Intermolecular Hydrogen-atom Abstraction by Vinyl Radicals derived from Hydroxyalkyl Radicals and Alkynes: an Electron Spin Resonance Investigation

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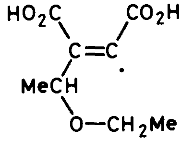
The rapid addition of α-hydroxyalkyl radicals $^{\bullet}CR^1R^2OH$ (R^1 = H, Me; R^2 = H, Me) to butynedioic acid to give intermediate vinyl radicals (*k ca.* 10^7 dm^3 mol^{-1} s^{-1}) is followed by intermolecular hydrogen-transfer (*k ca.* 10^6 dm^3 mol^{-1} s^{-1}) from the parent alkanols. The alkenes thus formed also undergo subsequent ready addition of $^{\bullet}CR^1R^2OH$ to give radicals which in some cases demonstrate unusual line-broadening effects.

We have previously employed the Ti^{III}–H_2O_2 couple in aqueous solution as a source of the hydroxyl radical to generate a variety of substrate-derived radicals whose ready addition to triple bonds yields the appropriate vinyl radicals.[1,2] E.s.r. spectroscopy has enabled some novel reactions of these intermediates to be characterized: these include the 1,5-shift[1–3] and subsequent fragmentation of ether-derived species [*e.g.* in the conversion[2] of (**1**), from butynedioic acid and $^{\bullet}CHMeOEt$, into (**2**)] and the further addition and subsequent 1,5-shift whereby radicals (**3**) react to give the pentadienyl species (**4**) [reaction (1)].[1]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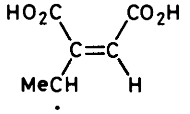
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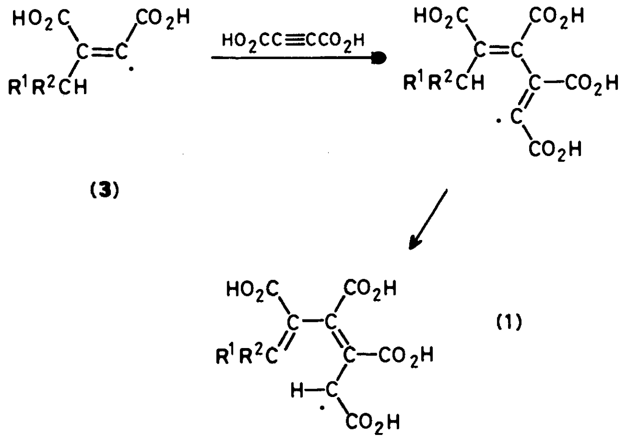
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We have now investigated the possibility of employing this approach to determine whether information could be obtained concerning the *intermolecular* reactivity of vinyl radicals and, in particular, to determine whether intermolecular hydrogen-abstraction can compete with intramolecular hydrogen-transfer [*e.g.* reaction (1)] and addition to triple bonds (for which *k* is[1] 10^6 dm^3 mol^{-1} s^{-1}).

Results and Discussion

We have employed a three-stream aqueous flow system driven by a peristaltic pump. Substrate-derived radicals were generated by the inclusion of the appropriate parent compound in the first stream, with Ti^{III} (typically 8×10^{-3} mol dm^{-3}) and H_2O_2 (typically 3×10^{-2} mol dm^{-3}) contained separately in the other two streams. Experiments were normally carried out both in acid solutions (typically in the pH range 1—2) and in basic solution with EDTA to sequester titanium ions (pH 7.5—9). In the majority of our experiments we employed butynedioic acid, normally at a relatively low concentration in order to discourage sequential additions [*cf.* reaction (1)], though this reaction is in any case severely retarded at high pH (on account of charge repulsion in the reacting species).[1]

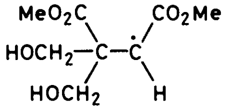
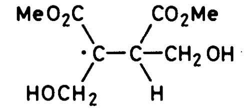
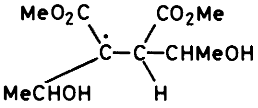
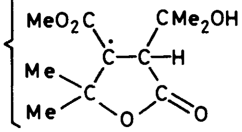
Reactions of α-Hydroxyalkyl Radicals.—A series of experiments was first carried out in which we utilized the known selectivity of $^{\bullet}OH$ in favour of abstraction of hydrogen atoms attached to carbon atoms bearing (+*M*) oxygen substituents to generate hydroxyalkyl radicals from several simple alcohols.

(a) $^{\bullet}CH_2OH$. When butynedioic acid (at an overall concentration of 2×10^{-3} mol dm^{-3}) was included in experiments with Ti^{III}, H_2O_2, and CH_3OH (0.5 mol dm^{-3}) at pH *ca.* 1, the signal from $^{\bullet}CH_2OH$ was partially replaced by that from the vinyl radical (**3**; R^1 = H, R^2 = OH) and a signal, enhanced as [alkyne] was increased, attributed to (**4**; R^1 = H, R^2 = OH) (see ref. 2) together with two other sets of lines (see Figure 1a). Experiments were then carried out in which the concentration of methanol was significantly increased (to *ca.* 5 mol dm^{-3}) with [alkyne] held at a relatively low levels (2×10^{-3} mol dm^{-3}).

As shown in Figure 1, the spectrum still shows the signal from $^{\bullet}CH_2OH$ [but not (**3**; R^1 = H, R^2 = OH) or (**4**; R^1 = H, R^2 = OH)], together with considerably stronger signals from the two extra radicals. One set of lines (marked Δ) appears to be a doublet (2.07 mT) of small triplets (0.05 mT), with *g* 2.0031, and the remaining six lines (marked ×) are apparently grouped into three doublets [with *a*(1H) 0.58 mT] of which the inside pair appears to be somewhat sharper than the outer lines (and also to exhibit a small doublet splitting of 0.07 mT); we ascribe this signal (with *g* 2.0030) to a single species (see Table 1) with broadening of the wing lines of the 1:2:1 triplet. Our evidence for this is derived in part from results for model compounds (see later) but also from the observation that the two sets of lines grew together [at the expense of signals from radicals (**3**; R^1 = H, R^2 = OH) and (**4**; R^1 = H, R^2 = OH)] when the concentration of CH_3OH was increased and decreased together at lower [CH_3OH]. The *relative* intensities of the six lines within the second spectrum remained constant.

