592. *Fatty Acids. Part IX.* The Partial Oxidation of Mixtures of Unsaturated Acids with Various Peracids.*

By F. D. Gunstone and P. J. Sykes.

The relative rates of reactions of long-chain mono- and di-olefinic acids of various types with several peracids have been examined in a series of competitive oxidations. The rate of reaction of a dienoic acid depends on the relative positions of the two olefinic centres and on the pH of the reaction mixture.

This work began with an examination of the relative rates of reaction of various unsaturated acids with performic acid in the hope that polyethenoid acids such as linoleic and linolenic acid would be so much more reactive than monoethenoid acids such as oleic acid that in a competitive reaction with insufficient performic acid only the polyethenoid acids would react. This situation is known to exist in hydrogenation and in autoxidation.[1] Although a good deal is known about the rates of reaction of mono-olefinic compounds with peracetic and perbenzoic acids there is little information concerning that of polyethenoid compounds with performic or any other peracid.[2]

The usual procedure for studying the rate of peracid oxidation involves measuring the disappearance of peracid by titrating aliquot portions of the reaction mixture, but this method is not applicable with performic acid since the acid is unstable and loses oxygen on storage.[3] In the present study relative, rather than absolute, reaction rates have been measured by examining the products of competitive oxidation of a mixture of two acids. Approximately equimolecular portions of two unsaturated acids are treated with less than the equivalent amount of performic acid and the mixture produced is submitted to alkaline hydrolysis, hydrogenation, and to oxidative fission by von Rudloff's reagent as described in an earlier paper.[4] The product which is then a mixture of mono- and di-basic acids resulting from unoxidised molecules and from molecules which have been oxidised at an unsaturated centre, is examined quantitatively by gas–liquid chromatography.

Besides having the degree of unsaturation required, the acids which are paired in the oxidation experiments must be selected so that in the chromatographic analysis there is no serious overlap of peaks. Difficulties arise because the C_n dibasic acid overlaps to some

---

* Part VIII, preceding paper.

[1] Hilditch, *Nature*, 1946, **157**, 586.

[2] Swern, *J. Amer. Chem. Soc.*, 1947, **69**, 1692; *Organic Reactions*, 1953, **7**, 385.

[3] Greenspan, *J. Amer. Chem. Soc.*, 1946, **68**, 907.

[4] Gunstone and Sykes, preceding paper.

extent with the C_{n+3} monobasic acid and such pairs of acids are avoided as far as possible. In addition, acids which give rise to a common oxidation fragment are not usually paired, though sometimes this cannot be avoided and it does not, necessarily, prevent useful results.

It was expected that linoleic acid would be oxidised at least twice as extensively as a monoethenoid acid and it was hoped that this factor might considerably exceed two because of activation in the diene acid arising from hyperconjugation with the CH_2 group between the two double bonds. Suhara [5] has in fact reported that linoleic and linolenic acid are oxidised faster than oleic acid with peracetic acid.

Preliminary experiments showed, however, that this was not the case. In the following list of polyunsaturated acids the value given is the ratio of the extent of oxidation of the polyunsaturated acid to the extent of oxidation of a mono-olefinic acid such as oleic or tetradec-7-enoic acid: linoleic acid 0·4, homolinoleic acid 0·6, arachidonic acid 0·7, octadeca-7,11-dienoic acid 1·0, elæostearic acid 1·3, tetradec-7-ynoic acid 0·1, and hexadeca-8,10-diynoic acid 0·0. A cross-check on these results is provided by competitive oxidation of linoleic acid with octadeca-7,11-dienoic acid; the observed ratio of 0·6 is to be compared with a value of 0·4—0·6 calculated from the results in which monoethenoid acids are used as competitors.

It appears that a mono-olefinic acid is oxidised as readily as methylene-interrupted acids such as linoleic acid with two unsaturated centres and arachidonic acid with four unsaturated centres. When the two double bonds are separated by two CH_2 groups, as in octadeca-7,11-dienoic acid, the mono- and di-olefinic acids are oxidised at about the same rate, but still not at the expected relative rate of 2 : 1. The conjugated trienoic acid, elæostearic acid, is oxidised only a little faster than the mono-olefinic acid (1·3 : 1), and the acetylenic acids are oxidised very slowly. The last result is not surprising as it is known that acetylenic compounds react much less readily than olefinic compounds with peracids,[6] but the depressed reactivity of polyethenoid acids containing the group $-CH{:}CH{\cdot}[CH_2]_n{\cdot}CH{:}CH-$ ($n = 1$ or 2) was unexpected and further experiments were carried out with a range of peracids and of diolefinic acids.

