Nuclear Magnetic Resonance Spectroscopy. Carbon-13 Chemical Shifts in Acyclic and Alicyclic Alcohols[1]

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Abstract: The chemical shifts of ^{13}C in a variety of acyclic and alicyclic alcohols have been determined by high-resolution nmr spectroscopy with the aid of proton decoupling. It has been found that there are rather good linear relationships between carbon chemical shifts in alcohols and analogously constituted hydrocarbons, wherein a methyl group replaces the hydroxyl group. The linear correlation coefficients for relationships of the general type $\delta_C^{ROH} = A\delta_C^{RCH_3} + B$ are better than 0.98 for shifts of corresponding α (directly attached hydroxyl), β, γ, and δ carbons for a variety of primary, secondary, and tertiary acyclic alcohols and cyclohexanols carrying both axial and equatorial substituents. The shifts of the carbons of a number of cycloalkanols have been investigated in hope of providing information about conformations in medium-sized ring compounds.

Chemical shifts of ^{13}C are well known to be generally much larger than chemical shifts of protons but the low resolution attendant to rapid-passage determination[5] of ^{13}C resonance-line positions with ^{13}C in natural abundance has hampered the study of other than direct substituent effects.[6,7] Complete proton decoupling under slow-passage conditions can give high-quality spectra which allow many more subtle substituent effects to be conveniently studied.[8] Substituent effects on other than the directly bound carbons have been previously reported for continuous and branched-chain alkanes,[8] substituted continuous-chain alkanes,[9] and methyl-substituted cyclohexanes[10] and benzenes.[11] The results have been interpreted in terms of inductive, bond delocalization, and steric effects.[8-12] We have determined the chemical shifts of the carbons of a variety of acyclic and alicyclic alcohols by high-resolution nmr spectroscopy and have found that they are rather simply related to carbon shifts determined for hydrocarbons by Grant and his coworkers.[8,10]

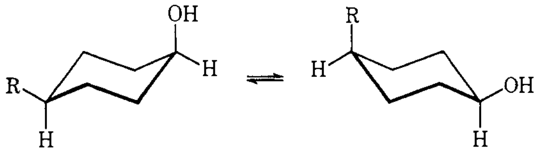
Experimental Section

The alcohols used in the present research were almost all commercial materials and were used without further purification because the effects of even moderate amounts of impurities on the ^{13}C chemical shifts are small. The six isomeric methylcyclohexanols were prepared following Noyce and Denny[13] and were examined as *cis–trans* mixtures. Dioxane or methylene chloride was added to the extent of 10% v/v to provide a proton field frequency lock and an internal ^{13}C standard. The digital-frequency sweep spectrometer and its associated proton-decoupling equipment have been described earlier.[14,15] The operating frequency was 15.1 MHz. In general, the sweep rates were 2 Hz/sec although when necessary to resolve closely spaced resonances, sweep rates as low as 0.1 Hz/sec were employed.

Most of the chemical-shift measurements were made by first taking a wide frequency sweep with proton decoupling which gave approximate positions of the resonances, then the optimum proton decoupling frequency for each resonance was determined with a 50-Hz sweep width. Finally, the positions of the resonances were determined in a single sweep while adjusting the decoupling frequency between peaks to optimize the sharpness of each resonance in turn. In later work, complete proton decoupling with a narrow-band pseudo-random noise generator to cover the proton resonance frequencies[15] gave much more direct and simple measurements of the chemical shifts of the various carbons. The chemical shifts so obtained were reproducible to ±0.1 ppm and agreed closely with those obtained for primary alcohols[9] by decoupler-shift values.[8] Dioxane seems to be a satisfactory internal reference for ^{13}C chemical shifts but benzene does not, there being an approximately 4-Hz downfield shift of the alcohol carbon resonances with benzene as an internal reference. All of the chemical shifts reported here (Tables I–III) have been corrected to carbon disulfide as external reference by the relation $\delta_C = \delta_C^{dioxane} + 125.5$ ppm.

There are some discrepancies between the reported chemical shifts for cyclohexanol[16a] as well as the carbinyl carbons of four-substituted cyclohexanols[16b] and the shifts given in Table II. To test the possibility that differential solvent effects might be involved in some of the discrepancies,[16b] the carbinyl carbon resonances of a mixture of cyclohexanol, and *cis*- and *trans*-4-*t*-butylcyclohexanol were located and found to agree with the values in Table II for the separate substances.

For many of the cyclohexanols in Table II equilibria are possible between two chair conformations, one with alkyl equatorial and hydroxyl axial, and one with alkyl axial and hydroxyl equatorial, such as between **1** and **2**. We will assume in all cases that the con-



1 2, R = alkyl

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(4) National Research Council of Canada Postdoctoral Fellow, 1968–1969.

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(8) D. M. Grant and E. G. Paul, *ibid.*, **86**, 2984 (1964).

(9) (a) T. D. Brown, Ph.D. Thesis, University of Utah, Salt Lake City, Utah, 1967; (b) E. Lippmaa and T. Pehk, *Kemian Teollisuus*, **24**, 1001 (1967); *Eesti NSV Tead. Akad. Toim., Keem., Geol.*, 17 (3), 210 (1968).

(10) D. K. Dalling and D. M. Grant, *J. Amer. Chem. Soc.*, **89**, 6612 (1967).

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(13) D. S. Noyce and D. B. Denny, *ibid.*, 72, 5743 (1950).

(14) F. J. Weigert and J. D. Roberts, *ibid.*, **89**, 2967 (1967); *ibid.*, **90**, 3543 (1968).

(15) F. J. Weigert, M. Jautelat, and J. D. Roberts, *Proc. Nat. Acad. Sci.*, 60, 1152 (1968).

