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CONFORMATION OF SUCCINIC AND METHYLSUCCINIC ACIDS

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Abstract—The NMR spectra of succinic and methyl succinic acids have been obtained and analysed, and from the measured vicinal couplings a value for the energy difference between *gauche* and *trans* conformers obtained. The indicated conformer populations are discussed in the light of those reported in previous work.

The effect of substituents on conformational equilibria is in general well understood, but so far little work has been done on the effect of vicinal carboxyl groups on the conformation of compounds containing —CH_2—CH_2— and —$CH_2CH(Me)$— fragments using the NMR technique, although halogenated derivatives have been studied.[1]

Here we present results of a NMR study of succinic and methyl succinic acids, the analysis of the spectra and interpretation of the NMR parameters in terms of the conformational equilibria existing in solution.

Analysis of the spectra

The analysis of the spectra of succinic acid and its ester was performed on the satellites of the —CH_2CH_2— signal *i.e.* on the aa'bb' subspectrum of the entire AA'BB'X spectrum, where $X = {}^{13}C$. The observed pattern was that of a typical AA'BB' spectrum with $M = J_A - J_B = 0$ and with a value of $K = J_A + J_B$ relatively high with respect to $L = J - J'$.[2] With such parameter values transition *9* coincides with *10* and *11* with *12*, their separation being very small, whereas for transitions *5*, *6*, *7* and *8* the intensities of *5* and *8* are virtually zero and those of *6* and *7* relatively very high, the two transitions occuring at similar frequencies. Finally considering that the effective chemical shift of the aa'bb' subspectrum

$$\delta_{ab} = \delta_{AB} + \tfrac{1}{2}(J_{AX} + J_{BX}) = \text{isotope shift} + \tfrac{1}{2}(J_{CH} + J_{CCH})$$

is rather high relatively to N, transitions *1*, *2* and *3*, *4* are very close to each other, approaching the AA'XX' limit. Thus we assigned transitions *1* and *2* to the lowfield doublet and *3* and *4* to the upfield band in view of its relatively broad line-width; therefore the N parameter can be obtained from the separation between one component of the low field doublet and the upfield band while the inner splitting gives an approximate value for L.

Assuming a K value of 32·0 Hz and considering that $M = 0$ by symmetry we calculated the spectrum using the computer program LAOCN3.[3] The best agreement was obtained by assigning transition *1* to the low field peak, the calculated spectrum being independent of the assumed value of *K* within a range of 15 Hz.* In the refinement performed only on the vicinal couplings, transitions *3* and *4* were assigned to the high field band frequency plus or minus one half of the line width, in order to avoid large deviations between the observed and calculated spectrum.

The methylsuccinic compounds were treated as $ABCD_3$ systems. Irradiation of the methyl group simplified the spectrum to an ABC case from which the parameters used in the calculation of the complete spectrum were obtained. Refinement was carried out using LAOCN3, very low parameter probable errors and a good r.m.s. error being obtained with the assignment of more than 160 transitions.

Results

The calculated and observed spectra of the acids are shown in Figs 1 and 2 and parameters collected in Table 1.