We propose that the two new radicals observed in the reaction at low pH are formed following reaction of the

Table 1. E.s.r. parameters of radicals derived *via* addition of hydroxyalkyl radicals to butynedioic acid and related compounds[a]

Substrate	Reactant radical	Alkyne	Radical detected	Hyperfine splitting (mT)[b] a(α-H)	a(β-H)	a(other)	g[c]
CH_3OH	$^{\bullet}CH_2OH$	$HO_2CC{\equiv}CCO_2H$	(**3**; $R^1 = H, R^2 = OH$)			0.06(2)	2.0028
			(**4**; $R^1 = H, R^2 = OH$)	1.08		0.16	2.0032
			(**5**)	2.07		0.05(2)	2.0031
			(**6**)		2.17(2) 0.58	0.07	2.0030
		$MeO_2CC{\equiv}CCO_2Me$		2.05		0.14(3)[d]	2.0031
					2.18(2) 0.63	0.14(3)[d]	2.0031
EtOH	$^{\bullet}CHMeOH$	$HO_2CC{\equiv}CCO_2H$	(**3**; $R^1 = Me, R^2 = OH$)			0.10(3) 0.03(2)	2.0029
			(**4**; $R^1 = Me, R^2 = OH$)	1.15		0.08(4)	2.0031
			(**11**)		1.35 0.30	*d*	2.0031
		$MeO_2CC{\equiv}CCO_2Me$			1.35 0.30	0.13[e]	2.0031
Me_2CHOH	$^{\bullet}CMe_2OH$	$HO_2CC{\equiv}CCO_2H$	$Me_2C(OH)(HO_2C)C{=}C(CO_2H)^{\bullet}$			0.05(6)	2.0029
			(**12**)		0.35	*d*	2.0031
			(**13**)[f]		2.68	*d*	2.0031
		$MeO_2CC{\equiv}CCO_2Me$	$Me_2C(OH)(MeO_2C)C{=}C(CO_2Me)^{\bullet}$			0.05[g]	2.0029
					2.625	*d*	2.0031

[a] pH 1—2 unless otherwise indicated. [b] ±0.005 mT. [c] ± 0.0001. [d] With further unresolved long-range coupling. [e] Long-range coupling to α-CO_2Me protons and other γ-C–H protons (number not unambiguously determined). [f] Replaced (**12**) at pH < 1.0. [g] Coupling to γ-methyl group protons and at least one of the OMe groups.

intermediate vinyl radicals with more methanol, to give the appropriate alkene* (a reaction previously demonstrated for vinyl radicals and thiols[4,5]); the alkene would then be expected to react with either $^{\bullet}CH_2OH$ or $^{\bullet}OH$, but since the latter should be totally scavenged by the excess of methanol present, we attribute the signals observed to the adducts of $^{\bullet}CH_2OH$ and the alkene, (**5**) and (**6**) (see Scheme 1 and arguments presented below). If the assignments are correct, then the ratio of steady-state concentrations of the adducts, [(**5**)]:[(**6**)] *ca.* 1:5, presumably reflects the dominance of steric effects in the addition.

The doublet with a 2.07 mT and g 2.0031 is exactly as expected for a radical with an α-carboxylic acid substituent (see *e.g.* ref. 6), as anticipated for (**5**): the small long-range triplet splitting may be assigned either to the γ-protons in *one* β-CH_2OH group (with non-equivalence as a result of restricted rotation) or to one proton in each methylene group (though these possibilities cannot be distinguished). Evidence that (**6**), with the expected doublet of triplets, is also correctly assigned was sought by the generation of related species by the addition of $^{\bullet}OH$ (and other radicals) to some model compounds.

For example, the reaction of $^{\bullet}OH$ with but-3-ene-1,2,3-tricarboxylic acid (**7**) at pH 1—2 gives a signal attributed to (**8**), in which $^{\bullet}OH$ has, as would be expected, added preferentially to the least substituted position. This spectrum possesses not only

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* We are unable to distinguish the *cis* and *trans* isomers of the precursor vinyl radical (and the alkene).

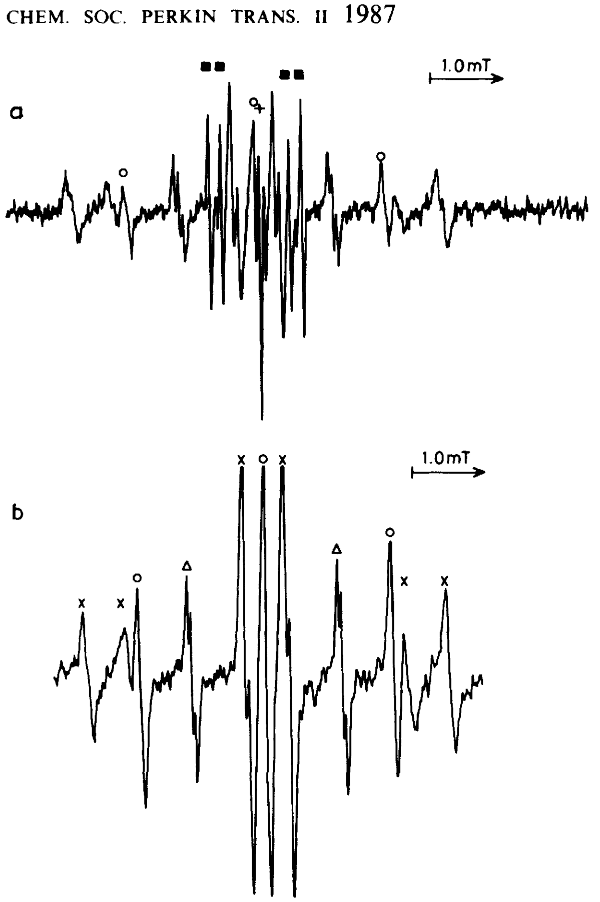
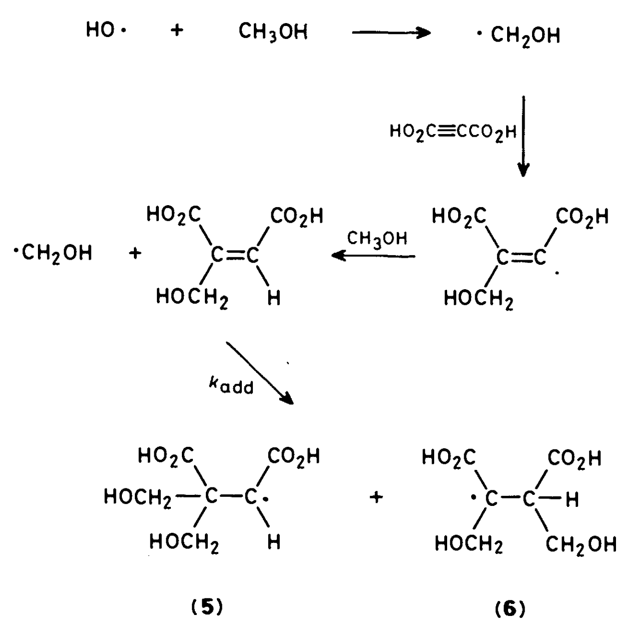


