Ring–chain Tautomerism. Part IV.[1] *cis*-3-Acylacrylic Acids

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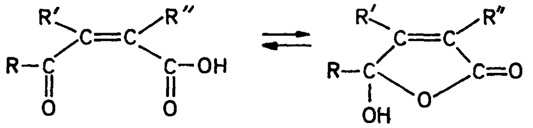
The equilibrium constants for ring-chain tautomerism in a series of *cis*-3-acylacrylic acids have been determined by using the observed pK_a and true pK_a (pK_a^T) values in 80% (w/w) 2-methoxyethanol–water. The latter were estimated from the relation between pK_a values of a series of *cis*- and *trans*-3-substituted acrylic acids. The results are discussed.

EARLIER investigations [2-4] demonstrated the occurrence of ring–chain tautomerism in *cis*-3-acylacrylic acids, (I). and (II), as shown in equation (1). No quantitative studies of these equilibria appear to have been made



(1)

(II)(Chain) (I)(Ring)

Recently, quantitative investigations of this tautomerism in 2-benzoylbenzoic [5,6] and *cis*-3-aroylacrylic acids [1] have been described. The qualitative evidence [2-4] regarding the *cis*-3-acylacrylic acids indicates that these compounds exist predominantly as the ring isomer. The equilibrium constants, K_e, are given by the relation (2).

$$K_e = a_{\text{Ring}}/a_{\text{Chain}} \qquad (2)$$

The observed pK_a can be related [7] to the true pK_a^T by the relation (3). If a reliable estimate of pK_a^T can be

$$\text{p}K_a^T = \text{p}K_a - \log(K_e + 1) \qquad (3)$$

made, K_e can be found by measuring the observed pK_a.

In the present study, we have investigated the ionisation of a series of *cis*- and *trans*-3-substituted acrylic acids. An analysis of these results is used to investigate ring–chain tautomerism in several *cis*-3-acylacrylic acids.

EXPERIMENTAL AND RESULTS

Both *cis*- and *trans*-crotonic, 3-chloro-, 3-bromo-, and 3-iodo-acrylic acids were available from previous studies.[8,9] Acrylic acid was redistilled under reduced pressure immediately before use. The *trans*-3-acylacrylic acids were prepared by three routes. Firstly, the chloralmethyl alkyl ketone was synthesised by the condensation of chloral hydrate and the methyl alkyl ketone in an acetic acid–acetic anhydride solvent.[10] The chloralmethyl alkyl ketone was hydrolysed by sodium hydroxide in aqueous acetone.[11] This method gave *trans*-3-pivaloyl- and 3-isobutyryl-acrylic acids, which were twice sublimed at 65—70 °C/0·7 mmHg and, then, recrystallised from light petroleum (b.p. 60—80 °C). Chloralmethyl methyl ketone gave a rearranged product,[12] 5-chloropent-2,4-dienoic acid,[13] on alkaline hydrolysis. Secondly, the condensation of acetone and pyruvic acid, catalysed by diethylamine, gave *cis*-3-acetyl-2-methylacrylic acid.[14] Thirdly, *trans*-3-acetylacrylic acid was prepared by Wolff's method [15] by bromination of levulinic acid, followed by dehydrobromination of the 3-bromo-product. *cis*-3-Pivaloylacrylic acid was prepared from the *trans*-isomer by exposure to sunlight for 2 days of a solution of the *trans*-isomer dissolved in ether in a Pyrex vessel. After repeated recrystallization to constant m.p. and drying in a vacuum desiccator (P_2O_5), the acids had m.p.s in good agreement with literature

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[1] Part III, K. Bowden and M. P. Henry, preceding paper.

[2] (*a*) N. Hellström, *Nature*, 1960, **187**, 146; N. Hellström, *Kgl. Lantbruks-Högskol. Ann.*, 1957, **23**, 519; *ibid.*, 1962, **28**, 93; (*b*) N. Hellström and S. Gronowitz, *Kgl. Lantbruks-Högskol. Ann.*, 1959, **25**, 363.