(16) (a) The chemical shifts of the carbons of cyclohexanol published by O. A. Reutov, T. N. Shatkina, E. T. Lippmaa, and T. Pehk, *Dokl. Chem.*, 181, 770 (1968) are consistently about 2 ppm toward higher fields than those reported here; (b) G. W. Buchanan, D. A. Ross, and J. B. Stothers, *J. Amer. Chem. Soc.*, **88**, 4301 (1966).

Table I. Carbon-13 Chemical Shifts in Alcohols Relative to Carbon Disulfide

Alcohol	Chemical shift, ppm									
	α	β	γ	δ	ϵ	ζ	η	θ	ι	κ
Methanol	143.5									
Ethanol	135.5	174.9								
1-Propanol	128.9	166.7	182.5							
1-Butanol	131.1	157.5	173.4	178.9						
1-Pentanol	130.7	160.0	164.3	169.9	178.7					
1-Hexanol	130.6	159.7	166.7	160.5	169.7	178.3				
1-Heptanol	130.6	159.6	166.4	163.1	160.4	169.7	178.6			
1-Octanol	130.6	159.6	166.4	162.8	162.9	160.4	169.7	178.6		
1-Nonanol	130.5	159.6	166.3	162.7	162.6	162.9	160.3	169.6	178.5	
1-Decanol	130.6	159.6	166.4	162.7	162.7	162.6	162.9	160.3	169.7	178.5
2-Propanol	129.1	167.4								
2-Butanol	123.8	169.9 C-1								
		160.5 C-3	182.6							
2-Pentanol	125.5	169.2 C-1								
		150.9 C-3	173.4	178.5						
2-Hexanol	125.3	169.2 C-1								
		153.3 C-3	164.2	169.6	178.6					
2-Heptanol	125.3	169.2 C-1								
		153.0 C-3	166.7	160.2	169.6	178.6				
2-Octanol	125.3	169.1 C-1								
		152.9 C-3	166.4	162.8	160.3	169.7	178.5			
2-Decanol	125.3	169.1 C-1								
		152.9 C-3	166.3	162.4	162.5	162.9	160.3	169.6	178.5	
3-Pentanol	118.7	162.8	182.7							
3-Hexanol	120.2	153.1 C-4	182.6 C-1							
		162.2 C-2	173.1 C-5	178.5						
3-Heptanol	119.9	155.6 C-4	182.5 C-1							
		162.8 C-2	164.3 C-5	169.5	178.5					
3-Octanol	119.9	155.3 C-4	182.5 C-1							
		162.2 C-2	166.8 C-5	160.2	169.6	178.6				
4-Heptanol	121.9	152.5	173.4	178.4						
4-Octanol	121.6	155.0 C-5	164.3 C-6	169.5 C-7						
		152.5 C-3	173.4 C-2	178.5 C-1	178.5					
5-Nonanol	121.4	155.0	164.2	169.5	178.5					
2-Methyl-1-propanol	123.6	161.7	173.6							
2-Methyl-2-propanol	124.1	161.2								
2,2-Dimethyl-1-propanol	119.9	159.9	166.2							
2-Methyl-1-butanol	125.6	155.0	166.6 C-3	181.4						
			176.5 C-3′							
3-Methyl-1-butanol	132.3	150.7	167.7	170.0						
3-Methyl-2-butanol	120.5	172.8 C-1								
		157.4 C-3	174.4[a]							
2-Methyl-2-butanol	122.2	163.9 C-1	184.0							
		156.0 C-3								
4-Methyl-2-pentanol	127.3	168.5 C-1	167.7	169.7[b]						
		143.6 C-3								
3,3-Dimethyl-1-butanol	133.6	146.1	162.8	162.7						
2,3-Dimethyl-2-butanol	120.3	166.2 C-1	175.0							
		153.7 C-3								
3,3-Dimethyl-2-butanol	117.7	174.6 C-1								
		157.5 C-3	167.0							
2,3,3-Trimethyl-2-butanol	118.4	167.1 C-1	166.9							
		155.0 C-3								

[a] Average of 174.3 and 174.5 ppm for nonequivalent methyls, see J. I. Kroschwitz, M. Winokur, H. J. Reich, and J. D. Roberts, *J. Amer. Chem. Soc.*, **91**, 5927 (1969). [b] Average of 169.3 and 170.1 ppm for nonequivalent methyls.

formational preference for equatorial alkyl, *viz.* **1**, over equatorial hydroxyl will be sufficiently great so that there will be no substantial contribution from the conformer with axial alkyl and equatorial hydroxyl, *viz.* **2**.

Results and Discussion

A. General Considerations. An important problem with nmr spectra of complex molecules with many resonances is the assignment of the resonances to particular atoms. In general, we have used much the same procedures for this as used by Grant and coworkers:[8–10] the large inductive shift of a hydroxyl group on the resonance of the directly attached carbon, proton-decoupling frequencies where the proton resonances themselves can be unambiguously identified, resonance intensities where two or more carbons are equivalent by symmetry and, for long-chain alcohols, where the methylene resonances are rather close together and often have no distinguishing characteristics, minimal substituent effects were assumed with respect to the corresponding hydrocarbons. This latter procedure is expected to lead to some ambiguities but the shift differences involved are only a few cycles per second and reversal of the uncertain assignments would be of little consequence to the correlations to be presented later.

