Studies in Nuclear Magnetic Resonance Spectroscopy. Part VII.[1] ^{13}C and ^{1}H Spectra of Aliphatic Ketones and Secondary Alcohols. The Negative Inductive Effect of Methyl Groups

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^{13}C and ^{1}H N.m.r. parameters have been obtained for the series of aliphatic ketones, acetone to 2,2,4,4-tetramethylpentan-3-one, and secondary alcohols, propan-2-ol to 2,2,4,4-tetramethylpentan-3-ol. The downfield shift of the carbinol carbon atoms with increasing substitution is explained in terms of a *negative* inductive effect ($-I$) of a methyl group. These shifts can be predicted by use of a modification of a known empirical relationship. The resonances of the carbonyl carbons of the ketones also move downfield with increasing substitution as shown previously. Values of J(CH) for the α-positions of the ketones were found to be insensitive to methyl substitution. However, the geminal HH coupling constants for the α-positions were found to be greater in ethyl ketones (J_{av} −17·6 Hz) than in methyl ketones (J_{av} −14·5 Hz), indicating that ethyl ketones exist predominantly in a conformation in which the methyl group eclipses the plane of the carbonyl double bond. Populations of conformations of the secondary alcohols have been determined from the values of the vicinal coupling constants. From these populations, values of the carbinol methine proton chemical shift have been estimated from additivity relations and shown to agree closely with the observed values.

IN connection with the interpretation of the heats of hydrogenation of a series of acyclic ketones,[2] it became desirable to investigate systematically the n.m.r. parameters of these ketones and the corresponding alcohols in order to obtain information concerning the electronic and conformational factors which might be operative. We have therefore examined the ^{1}H and ^{13}C spectra of acetone and propan-2-ol and their homologues in which the six protons are successively replaced by methyl groups. The literature contains some isolated results (see Tables) including ^{13}C chemical shifts for the carbonyl carbon atoms of all but three of the ketones.[3]

EXPERIMENTAL

Materials.—Commercial samples of acetone, butan-2-one, 3-methylbutan-2-one, pentan-3-one, 3,3-dimethylbutan-2-one, propan-2-ol and butan-2-ol were fractionated; all gave single peaks on g.l.c.

3-Methylbutan-2-ol, 3,3-dimethylbutan-2-ol, pentan-3-ol and 2-methylpentan-3-ol were prepared by reducing the corresponding ketones with lithium aluminium hydride in ether at 0—5°. The products were fractionated to give alcohols with the physical properties shown in Table 1.

2-Methylpentan-3-one, 2,2-dimethylpentan-3-one, 2,4-dimethylpentan-3-one and 2,2,4-trimethylpentan-3-one were prepared from the corresponding alcohols by chromate oxidation.[4] The ketones have the physical properties shown in Table 1.

2-Methylpentan-3-ol, 2,2-dimethylpentan-3-ol, 2,4-dimethylpentan-3-ol, and 2,2,4-trimethylpentan-3-ol were prepared by Grignard reactions.[5] 2,2,4,4-Tetramethylpentan-3-one and its corresponding alcohol were prepared according to the method of Bartlett and Schneider [6] from t-butyl chloride and methyl 2,2-dimethylpropionate.[7]

The ketones with α-hydrogen atoms were deuteriated by repeated catalysed exchange (K_2CO_3) with deuterium oxide under reflux.[8]

Spectra.—The ^{13}C spectra were recorded with a Varian HR-60 spectrometer at 15·085 MHz. The samples were run as equimolar solutions in carbon disulphide in 15 mm. o.d. non-spinning tubes filled to a depth of *ca.* 6 cm. The spectrometer was calibrated by use of the separation between the methyl carbon and the carbonyl carbon chemical shifts of acetone [9] (176 p.p.m.). A minimum of six spectra (three in each direction of sweep) were averaged to gain the figures given in Table 2. Unless otherwise specified the chemical shifts have standard deviations of ±0·2 p.p.m. and the ^{13}C—^{1}H coupling constants of ±3Hz.

The ^{1}H spectra were recorded with Varian HR-60, A-60A, and HA-100 instruments. The error of measurements of chemical shifts (p.p.m. from internal tetramethylsilane) and coupling constants are given in the appropriate Tables. The error in measurement of the H–D coupling constants is ±0·1 Hz and therefore that of the geminal H–H coupling constants is ±0·65 Hz. As the H–D splittings were taken as the average within each multiplet, the error in J_{gem} is probably less than ±0·65 Hz.

The spectra of 2,2-dimethylpentan-3-ol were analysed with the aid of computer programs DPENMR,[10] LAOCN3,[11] ‡ and PLOT.[12]

RESULTS

^{13}C *Spectra.*—The carbonyl chemical shifts agree satisfactorily with those previously reported [3] and follow a nearly linear relation with the number of α-protons (Table 2

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[1] Part VI, P. J. Black, M. L. Heffernan, L. M. Jackman, Q. N. Porter, and G. R. Underwood, *Austral. J. Chem.*, 1964, **17**, 1128.

[2] L. M. Jackman, D. P. Kelly, J. M. Lawlor, and M. E. D. N. Moussa, to be published.

[3] J. B. Stothers and P. C. Lauterbur, *Can. J. Chem.*, 1964, **42**, 1563.

[4] L. T. Sandborn, *Org. Synth.*, 1944, Coll. Vol. I, p. 340.

[5] F. C. Whitmore, W. L. Ivers, and H. S. Rothrock, *Org. Synth.*, 1944, Coll. Vol. II, p. 408.

[6] P. D. Bartlett and A. Schneider, *J. Amer. Chem. Soc.*, 1945, **67**, 141.

[7] F. C. Whitmore and W. S. Forster, *J. Amer. Chem. Soc.*, 1942, **64**, 2966.

[8] V. J. Shriner and S. Cross, *J. Amer. Chem. Soc.*, 1957, **79**, 3599.

[9] P. C. Lauterbur, *J. Chem. Phys.*, 1957, **26**, 217.

[10] R. C. Ferguson and D. W. Marquardt, *J. Chem. Phys.*, 1964, **41**, 2087.

[11] S. Castellano and A. A. Bothner-By, *J. Chem. Phys.*, 1964, **41**, 3863.

[12] D. P. Kelly, *J. Mol. Spectroscopy*, 1968, **28**, 204.