[3] N. L. Wendler and H. L. Slates, *J. Org. Chem.*, 1967, **32**, 849.

[4] M. Kuchar, *Coll. Czech. Chem. Comm.*, 1968, **33**, 880.

[5] M. V. Bhatt and K. M. Kamath, *Tetrahedron Letters*, 1966, 3885; *J. Chem. Soc.* (*B*), 1968, 1036.

[6] K. Bowden and G. R. Taylor, *J. Chem. Soc.* (*B*), 1971, 1390.

[7] C. Pascual, D. Wegmann, U. Graf, R. Scheffold, P. F. Sommer, and W. Simon, *Helv. Chim. Acta*, 1964, **47**, 213.

[8] K. Bowden, *Canad. J. Chem.*, 1965, **43**, 3354.

[9] K. Bowden and M. J. Price, *J. Chem. Soc.* (*B*), 1970, 1466.

[10] W. Koenigs and E. Wagstaffe, *Ber.*, 1893, **26**, 554.

[11] F. L. Breusch and H. Keskin, *Arch. Biochem.*, 1948, **18**, 305.

[12] P. Uschakov, *J. Phys. Chem.* (*Russ.*), 1898, **29**, 113 (*Chem. Zentr.*, 1897, **97**, 1018); J. Salkind, *J. Phys. Chem.* (*Russ.*), 1899, **30**, 906 (*Chem. Zentr.*, 1899, **99**, 596).

[13] K. Bowden and M. P. Henry, unpublished studies.

[14] E. Buchta and G. Satzinger, *Chem. Ber.*, 1959, **92**, 449.

[15] L. Wolff, *Annalen*, 1891, **264**, 229; W. G. Overend, L. M. Turton, and L. F. Wiggins, *J. Chem. Soc.*, 1950, 3500.

values.[2b,3,8,9,14,15] The physical constants of 3-acylacrylic acids are listed in Table 1, together with their appearance and recrystallization solvent. Neutralization equivalents of the acids were determined by titration to be within ±1% of the calculated values (see also spectral studies below). The methyl esters (both normal and pseudo) were prepared by standard methods.[3] Solvents were purified as previously described.[6]

Table 1

Physical constants of the 3-acylacrylic acids

Substituent	M.p./°C	Lit. m.p./°C	Ref.
trans-3-Acetyl	124—125 [a]	125—126	15
trans-3-Isobutyryl	78—79 [b]	—	
trans-3-Pivaloyl	93—94 [b]	94—95	2*b*
cis-3-Pivaloyl	82—83 [c]	84—85	2*b*
cis-3-Acetyl-2-methyl	99—100 [d]	100—101, 102	3, 14

[a] Colourless needles from benzene–chloroform. [b] Pale yellow needles from light petroleum (b.p. 60—80 °C); trans-3-*Isobutyrylacrylic acid* (Found: C, 59·0; H, 7·2; O, 33·7. $C_7H_{10}O_3$ requires C, 59·1; H, 7·1; O, 33·8%). [c] Colourless plates from light petroleum (b.p. 60—80 °C). [d] Colourless needles from light petroleum (b.p. 60—80 °C).

pK_a *Measurements*.—The observed pK_a values of the acids were measured in 80% (w/w) 2-methoxyethanol–water, as described previously,[16] and are shown in Table 2.

Table 2

Ionisation of substituted acrylic acids in 80% (w/w) 2-methoxyethanol–water at 25 °C *

Substituent		pK_a	
3	2	*trans*	*cis*
H	H	6·50	6·50
Cl	H	5·65	5·90
Br	H	5·54	5·76
I	H	5·59	5·85
Me	H	7·07	6·77
COMe	H	5·40	
$COCHMe_2$	H	5·48	
$COCMe_3$	H	5·47	7·74
COMe	Me		7·58
COPh	H	5·33 [a]	5·78 [b]
COPh	Me	5·74 [a]	6·8 [b,c]
COAd †	H	5·55 [d]	7·65 [d]

* The pK_a values were reproducible to ±0·02 unit. † COAd ≡ 1-adamantoyl.