Of special value for identification of resonances arising from carbons with directly attached hydrogens is to introduce sufficient proton-decoupling power off resonance to eliminate all of the couplings between

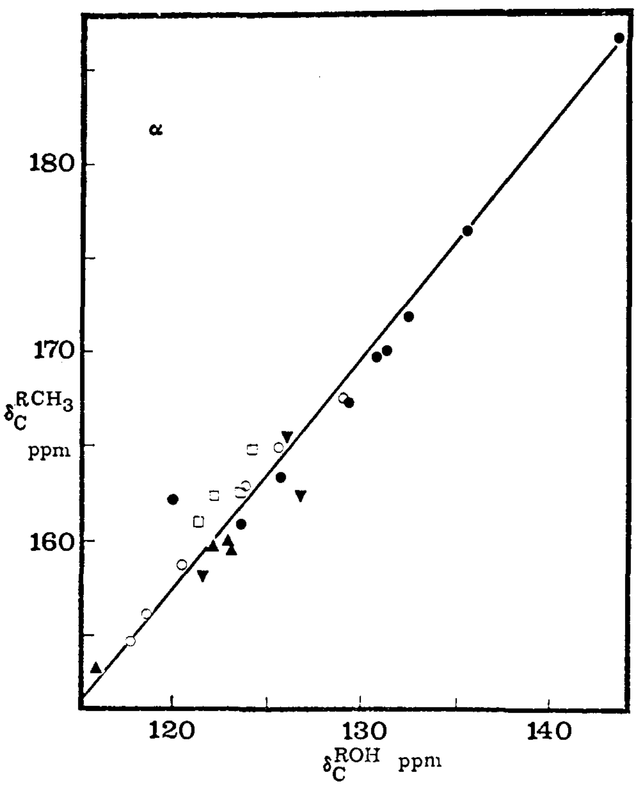

Figure 1. Correlation between the α ^{13}C shifts in alcohols and correspondingly constituted hydrocarbons with CH_3 in place of OH. The points shown are for a selection of different types of alcohols in Tables I and II. The line is drawn in accord with eq 1. The points are: ●, primary acyclic alcohol; ○, secondary acyclic alcohol; □, tertiary alcohol; ▲, cyclohexanol with equatorial hydroxyl; ▼, cyclohexanol with axial hydroxyl.

the carbons and nondirectly attached protons. This results in perturbed triplets centered at the chemical shifts of methylene carbons and perturbed quartets centered at the chemical shifts of the methyl carbons. It is usually sufficient to observe the gap created by superposition of a partially decoupled methyl quartet on a completely decoupled methyl singlet to distinguish between methyl and methylene groups.[17]

Table II. Carbon-13 Chemical Shifts of Substituted Cyclohexanols[a]

	C-1	C-2	C-3	C-4	C-5	C-6	Methyl
Cyclohexanol	123.0	157.0	168.1	166.6			
trans-2-Methyl	115.9	152.8	158.5	166.7	167.1	157.4	173.7
cis-3-Methyl	122.0	148.5	160.8	157.7	168.1	158.1	170.0
trans-4-Methyl	122.8	*b*	*b*	161.1			170.8
trans-4-*t*-Butyl	122.4	157.1	167.1	145.5			*c*
1-Methyl[d]	123.5	152.8	169.7	166.5			163.0
cis-2-Methyl	121.4	156.7	163.2	168.3	171.0	160.7	176.3
trans-3-Methyl	126.0	151.3	165.9	158.1	172.3	159.7	172.3
cis-4-Methyl	126.6	161.1	163.8	161.9			171.6
cis-4-*t*-Butyl	127.8	159.5	171.8	144.6			*e*

[a] In parts per million upfield from carbon disulfide; *cis–trans* pairs were determined as mixtures. The upper group are assumed to have hydroxyl equatorial, the lower group hydroxyl axial. [b] Resonances at 159.4 and 157.7 ppm were unassigned. [c] Quaternary carbon 160.7; methyl carbon 165.3. [d] For study of conformational preference in this substance see J. J. Uebel and H. W. Goodwin, *J. Org. Chem.*, **33**, 3317 (1968); N. L. Allinger and C. D. Liang, *ibid.*, **38**, 3319 (1968). [e] Quaternary carbon 160.4; methyl carbon 165.4.

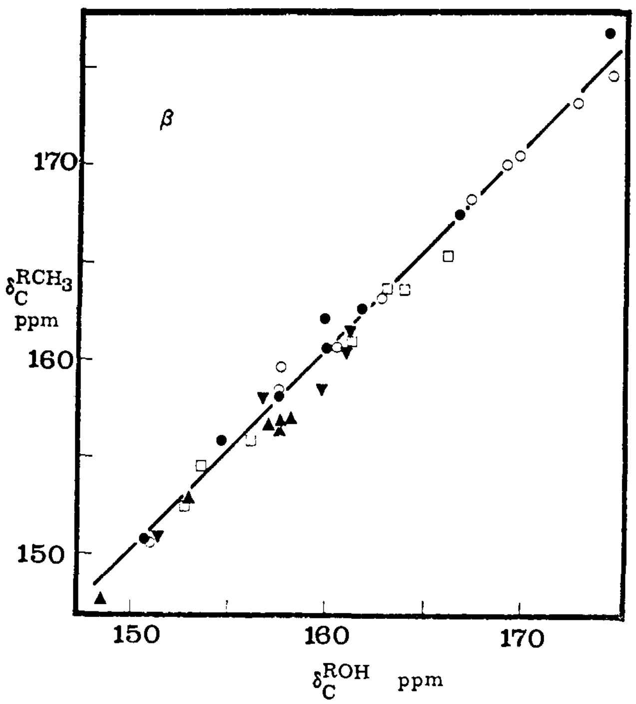

Figure 2. As in Figure 1, for the β ^{13}C shifts of alcohols and hydrocarbons. The line is in accord with eq 2.

The ^{13}C chemical shifts for a number of acyclic alcohols are given in Table I, cyclohexanols in Table II, and a few relevant reference hydrocarbons in Table III. For comparisons with the previously reported[8,10] hydrocarbon chemical shifts which are referenced to benzene, we have used the conversion $\delta_C^{CS_2} = \delta_C^{C_6H_6} + 64.1$ ppm.