TABLE 1

Physical constants for aliphatic ketones and secondary alcohols

Compounds	B.p. (°c)		n_D^{20}	
	obs.	lit.	obs.	lit.
3,3-Dimethylbutan-2-one	104—106	106 [a]	1·3978	1·3960 [a]
2-Methylpentan-3-one	115—116	111—113/740 [b] mm.	1·3987	1·3975 [b]
2,2-Dimethylpentan-3-one	125·5	125—126 [a]	1·4050	1·4013 [a]
2,4-Dimethylpentan-3-one	124	124—125 [a]	1·4000	1·4001 [a]
2,2,4-Trimethylpentan-3-one	135	134—135 [a]	1·4060	1·4051
2,2,4,4-Tetramethylpentan-3-one	153—154	153 [c]	1·4202	1·4188 [c,d]
3-Methylbutan-2-ol	111—112	112/742	1·4075	1·4092 [e]
Pentan-3-ol	114—115	115/754 [a]	1·4095	1·4077 [a,f]
3,3-Dimethylbutan-2-ol	120	120·4 [g]	1·4151	1·4148 [g]
2-Methylpentan-3-ol	124—125	129—130 [a]	1·4170	1·4175 [a]
2,2-Dimethylpentan-3-ol	134·5	133—134/732 [h]	1·4219	1·4223 [h]
2,4-Dimethylpentan-3-ol	139	139 [a]	1·4247	1·4226 [a]
2,2,4-Trimethylpentan-3-ol	149—150	150—151 [a]	1·4292	1·4288
2,2,4,4-Tetramethylpentan-3-ol	40—45	50 [i]		

[a] I. Heilbron and H. M. Bunbury, 'Dictionary of Organic Compounds,' Oxford University Press, 1965. [b] F. C. Whitmore and L. P. Block, *J. Amer. Chem. Soc.*, 1942, **64**, 1620. [c] Ref. 6. [d] n_D^{22}. [e] F. C. Whitmore and A. Mosher, *J. Amer. Chem. Soc.*, 1941, **63**, 1120. [f] n_D^{25}. [g] F. C. Whitmore and P. L. Meunier, *J. Amer. Chem. Soc.*, 1933, **55**, 3721. [h] F. C. Whitmore, R. E. Meyer, G. W. Pedlow, and A. H. Popkin, *J. Amer. Chem. Soc.*, 1938, **60**, 2788. M.p. and g.l.c. showed a small amount of ketone was present. This in no way affected the results.

TABLE 2

^{13}C Chemical shifts [a] and ^{13}C–^1H coupling constants [b] for aliphatic ketones and secondary alcohols [c]

Compounds	δ[C(1)]	*J*[C(1)H]	δ[C(2)]	*J*[C(2)H]	δ[C(3)]	*J*[C(3)H]	δ[C(4)]	*J*[C(4)H]	δ[C(5)]	*J*[C(5)H]
$CH_3{\cdot}CO{\cdot}CH_3$ 3 1 2	−11·31 [e] (−12·3) [f]		164·7 (164) [g]	126 126·8 [h] (126) [g]	164·7 (164)	126 126·8 (126) [g]				
$CH_3{\cdot}CO{\cdot}CH_2{\cdot}CH_3$ 3 1 2 4	−13·75 (−13·5) [f]		157·3	121 125·4 [h]	165·0	126 126·8 [h]	185·5	127		
$CH_3{\cdot}CO{\cdot}CH(CH_3)_2$ 3 1 2 4	−16·80 (−17·4) [f]		152·0	127 126·0 [h]			174·9	127		
$CH_3{\cdot}CO{\cdot}C(CH_3)_3$ 3 1 2 4	−17·90 (−18·2) [f]		149·1			127·2 [h] (127) [k]	166·2	129 127·2 [h]		
$CH_3{\cdot}CH_2{\cdot}CO{\cdot}CH_2{\cdot}CH_3$ 5 3 1 2 4	−16·20 (−16·5) [f]		157·5	124	157·5	124	185·5	125	185·5	125
$CH_3{\cdot}CH_2{\cdot}CO{\cdot}CH(CH_3)_2$ 5 3 1 2 4	−19·30			128·8 [h]		123·8 [h]				
$CH_3{\cdot}CH_2{\cdot}CO{\cdot}C(CH_3)_3$ 5 3 1 2 4	−20·58		150·1				167·3	126 126·0 [h]		
$(CH_3)_2{\cdot}CH{\cdot}CO{\cdot}CH(CH_3)_2$ 5 3 1 2 4	−22·62 (−22·8) [f]		154·5	128	154·5	128	174·7	128 127·0 [h]	174·7	128 127·0 [h]
$(CH_3)_2CH{\cdot}CO{\cdot}C(CH_3)_3$ 5 3 1 2 4	−24·57		149·3				167·7	126		
$(CH_3)_3C{\cdot}CO{\cdot}C(CH_3)_3$ 5 3 1 2 4	−22·63 (−23·0) [f]		148·0		148·0		164·7	128 126·6 [h]	164·7	128 126·6 [h]
$CH_3{\cdot}CHOH{\cdot}CH_3$ 3 1 2	129·4 (130·0) [i]	141 140·9 [h]	167·8 (168·2) [i]	125	167·8 (168·2) [i]	125				
$CH_3{\cdot}CHOH{\cdot}CH_2{\cdot}CH_3$ 3 1 2 4	124·1	136								
$CH_3{\cdot}CHOH{\cdot}CH(CH_3)_2$ 3 1 2 4	120·7	136	157·8	124			174·0 [j]	125		
$CH_3{\cdot}CHOH{\cdot}C(CH_3)_3$ 3 1 2 4	117·5	135	157·9				166·9	124		
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}CH_2{\cdot}CH_3$ [p] 5 3 1 2 4	119·1	138	163·1	126	163·1	126	182·9	130	182·9	130
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}CH(CH_3)_2$ 5 3 1 2 4	115·2	141								
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	111·6	136								
$(CH_3)_2CH{\cdot}CHOH{\cdot}CH(CH_3)_2$ 5 3 1 2 4	112·1 [l]	142 (136) [n]								
$(CH_3)_2CH{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	109·7 [l]	135 (137·2) [h]								
$(CH_3)_3C{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	107·8	139 (136·8) [m]	155·6		155·6		164·0	126	164·0	126