[a] See ref. 22. [b] See ref. 1. [c] Estimated value; pK_a^T (estimated) is equal to 5·96.[1] [d] Lit. values.[4]

I.r. Measurements.—The spectra of *cis*-3-acylacrylic acids were measured in dioxan, as described previously.[1] The absence of any detectable chain isomer for the *cis*-3-acylacrylic acids precluded determination of the equilibrium constants, K_e, in the manner described previously.[1] The i.r. spectra results are shown in Table 3.

Table 3

I.r. spectral results for the *cis*-3-acylacrylic acids in dioxan

Substituent		$\nu_{max.}$ (cm.$^{-1}$) (ring lactone CO)
3	2	
$COCMe_3$	H	1765
COMe	Me	1763

^1H *N.m.r. Measurements*.—The spectra of the *cis*-3-acylacrylic acids and their methyl esters (both normal and pseudo) were measured using a Varian A60-A spectrometer operating at 60 MHz. A 10% solution of the compound, containing 2% tetramethylsilane (TMS) as the internal standard, was used for each spectrum. The chemical shifts were measured on the δ scale relative to TMS in p.p.m., before conversion into τ values. The chemical shifts of the averaged signal from the *cis*-3-acylacrylic acids were identical, within the experimental uncertainties, with those for their pseudo methyl ester, precluding determination of the equilibrium constants, K_e, in the manner described previously.[1] The ^1H n.m.r. spectra results are shown in Table 4. The structures of the acids were confirmed and the acids were shown to be >98% pure by this spectral method.

Table 4

^1H N.m.r. spectral results for *cis*-3-acylacrylic acids in [$^2H_6$]acetone

Acid	τ		
	2-*H*	3-*H*	3-COC(C*H*$_3$)$_3$
cis-3-Pivaloyl	3·68 *	2·34 *	9·11
	2-C*H*$_3$	3-*H*	3-COC*H*$_3$
cis-3-Acetyl-2-methyl	8·18 †	2·81 †	8·45

* Coupling constant, *J*, equal to 5·7 ± 0·3 Hz. † Coupling constant, *J*, equal to 1·8 ± 0·3 Hz.

DISCUSSION

Direct measurements, by an i.r. or a ^1H n.m.r. method, of the equilibrium constants for ring-chain tautomerism in the *cis*-3-acylacrylic acids were precluded by the predominance of the ring tautomer, *i.e.* large values of K_e of *ca.* >30. However, if a reliable estimate of pK_a^T can be made, such values of K_e can be found by measuring the observed pK_a of the acid and using equation (3).

Relation between pK_a *Values of* cis- *and* trans-3-*Substituted Acrylic Acids*.—Previous studies[8,17,18] have shown that the ionisation of *trans*- and/or *cis*-3-substituted acrylic acids can be correlated by use of the Hammett equation (4)[19] and *para*-σ values.[20] These

$$\log (K/K_0) = \rho\sigma \qquad (4)$$

correlations for the acids studied here are shown in Table 5 and are successful, as were those for the ionisation of the same acids in water in our previous study.[8]

Table 5

Hammett reaction constant for the ionisation of the 3-substituted acrylic acids in 80% (w/w) 2-methoxyethanol–water at 25 °C *

Series	ρ	log K_0	*r*	*s*	*n*
trans-Acids	3·62	−6·48	0·995	0·20	5
cis-Acids	2·24	−6·38	0·987	0·25	4

* *r* Is the correlation coefficient, *s* the standard deviation, and *n* the number of substituents studied (Table 2; *trans*, 1 to 5; *cis*, 2 to 5).