Table III. Carbon-13 Chemical Shifts of Hydrocarbons[a]

	C-1	C-2	C-3	C-4	Methyl
2,2,3-Trimethylbutane	165.6	159.9	154.7	174.9	
Methylcyclohexane[b]	159.3	156.6	165.7	165.8	169.6
t-Butylcyclohexane	143.9	164.6	165.0	165.6	*c*
trans-1,4-Di-*t*-butylcyclohexane	144.2	164.5			*d*
cis-1,4-Di-*t*-butylcyclohexane	149.8	168.8			*e*

[a] Chemical shifts are given in parts per million upfield from carbon disulfide. [b] Slightly different values (±0.4 ppm) reported by Dalling and Grant.[10] [c] Quaternary carbon 160.1, methyl carbon 165.1. [d] Quaternary carbon 160.5, methyl carbon 164.9. [e] Quaternary carbon 159.8, methyl carbon 164.8.

It turns out that there are simple linear correlations between the carbon chemical shifts of alcohols and the corresponding hydrocarbon wherein a methyl group takes the place of hydroxyl. Thus we compare the chemical shifts of isopropyl alcohol with isobutane and 1-methylcyclohexanol with 1,1-dimethylcyclohexane, etc.[18] Figures 1–4 show the degree of correspondence

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(17) A more general technique for off-resonance decoupling has been elegantly and independently developed by L. F. Johnson of Varian Associates, private communication.

(18) A relationship of this kind has been suggested by E. Lippmaa and T. Pehk[9b] for ^{13}C shifts and demonstrated for ^{11}B chemical shifts in aminoboranes as compared to ^{13}C shifts in analogously constituted hydrocarbons[8] by B. F. Spielvogel and J. M. Purser, *J. Amer. Chem. Soc.*, **89**, 5294 (1967); see also J. M. Purser and B. F. Spielvogel, *Chem. Commun.*, 386 (1968); *Inorg. Chem.*, 7, 2156 (1968). (b) The alcohols

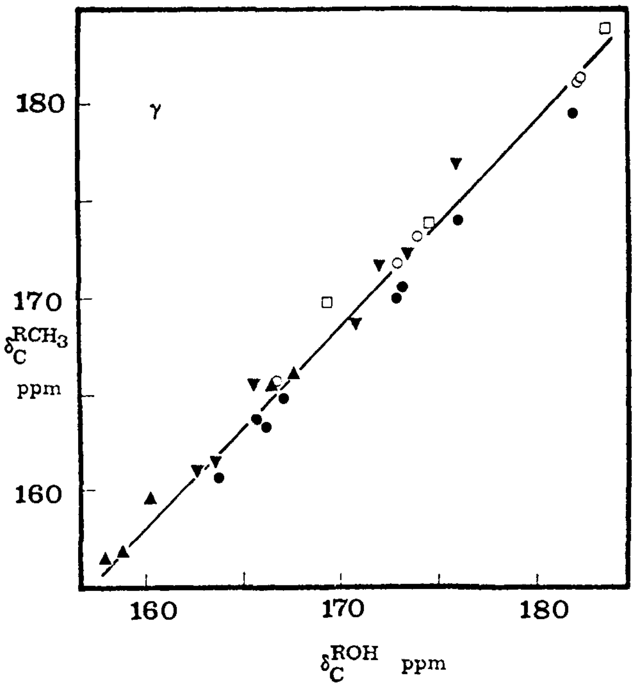

Figure 3. As in Figure 1, for the γ ^{13}C shifts of alcohols and hydrocarbons, the line corresponds to eq 3.

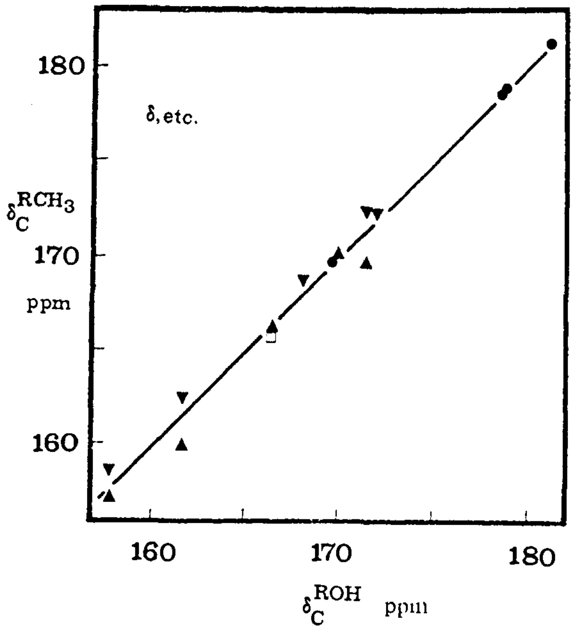

Figure 4. As in Figure 1, for the δ and beyond ^{13}C shifts of alcohols and hydrocarbons, the line corresponds to eq 4.

of the chemical shifts of correspondingly located carbons in alcohols and hydrocarbons—at the site of hydroxyl substitution (α), at the carbon next removed (β), etc.

There are several significant features to these correlations—one, which can be seen in Figures 1–4, is that the quality of the fit is substantially (although not completely) independent of whether the alcohol is primary, secondary, or tertiary, or a cyclohexanol with axial or equatorial hydroxyl. Perhaps the most striking result is the degree of fit to the lines of unit slope drawn in Figures 2–4 for the carbon shifts of alcohols relative to the corresponding hydrocarbon shifts for the β, γ, and δ, etc. carbons. For the α shifts, unit slope does not seem correct and as can be seen in Figure 5, there is a significant upward trend of $\delta_C^{RCH_3}(\alpha) - \delta_C^{ROH}(\alpha)$ with increasing $\delta_C^{RCH_3}(\alpha)$. Primary, secondary, and tertiary acyclic alcohols seem to tend to fall on different lines of about the same slope in Figure 5. No clear trend is evident for the alicyclic alcohols.