[a] ±0·2 p.p.m. from internal CS_2. [b] ±3 Hz. [c] Due to resolution difficulties some values for unsymmetrical molecules were not obtained. Values of δ[C(2)] − δ[C(5)] for unsymmetrical ketones are ±0·2—0·5 p.p.m. [d] The carbon skeleton is numbered C(5)C(3)C(1)C(2)C(4) where the functional group is on carbon 1. [e] Carbonyl carbon shifts are ±0·1 p.p.m. [f] Reference 5, ±0·5 p.p.m. from external CS_2. [g] P. C. Lauterbur, *J. Chem. Phys.*, 1957, **26**, 217. [h] From proton spectrum. [i] P. C. Lauterbur, *Ann. N.Y. Acad. Sci.*, 1958, **70**, 841. [j] ±1·0 p.p.m. [k] J. Ranft, *Ann. Physik*, 1963, **10**, 399. [l] ±0·4 p.p.m. [m] G. J. Karabatsos and C. E. Orzech, jun., *J. Amer. Chem. Soc.*, 1965, **87**, 560. [n] For long range C–H couplings see G. J. Karabatsos, *J. Amer. Chem. Soc.*, 1961, **83**, 1230. [p] G. J. Karabatsos, J. D. Graham, and F. M. Vane, *J. Amer. Chem. Soc.*, 1962, **84**, 37.

and Figure 1). The only anomaly is the shift of 2,2,4,4-tetramethylpentan-3-ol noted previously and its chemical shift has not been included in the least-squares analysis.* Because of the overlapping of signals not all the alkyl carbon chemical shifts [and $J(^{13}CH)$] could be obtained.

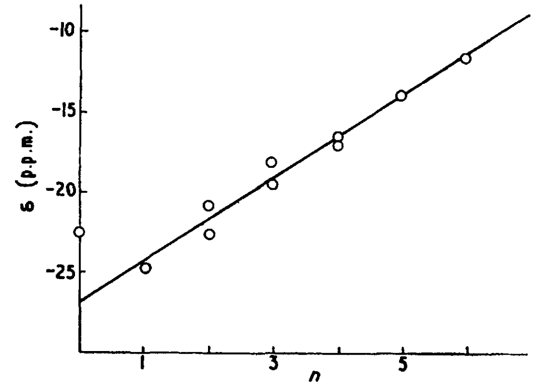

FIGURE 1 Carbonyl ^{13}C chemical shifts *vs.* number of α-protons for aliphatic ketones

The average shielding for the carbon atoms for each type of substitution is in the same order as that for the attached proton (Table 3, which summarizes Tables 2 and 5). As well as the series of secondary alcohols, propan-2-ol to 2,2,4,4-tetramethylpentan-3-ol, chemical shifts for methanol, ethanol, and 2-methylpropan-2-ol were measured (Table 4) and found to agree closely with those of Lauterbur,[13] with the exception of methanol for which the reported value is 146·6 p.p.m. Lauterbur has noted a linear relationship between these shifts and the degree of alkylation of the carbon atom and our revised value for methanol improves the fit. The chemical shifts of the carbinol carbon atoms of the secondary alcohols also show a near linear † downfield shift with increasing substitution (Figure 2).

TABLE 3

Average ^{13}C and ^{1}H chemical shifts of the alkyl groups in acyclic ketones

Group	$\delta(^{13}C)$ [a]	$\delta(^{1}H)$ [b]
Me(CO) [c]	165·3	2·068
$CH_2(CO)$	157·4	2·462
CH(CO)	153·2	2·790
C(CO)	149·1	
$Me(CH_2)$	185·5	0·960
Me(CH)	174·8	1·032
Me(C)	166·5	1·141

[a] P.p.m. from CS_2. [b] P.p.m. from tetramethylsilane. [c] Groups in parentheses are the adjacent groups.

TABLE 4

^{13}C Chemical shifts, ^{17}O chemical shifts, and acidities of aliphatic alcohols

	$\delta(^{13}C)$ [a]			
	α	β	$\delta(^{17}O)$ [b]	pK_a [c]
MeOH	143·7		37	16
EtOH	135·2	174·5	−6	18
Pr^iOH	129·4	167·8	−38	18
Bu^tOH	124·5	161·7	−70	19

[a] P.p.m. from internal CS_2, *cf.* ref. 13. [b] P.p.m. from external water, H. A. Christ, P. Diehl, H. R. Schneider, and H. Dahn, *Helv. Chim. Acta*, 1961, **44**, 865. [c] W. K. McEwen, *J. Amer. Chem. Soc.*, 1936, **58**, 1124.

^{1}H *Spectra*.—The proton spectra for the ketones were analyzed directly to give the parameters listed in Table 5. The geminal coupling constants were obtained from the spectra of the deuteriated ketones by multiplying the HD coupling constant by 6·55. Vicinal HD couplings were observed for all the deuteriated ketones (except acetone) and yielded values of J(HH) in agreement with those measured directly. As most of the spectra were not recorded on a frequency-locked spectrometer, the isotope shifts were not recorded. However, there is no reason why they should not be similar to those for butan-2-one (0·017 p.p.m. upfield for each deuterium substitution).[14]

The ^{1}H results for secondary alcohols are summarized in Tables 6 and 7. The symmetrical alcohols propan-2-ol and 2,2,4,4-tetramethylpentan-3-ol have trivial spectra. The spectrum of 2,4-dimethylpentan-3-ol shows the expected non-equivalence of the two methyl groups attached to the same carbon atom (Table 6). 3-Methylbutan-2-ol also exhibits non-equivalent methyl groups as well as a regular quintet for the C(2) proton, thus $J_{1,3} = J_{1,2} = 6{\cdot}3$ Hz (Table 7). The multiplet is unchanged on dilution which may indicate that the relative populations of conformers are independent of concentration. Pentan-3-ol also exhibits a symmetrical quintet for the C(3) proton which may indicate an equality of the two vicinal coupling constants or accidental equivalence of the methylene protons. The complex 100 MHz spectrum of butan-2-ol has previously been analyzed [15] and the parameters are listed in Tables 6 and 7. The C(3) proton of 2-methylpentan-3-ol gives a doublet of triplets at 60 MHz, the spacings being 7·2 and 5·1 Hz, whereas at 100 MHz eight transitions are observed, corresponding to 7·50, 5·1, and 4·5 Hz. The common spacing must be equal to the coupling between the two methine protons [C(3) and C(2)] ($J_{1,2} = 5{\cdot}1$ Hz). The sum of the vicinal coupling constants between the methine C(3) and methylene C(2) protons is 12 Hz, and 7·5 and

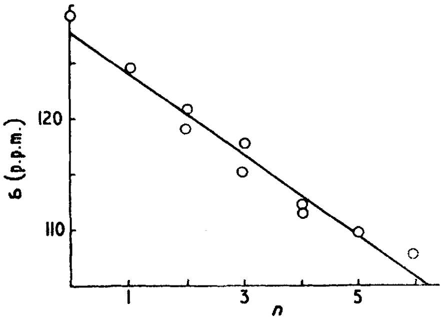

FIGURE 2 ^{13}C Chemical shifts of the hydroxy-substituted carbon atoms *vs.* number of α-methyl substituents for aliphatic secondary alcohols

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* For the relation $\delta(C{=}O) = an + b$, $a = 2{\cdot}61 \pm 0{\cdot}18$ and $b = -26{\cdot}82$ p.p.m.