As mono-olefinic acid tetradec-7-enoic, hexadec-10-enoic, or oleic acid was used [abbreviated to **14(7)**, **16(10)**, and **18(9)** respectively in Table 1] and these were paired with linoleic [18(9,12)], octadeca-7,11-dienoic [18(7,11)], and eicosa-7,13-dienoic acid [20(7,13)], in which the two olefinic centres are separated by one, two, and four CH_2 groups, respectively. Each pair was oxidised with pertrifluoroacetic acid, performic acid, peracetic acid (a reaction effected in the presence of concentrated sulphuric acid), perbenzoic acid in the presence of concentrated sulphuric acid, and perbenzoic acid without added sulphuric acid. Detailed results are given in Table 1 and a summary in Table 2. The methods of calculation are explained and discussed in the Experimental section.

It is clear that the rate of reaction of a diethenoid acid with peracids depends both on the pH of the solution and on the structure of the dienoic acid. With the C_{20} acid having four CH_2 groups between its unsaturated centres the relative rate of reaction for all peracids is around two, the value to be expected if there is neither activation nor deactivation. (These results have no bearing on the effect of one oxidised centre on the remaining unsaturated centre because, with the small amount of oxidant being used, reaction is limited to one unsaturated centre in any molecule.) With isolinoleic acid [18(7,11)], and even more with linoleic acid, there seems to be a deactivating influence which increases with the pH of the reaction mixture. This effect is strongest with pertrifluoroacetic and performic acid, less strong with peracetic acid in the presence of sulphuric acid, and weakest with perbenzoic acid alone. If, however, sulphuric acid is added to the oxidation occurring with perbenzoic acid the relative rate values for linoleic and isolinoleic acid are

---

[5] Suhara, *J. Japan. Oil Chem. Soc.*, 1960, **9**, 607.

[6] Raphael, "Acetylenic Compounds in Organic Synthesis," Butterworths, London, 1955, p. 33; Gunstone and Russell, *J.*, 1955, 3782.

TABLE 1.

Results from competitive partial oxidations.

	Dienoic acid					Monoenoic acid			Ratio		
Peracid R·CO$_3$H	unoxidised	oxidised		oxidised (total)	oxidised (%)	unoxidised	oxidised	oxidn. (%)	A	B	C
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Series I.	18 (9, 12) *v.* 14 (7)										
CF$_3$	108·7	11·5, †	14·7, 12·6	26·2	19·4	68·3	57·8, 44·9	45·8	1·07	1·07	0·39
H	84·3	11·7, †	12·3, 10·1	24·8	22·7	45·4	28·9, 16·5	38·9	1·32	1·47	0·44
Me *	74·6	15·0, †	16·5, 10·7	31·5	29·7	62·1	23·1, 17·4	27·1	1·21	1·25	0·91
Ph *	68·0	19·1, †	17·6, †	36·7	35·1	73·7	40·2, 35·6	35·3	0·97	0·92	1·02
Ph	58·0	21·6, †	18·5, †	40·1	40·9	67·3	23·6, 21·5	26·0	1·12	1·08	1·40
Series II.	18 (7, 11) *v.* 18 (9) or 16 (10)										
CF$_3$ (16)	111·9	10·8, 9·5	10·5, 10·8	21·6	16·2	100·7	37·9, †	27·3	1·00	0·96	0·59
H (18)	(145·0)	17·3, 12·7	20·1, 14·0	37·4		(145·0)	40·2, 38·6		1·05		(0·89)
Me * (18)	(146·6)	19·4, 22·0	22·7, 16·5	44·7		(146·6)	27·6, 26·6		0·99		(1·64)
Me * (16)	86·1	16·9, 16·0	15·9, 16·3	33·2	27·8	98·4	22·2, †	18·4	0·98	0·99	1·54
Ph * (16)	65·6	15·2, 14·8	15·2, 15·7	30·9	32·0	72·9	21·0, †	22·4	1·14	1·03	1·26
Ph (16)	79·3	23·5, 19·6	19·7, 21·3	44·8	36·1	100·7	24·2, †	19·4	1·07	0·99	1·74
Series III.	20 (7, 13) *v.* 18 (9)										
CF$_3$	51·4	16·2, 14·8	14·7, 14·3	30·9	37·5	66·2	18·0, 17·1	21·4	0·94	0·98	1·85
H	59·4	19·3, 18·3	17·4, 18·4	37·7	38·8	78·8	20·4, 19·4	20·6	1·05	0·98	1·79
Me *	56·0	16·3, 14·1	14·0, 15·1	31·4	35·9	71·1	15·1, 14·2	17·5	1·13	1·01	1·81
Ph *	47·2	14·7, 13·4	14·2, 14·3	29·0	38·1	57·6	12·8, †	18·2	1·10	1·08	1·90
Ph	74·6	15·2, 14·8	13·8, 14·2	29·4	28·3	98·0	14·2, †	12·7	0·99	0·93	2·25

Notes: Column 1. * An asterisk indicates the presence of H_2SO_4. In series II, the chain-length of the mono-olefinic acid is given in parentheses. Columns 2, 3, 4, 7, and 8. Each of these figures is the mean of three integrated areas, expressed on a molar basis in arbitrary units.