For practical purposes in predicting shifts of alcohols, we propose the relations of eq 1–4 for shifts in parts per million relative to CS_2. For many situations where the shifts of the hydrocarbons are unknown these can be predicted with reasonable accuracy by the procedure of Grant and Paul.[8]

$$\alpha\text{: } \delta_C^{ROH}(\alpha) = 0.83\delta_C^{RCH_3}(\alpha) - 10.5 \qquad (1)$$

linear correlation coefficient = 0.987; standard deviation = ±1.0 ppm

$$\beta\text{: } \delta_C^{ROH}(\beta) = \delta_C^{RCH_3}(\beta) - 0.5 \qquad (2)$$

linear correlation coefficient = 0.992; standard deviation = ±1.0 ppm

$$\gamma\text{: } \delta_C^{ROH}(\gamma) = \delta_C^{RCH_3}(\gamma) + 1.7 \qquad (3)$$

linear correlation coefficient = 0.993; standard deviation = ±1.0 ppm

$$\delta\text{, etc.: } \delta_C^{ROH}(\delta\text{, etc.}) = \delta_C^{RCH_3}(\delta\text{, etc.}) \qquad (4)$$

linear correlation coefficient = 0.995; standard deviation = ±0.8 ppm.

The fact that eq 1 has other than a unit slope for the relations between $\delta_C^{ROH}(\alpha)$ and $\delta_C^{RCH_3}(\alpha)$ is probably indicative of some kind of polarizability effect of the hydroxyl group on the α-carbon which is dependent on the kind of attached groups (hydrogen or alkyl). For the average alcohol, −38.5 ppm can be taken as the difference in inductive shift of hydroxyl and methyl on an α-carbon resonance.

The additive constants −0.5 and +1.7 ppm in eq 2 and 3 represent either net average inductive or steric perturbation effects of hydroxyl *vs.* methyl for these positions. Because of its sign, it seems most reasonable to ascribe the −0.5-ppm constant to an inductive effect (or more likely the net of an average downfield inductive shift and an upfield steric effect). The +1.7-ppm constant for γ substitution suggests that the steric effect of hydroxyl is somewhat greater than for methyl although studies of conformational equilibria in cyclohexane derivatives show that this type of interaction is energetically more severe for methyl than for hydroxyl.[19] However, there seems no reason to expect that the shift perturbations produced by steric effects involving C-H···H-O and/or C-H···O-H interactions should be identical with those involving C-H···H-C interactions.[12,20] In any event, it seems clear

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whose shifts we compare with hydrocarbons were selected with the aim of having the widest possible range of structures without a predominance of data representing simple primary and secondary alcohols. This aim was not wholly achieved because insufficient data were available on tertiary alcohols and/or the corresponding hydrocarbons.

(19) (a) J. A. Hirsch in "Topics in Stereochemistry," Vol. I, N. L. Allinger and E. L. Eliel, Ed., Interscience Division, John Wiley & Sons, Inc., New York, N. Y., 1967, pp 204, 209; (b) and (c) see Table II, footnote *d*.

(20) Further, albeit less direct, evidence on this point is provided by the 6.3-ppm upfield shift of the γ-carbon resonance produced by the fluorine in 1-fluorohexane, although fluorine is a less bulky group than

Table IV. Carbon-13 Chemical Shifts in Alcohols Relative to the Respective Alkanes[a]

Alcohol	Chemical shifts, ppm									
	α	β	γ	δ	ϵ	ζ	η	θ	ι	κ
Methanol	−51.4									
Ethanol	−51.4	−11.6								
1-Propanol	−48.3	−10.0	+5.3							
1-Butanol	−48.5	−10.3	+5.6	−0.7						
1-Pentanol	−48.4	−10.2	+6.0	−0.3	−0.4					
1-Hexanol	−48.3	−10.2	+5.9	−0.3	−0.2	−0.6				
1-Heptanol	−48.2	−10.2	+6.0	−0.2	0.0	−0.1	−0.2			
1-Octanol	−48.2	−10.2	+6.0	−0.3	−0.2	0.0	−0.1	−0.1		
1-Nonanol	−48.3	−10.1	+5.9	−0.3	−0.1	−0.1	−0.1	−0.1	−0.3	
1-Decanol	−48.1	−10.2	+6.0	−0.1	−0.1	−0.1	0.0	−0.1	−0.1	−0.1
2-Propanol	−47.6	−9.8								
2-Butanol	−44.0	−9.7 C-1 −7.3 C-3	+3.0							
2-Pentanol	−44.7	−9.9 C-1 −7.4 C-3	+3.2	−0.6						
2-Hexanol	−44.6	−9.7 C-1 −7.5 C-3	+3.4	−0.3	−0.3					
2-Heptanol	−44.5	−9.7 C-1 −7.4 C-3	+3.4	−0.2	−0.2	−0.4				
2-Octanol	−44.5	−9.7 C-1 −7.5 C-3	+3.3	−0.3	−0.1	−0.1	−0.3			
2-Decanol	−44.5	−9.6 C-1 −7.5 C-3	+3.4	−0.1	0.0	0.0	−0.1	−0.2	−0.2	
3-Pentanol	−39.6	−7.4	+3.6							
3-Hexanol	−40.6	−7.7 C-4 −7.6 C-2	+3.7 C-1 +3.3 C-5	−0.4						
3-Heptanol	−40.5	−7.8 C-4 −7.0 C-2	+3.9 C-1 +3.6 C-5	−0.3	−0.4					
3-Octanol	−40.5	−8.7 C-4 −7.6 C-2	+3.7 C-1 +2.8 C-5	−0.2	−0.2	−0.2				
4-Heptanol	−41.4	−7.9	+3.6	−0.5						
4-Octanol	−41.5	−8.1 C-5 −7.9 C-3	+3.9 C-6 +3.6 C-2	−0.3 C-7 −0.3 C-1	−0.3					
5-Nonanol	−41.3	−8.0	+3.8	−0.2	−0.3					
2-Methyl-1-propanol	−44.9	−5.9	+5.1							
2-Methyl-2-propanol	−43.5	−7.2								
2,2-Dimethyl-1-propanol	−41.4	−5.0	+4.9							
2-Methyl-1-butanol	−45.2	−7.9	+5.6 C-3 +5.7 C-3′	+0.1						
3-Methyl-1-butanol	−49.0	−10.3	+2.7	+0.6						
3-Methyl-2-butanol	−40.5	−8.5 C-1 −5.5 C-3	+3.6							
2-Methyl-2-butanol	−40.7	−6.9 C-1 −5.0 C-3	+2.7							
4-Methyl-2-pentanol	−44.8	−10.2 C-1 −7.4 C-3	+2.7	−0.6						
3,3-Dimethyl-1-butanol	−50.5	−10.0	0.4	−1.2						
2,3-Dimethyl-2-butanol	−38.4	−7.3 C-1 −5.0 C-3	+1.5							
3,3-Dimethyl-2-butanol	−38.4	−9.5 C-1 −4.9 C-3	+3.1							
2,3,3-Trimethyl-2-butanol	−36.3	−7.8 C-1 −4.9 C-3	+1.3							