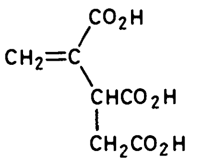
Figure 1. a, E.s.r. spectrum of $^{\cdot}CH_2OH$ (○), (3; R^1 = H, R^2 = OH) (+), and (4; R^1 = H, R^2 = OH) (■) formed in the reaction of $^{\cdot}OH$ (from Ti^{III}–H_2O_2) and butynedioic acid (2×10^{-3} mol dm^{-3}) in the presence of methanol (0.5 mol dm^{-3}) at pH 1. b, E.s.r. spectrum attributed to (5) (marked △) and (6) (marked ×) as well as $^{\cdot}CH_2OH$ (○): conditions as for Figure 1a except [MeOH] 5 mol dm^{-3}

the pattern of β-proton splittings expected but also exactly the same type of line-broadening observed in the spectrum attributed to (**6**) (see Figure 2a). Close inspection of this spectrum suggests in addition that the two β-protons are non-equivalent (see Table 2). At high pH the spectrum sharpens somewhat (presumably due to the loss of unresolved couplings with ionization of the carboxy groups) to reveal a small triplet from the γ-protons as well as a clear indication that the methylene β-protons have different splittings (Figure 2b): the broadening of the wing lines in the spectrum of (**9**) (especially the innermost of each pair) is particularly pronounced and strongly supports the structural assignment to the signal from the closely related radical (**6**). Related adducts were generated by addition of other first-formed radicals (*e.g.* $^{\cdot}CH_2OH$) to this alkene as well as to (*E*)- and (*Z*)-propene-1,2,3-tricarboxylic acid [see (**10**)]; patterns of non-equivalence and line-broadening [as well as those for (**6**), (**8**), and (**9**)] are discussed in a subsequent section.

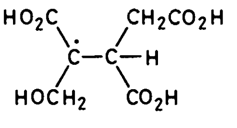
Behaviour similar to that found with butynedioic acid was observed for the reaction between $^{\cdot}CH_2OH$ and the ester $MeO_2CC{\equiv}CCO_2Me$ at pH *ca.* 1; radicals analogous to (**5**) and (**6**) (formed at high methanol concentrations) are characterized by an extra small hyperfine splitting from the methyl protons on the ester group at the radical centre (see Table 1). The complex mixture of signals observed from the reaction of $^{\cdot}OH$ and methanol with propynoic acid indicates that addition followed by further reactions (*cf.* Scheme 1) has taken place, though unambiguous analysis proved impossible. There was no evidence of reaction between $^{\cdot}CH_2OH$ and butyne-1,4-diol [the only signals seen in addition to that from $^{\cdot}CH_2OH$ itself were from $^{\cdot}CH(OH)C{\equiv}CCH_2OH$ and $^{\cdot}CH(CH_2OH)COCH_2OH$, derived by attack of $^{\cdot}OH$ on the alkyne [2]]. We conclude that the ready reaction between $^{\cdot}CH_2OH$ and the alkynes containing one or more carboxy substituents probably reflects facilitation of the reaction by polar effects of opposite type in the reacting entities (*cf.* ref. 7).



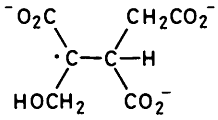
Scheme 1.



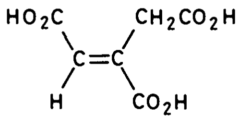
(**7**)



(**8**)



(**9**)



(**10**)

(b) $^{\cdot}CHMeOH$ *and* $^{\cdot}CMe_2OH$. Reaction of $^{\cdot}CHMeOH$ (from ethanol, present at a concentration of 0.3 mol dm^{-3}) with butynedioic acid (2×10^{-3} mol dm^{-3}) at pH 1 led to the detection of the vinyl radical (3; R^1 = Me, R^2 = OH) and at higher concentration of butynedioic acid (2×10^{-2} mol dm^{-3}) the radical (4; R^1 = Me, R^2 = OH), formed as in reaction (1). As the ethanol concentration was increased to *ca.* 3 mol dm^{-3}, new, broader signals were detected, assigned to the radical (**11**) formed as outlined for methanol in Scheme 1 (see Table 1). The larger of the two methine-proton splittings is evidently associated with the ethanol-derived moiety. Strong signals from the corresponding analogue of (**11**) were also obtained from reaction of $MeO_2CC{\equiv}CCO_2Me$ at relatively high ethanol concentrations.