† Least squares parameters: $a = -3{\cdot}69 \pm 0{\cdot}29$, $b = 127{\cdot}69$ p.p.m.

[13] P. C. Lauterbur, *Ann. N.Y. Acad. Sci.*, 1958, **70**, 841; see also C. B. Savitsky and K. Namikawa, *J. Phys. Chem.*, 1963, **67**, 2430.

[14] O. S. Tee and J. Warkentin, *Canad. J. Chem.*, 1965, **43**, 2424.

[15] L. M. Jackman and N. S. Bowman, *J. Amer. Chem. Soc.*, 1966, **88**, 5565.

TABLE 5

Proton chemical shifts and coupling constants for aliphatic ketones [a]

Compound [b]	δ [c] H(2)	δ [c] H(3)	δ [c] H(4)	δ [c] H(5)	J_{vic} [d] 2,4	J_{vic} [d] 3,5	$\lvert J_{gem} \rvert$ [e]
$CH_3{\cdot}CO{\cdot}CH_3$ 3 1 2	2·094 (2·086)[f] (2·17)[h]	2·094 (2·086)[f] (2·17)[h]					(14·9)[g]
$CH_3{\cdot}CO{\cdot}CH_2{\cdot}CH_3$ 3 1 2 4	2·442 (2·47)[h]	2·052 (2·13)[h]	0·950 (1·05)[h]		7·29 (7·35)		14·1 (15·1—15·7)[i] 17·4
$CH_3{\cdot}CO{\cdot}CH{\cdot}(CH_3)_2$ 3 1 2 4	2·586 (2·54)[k]	2·066	1·053 (1·08)[k]		6·95		14·3
$CH_3{\cdot}CO{\cdot}C(CH_3)_3$ 3 1 2 4		2·062	1·097 (1·12)[k]				14·8
$CH_3{\cdot}CH_2{\cdot}CO{\cdot}CH_2{\cdot}CH_3$ 5 3 1 2 4	2·427 (2·39)[f]	2·427 (2·39)[f]	0·978 (1·04)[f]	0·978 (1·04)[f]	 (7·5)[j]		17·3
$CH_3{\cdot}CH_2{\cdot}CO{\cdot}CH(CH_3)_2$ 5 3 1 2 4	2·610	2·467	1·043	0·965	6·80	7·34	17·7
$CH_3{\cdot}CH_2{\cdot}CO{\cdot}C(CH_3)_3$ 5 3 1 2 4		2·512	1·104	0·948		7·19	18·0
$(CH_3)_2CH{\cdot}CO{\cdot}CH(CH_3)_2$ 5 3 1 2 4	2·805	2·805	1·033	1·033	6·77 (6·49)	6·77 (6·49)	
$(CH_3)_2CH{\cdot}CO{\cdot}C(CH_3)_3$ 5 3 1 2 4		3·158	1·137	1·001	6·57[e]		
$(CH_3)_3C{\cdot}CO{\cdot}C(CH_3)_3$ 5 3 1 2 4			1·225	1·225			

[a] As 'neat' liquids at 60 MHz. [b] The protons are numbered according to the carbon to which they are attached, C(5)C(3)CO-C(2)C(4). [c] ±0·01 p.p.m. from internal Me_4Si. [d] ±0·2 Hz. [e] α-Protons only. [f] As dilute solutions (3—5%), G. V. D. Tiers, 'Characteristic NMR Shielding Values for Hydrogen in Organic Structures,' Minnesota Mining and Manufacturing Company, 1958. [g] ±0·3 Hz, H. S. Gutowsky, *J. Chem. Phys.*, 1959, **31**, 1683. [h] Varian Associates Catalog, Vol. I. [i] O. S. Tee and J. Warkentin, *Can. J. Chem.*, 1965, **43**, 2424. [j] G. J. Karabatsos, J. D. Graham, and F. Vane, *J. Amer. Chem. Soc.*, 1961, **83**, 2778. [k] ~7% solutions in CCl_4, L. M. Jackman and S. Sternhell, unpublished observations. [l] R. E. Glick and A. A. Bothner-By, *J. Chem. Phys.*, 1956, **25**, 361.

TABLE 6

Proton chemical shifts for aliphatic secondary alcohols [a]

Compound [b]	Conc. % [c]	H(1)	H(2)	H(3)	H(4)	H(5)
$CH_3{\cdot}CHOH{\cdot}CH_3$ 3 1 2	100	3·935 (3·94)[d]	1·145 (1·16)[d]	1·145 (1·16)[d]		
$CH_3{\cdot}CHOH{\cdot}CH_2{\cdot}CH_3$[e] 3 1 2 4	100	3·618	1·481/ 1·371[f]	1·140	0·877	
		3·593	1·406/ 1·378[f]		0·880	
$CH_3{\cdot}CHOH{\cdot}CH(CH_3)_2$ 3 1 2 4	100	3·485	1·580	1·100	0·911/ 0·876[f]	
	10	3·490	1·532	1·090	0·897/ 0·877[f]	
$CH_3{\cdot}CHOH{\cdot}C(CH_3)_3$ 3 1 2 4	100	3·417		1·083	0·875	
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}CH_2{\cdot}CH_3$ 5 3 1 2 4	100	3·367	1·397	1·397	0·925	0·925
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}CH{\cdot}(CH_3)_2$ 5 3 1 2 4	100	3·170	1·49[g]	1·49[g]	0·899/ 0·888[f]	0·939
	10	3·173	1·54[g]	1·50[g]	0·897/ 0·890[f]	0·933
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	[h]					
$(CH_3)_2CH{\cdot}CHOH{\cdot}CH(CH_3)_2$ 5 3 1 2 4	100	2·945	1·695	1·695	0·918/ 0·894[f]	0·918/ 0·894[f]
	10	2·910	1·740	1·740	0·895	0·895
$(CH_3)_2CH{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	100	3·075		1·914	0·937	0·993/ 0·921[f]
	10	3·031		1·907	0·918	0·975/ 0·886[f]
$(CH_3)_3C{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	5[i]	2·970			1·022	1·022

[a] ±0·005 p.p.m. from internal tetramethylsilane. [b] The protons are numbered according to the carbon to which they are attached, C(5)C(3)C(1)OHC(2)C(4). [c] *Ca.* % w./v. in CCl_4. [d] J. R. Cavanaugh and B. P. Dailey, *J. Chem. Phys.*, 1961, **34**, 1099. [e] L. M. Jackman and N. S. Bowman, *J. Amer. Chem. Soc.*, 1966, **88**, 5565. [f] Non-equivalent protons. [g] Taken at the approximate centre of the multiplet. [h] For 2,2-dimethyl-3-pentanol, see Table 8. [i] Saturated solution in $CDCl_3$. [j] 0·03 mole fraction.