[a] The chemical shifts of the carbon atoms relative to carbon disulfide are given in Table I. The figures here are for ($\nu_{\text{alcohol}} - \nu_{\text{alkane}}$) in parts per million calculated using the values for the alkanes taken from ref 8 or Table III. Negative values represent shifts to lower field.

that the general problem of predicting the chemical shifts of carbons in alcohols, except for the α-carbons is essentially the same as that for predicting the shifts of carbons in hydrocarbons and, for practical purposes, this can be done with considerable accuracy by appropriate combinations of eq 1–4 with the substituent parameters suggested by Grant and coworkers[8,10] for hydrocarbons.

B. Substitution Effects of Hydroxyl. Cyclohexanols. In many cases, such as with natural products, the effect of substitution of a hydroxyl group on the ^{13}C resonances of a hydrocarbon will be more helpful for structural analysis than comparison of the resonances of the alcohol with the corresponding methyl-substituted hydrocarbon, which is much less likely to be available. The perturbations caused by hydroxyl groups taken as the differences between the chemical shifts of the respective carbons of alcohols and the corresponding hydrocarbons with the same number of carbons as given in Table III[21] or previously reported[8,10] are given in Tables IV and V.

hydroxyl or methyl; F. J. Weigert, Ph.D. Thesis, California Institute of Technology, Pasadena, California, 1968.

(21) The rather large differences in the chemical shifts between the ring carbons in methylcyclohexane and *t*-butylcyclohexane are quite consonant with the results of Grant and Paul.[8] The carbon-1 of *t*-butylcyclohexane is expected to experience a large downfield shift relative to cyclohexane from the combined effect of one α and three β carbons of the *t*-butyl group. The carbon-2 is expected to show effects of opposite sign from one β and three γ carbons giving only a small net shift. In this connection, it is interesting that the ***trans*** isomer of 1,4-di-*t*-butyl-

Table V. Substituent Effects (in parts per million) of Hydroxyl Groups in Alkylcyclohexanols Relative to Corresponding Carbons of Alkylcyclohexanes[a]

Substituent	C-1	C-2	C-3	C-4	C-5	C-6
None	−42.5	−8.5	2.6	1.1		
trans-2-Methyl	−41.0	−6.5	1.5	1.0	1.3	−8.3
cis-3-Methyl	−43.7	−8.1	1.5	1.1	1.4	−7.7
trans-4-Methyl	−43.0	*b*	*c*	1.8		
trans-4-*t*-Butyl	−43.2	−7.9	1.1	1.6		
1-Methyl	−35.8	−3.8	4.0	0.7		
cis-2-Methyl	−35.2	−2.6	6.6	2.6	5.2	−5.0
trans-3-Methyl	−39.7	−5.3	6.6	1.5	7.1	−6.1
cis-4-Methyl	−38.9	−4.6	7.2	2.6		
cis-4-*t*-Butyl	−37.8	−5.5	6.8	0.7		

[a] The shift data are grouped according to whether the hydroxyl is expected to be predominantly equatorial (first group) or predominantly axial (second group). [b] Either −6.3 or −8.0 ppm. [c] Either 1.1 or 2.8 ppm.

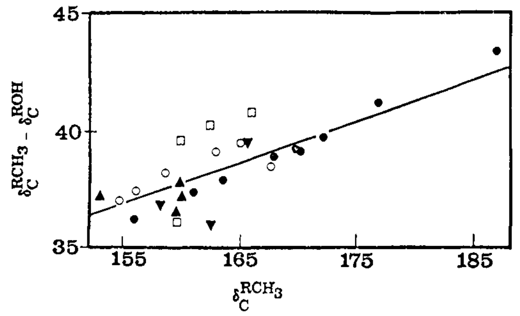


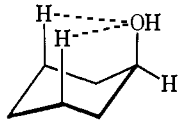
Figure 5. Variation of $\delta_C^{RCH_3}(\alpha) - \delta_C^{ROH}(\alpha)$ with $\delta_C^{RCH_3}(\alpha)$ for the same alcohols and hydrocarbons whose shifts are shown in Figure 1; all data in parts per million.

For analysis of the effect of substitution of a hydroxyl on the ^{13}C resonances of a hydrocarbon, it is particularly useful to look first at cyclohexanols because with these the conformations are either well known or can be inferred.[19a] The major contribution to the ^{13}C shifts results from the second-order paramagnetic effect which arises from partial unquenching of the orbital angular momentum of the valence electrons in the magnetic field.[22] Rigorous calculation of second-order paramagnetic effects in complex molecules is presently impossible and we will proceed here on the same basis as Grant and coworkers[8–12] that the second-order paramagnetic effect is to a substantial degree influenced by inductive, resonance, and steric effects in a manner which is familiar for a variety of phenomena involving organic compounds.