Similarly, as the concentration of added propan-2-ol was increased in experiments with a relatively low concentration of

Table 2. E.s.r. parameters of radicals derived by addition of $^{\bullet}OH$ and carbon-centred radicals to but-3-ene-1,2,3-tricarboxylic acid (**7**) and (*E*)- and (*Z*)-propene-1,2,3-tricarboxylic acid [see (**10**)]

Alkene	Reacting radical	pH	Radical detected	Hyperfine splitting (mT)[a] a(α-H)	a(β-H)	a(α-other)	g[b]
(**7**)	$^{\bullet}OH$	1—2	(**8**)		2.26 2.34 0.48		2.0030
		8—9	(**9**)		1.85 1.52 0.64	0.06(2)	2.0030
	$^{\bullet}CH_2OH$	1—2	(**16**; X = CH_2OH)		1.46(2) 0.54		2.0030
	$^{\bullet}CHMeOH$	1—2	(**16**; X = CHMeOH)		1.62 1.25 0.50		2.0032
	$^{\bullet}CMe_2OH$	1—2	(**16**; X = CMe_2OH)		1.35 1.19 0.45		2.0030
	$Me^{\bullet}$	1—2	(**16**; X = Me)		1.46(2) 0.49		2.0031
		8—9	(**16**; X = Me)		1.25(2) 0.61		2.0031
(**10**) and its isomer	$^{\bullet}OH$	1—2	(**17**; X = OH)		1.45 1.34 1.01		2.0030
			$^{\bullet}CH(CO_2H)C(OH)(CO_2H)(CH_2CO_2H$	2.08			2.0030
		8—9	(**17**; X = OH)		1.36 1.23 0.81	0.09	2.0030
			$^{\bullet}CH(CO_2^-)C(OH)(CO_2^-)CH_2CO_2^-$	2.10		0.03(2) 0.05	2.0031
	$^{\bullet}CH_2OH$	1—2	(**17**; X = CH_2OH)		1.42 1.29 0.68		2.0030
	$^{\bullet}CHMeOH$	1—2	(**17**; X = CHMeOH)		1.46 1.16 0.43		2.0031
	$^{\bullet}CMe_2OH$	1—2	(**17**; X = CMe_2OH)		1.57 1.03 0.39		2.0032
	$Me^{\bullet}$	1—2	(**17**; X = Me)		1.39(2) 0.76	0.06(2)	2.0031
		8—9	(**17**; X = Me)		1.36 1.11 0.88		2.0031

[a] ±0.005 mT. [b] ±0.0001.

butynedioic acid at pH *ca.* 1.5, signals from the first-formed vinyl radical $Me_2C(OH)(HO_2C)C{=}C(CO_2H)^{\bullet}$ were removed to be replaced by a doublet spectrum (a 0.35 mT, g 2.0031) which also exhibited further incompletely resolved long-range couplings (presumably to the γ-protons). This spectrum is attributed to (**12**): the very small β-proton coupling is entirely consistent with such an assignment since a conformation will be favoured in which this proton is confined close to the nodal plane of the orbital of unpaired electron (*cf. e.g.* ref. 8).

When the experiments with propan-2-ol were repeated at even lower pH (other conditions remaining the same) the signal attributed to (**12**) was itself replaced by a strong signal which differs from (**12**) in the considerably enhanced magnitude of the doublet splitting (2.68 mT: see Table 1 and Figure 3). This

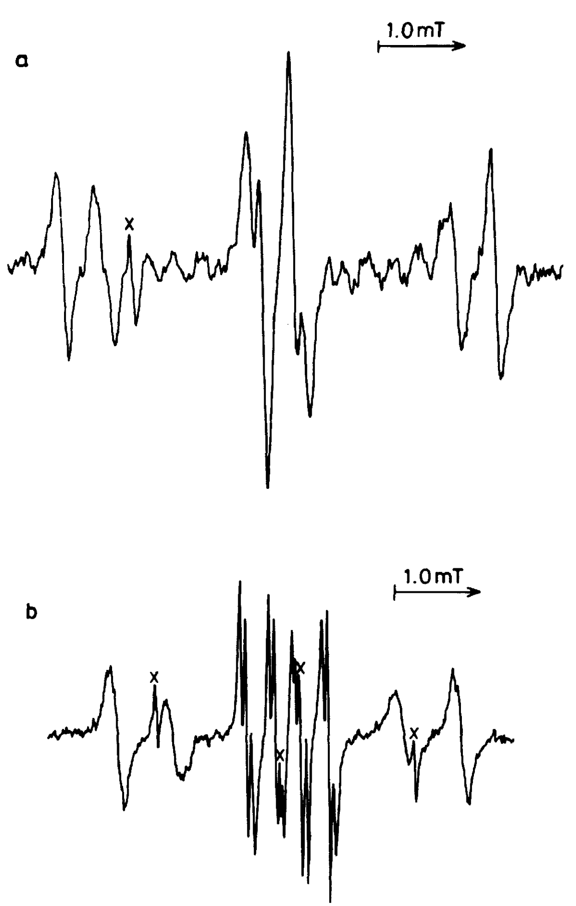
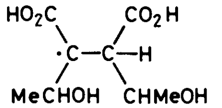


Figure 2. E.s.r. spectrum of the radical $^•C(CO_2H)(CH_2OH)CH(CO_2H)CH_2CO_2H$ (**8**) formed from reaction of but-3-ene-1,2,3-tricarboxylic acid (**7**) with $^•OH$ at pH 1. The peak marked × is from a Ti^{IV}-$HO_2^•$ complex. b, E.s.r. spectrum of the radical (**9**) formed from the reaction of (**7**) and $^•OH$ at pH 8, showing marked broadening of the outermost lines. The minor peaks (marked ×) are unassigned.



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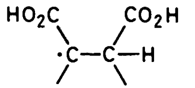

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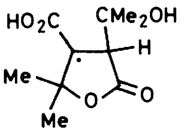

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splitting is characteristic of a methine proton held in a position for favourable hyperconjugative overlap with the unpaired electron, as in a *cyclic* structure (see *e.g.* ref. 3). This behaviour can be understood if the cyclic (lactone-type) structure (**13**) is produced rather than the open-chain analogue (**12**). Similar behaviour was observed in the reaction between $^•CMe_2OH$ and $MeO_2CC{\equiv}CCO_2Me$, for which signals from a vinyl radical (at low [Me_2CHOH]) and cyclized analogue (at pH <1) were clearly observed (see Table 1).