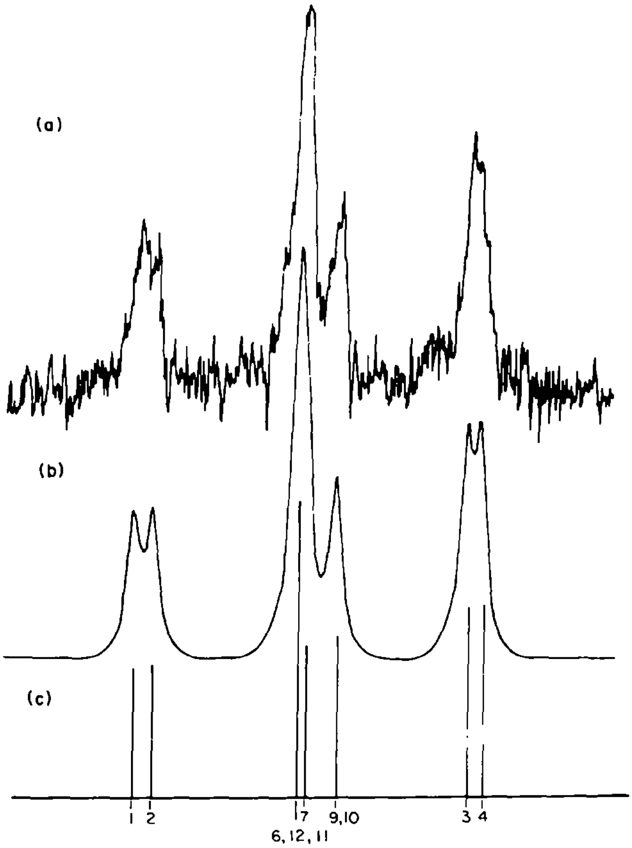

FIG 1. Spectra of succinic acid. (a) observed spectrum in dioxane at 66°C; (b) calculated spectrum with 0·5 Hz linewidth; (c) calculated "stick" spectrum.

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* This means that the analysis cannot determine the value of J_{gem} and that the values of *J* and *J′* obtained are independent of the assumed value of *K*.

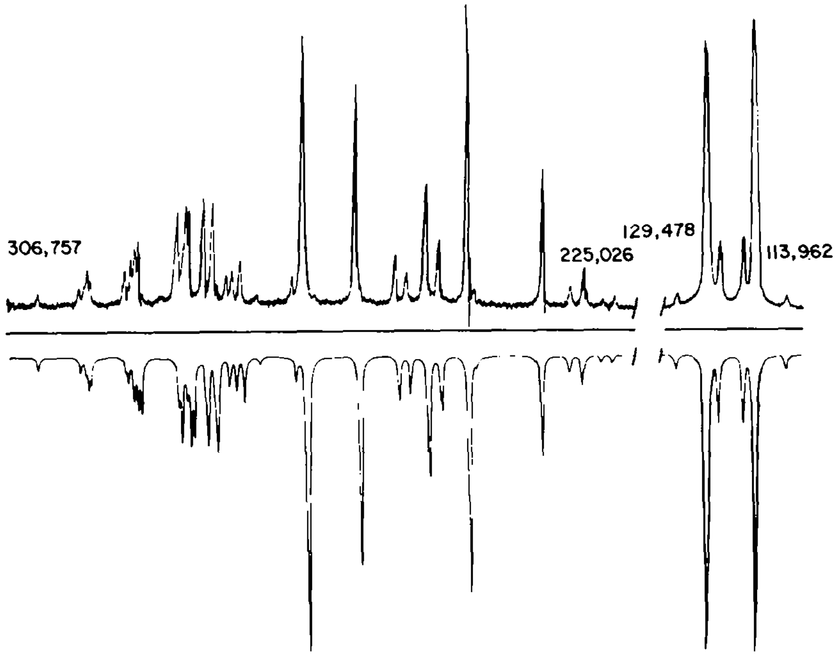


FIG 2. Methylsuccinic acid: observed (top) and calculated spectrum (bottom).

TABLE 1
SPECTRAL PARAMETERS OF SUCCINIC ACIDS

Compound	J_{12}	J_{14}	J_{24}	J_{H_1Me}	J_{H_2Me}	J_{H_4Me}	RMS error
Succinic acid[a]	—	5·84	7·33	—	—	—	0·08
Dimethyl ester[a]	—	6·04	7·41	—	—	—	0·09
Dipotassium salt[b]	—	6·4	9·2	—	—	—	—
Methylsuccinic acid[c]	−16·87	5·94	8·06	−0·06	−0·13	7·23	0·07
Dimethyl ester[d]	−16·84	6·12	8·31	−0·06	−0·04	7·21	0·09

[a] J_{CH} = 130·0 Hz

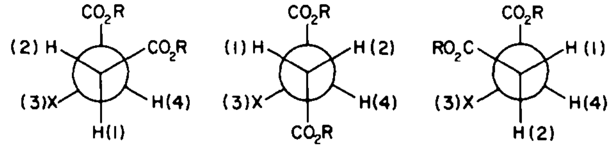
[b] J_{CH} = 128·0 Hz

[c] ν_1 = 242·85 ν_2 = 271·52 ν_4 = 288·17 ν_{Me} = 121·85

[d] ν_1 = 242·78 ν_2 = 266·90 ν_4 = 286·23 ν_{Me} = 116·81 in Hz from internal TMS