The *inductive effect* of hydroxyl (or other groups) on the chemical shifts of the various ring atoms in cyclohexanols will be assumed (although perhaps incorrectly) to be independent of conformation but dependent on whether the hydroxyl is substituted to give a primary, secondary, or tertiary alcohol. Equations 2–4 indicate that the inductive effect of hydroxyl is not much different than that of methyl beyond the α position.[23]

The *resonance effect* to be considered with cyclohexanols relates to the kinds and stereochemical relationships between pairs of atoms on vicinal carbons and is assumed to affect only the shifts of the carbons directly involved. This effect which has been considered by Grant and coworkers[8,12b] is expected to be sensitive to the conformation. *Steric effects* have been shown to be very important in various kinds of hydrocarbons and, of course, are expected to be especially sensitive to conformational changes.[10–12]

The problem in sorting out these influences (and others which might be foreseen later) is that with many substitutions a composite of effects is to be expected. It might be expected that one could assume that the inductive and steric effects dominate at the α- and β-carbons while the steric effects dominate at the carbons farther from the point of substitution. While the latter assumption is likely to be valid, the former is probably much too naive because the steric effects are expected to operate at two or more sites, not just at one. To illustrate the point, consider the chemical shifts of the carbons of 4-*t*-butylcyclohexanol relative to the corresponding carbons of *t*-butylcyclohexane. Substitution of an *equatorial* hydroxyl changes the α-carbon resonance by −43.2 ppm and that of γ-carbon by 1.1 ppm. The corresponding figures for an *axial* hydroxyl are −37.8 and 6.8 ppm. The effect of the axial hydroxyl corresponds to the similar 5.5-ppm steric effect produced at the γ-carbon by an axial methyl group.[10] Proceeding on the simplest possible basis, we can ascribe the equatorial hydroxyl effect to some combination of substituent parameters but the axial effect must involve, in addition, the steric effect of the γ-carbons and their axial hydrogens on the 1-carbon operating backwards through the hydroxyl group (**3**).[24] The difference between the axial



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and equatorial α shifts which could arise from this additional steric interaction is 5.4-ppm upfield and corresponds well to the 4.6-ppm upfield shift difference at the α-carbon with an axial, as compared to an equatorial, methyl group.

The β-carbon shifts in cyclohexanols are large and not easily comprehensible. The shift data presented in Table V show that, except where there is a methyl group at the β-carbon, an equatorial hydroxyl produces about a −8-ppm shift and an axial hydroxyl group produces about a −5-ppm shift at the β-carbon relative to the resonances of the corresponding hydrocarbons. The analogous shifts with equatorial and axial methyl groups are −8.9 and −5.2 ppm, respectively.[10,25] That

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cyclohexane is very much like *t*-butylcyclohexane itself while the corresponding *cis* isomer, which is surely in a twist-boat conformation, shows strong upfield perturbations of the C-1 and C-2 resonances as expected for increased steric congestion.

[22] See S. I. Chan and A. S. Dubin, *J. Chem. Phys.*, **46**, 1745 (1967), for references and discussion of structural influences on ^{19}F chemical shifts and especially the delineation of the relative contributions of diamagnetic and paramagnetic terms to the shielding constants.

[23] It seems likely that any small deviations from constancy in the sum of the first two terms of the shielding equation as discussed by Chan and Dubin[22] (their eq 2) will be included in, and be indistinguishable from, what we are assuming is the inductive effect.

[24] The concepts used here are to a degree corroborated by the fact that there is a 6-ppm upfield shift in the hydroxyl ^{17}O resonances on going from ethanol to 1-propanol: H. A. Christ, P. Diehl, H. R. Schneider, and H. Dahn, *Helv. Chem. Acta*, **44**, 865 (1961). It will be interesting to see if the same parallelism holds between the ^{17}O resonances of cyclohexanols with axial and equatorial hydroxyls.

[25] More significant figures are allowed here for the methyl effects because these are averages over many more examples.[10]

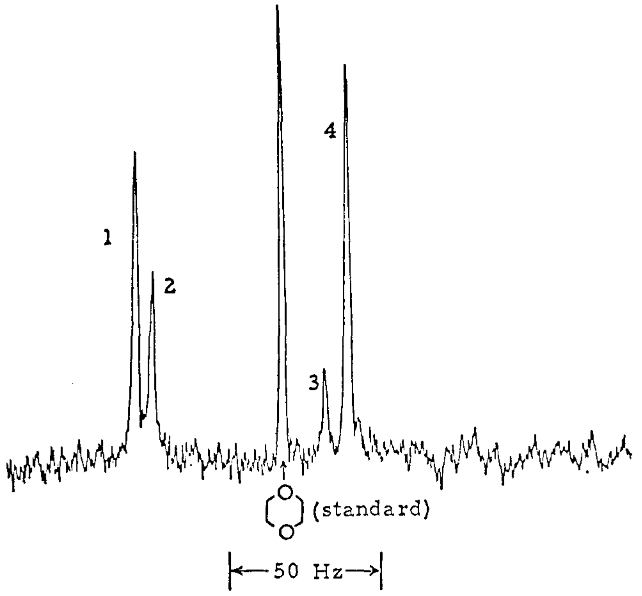
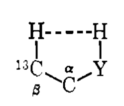
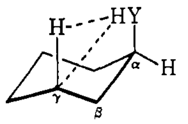


Figure 6. Nuclear magnetic resonance spectrum (with proton decoupling) of the ^{13}C of natural abundance of the carbinyl carbons in a mixture of the four possible *cis–trans* isomers of 3,4-dimethylcyclohexanol with dioxane as internal reference. The peaks are assigned as described in the text: 1, *cis*-3-methyl-*cis*-4-methylcyclohexanol (**5**); 2, *cis*-3-methyl-*trans*-4-methylcyclohexanol (**7**); 3, *trans*-3-methyl-*cis*-4-methylcyclohexanol (**8**); and 4, *trans*-3-methyl-*trans*-4-methylcyclohexanol (**6**).