At least two mechanisms may be envisaged for the formation of the cyclized radicals [*e.g.* (**13**)], which differ in the timing of the various stages. For example, the addition of $^•CMe_2OH$ to the intermediate alkene [to give (**12**)] may be followed by acid-catalysed loss of the β-hydroxy group to give a radical-cation (stabilized by the electron-donating effect of the two methyl groups), followed by intramolecular attack by the carboxy group [see Scheme 2, route (a)]. Such rapid cyclization of a radical-cation would be closely analogous to the ring-closure brought about by reaction of hex-4-enoic acid and $SO_4^{-•}$ under similar conditions;[9] our failure to detect similar cyclization in corresponding reactions of $^•CH_2OH$ and $^•CHMeOH$ at pH <1 is readily understandable in terms of the reduced stability associated with the production of the cationic centre *via* loss of the alcoholic hydroxy group. On the other hand, attack of the radical $^•CMe_2OH$ may be preceded by lactonization of the intermediate alkene to give the appropriate butenolide [Scheme 2, route (b)], a process which is expected to be extremely rapid under acidic conditions (see *e.g.* ref. 10). Our observation that the corresponding *ester* also undergoes rapid reaction in this way suggests that the latter explanation is correct, since the rate-determining step (which is expected to be attack by the alcoholic oxygen on the protonated carbonyl group) should be largely unaffected by methylation. If this is the correct interpretation, then the acceleration achieved by the CMe_2OH group is likely to be a further manifestation of the *gem*-dialkyl group (Thorpe–Ingold) effect.[11] Whatever the precise details of the mechanism, we note that our observations account for the formation of (**14**) and (**15**) in the photolysis of benzophenone, butynedioic acid, and propan-2-ol.[12]

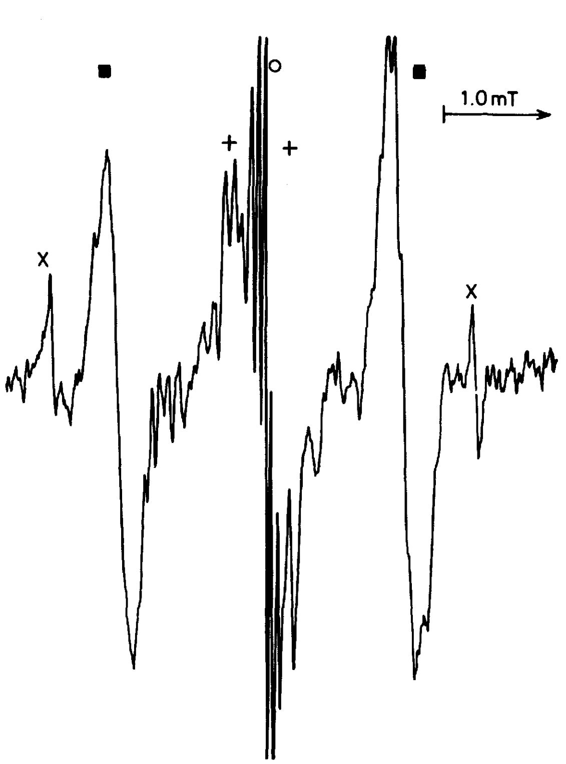
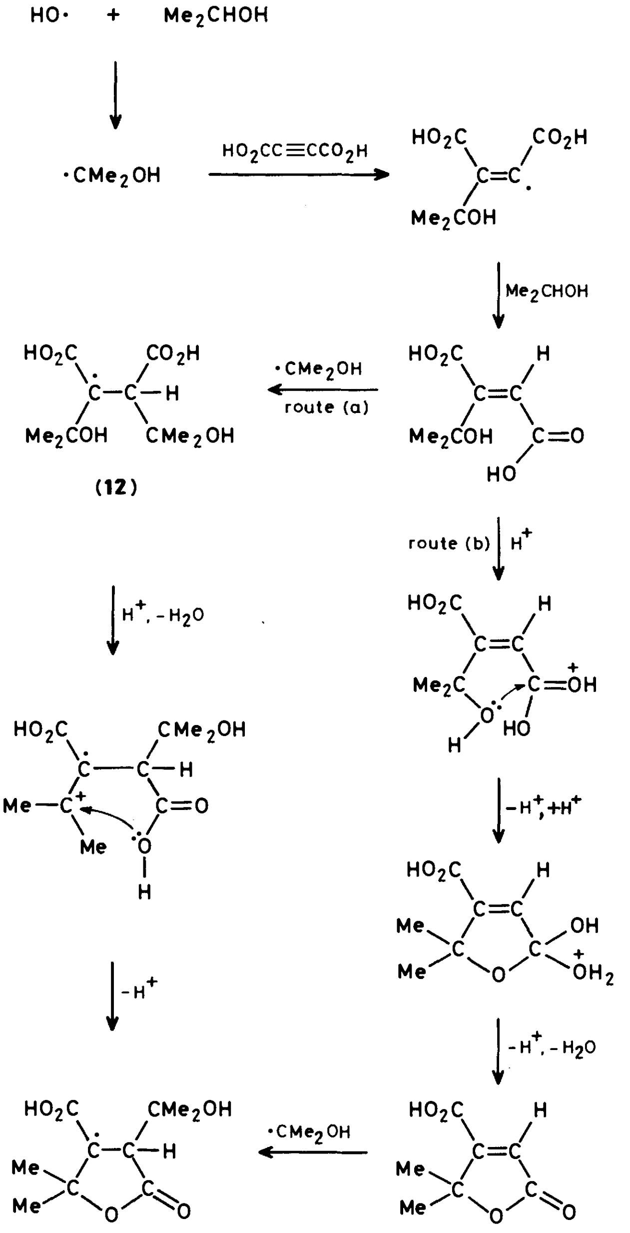