However, the reaction constants, ρ, for ionisation of the *cis*- and *trans*-series in water were comparable, *i.e.* 2·45

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[16] K. Bowden, *J. Chem. Soc.* (*B*), 1971, 145.

[17] M. Charton and H. Meislich, *J. Amer. Chem. Soc.*, 1958, **80**, 5940; M. Charton, *J. Org. Chem.*, 1965, **30**, 552, 557, 974.

[18] J. Hine and W. C. Bailey, *J. Amer. Chem. Soc.*, 1959, **81**, 2075.

[19] H. H. Jaffé, *Chem. Rev.*, 1953, **53**, 191.

[20] D. H. McDaniel and H. C. Brown, *J. Org. Chem.*, 1958, **23**, 420; R. A. Robinson and K. P. Ang, *J. Chem. Soc.*, 1959, 2314.

(*cis*) and 2·25 (*trans*);[8] whereas, the reaction constants for ionisation in 80% 2-methoxyethanol–water are distinctly different, *i.e.* 2·24 (*cis*) and 3·62 (*trans*). The insensitivity of the reaction constants for the *cis*-series to variation in the solvent corresponds to the behaviour of *ortho*-substituted benzoic acids, *i.e.* 2·43 (water) and 2·40 (80% 2-methoxyethanol–water);[21] while the dependence of the *trans*-series compares closely to that of the *meta-/para-* substituted benzoic acids, *i.e.*, 1·00 (water) and 1·66 (80% 2-methoxyethanol–water).[21] This appears to confirm our previous interpretation of the variation in ρ for the two benzoic acid systems.[21] The transmissive cavity for polar effects in the *trans*-series is occupied by the molecular cavity and the medium, while that for the *cis*-series is composed almost entirely of the molecular cavity itself.

The relations in Table 5 allow us to predict the unknown pK_a^T values of *cis*-3-acylacrylic acids if the pK_a values of the corresponding *trans*-acids are known. Observed σ values (see also below) can be calculated from the pK_a values and the *trans*-series correlation in Table 5 as 0·30 (acetyl), 0·28 (pivaloyl), 0·32 (benzoyl),[22] and 0·26 (1-adamantoyl). Estimated pK_a^T values are shown in Table 6, calculated from the latter values and the *cis*-series correlation in Table 5. The estimated pK_a^T values of *cis*-3-acetyl-2-methylacrylic acid can be calculated from the pK_a^T value of *cis*-3-benzoyl-2-methylacrylic acid together with the small difference in the polar effects of the 3-acetyl and -benzoyl group found above.

TABLE 6

Estimated pK_a^T and K_e values for *cis*-3-acylacrylic acids

Substituent		pK_a^T (estimated) *	K_e
3	2		
$COCMe_3$	H	5·76	94 (±11)
COMe	Me	6·03	34 (±4)
COPh	H	5·67	0·3 (±0·2)
COAd †	H	5·80	70 (±8)

* The estimated pK_a^T values are considered to be ±0·03 unit. † See Table 2.

An important point to note is the difference between the observed σ values for the acyl groups found in this study and those calculated directly from the ionisation of *para*-acylbenzoic acids, *i.e.* 0·44 (acetyl), 0·29 (pivaloyl), and 0·46 (benzoyl).[23] Steric interactions reduce the effect of the pivaloyl group in benzoic acid. However, the other substituents have a markedly reduced effect in the acrylic acid system, compared to the *para*-substituted benzoic acid system.* A similar reduction was noted for the *ortho*-acylbenzoic acids, whose pK_a^T values were unexpectedly large.[6] In the latter study, it was considered that this could be caused by the particular conformation likely for these *ortho*-acids. However, a similar explanation cannot apply to the *trans*-3-acylacrylic acids studied here. A more likely reason appears to be that the substituent dipole in the acyl groups is principally situated in the carbonyl group; whereas, the substituent dipole of most other groups is situated in the molecule carbon atom-substituent bond. This would cause a differential effect when comparing the effects of these two types of substituents at distant and proximate positions.