TABLE 7

Proton coupling constants for aliphatic secondary alcohols

Compound [b]	Conc. % [c]	H(1)H(2)	H(1)H(3)	H(2)H(4)	H(3)H(5)
$CH_3{\cdot}CHOH{\cdot}CH_3$ 3 1 2	100	6·10 (6·05) [d]	6·10 (6·05) [d]		
$CH_3{\cdot}CHOH{\cdot}CH_2{\cdot}CH_3$ [e] 3 1 2 4	100	6·45/5·85 [f]	6·13	7·32/7·50 [f]	
	[g]	7·07/5·43 [e,]		7·63/7·09 [e,f]	
$CH_3{\cdot}CHOH{\cdot}CH(CH_3)_2$ 3 1 2 4	100	6·30	6·30	6·50	
	10	6·30	6·30	6·75	
$CH_3{\cdot}CHOH{\cdot}C(CH_3)_3$ 3 1 2 4	100		6·43		
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}CH_2{\cdot}CH_3$ 5 3 1 2 4	10	5·92	5·92	6·30 (6·80) [h]	6·30 (6·80) [h]
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}CH(CH_3)_2$ 5 3 1 2 4	100	5·1	(4·55,[i] 7·52 [i])	6·55	[j]
	10	5·1	(4·6,[i] 7·50 [i])	6·80	[j]
$CH_3{\cdot}CH_2{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	[k]				
$(CH_3)_2{\cdot}CH{\cdot}CHOH{\cdot}CH(CH_3)_2$ 5 3 1 2 4	100	5·50	5·50	6·70	6·70
	10	5·75	5·75	6·50	6·50
$(CH_3)_2CH{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	100		2·20		7·24
	10		2·55		7·24
$(CH_3)_3C{\cdot}CHOH{\cdot}C(CH_3)_3$ 5 3 1 2 4	1				

[a] ±0·1 Hz. [b] The protons are numbered according to the carbon atom to which they are attached, C(5)C(3)C(1)OHC(2)C(4). [c] *Ca.* % w./v. in CCl_4. [d] R. E. Glick and A. A. Bothner-By, *J. Chem. Phys.*, 1956, **25**, 362. [e] L. M. Jackman and N. S. Bowman, *J. Amer. Chem. Soc.*, 1966, **88**, 5565; geminal coupling constants J[H(2)H(2)] are −13·24 and −13·00 Hz for neat liquid and dilute solution respectively. [f] Non-equivalent protons. [g] 0·03 mole fraction. [h] ±0·3, G. J. Karabatsos, J. D. Graham, and F. Vane, *J. Amer. Chem. Soc.*, 1961, **83**, 2778. [i] These are line spacings ≠J, see text. [j] Complex multiplet. [k] For 2,2-dimethyl-3-pentanol, see Table 8. [l] For J(HCOH) coupling constant of 2,2,4,4-tetramethyl-3-pentanol, see L. K. Patterson and R. M. Hammaker, *J. Phys. Chem.*, 1966, **70**, 3745.

TABLE 8

Iterated n.m.r. parameters for 2,2-dimethylpentan-3-ol [a]

Conc. %	δ(A)	δ(B)	δ(C)	δ(X)	J(AB)	J(AC)	J(AX)	J(BC)	J(BX)	J(CX)
100	302·828	154·090	124·279	100·264	1·958	10·609	−0·230	−13·814	7·472	7·347
10 [b]	299·637	152·563	119·439	96·404	1·984	10·303	−0·114	−13·449	7·448	7·392
Error [c]	0·015	0·016	0·018	0·016	0·023	0·026	0·016	0·023	0·015	0·017

[a] At 100 MHz, chemical shifts are in Hz from internal tetramethylsilane, coupling constants are in Hz. The letters in parentheses refer to conformation (V), where R = *t*-Bu and X refers to Me. The *t*-butyl peaks were not considered in the analysis, but have chemical shifts of 0·884 and 0·870 p.p.m. for the 'neat' liquid and 10% solution respectively. [b] Approx. 10% w./v. in CCl_4. [c] Standard deviations from LAOCN3.

4·5 are lower and upper limits, respectively, for the individual values. The methyl region (insert, Figure 3) is a triplet superimposed on a doublet of doublets arising from the non-equivalent methyl protons of the isopropyl group.

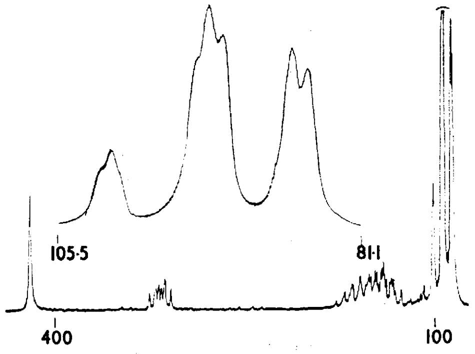

FIGURE 3 100 MHz spectrum of 2-methylpentan-2-ol (neat) (insert: methyl region)

The spectrum of 2,2-dimethylpentan-3-ol exhibits a complex multiplet for the methylene protons (Figure 4). In this case it was possible to perform an exact analysis, and the parameters are listed in Table 8. The computed and observed spectra for the methyl and methine protons of an undiluted sample are compared in Figures 5 and 6 respectively. The spectra of diluted samples were very similar to those of the neat liquids, as evidenced by the small changes in the spectral parameters. The fact that the methyl protons of the isopropyl group of 2,2,4-trimethylpentan-3-ol give rise to a triplet (Figure 7) suggests that the chemical shift difference of the non-equivalent protons must be equal to the value of the vicinal coupling constant (7·24 Hz). This coincidence is removed by dilution (Figure 8), the two doublets moving away from each other. This enhanced non-equivalence on dilution is in