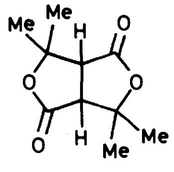
Figure 3. E.s.r. spectrum attributed to the vinyl radical $Me_2C(OH)(HO_2C)C{=}C(CO_2H)^•$ (○), (**12**) (+), and (**13**) (■) formed in the reaction between $^•OH$ and propan-2-ol (0.5 mol dm^{-3}) in the presence of butynedioic acid (2×10^{-3} mol dm^{-3}) at pH 0.86. Signals marked × are from $^•CMe_2OH$

(c) *Other alcohol-derived radicals.* As previously reported,[3] reaction of $^•CHEtOH$ (from propan-1-ol), $^•CH_2CMe_2OH$ (from 2-methylpropan-2-ol), and $^•CH(OH)(CH_2)_nCH_2OH$ (n = 1,2) (from propane-1,3-diol and butane-1,4-diol) with $HO_2CC{\equiv}CCO_2H$ gives cyclized radicals resulting from intramolecular 1,5-hydrogen abstraction. Even at high concentrations of added alcohol (up to *ca.* 1 mol dm^{-3}) we were unable to intercept the intermediate vinyl radicals and add radicals to the alkenes which would thus have been formed.

Line-broadening and Magnetic Non-equivalence in Alkene Adducts.—The non-equivalence of the methylene β-proton



Scheme 2.



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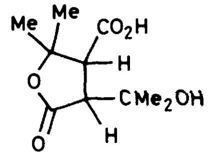

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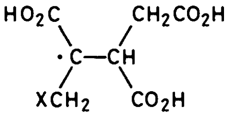

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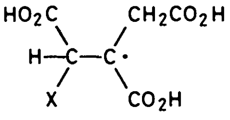

(17)

splittings in the radicals (**8**) and (**9**) might be expected to be a consequence of the chirality of the other β-carbon atom in the radical (the two protons concerned are diastereotopic). Many examples have been provided of the non-equivalence of methylene protons in the vicinity of an asymmetric carbon,[13] though the difference in splittings is likely to be less in this case than when CH_2 is directly attached to a carbon bonded to three different groups.

On the other hand the broadening of the outside lines associated with (**6**), (**8**), and (**9**) is in marked contrast with the broadening normally detected on the innermost pairs of lines when a pair of non-equivalent protons are interconverted by a restricted rotation; this suggests the occurrence, for example, of two (or more) conformations of each radical with similar (or identical) methine proton couplings and somewhat different methylene splittings (with slightly different β-proton triplets), so that the latter are modulated. Then the overlap of the signals will be closer in the centre of the spectrum than in the wings: this phenomenon has been observed,[8] for example, for the radical $^{\bullet}CH_2CH_2CH_2Cl$ in which the line-broadening is attributed to modulation of *a*(β-H) by the interconversion of conformers *via* restricted rotation about the C_β–C_γ bond.

In an attempt to gain a better understanding of the possible structural features involved we generated a series of related radicals by addition of $^{\bullet}CH_2OH$, $^{\bullet}Me$ (from dimethyl sulphoxide[14]), $^{\bullet}CHMeOH$, and $^{\bullet}CMe_2OH$ to both (**7**) and (**10**) (and the *Z*-isomer of the latter); spectra (see Table 2) were analysed largely in terms of addition to the least substituted (hindered) terminus of the double bond, to give (**16**) and (**17**). Signals from adducts of hydroxy-conjugated carbon-centred radicals were only detected at low pH: at high pH, only signals from the addition of the electrophilic hydroxyl radical and the methyl radical could be characterized (ionization of the acids presumably retards addition by the more nucleophilic carbon-centred species).

The spectrum from (**16**; X = CH_2OH) shows two apparently equivalent (β) methylene protons with some broadening of the inner lines in each of the outside pairs of lines (as in Figure 2a); with (**16**; X = Me) a (β)-methylene proton triplet (1:2:1) with undistorted intensity distributions was detected (both at high and low pH). For the adduct of $^{\bullet}CHMeOH$, the marked non-equivalence of the β-methylene protons and broadening of the associated central lines (see Figure 4) is as expected from the presence of the adjacent chiral carbon in (**16**; X = CHMeOH) and some restriction of rotation.[13] With the larger substituent in (**16**; X = CMe_2OH) some restriction of rotation about C_α–CH_2 is presumably implied, evidently on account of the bulky substituents at both β-carbons. Thus the behaviour of (**16**; X = CH_2OH, Me, CHMeOH, and CMe_2OH) is largely as anticipated.

The adducts (**17**) show some non-equivalence of the β-protons, which is more marked for X = CHMeOH and CMe_2OH than CH_2OH (see Table 2). However, particularly dramatic effects are also observed for the adducts (**17**; X = OH) and the ionized counterpart: in the former, there are clearly three different β-protons, whereas in the latter a similar pattern shows again the marked broadening of the outside lines.

In comparing the splitting patterns observed for the various radicals (**16**) and (**17**) generated in this way [as well as (**6**), (**8**), and (**9**)], it is notable that neither (**16**; X = Me) nor (**17**; X = Me) (at low pH) shows non-equivalent proton splittings and line broadening: this suggests that the presence of one chiral β-carbon in each radical is not sufficient to cause observable non-equivalence of the methylene protons on the other β-carbon. However, when X is hydroxy or contains a hydroxy group, then non-equivalence is induced both in the neighbouring CH_2 group [in (**16**)] and, more remarkably, in the distant CH_2 group

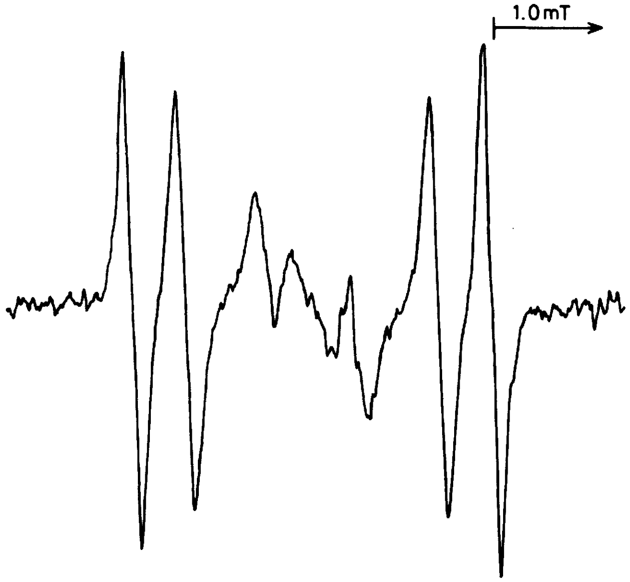

Figure 4. E.s.r. spectrum of (**16**; X = CHMeOH) obtained by the addition of $^{\cdot}\mathrm{CHMeOH}$ to but-3-ene-1,2,3-tricarboxylic acid at pH *ca.* 1