DISCUSION

The possible conformations of succinic and methylsuccinic acid (and corresponding esters) are as follows:



G_1 T G_2

R = H, CH_3 X = H, CH_3

For succinic acid and its ester the two gauche conformations are energetically equivalent and the conformational equilibrium is controlled by only one parameter, the energy difference $\Delta E = E_g - E_t$. Assuming fast exchange between the rotational isomers (relative to the NMR time scale) one can describe the observed vicinal coupling constant in the usual way, i.e. as the molar average of the individual conformers couplings, $J = \Sigma\, n_i J_i$. Inspection of the two vicinal coupling constants, which are quite similar rules out the two extreme cases of $n_g = 0$ or $n_t = 0$. Since if it were present in only the *trans* conformation, we would have $J_{14} \gg J_{24}$ and conversely if only in the *gauche* conformation we would have $J_{24} \gg J_{14}$. Therefore, since the two J_{vic} are of comparable size, there exists an equilibrium with a relatively small value of ΔE.

In order to obtain a more quantitative results we have evaluated the energy difference between the *gauche* and *trans* conformers using the relationship[4]

$$\Delta E = E_g - E_t = RT \ln 2 \frac{J_{24} - J_g^g}{J_t^t - J_{24}}$$

For the coupling values in the individual conformers, we used those of the model compounds: 1,2di-tert-butyl-ethane[4] for the *trans* conformation and cyclohexane for the gauche conformation,[5] assuming that the difference in the electronegativity value of an alkyl group of a carboxylic group is not so large as to considerably affect the coupling constants. The energy difference obtained by this method was 0·22 Kcal/mole.

The substitution of a hydrogen atom by a methyl group apparently does not substantially change the situation described above. In the methyl-succinic acid the two vicinal coupling constants of the —CH—CH_2— fragment (Table 1) are not very different, which again rules out the presence of only one strongly populated conformation.

Using the approximate method of Snyder,[6] which neglects the gauche form G_2, we have calculated the energy difference at each temperature between the G_1 and T forms with the relationship:

$$\Delta E = RT \ln \frac{r - 0{\cdot}18}{1 - 0{\cdot}18r}$$

where $r = J_{14}/J_{24}$.

The ΔE value obtained at 30°C (Table 2) is comparable with that for succinic acid. In view of the assumptions made in the calculation of this result the small variation of the calculated ΔE with temperature could be due either to the assumption that the couplings of individual conformers are temperature independent or to a real change of the conformers solvation energy with temperature. In any case this change is not so large as to affect substantially the conclusion reached as to relative conformer populations and stabilities. Further the assumption that $J_{14} > J_{24}$ corresponds to the postulate that the *trans* isomer is the more stable in agreement with the succinic acid case.

TABLE 2
TEMPERATURE DEPENDENCE OF VICINAL COUPLING IN METHYL SUCCINIC ACID

T(°C)	−13	0	+30	+70	+83
J_{14}	5·3	5·5	5·9	6·4	6·6
J_{24}	8·7	8·4	8·1	7·6	7·4
ΔE (kcal/mole)	0·38	0·35	0·28	0·20	0·11

Thus in both cases our results show that the *trans* rotamer is energetically favoured, but by such a relatively small energy difference that significant amount of the *gauche* rotamer exist in solution.

On the basis of the interpretation of the Raman spectrum[7] in aqueous solution it has been concluded recently that succinic acid adopts the gauch conformation in this solvent with the two carboxylic group linked by one intramolecular hydrogen bond.

However from the value of the dipole moment of succinic acid (2·08 D, measured in dioxane) Eberson *et al.*[8] previously concluded that the *trans* conformation is energetically favoured.

Further, according to Eberson[9] there is no evidence from ionisation constant data of intramolecular hydrogen bonding in succinic acid, this statement being based on the fact that intramolecular hydrogen bonding in the dicarboxylic acid ion facilitates the first ionisation step and hinders the second, thereby increasing $\log k_1/k_2$. It has been observed in a large number of cases that a value of $\log k_1/k_2$ in excess of 2–2·5 indicates the presence of intramolecular hydrogen bonding whereas for succinic acid $\log k_1/k_2$ is 1·29 in water and 1·91 in ethanol–water 50% solution, the interpretation being the absence of intramolecular hydrogen bonding.