Columns 3, 4, and 8. The two figures given in each column refer to a paired dibasic and monobasic acid. In column 3 the figures are for the longer of the two possible dibasic acids and its paired monobasic acid; in column 4 they refer to the shorter dibasic acid and the appropriate monobasic acid. † Indicates that the acid was detected qualitatively but not measured quantitatively.

Columns 10, 11, and 12. These are molar ratios diene : monoene. A is the ratio of the two substrate acids; B is the ratio of (oxidised and unoxidised) products determined at the end of the experiment, *i.e.*, [(2) + (5)]/[(7) + (8)]; C is the ratio of the extent of oxidation of the two substrate acids, *i.e.*, (6)/[(9) × (10)].

depressed and become very similar to those with peracetic acid, a reaction also occurring in the presence of sulphuric acid. Peracid oxidation is an electrophilic reaction due to HO^+ or some complex of this entity and it is conceivable that H^+ may be a competing electrophilic reagent. The proton apparently reacts with dienes more readily than with monoenes to give, reversibly, a positively charged entity which does not then react with HO^+ and regenerates the diene acid during the working-up. For dienes containing the system $-CH{:}CH{\cdot}[CH_2]_n{\cdot}CH{:}CH-$ the protonated complex is formed more readily when $n = 1$ than when $n = 2$ and hardly at all when $n = 4$. A careful examination of the products has revealed no unexpected end-product and for this reason the protonation is considered to be reversible.

EXPERIMENTAL

Materials.—The unsaturated acids used in these experiments were obtained as described in the preceding paper.

Partial Oxidation.—Mixtures of two olefinic acids (about 0·16 mmole of each) were oxidised as indicated below.

(*a*) *Performic and pertrifluoroacetic acid.* These oxidations were carried out as already described,[4] trifluoroacetic replacing formic acid where appropriate.

(*b*) *Peracetic acid.* The oxidant was a mixture of glacial acetic acid (6 ml. per g. of olefinic acid), 30% hydrogen peroxide (0·6 mmole per mmole of olefinic acid), and concentrated sulphuric acid (40 mg. per g. of olefinic acid). The reaction sequence was the same as for performic acid except that after destruction of the excess of peroxide with sulphur dioxide the product was refluxed with acetic acid for 15 min. (to open any epoxide rings) before the alkaline hydrolysis.

TABLE 2.

Relative rates of peracid oxidation of dienoic and monoenoic acids (diene : monoene).

Peracid ($R{\cdot}CO_3H$) R =	CF_3	H	Me *	Ph *	Ph
Dienoic acid					
18 (9, 12)	0·4	0·4	0·9	1·0	1·4
18 (7, 11)	0·6	0·9	1·6	1·3	1·7
20 (7, 13)	1·9	1·8	1·8	1·9	2·3

* Indicates the presence of sulphuric acid in the reaction mixture.

(*c*) *Perbenzoic acid.* An ~0·02M-solution of perbenzoic acid in chloroform was prepared from benzoyl peroxide[7] and its exact strength determined iodometrically. This solution of perbenzoic acid (0·6 mmole per mmole of olefinic acid) was added to the olefinic acids dissolved in acetone (10 ml. per g. of acid), and oxidation effected at 5° for 15 min. Excess of peroxide was then destroyed with sulphur dioxide, and the epoxide ring opened by refluxing acetic acid (15 min.), followed by alkaline hydrolysis and the later reactions previously described. In some experiments concentrated sulphuric acid (40 mg. per g. of olefinic acids) was also added to the oxidation mixture.

Calculations. . Quantitative analysis of the final product was carried out by gas–liquid chromatography in a Pye Argon Chromatograph fitted with a 10% Apiezon column. For the preliminary experiments peak areas were measured or calculated as described earlier,[4] the detector used (Radium D) giving a molar response. The later experiments were carried out with a different detector (^{90}Sr), which had a weight response, and in conjunction with an integrating amplifier which gives more accurate results.[8] The figures give in Table 1 (columns 2, 3, 4, 7, and 8) are the means of values taken from three integrams and corrected to a molar ratio. Some of the results were calculated by the use of an internal standard and showed that virtually all the material put on the column was being eluted.

The yield of a monobasic- and dibasic-acid pair resulting from fission of a particular unsaturated centre should be equal, but losses occur because of the volatility of short-chain

---

[7] Braun, *Org. Synth.*, 1941, **1** (2nd edn.), 431.

