation of an intermediate by Fe^{3+}. Examination of the complex mixture of products yielded a small amount (2.7%) of the tetramethyl ester of furantetracarboxylic acid. In the presence of 0.05 M Fe^{3+} the yield was increased to 12%. In view of this increase in yield, a plausible reaction path for its formation is shown in eq 5.


(5)

Discussion

Our results on the six acetylenes investigated are sum-

Table I. Fenton's Reagent Oxidation of Acetylenes

Compd	k_{3k}	Redn by Fe^{2+}	Oxidn by Cu^{2+}
Acetylene		Yes	Yes
3-Hexyne		Yes	No
Propargyl alcohol	$>10^9$ [a]	Yes	Yes
$HOC(CH_3)_2C{\equiv}CC(CH_3)_2OH$	4.65×10^9 [b]	Yes	No
$HC{\equiv}CC(CH_3)_2OH$		Yes	Some
$MeOCOC{\equiv}CCOOMe$		Yes	

[a] Estimated from the ratio of addition to H abstraction since $k_{3i} > 10^9$ for alcohols. [b] Calculated from k_{3k}/k_{3i} in text using $k_{3i}/k_2 = 4.3$[3] and $k_2 = 3.2 \times 10^8$.

marized in Table I and lead to three general conclusions. First, hydroxyl radicals add readily to triple bonds with rates, where measured, comparable with those of additions to double bonds.[4] Second, the resulting vinyl radicals are readily reduced by Fe^{2+}, the principle overall reaction thus being hydration of the triple bond. Third, some, but not all, vinyl radicals are oxidized by Cu^{2+}. The only correlation which we can deduce from the table is that oxidation fails with bulky molecules and thus appears to be very sensitive to steric factors. Such a finding is consistent with an organo-copper intermediate in the oxidation,[3] an argument which we will develop later. As we have seen in the oxidation of 3-hydroxy-3-methylbutyne, the leveling off of chain length at a low value with increasing Cu^{2+} implies two intermediate radicals, only one of which is oxidized, and suggests that addition may be occurring at both ends of the double bond with only the less-hindered radical undergoing oxidation.[10] A discussion of the relative ease of oxidation–reduction of vinyl and alkyl radicals will be given in a following paper, but we mention here the unique behavior of dimethyl acetylenedicarboxylate, the only substrate giving rise to a vinyl radical oxidized by Fe^{3+}. If oxidation gives rise to a carbonium ion, the π-electron systems of the double bond and β-carbonyl group are presumably coplanar and the vacant orbital could interact strongly with the unshared electron pairs of the adjacent oxygen and thus gain added stability.

Experimental Section

Competitive Kinetics. Experiments were carried out as described previously by slowly adding H_2O_2 to $Fe(ClO_4)_2$–substrate solutions in 0.1 *N* $HClO_4$ under N_2 and determining the amount of Fe^{2+} oxidized either by dichromate titration or spectrophotometrically using the ferric thiocyanate complex.[11] In acetylene runs, air was removed and the system kept saturated by slowly bubbling acetylene (purified by washing with H_2SO_4 and water) through the solution.

Products. In acetylene experiments, acetaldehyde was determined by flame ionization glc on reaction mixtures after neutralization and removal of iron salts. Glycolaldehyde was determined spectrophotometrically on deionized solutions after reaction with diphenylamine reagent as described by Dische and Borenfreund.[12] 3-Hexanone was separated by preparative glc and identified by retention time and conversion to its dinitrophenylhydrazone. 2,5-Dimethyl-2-hydroxyhex-4-en-3-one was isolated by extracting a reaction mixture from the oxidation of 2,5-dihydroxy-2,5-dimethyl-3-hexyne with petroleum ether, evaporating, and collecting the major peak by preparative glc (20% Carbowax 20M column at 130°). It was identified by ir and nmr spectra: ir bands 3500 (O–H), 2950 (methyl C–H), 3050 (vinyl C–H), 1680 cm^{-1} (conjugated C=O); nmr at 60 MHz in CCl_4 *vs.* TMS δ 1.3 (s, 6 H) (methyls between OH and C=O), 2.05 (d, 3 H, $J \cong 2$ Hz, vinyl methyl), 2.2 (d, 3 H, $J \cong 2$ Hz, vinyl methyl), 3.8 (s, 1 H, disappears on adding D_2O, O–H), 6.5 (septet, 1 H, $J \cong 2$ Hz, vinyl H). Spin decoupling in $CDCl_3$ at 100 MHz showed that the two vinyl methyls were coupled with the vinyl H. Tetramethyl furantetracarboxylate was obtained from oxidation of dimethyl acetylenedicarboxylate by extraction with ether and recrystallization from aqueous methanol: mp 104–105°, analysis, molecular weight, and ir spectra consistent with structure. Products from 3-hydroxy-3-methyl-1-butyne were only examined qualitatively. Reaction solutions gave a strong test for aldehyde with Benedict's solution and showed a clean uv spectra with λ_{max} 235 mμ, the expected point for β-methylcrotonaldehyde. They also gave a moderate iodoform test for the CH_3CO function.

Solvolysis of 2-Buten-2-yl Triflate. The ester, 2.5 mmol, prepared according to Stang and Summerville,[9] was injected over 15 min with stirring into 20 ml of an O_2-free solution containing 30 mmol of acrylonitrile, 5 mmol of $Fe(ClO_4)_2$, and 2.5 mol of $HClO_4$. A copious precipitate of polymer appeared during the addition, and titration showed the oxidation of 0.045 mmol of ferrous ion. A comparable experiment without Fe^{2+} gave no polymer after 12 hr.

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(10) Hydroxyl radicals add to acrylic, crotonic, and fumaric acids at almost identical rates,[4] indicating little steric hindrance to addition, presumably because of the small size of the radical.

(11) S. Abbey, *Anal. Chem.*, **20**, 630 (1948).

(12) Z. Dische and E. Borenfreund, *J. Biol. Chem.*, **180**, 1297 (1949).