Equilibrium Constants for Ring–Chain Tautomerism, K_e.—The most significant factor that can be noted from the values of K_e in Table 6 is the very large difference between the effect of the phenyl and alkyl groups on the equilibrium constants. This is caused by the stabilisation of the chain tautomer in *cis*-3-benzoylacrylic acid by the resonance interaction between the phenyl and the keto-carbonyl groups. No such interaction can occur in the corresponding ring tautomer. This comparison is exactly analogous to that between 2-benzoylbenzoic and the relevant 2-acylbenzoic acids.[6] The *cis*-3-acylacrylic acids are considerably more inclined to formation of the cyclic tautomer than the corresponding 2-acylbenzoic acids. This appears to be due to more effective resonance interactions between the carbonyl groups and the aromatic system than those between the carbonyl group and the ethylenic double bond in the chain tautomers.

Structure–Acidity Relations in cis-/trans-3-*Substituted Acrylic Acids.*—McCoy and his co-workers[24] have critically examined structure–acidity relations in some 3-substituted acrylic acids in water. Other studies[25,26] of the ionisation of various 3-substituted acrylic acids in 50% ethanol–water have been recently made. Our investigations of these relations for similar systems have been made in water[8] and in 80% 2-methoxyethanol-water (this study). It had been considered that *cis*-3-substituents would, in general be more acidic than their *trans*-isomers and this has been interpreted in terms of steric inhibition of resonance between the carboxylic and ethylenic groups.[27,28] Our conclusions from the results of the present study and of other workers[24–26] are that the relativity acidity of *cis*- and *trans*-isomeric acids are very dependent on the medium used in the study. Although steric inhibition of resonance will very probably be important, especially for 'bulky' substituents, solvents effects are very important. These can affect the relative acidity in two ways. Firstly, the susceptibility to polar effects of the *cis*- and *trans*-systems will vary with medium in different ways and, secondly, the solvation of the carboxylic acid and

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* Previously, Hine and Bailey[18] found a similar reduced reactivity of *trans*-3-acetylacrylic acid, compared to other *trans*-3-substituted acids, in the esterification with diazodiphenylmethane in ethanol.

[21] K. Bowden and G. E. Manser, *Canad. J. Chem.*, 1968, **48**, 2941.

[22] K. Bowden and M. P. Henry, following paper.

[23] K. Bowden and M. J. Shaw, *J. Chem. Soc.* (*B*), 1971, 161.

[24] L. L. McCoy and G. W. Nachtigall, *J. Amer. Chem. Soc.*, 1963, **85**, 1321; E. A. McCoy and L. L. McCoy, *J. Org. Chem.*, 1968, **33**, 2354.

[25] H. Hogeveen, *Rec. Trav. Chim.*, 1964, **83**, 813, 836.

[26] C. Sandris, *Tetrahedron*, 1968, **24**, 3583.

[27] C. K. Ingold, 'Structure and Mechanism in Organic Chemistry,' Cornell Univ. Press, New York, 1953, p. 744.

[28] G. S. Hammond, 'Steric Effects in Organic Chemistry,' ed. M. S. Newman, Wiley, New York, 1956, ch. 9.

carboxylate anion group will change with variation of the solvent. Effects on the structure of the solvation shell have been postulated as an alternative and/or additional explanation to the steric effect discussed above in accounting for increased acidity by *ortho*-substituents in benzoic acids,[29] which are closely related to *cis*-**3**-substituents in acrylic acids. Thus, it would appear that the relative acidity of *cis*-/*trans*-isomeric acrylic acids are dependent on the solvating power of the medium.

We thank Geigy (U.K.) Ltd. for financial support (to M. P. H.).

[1/1534 *Received, August* 23*rd*, 1971]

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[29] J. Steigmann and D. Sussman, *J. Amer. Chem. Soc.*, 1967, **89**, 6406.