[in (**17**)]. It is tempting to speculate that internal hydrogen bonding is in some way involved, though we can rule out interaction of the carboxylic acid protons (since the effect is also observed at high pH) and we can also eliminate the formation of a five-membered ring on account of the magnitude of a(β-H) (for a locked five-membered ring, much bigger β-splittings would be expected[3]).

We explored the possibility that the unusual broadening of the outer lines in certain spectra [*e.g.* for (**8**) and (**9**)] is due to proton-exchange between, or overlap of, signals from radicals which simply differ in the state of protonation of one or more carboxy groups: a more detailed study was therefore made of the spectra obtained by addition of $^{\cdot}\mathrm{OH}$ to but-3-ene-1,2,3-tricarboxylic acid (see Figure 2) as a function of pH. The spectrum attributed to (**8**) (fully protonated, at least at very low pH), remained unchanged (Figure 2a) in the whole of the pH range 1—3.5; similarly the spectrum of (**9**), the deprotonated form, remained unaltered in the pH range 5.5—9.* Between pH 3.5 and 5.5 a mixture of both signals was detected. The lack of any observable change *within* each of the low and high pH ranges suggests that exchange or overlap involving radicals with different levels of protonation is not responsible for the line-broadening (since progressive effects should then have been observable as the pH was altered through the appropriate pK_a). On the other hand the changes which take place around pH *ca.* 4.5 probably do refect the ionization of the carboxy group at the radical centre.[15]

In summary we note that the unusual line-broadening effects observed for (**6**), (**8**), (**9**), and (**17**; X = OH) must reflect minor conformational changes, since these modulate the sum of the (β) $\mathrm{CH_2}$-splittings without inducing significant non-equivalence or causing significant conformational change in the position or splitting of the (β) methine proton. Whilst hydrogen-bonding involving β-OH groups appears to be in some way involved, there is no evidence (*e.g.* from the splittings) to suggest that specific tightly bonded cyclic structures are adopted. Further speculation appears unjustified.

Kinetic Analysis.—It has been shown that when the $\mathrm{Ti^{III}}$–$\mathrm{H_2O_2}$ redox couple is employed with a rapid-flow system to generate radicals then a pseudo-steady-state is achieved in the e.s.r. spectrometer cavity (and that radicals detected are those formed within the cavity): a steady-state analysis is thus applicable.[16,17] Use of this principle enables an estimate to be obtained for the rate constant for the abstraction of hydrogen from methanol by the vinyl radical obtained from $^{\cdot}\mathrm{CH_2OH}$ and butynedioic acid (see Scheme 1).

The overall reaction scheme is believed to be represented by reactions (2)—(12),† though we have made the simplifying assumption that only one adduct (**6**) is formed by addition of $^{\cdot}\mathrm{CH_2OH}$ to the intermediate alkene [we have ignored the formation of the isomer (**5**) present in much smaller concentrations].

$$\mathrm{Ti^{III}} + \mathrm{H_2O_2} \longrightarrow \mathrm{Ti^{IV}} + \mathrm{HO^-} + {}^{\cdot}\mathrm{OH} \qquad (2)$$

$$^{\cdot}\mathrm{OH} + \mathrm{CH_3OH} \longrightarrow {}^{\cdot}\mathrm{CH_2OH} + \mathrm{H_2O} \qquad (3)$$

$$^{\cdot}\mathrm{CH_2OH} + \mathrm{BDA} \longrightarrow \text{vinyl} \qquad (4)$$

$$\text{vinyl} + \mathrm{BDA} \longrightarrow \text{dimer} \qquad (5)$$

$$\text{vinyl} + \mathrm{CH_3OH} \longrightarrow \text{alkene} + {}^{\cdot}\mathrm{CH_2OH} \qquad (6)$$

$$\text{alkene} + {}^{\cdot}\mathrm{CH_2OH} \longrightarrow \mathrm{R^{1\cdot}} \qquad (7)$$

$$\left.\begin{array}{r} \text{vinyl} + \text{vinyl} \longrightarrow \\ ^{\cdot}\mathrm{CH_2OH} + {}^{\cdot}\mathrm{CH_2OH} \longrightarrow \\ \mathrm{R^{1\cdot}} + \mathrm{R^{1\cdot}} \longrightarrow \\ \text{dimer} + \text{dimer} \longrightarrow \\ \text{cross-termination of radicals} \longrightarrow \end{array}\right\} \begin{array}{c}\text{non-radical}\\ \text{products}\end{array} \qquad \begin{array}{c}(8)\\(9)\\(10)\\(11)\\(12)\end{array}$$