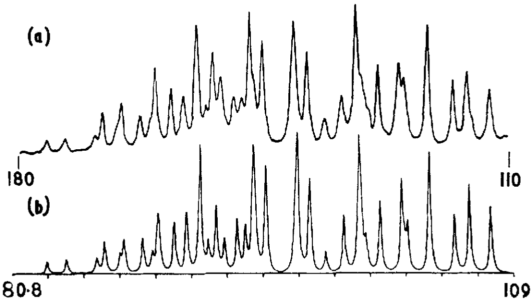

FIGURE 4 (a) Observed and (b) computed methylene proton region of 100 MHz spectrum of 2,2-dimethylpentan-3-ol

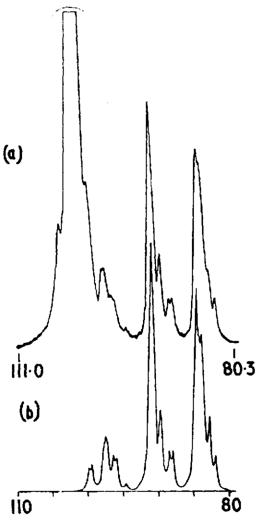

FIGURE 5 (a) Observed and (b) computed methyl proton region of 100 MHz spectrum of 2,2-dimethylpentan-3-ol (t-butyl group was not included in the analysis)

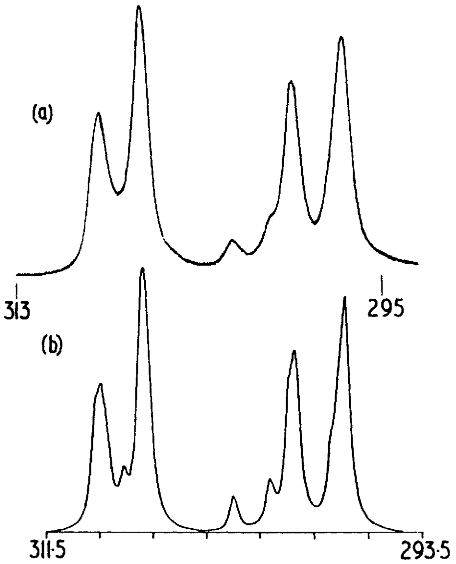

FIGURE 6 (a) Observed and (b) computed methine proton region of 100 MHz spectrum of 2,2-dimethylpentan-3-ol

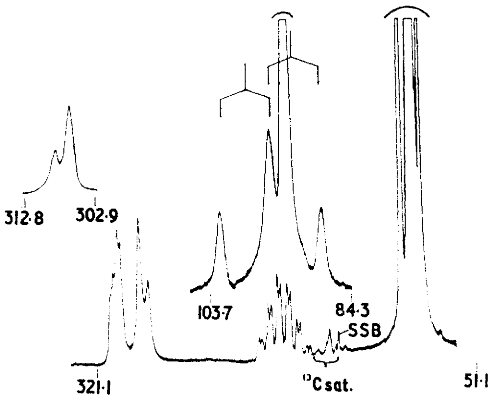

FIGURE 7 100 MHz spectrum of 2,2,4-trimethylpentan-3-ol (neat) (inset obtained with sample containing a trace of acid)

contrast to that observed for the other alcohols studied here.[16]

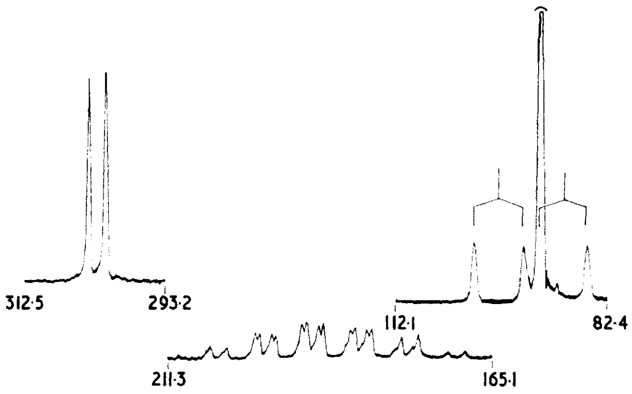

FIGURE 8 100 MHz spectrum of 2,2,4-trimethylpentan-3-ol (dilute solution)

DISCUSSION

Interpretation of the n.m.r. data must include consideration of electronic (inductive and hyperconjugative) effects and their relationship to the conformations of the molecules, and in the more highly-branched structures, to steric interactions. A major difficulty in predicting the contribution of electronic effects in even a qualitative sense is the uncertainty of the direction of the inductive effect of an alkyl group. Before discussing the data we will consider this problem.

Inductive Effect of Alkyl Groups.—In the electronic theory of organic chemistry the methyl group has always been assigned a positive (+*I*) inductive effect. Much of the data on which this assignment is based relates to thermodynamic or reactivity data in which the alkyl group is attached to an sp^2 carbon atom where it is difficult to separate inductive from hyperconjugative effects. Furthermore, in many systems where the alkyl groups are introduced close to the reaction centre, it is difficult to separate electronic effects from steric effects relating either to the attacking reagent, or to the solvation of reactant and/or product. Indeed, it has been pointed out [17-21] that in purely saturated systems, the introduction of alkyl substituents well removed from the reaction site is associated with effects consistent with *electron withdrawal.* Schleyer and Woodworth have recently had reservations about the −*I* effect of alkyl substituents determined from small rate depressions of the solvolyses of adamant-1-yl and bicyclo[2,2,2]oct-1-yl derivatives.[21] Evidence for a −*I* effect of alkyl

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[16] See also H. J. Jakobsen, P. Madsen, and S.-O. Lawesson, *Tetrahedron*, 1966, **22**, 1851 and C. van der Vlies, *Rec. Trav. chim.*, 1965, **84**, 1289.

[17] H. Kwart and L. J. Miller, *J. Amer. Chem. Soc.*, 1964, **83**, 4552.

[18] H. Kwart and T. Takeshita, *J. Amer. Chem. Soc.*, 1964, **86**, 1161.

[19] R. C. Fort and P. von R. Schleyer, *J. Amer. Chem. Soc.*, 1964, **86**, 4194.

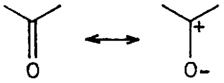
[20] H. D. Holtz and L. M. Stock, *J. Amer. Chem. Soc.*, 1965, **87**, 2404.