[8] James, " Methods of Biochemical Analysis," ed. Glick, Interscience Publ. Inc., London, 1960, p. 40.

monobasic acids and the water-solubility of short-chain dibasic acids. When the amounts of oxidation fragments are added the larger value in each pair is used. Sometimes one member of a pair has been detected only qualitatively.

The extent of oxidation is given by the expression:

$$\text{Oxidation (\%)} = \frac{[\text{Degradation fragments (\% mole) from each double bond}] \times 100}{[\text{Degradation fragments (\% mole) from each double bond}] + (\text{Unoxidised acid})}$$

In view of the unequal losses of various products this result can only be approximate but the errors are considered to be much less than the variations of the final results, which must therefore be significant. The ratio A is the proportion of diene to monoene in the oxidation experiment and the ratio B is the proportion of the total products recovered from the diene to those recovered from the monoene. The general agreement between these two values is considered to be a justification of the assumption made in the above calculation.

The ratio C, which is the proportion of diene oxidised to monoene oxidised, corrected for any inequality in the relative amounts of the two acids oxidised, is a measure of the relative rates of oxidation of the two acids concerned. A similar value can be obtained in a slightly different way from the expression:

$$\frac{\text{Degradation fragments (\% mole) for each double bond in the dienoic acid}}{[\text{Degradation fragment (\% mole) for the monoenoic acid}] \times (\text{Ratio A})}$$

This determination is useful when two acids of equal chain length are being oxidised, since only the proportion of total unoxidised acid is then known and not the separate amounts from the mono- and di-enoic acids. This procedure has been used for the two results given in parentheses in column 12 of Table 1. The values of the ratio C calculated in this way are given here along with those calculated in the usual manner in parentheses. The general agreement justified the use of this procedure where necessary: CF_3 0·57 (0·59), H 0·89 (—), Me* 1·64 (—), Me* 1·52 (1·54), Ph* 1·29 (1·26), and Ph 1·73 (1·74). C_{14}, C_{18}, and occasionally C_{16}, mono-olefinic acids were used as standards in this series of experiments; a competition experiment with the C_{14} and C_{18} acids showed that they were oxidised to an equal extent.

To make Table 1 clearer the first set of results in Series III is elaborated. The integrated areas corresponding to each peak are as follows:

	Monobasic acids					Dibasic acids		
Origin of products	C_7	C_9	C_{13}	C_{18}	C_{20}	C_{13}	C_9	C_7
C_{20} (7, 13)	14·8	—	14·3	—	51·4	16·2	—	14·7
C_{18} (9)	—	17·1	—	66·2	—	—	18·0	—

Apart from the C_{18} and C_{20} monobasic acids the remaining acids are pairs resulting from reaction at each of the three possible olefinic centres. The values for each member of a pair should be the same, but minor errors cause them to differ and the larger value is used in subsequent calculations. The extent of oxidation of the C_{18} acid was 18·0 × 100/(66·2 + 18·0), *i.e.*, 21·4%, and of the C_{20} acid (16·2 + 14·7)100/(51·4 + 16·2 + 14·7), *i.e.*, 37·5%. The molar ratio of the C_{20} and C_{18} acid used in the experiment was 0·94; the molar ratio of recovered products was (51·4 + 16·2 + 14·7)/(66·2 + 18·0), *i.e.*, 0·98. The relative extent of oxidation was 37·5/21·4 × 0·94, *i.e.*, 1·85.

Partial Oxidation of Octadeca-7,11-*dienoic Acid*.—This experiment was carried out to make a more careful search for cyclisation products. Octadeca-7,11-dienoic acid (500 mg.) was oxidised with performic acid as described. After von Rudloff oxidation the aqueous solution was concentrated to 50 ml. in a rotary film evaporator and extracted with ether, and the product was methylated (378 mg.). Extraction of the aqueous solution with chloroform gave no additional material. These esters were treated with methanol and urea;[9] 213 mg. of esters were present in the urea complex and 113 mg. did not form a complex (86% recovery). The larger fraction contained C_{11} dibasic acid and C_{11} and C_{18} monobasic acids, 98% of the material

---

[9] Schlenk, " Progress in the Chemistry of Fats and Other Lipids," ed. Holman, Lundberg, and Malkin, Pergamon Press, London, 1954, Vol. II, p. 251.

put on the column being accounted for. The smaller fraction contained C_7 and C_{11} dibasic acids and some C_{11} monobasic acid, 95% of the material put on the column being accounted for. It was concluded that no cyclic material was present at the end of the oxidation.

We thank the D.S.I.R. for an equipment grant and the Carnegie Trust for financial assistance (to P. J. S.).

CHEMISTRY DEPARTMENT, UNIVERSITY OF ST. ANDREWS. [*Received, November 6th*, **1961**.]