Initially very low concentrations of alkyne (10^{-3} mol dm^{-3}) were added in experiments in which $^{\cdot}\mathrm{OH}$ reacts with an excess of methanol to give $^{\cdot}\mathrm{CH_2OH}$ (with $[^{\cdot}\mathrm{CH_2OH}]_0$ *ca.* 4×10^{-6} mol dm^{-3}). The small decrease in $[^{\cdot}\mathrm{CH_2OH}]$ was monitored under conditions in which only extremely low concentrations of other radicals (derived from its reaction) are present, so that the behaviour is governed largely by reactions (2)—(4) and (9). Competition between (4) and (9) for the destruction of ($^{\cdot}\mathrm{CH_2OH}$) is effectively employed to determine k_4 (following the procedure outlined previously[2] for the reaction of $\mathrm{Pr^{i\cdot}}$ and the same alkyne). Taking $2k_t$ for reaction (9) as 10^9 dm^3 mol^{-1} s^{-1} (as for other termination and cross-termination reactions, see *e.g.* ref. 15) gives k_4 as 1×10^7 dm^3 mol^{-1} s^{-1}: the increase in rate constant compared with addition of $\mathrm{Pr^{i\cdot}}$ (3.3×10^6 dm^3 mol^{-1} s^{-1}) is believed to reflect a favourable polar contribution in a reaction in which a radical with a $+M$ substituent at the radical centre attacks an alkene with $-M$ substituents (see earlier). Parallel experiments in which small quantities of maleic acid (as a model for the alkene formed) were added in experiments with $^{\cdot}\mathrm{CH_2OH}$ gave a similar value to that for butynedioic acid (the similarity between rates of addition of radicals to a number of alkynes and corresponding alkenes has previously been noted[18]).

We next employed these values for k_4, k_7 and termination rate constants k_8—k_{12} together with k_2 2×10^3 dm^3 mol^{-1} s^{-1} (ref. 19) and k_3 8×10^8 dm^3 mol^{-1} s^{-1} (ref. 20) in a kinetic

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* Other radicals with broad outside lines similarly appeared to be insensitive to corresponding pH variation.

† The abbreviations vinyl [(**3**)], BDA (butynedioic acid), dimer [(**4**)], $\mathrm{R^{1\cdot}}$ [(**6**)] refer to radicals depicted in the competing reactions (1) ($\mathrm{R^1}$ = H, $\mathrm{R^2}$ = OH) and Scheme 1.

simulation program in which reactions (2)—(12) were incorporated (all cross-termination reactions being considered). We have calculated steady-state concentrations of all radicals at a time 0.040 s after mixing as a function of [CH_3OH] and [$HO_2CC{\equiv}CCO_2H$], in an attempt to match the observed behaviour (*cf. e.g.* Figures 1a and b). Using all other concentrations as employed in the experiments and varying both k_5 and k_6 led to optimum agreement for the observed dependence of the concentrations of $^{\bullet}CH_2OH$ (**3**; $R^1 = H, R^2 = OH$), (**4**; $R^1 = H, R^2 = OH$) and (**6**) with values of k_5 5×10^6 $dm^3 mol^{-1} s^{-1}$ and k_6 1×10^6 $dm^3 mol^{-1} s^{-1}$. From our results for other substrates we also conclude that abstraction of α-H from ethanol and propan-2-ol proceeds at approximately the same rate.

Whilst the values thus obtained for individual steps should perhaps only be regarded as approximate (*e.g.* in view of the significant number of steps involved) certain conclusions are possible. Thus we believe that the results of the kinetic analysis add considerable support to our assertion that reaction (1) and the reactions in Scheme 1 are in competition and that the structural and mechanistic assignments are correct. We note that the value for the rate constant for addition of the vinyl radical to more alkyne (k_5) is somewhat greater than that for the addition of simple alkyl radicals to the same alkyne (which is not unexpected in view of the increased reactivity anticipated for vinyl radicals) though less than for alkyl radicals in which substantial polar effects accelerate the reaction (*e.g.* $^{\bullet}CH_2OH$, see above). Lastly, the rate of abstraction by the vinyl radicals of alcoholic α-hydrogen atoms is, as might be expected, less than the analogous hydrogen-transfer from added thiols[5] (k *ca.* 10^7 $dm^3 mol^{-1} s^{-1}$) but is significantly faster than values reported for the corresponding abstraction reactions of simple alkyl radicals under similar conditions (*cf.*, for example, values of *ca.* 10^3 $dm^3 mol^{-1} s^{-1}$ for the reactions of $^{\bullet}Me$ with MeOH, EtOH, and Pr^iOH in water at 25 °C[21]). Whilst a substantial polar contribution might be envisaged for this reaction, it also seems likely that the dramatic acceleration observed also reflects the extra reactivity associated with the hybridization of the vinyl-radical centre.

Experimental

E.s.r. spectra were recorded at room temperature on a Varian E-104 spectrometer equipped with an X-band Klystron and 100 kHz modulation. Splitting constants were measured to within ±0.005 mT and *g*-values to within ±0.0001 by comparison with an aqueous solution of Fremy's salt [a(N) 1.309 mT,[22] g 2.0055[23]]. A mixing chamber was employed which allows simultaneous mixing of three reagent streams *ca.* 40 ms before passage through the cavity of the e.s.r. spectrometer. The flow was maintained using a Watson–Marlowe 502 peristaltic pump positioned on the inlet tubing. The solutions used were as follows: stream (*i*) contained titanium(III) chloride (0.008 mol dm^{-3}), stream (*ii*) contained hydrogen peroxide (0.03 mol dm^{-3}), and the third stream contained the substrate (at a concentration up to *ca.* 2 mol dm^{-3}), and in most experiments butynedioic acid or its dimethyl ester (up to *ca.* 0.1 mol dm^{-3}). The pH was usually adjusted to *ca.* 1, by the addition of concentrated sulphuric acid to one of the streams, or to *ca.* 8 with the sodium salt of EDTA (3 g dm^{-3}) added to the titanium(III) stream together with the required volume of aqueous ammonia. pH Measurements were made using a Pye-Unicam PW9410 pH meter with the electrode inserted into the effluent stream. All solutions were deoxygenated both before and during use by purging with oxygen-free nitrogen.

Relative radical concentrations were estimated either by spectrum simulation (using a program supplied by Dr. M. F. Chiu) or from relative line-heights (in cases where line-widths were approximately the same); the steady-state concentration of $^{\bullet}CH_2OH$ (in experiments with methanol as the sole substrate) was estimated as *ca.* 4×10^{-6} mol dm^{-3} *via* double integration (with a Datalab DL4000 microcomputer) and comparison with signals from a standard solution of vanadyl sulphate.

The kinetic simulation program, executed on a DEC-10 computer, was kindly provided by Professor D. J. Waddington.

The chemicals employed were all commercial samples and used as supplied.

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