[21] P. von R. Schleyer and C. W. Woodworth, *J. Amer. Chem. Soc.*, 1968, **90**, 6528.

groups in saturated systems has also been provided by the deuterium isotope effect in hydrocarbons.[22] Finally, most theoretical estimates of the polarity of the C–H bond, and by implication the sign of the inductive effect, are in agreement with this finding.[23]

A considerable body of n.mr. data, including those presented above, can be rationalized in terms of the electron-withdrawing power of alkyl substituents. A particularly instructive case is provided by the series of alcohols, methanol, ethanol, propan-2-ol, and 2-methylpropan-2-ol. It has been amply demonstrated that the shielding of nuclei other than hydrogen isotopes is related to the electron density at the atom concerned, such that decreased electron density corresponds to deshielding.[24] Inspection of the ^{13}C chemical shifts of both α and β carbon atoms and also the ^{17}O shifts for the four alcohols listed in Table 4 indicates clearly that increased alkylation results in a decrease of electron density, not only at the α- and adjacent β-positions, but also at the oxygen atom itself, a result which is only compatible with a $-I$ effect of a methyl group. These conclusions are opposite to those which would be drawn from consideration of the pK_a values of these alcohols (Table 4). This may be rationalized in terms of increasing difficulty of solvating the alkoxide ion as the alkyl substitution at the α carbon increases. Indeed, it has recently been observed that in the gas phase, where solvation problems are absent, the acidity order of the alcohols is reversed, so that 2-methylpropan-2-ol is more acidic than methanol.[25]

^{13}C *Spectra of Ketones*.—The trend of the carbonyl carbon chemical shifts of acyclic ketones has been considered by Maciel,[26] who has noted that the observed shifts are consistent with an increase in the dipolar canonical form to the structure of the carbonyl group. We note that this interpretation agrees with the observed ^{17}O shifts,[27,28] which, in contrast to the case of the alcohols discussed above, correspond to increased shielding with increased alkylation. The trend observed for the carbonyl carbon and oxygen atoms has also been shown to occur for similarly constituted alkenes.[29] The inductive effect alone should cause the chemical shifts of both the carbonyl carbon atom and the oxygen atom to vary in the same direction. That this is not observed indicates the interplay between an inductive ($-I$) effect and a somewhat stronger hyperconjugative ($+M$) effect, since the latter will increase the electron density of the oxygen atom while presumably having little effect on the carbonyl carbon atom.



The chemical shifts of the carbonyl carbon atoms, which decrease monotonically with increased methyl substitution of acetone (Figure 1) are controlled only by the inductive effect and provide no evidence for the importance of hyperconjugation. Although the shifts of the α carbon atoms are expected to be influenced by hyperconjugation, it is not possible to separate the inductive and hyperconjugative contributions. In principle, hyperconjugation should also effect J(CH) of the α-carbon atoms, but the effect, if it exists, is too small to be observed.

As already noted, the carbonyl carbon chemical shift of di-t-butyl ketone is inconsistent, and anomalies have also been noted in the i.r. [30–32] and u.v. [33] spectra of this compound. By use of a value for the force constant K of $10{\cdot}2 \times 10^5$ dyne cm^{-1} the C–CO–C bond angle can be estimated [34] as 130° (compared to 115° in acetone), and there is little doubt that the chemical shift is associated with this distortion.

^{13}C *Spectra of Alcohols*.—The downfield shifts of the carbinol carbon atoms with increasing alkylation appears to be a consequence of a $-I$ inductive effect. We assume that the effect of β-alkylation is due to the combination of inductive, delocalization, and steric effects, which Cheney and Grant [23] have postulated to explain similar shifts in the case of hydrocarbons. Indeed, the shifts of the carbinol carbon atoms reported in Table 2 can be reproduced by using the empirical relation derived for hydrocarbons by Grant and Paul,[35] simply by reducing the $-I$ contribution of an α substituent from $-9{\cdot}09$ to $-6{\cdot}8$ p.p.m. This is not unreasonable, as the electron density of the hydroxy-substituted carbon atom has already been seriously depleted by the much stronger $-I$ effect of the attached oxygen atom. A branching correction for a tertiary carbon adjacent to a quaternary carbon atom, *i.e.* R_2CHBu^t or 3(4°), was not previously reported,[35] but from this work it should be *ca.* $+16$ p.p.m.

Geminal Coupling Constants of Ketones.—The study of ^{13}C chemical shifts did not provide a measure of the contribution of hyperconjugation to the ground state of the carbonyl group. However, this contribution is expected to be a function of the conformations of the ketones and the values of J_{gem} for the α-protons. Barfield

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[22] V. W. Laurie and J. S. Muenter, *J. Amer. Chem. Soc.*, 1966, **88**, 2884.

[23] B. V. Cheney and D. M. Grant, *J. Amer. Chem. Soc.*, 1967, **89**, 5319, and references therein.

[24] L. M. Jackman, 'Applications of N.M.R. Spectroscopy in Organic Chemistry,' Pergamon, London, 1959, p. 75.

[25] J. I. Brauman and L. K. Blair, *J. Amer. Chem. Soc.*, 1968, **90**, 6561.

[26] G. E. Maciel, *J. Chem. Phys.*, 1965, **42**, 2746.

[27] H. A. Christ and P. Diehl, *Helv. Phys. Acta*, 1963, **36**, 170.

[28] H. A. Christ, P. Diehl, H. R. Schneider, and H. Dahn, *Helv. Chim. Acta*, 1961, **44**, 865.

[29] R. A. Friedel and H. L. Retcofsky, *J. Amer. Chem. Soc.*, 1963, **85**, 1300.

[30] N. Fuson, M. L. Josien, and E. M. Shelton, *J. Amer. Chem. Soc.*, 1954, **76**, 2526.

[31] J. Lascombe, P. Grange, and M. L. Josien, *Bull. Soc. chim. France*, 1957, 773.

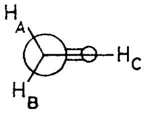
[32] J. E. Katon and F. F. Bentley, *Spectrochim. Acta*, 1963, **19**, 639.

[33] P. Maroni, *Ann. Chim.* (*France*), 1957, **2**, 757.

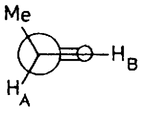
[34] J. O. Halford, *J. Chem. Phys.*, 1956, **24**, 830.

[35] D. M. Grant and E. G. Paul, *J. Amer. Chem. Soc.*, 1964, **86**, 2984.