The apparent discrepancies between the three methods of study however can be readily explained if one considers their inherent limitations.

Thus the conclusion drawn from the dipole moment study that the predominant form is *trans* does not exclude the existence of significant amounts of *gauche*. Indeed to have a dipole moment at all the *gauche* form must be present since the *trans* rotamer has zero dipole moment. Similarly while the Raman study apparently indicates the *gauche* form to be energetically more favoured the results cannot exclude the presence of some *trans* form.

We thus believe our results give a true picture of the conformational equilibria as being one with a low energy difference between the *trans* and *gauche* forms, and thus the presence of substantial ammounts of each.

Further, we also believe that the NMR method is more accurate than either the Raman or dipole moment methods, based as it is on the well known large difference between *trans* and *gauche* vicinal couplings in substituted ethane fragments.

The small energy difference which we have obtained also explains the apparent conflict between the conclusions as regard to the type of hydrogen bonding in solution reported in the Raman and dipole moment studies.

The fact that this energy difference is small indicates that any stabilisation of the *gauche* form by intramolecular hydrogen bonding is balanced in the *trans* form either by solute-solute or solute-solvent intermolecular hydrogen bonding. In other words the existence of either *only* intramolecular hydrogen bonding (which would lead to *only* the *gauche* form) or *only* intermolecular hydrogen bonding (which would lead to *only* the *trans* form) can be ruled out.

In an attempt to obtain more information on hydrogen bonding and the effect on the conformation preferred we also examined the dimethyl esters of both acids and the dipotassium salt of succinic acid, following the example of Erickson;[1] in his PMR study of the halo-succinic acids.

The changes in vicinal couplings in going from the acid to the esters (0·2 Hz on average, Table 1) are so small as to be insignificant, indicating that the conformational equilibrium is similar in both the acid and the ester.

On the other hand the difference in couplings between succincic acid and its dipotassium salt can reasonably be explained on the basis of the additional electrostatic stability of the *trans* rotamer of the salt.

Finally from a comparison of our results with those of Erickson for the halo-succinic acids it is possible to obtain an estimate of the effect of a methyl group relative to the halogens on the conformational equilibrium. The two vicinal couplings in methyl succinic acid (Table 1) and in chloro succinic acid are sufficiently different (the difference being greater in the chloro derivative) as to indicate a reasonable conformational energy difference between G_1 and T conformers. In the case of bromo succinic acid however the vicinal couplings are equal, indicating zero energy difference. Thus the order of the steric effect is $Br > CH_3 > Cl$, similar to that previously suggested.[1]

EXPERIMENTAL

All samples were degassed and sealed. The ^{13}C satellite spectrum of succinic acid was recorded as a 20% solution in dioxane and D_2O using a Bruker HFX90 spectrometer equipped with a Fabritek 1070 computer of average transients. The spectra were accumulated 10 times with a sweep rate of 0·37 Hz/sec. That of the dipotassium salt was similarly recorded for a 20% solution in aqueous dioxane (1:1), and that of the dimethyl ester as the neat liquid using a Varian HA-IOO, without accumulation.

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REFERENCES

[1] L. E. Erickson, *J. Am. Chem. Soc.* **87**, 1867 (1965)

[2] N. Sheppard, J. J. Turner, *Proc. Roy. Soc.* Scz. A252, 506 (1959)

[3] A. A. Bothner-By, S. Castellano, *J. Chem. Phys.* **41**, 3863 (1964)
[4] R. J. Abraham, G. Gatti, *J. Chem. Soc.* B, 961 (1969)
[5] E. W. Garbisch, M. C. Griffth, *J. Am. Chem. Soc.* **90**, 6543 (1968)
[6] E. I. Snyder, *Ibid*, **88**, 1165 (1971)
[7] L. Bardet, J. Maillals, H. Maillals, *C.R. Acad. Sc. Paris* **270**, 158 (1970)
[8] H. B. Thompson, L. Eberson, J. V. Dahlem, *J. Phys. Chem.* **66**, 1634 (1962)
[9] L. Eberson, *The Chemistry of Carboxylic Acids and Esters*, (Edited by S. Patai) pp. 272–284. Interscience, New York N.Y. (1969)