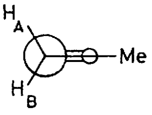
and Grant[36] have established the relationship between J_{gem} for α-protons and the dihedral angle between a line joining the two protons and the carbonyl group. This relationship satisfactorily predicts the value of 14—15 Hz found for J_{gem} of methyl ketones, for which it has been established[36] that only conformation (I) is populated. The two conformations (II) and (III) must be considered for the methylene group of an ethyl ketone. The Barfield–Grant relation predicts $J_{gem} = -12{\cdot}4$ and $-17{\cdot}1$ Hz* for (II) and (III) respectively, so that our observed values of $-17{\cdot}3$ to $-18{\cdot}0$ Hz indicate a very strong preference for the conformation (III). This conclusion agrees with the electron diffraction study by Romers and Creutzberg[37] of butan-2-one and pentan-3-one. There is evidence from vicinal coupling constants[38,39] and microwave[40] and electron diffraction[41] studies that aliphatic aldehydes also exist predominantly in conformation (III). On the other hand LeFèvre and his co-workers[42] have concluded from electric polarizability data that conformation (II) is preferred. However, we feel that the agreement between the electron diffraction and the n.m.r. results provides convincing evidence that the predominant conformer is indeed (III).



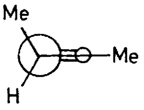
(I)



(II)



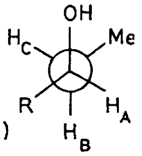
(III)



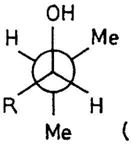
(IV)

Since H_C in (I) cannot participate in hyperconjugation, we concluded that in ketones the hyperconjugative effect of an ethyl group will be the same as for a methyl group. An isopropyl group will presumably prefer the conformation (IV) and its hyperconjugative effect will be half that of the ethyl and the methyl group. Similar conclusions concerning the dependence of hyperconjugation on conformation have been reached by Cotterill and Robinson.[43]

^{1}H *Spectra of Secondary Alcohols*.— The most important information that can be derived from the proton spectra of the alcohols concerns the relative populations of the conformations in solution. Application of the Karplus equation permits an estimate of the population of conformation (V) of the ethyl group in ethyl carbinols and of conformation (VI) in the isopropyl carbinols.



(V)

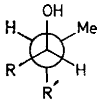


(VI)

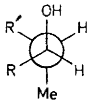
We have chosen the values of $J_{vic} = 2$ and 11 Hz corresponding to the dihedral angles of 60° and 180°, respectively. These values are in general agreement with the values expected for the parameters.[44] More particularly they agree with the values found for 2,2-dimethylpentan-3-ol, in which it is expected that the presence of the t-butyl group causes only one conformation to be populated, an observation which is consistent with the invariance of the vicinal coupling constants with dilution (Table 8). Table 9 gives the populations of conformations derived from the coupling constant data.

Table 9

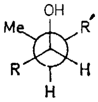
Populations of conformations of secondary alcohols determined from coupling constants



(VII)



(VIII)



(IX)

R	R′	(VII)	(VIII)	(IX)
Me	H	0·97		0·08
Et	H	0·87		0·13
Pr^i	H	0·91		0·09
Bu^t	H	1·00		0·00
Me	Me	0·48	0·52	
Et	Me	0·35	0·65	
Pr^i	Me	0·39	0·61	
Bu^t	Me	0·00	1·00	

Table 10

Calculated and observed chemical shifts of protons adjacent to hydroxy-groups

	δ (calc.)	δ (obs.)	Diff.
Me$_2$C*H*OH	(3·94)	(3·94)	
EtC*H*(OH)Me	3·62	3·62	0·00
Pr^{i}CH·C*H*(OH)Me	3·51	3·49	0·02
Bu^{t}C*H*(OH)Me	3·40	3·42	−0·02
Et$_2$C*H*OH	3·35	3·37	−0·02
Pr^{i}C*H*(OH)Et	3·25	3·17	0·08
Bu^{t}C*H*(OH)	3·03	3·03	0·00
Pr$_2^i$C*H*(OH)	3·15	2·95	0·20
Bu^{t}C*H*(OH)Pr^i	3·23	3·08	−0·15
Bu$^t_2$C*H*(OH)	2·86	2·97	−0·09

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* This value is based on J_{gem} of cyclohexane ($-12{\cdot}6$ Hz) rather than that of methane ($-12{\cdot}4$ Hz) used by Barfield and Grant.[36]

[36] M. J. Barfield and D. M. Grant, *J. Amer. Chem. Soc.*, 1963, **85**, 1899, and references therein.

[37] C. Romers and J. E. G. Creutzberg, *Rec. Trav. chim.*, 1956, **75**, 331.

[38] G. J. Karabatsos and N. Hsi, *J. Amer. Chem. Soc.*, 1965, **87**, 2864.

[39] R. J. Abraham and J. A. Pople, *Mol. Phys.*, 1960, **3**, 609.

[40] S. S. Butcher and E. B. Wilson, *J. Chem. Phys.*, 1964, **40**, 1671.

[41] L. S. Bartell, B. L. Carroll, and J. P. Guillory, *Tetrahedron Letters*, 1964, 705.

[42] M. Aroney, D. Izsak, and R. J. W. LeFèvre, *J. Chem. Soc.*, 1961, 4148; M. Aroney, R. J. W. LeFèvre, and A. N. Singh, *ibid.*, 1965, 564.

[43] W. D. Cotterill and M. J. T. Robinson, *Tetrahedron Letters*, 1963, 1833; *Tetrahedron*, 1964, **20**, 777.

[44] L. M. Jackman and S. Sternhell, 'Applications of N.M.R. Spectroscopy in Organic Chemistry,' Pergamon, London, 1969, p. 281.

Eliel and his co-workers[45] have examined the effect of vicinal methyl groups on the chemical shifts of protons adjacent to hydroxy-groups in alkylcyclohexanols and have concluded that a *gauche*-methyl group shields the proton by 0·3—0·45 p.p.m. whereas a *trans*-relation is associated with a deshielding of 0·2 p.p.m. By use of an average value of 0·37 p.p.m. for the former and the distribution of conformations given in Table 9, the chemical shifts of the α-protons in the series of acyclic alcohols were calculated. The results (Table 10) show that the agreement between the observed and calculated values is very good, the greatest deviations occurring in highly ramified systems in which deviations from the expected dihedral angles of 60 and 180° are expected. The orientation dependence of the shielding effect of a vicinal methyl group is presumably associated with the diamagnetic anisotropy of this group.

[8/1888 *Received, December* 20*th*, 1968]

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[45] E. L. Eliel, M. H. Gianni, Th. H. Williams, and J. B. Stothers, *Tetrahedron Letters*, 1962, 741.