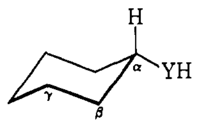
these substituent effects of hydroxyl and methyl are so similar seems to rule out ascribing any sizable influence on the chemical-shift differences of differences in contributions of HCCC exchange integrals of the type considered by Cheney and Grant,[12b] because it seems wholly unreasonable to expect that the corresponding HCCO exchange integrals would affect the shifts in a comparable way. In this connection, it is relevant that Cheney and Grant[12b] found that the effect of considering the vicinal exchange integrals in a valence-bond treatment of the β shifts accounted for no more than one-third of the observed β shifts. The treatment is either deficient or the resonance effect is accentuated by a steric effect which, in this case, must act to give a *downfield* shift change. For a structural change of the type H–C–^{13}C–H → H–Y–C–^{13}C–H where H–Y is hydroxyl or part of a methyl, the H···H interactions in the substituted fragment arranged to give maximum interaction (**4a**) should lead to no sizable effect according to Grant and Cheney[12a] because cos θ is zero. At this time, there seems no clear explanation for why something like an 8-ppm downfield β shift results on substitution of OH or CH_3. That axial hydroxyl (or methyl) on a cyclohexane ring produces about 3-ppm smaller downfield shift of the β-carbon than equatorial hydroxyl (or methyl) can be understood in terms of steric elongation of the C_β–C_γ bond by an axial substituent (**4b**), but not by an equatorial substituent (**4c**). Such an elongation of the C_β–C_γ bond is predicted by the theory of Lichtman and Grant[26] to produce an *upfield* shift of the β-carbon. This argument gains further support from the fact, as will be seen from Table IV, that substitution of hydroxyl at the 2 positions of linear alkanes produces a greater downfield β shift of C-1, the methyl group, than of the 3-carbon, the latter of which might be expected to experience more steric congestion.[27]



4a



4b



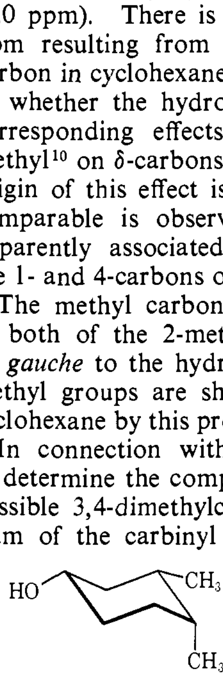
4c

Y = O or CH_2

Most of the substantial upfield shift at the γ-carbon of a cyclohexane with an axial hydroxyl of about 7 ppm as compared with about 1 ppm for equatorial hydroxyl can clearly be ascribed to a steric effect in the same way as done by Grant and coworkers[10–12] for axial methyl (+5.4 ppm) and equatorial methyl (0.0 ppm). There is a significant upfield shift of 1–3 ppm resulting from hydroxyl substitution at the δ-carbon in cyclohexanes which is not especially sensitive to whether the hydroxyl is axial or equatorial. The corresponding effects of either axial or equatorial methyl[10] on δ-carbons are just a few tenths ppm. The origin of this effect is unknown but, because nothing comparable is observed with acyclic alcohols, it is apparently associated with the forced proximity of the 1- and 4-carbons of the cyclohexane ring.

The methyl carbon in all favorable conformations of both of the 2-methylcyclohexanols is expected to be *gauche* to the hydroxyl group. As expected, these methyl groups are shifted upfield relative to methylcyclohexane by this proximity effect.

In connection with other work, it was desirable to determine the composition of a mixture of the four possible 3,4-dimethylcyclohexanols **5–8**. A ^{13}C spectrum of the carbinyl carbons of these alcohols with proton decoupling is shown in Figure 6.[28] The presence of all four isomers is clearly indicated and in combination with the data already discussed, only one additional fact is needed to identify the 1-carbon resonance of each isomer unambiguously. Oxidation of the alcohol mixture gave a mixture of *cis*- and *trans*-3,4-dimethylcyclohexanones and from the ^{13}C nmr spectrum of this mixture it was concluded that the ketone with *cis*-methyl groups was present to the



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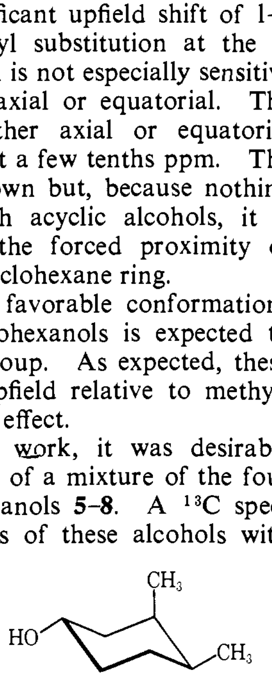

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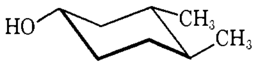

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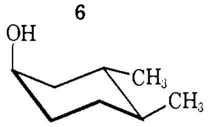

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[26] W. M. Lichtman and D. M. Grant, *J. Amer. Chem. Soc.*, **90**, 1400 (1968). We are indebted to Professor D. M. Grant for drawing our attention to this point.

[27] However, it should be remembered that the situation for substitution in cyclohexane and continuous-chain alkanes are perforce potentially different in that there could be a substantial change in conformational preferences between the hydrocarbon and the corresponding alcohol which will generally not be so with a cyclohexane and the corresponding cyclohexanol. Until we know more about conformational preferences in liquid hydrocarbons and alcohols this could be a serious uncertainty.

[28] Of the total of 32 different carbon resonances expected for the mixture of **5–8**, fully 30 were resolved. No attempt was made to assign these to specific carbons except for the 1-carbons.

extent of 75%. The only assignment of the ^{13}C carbinyl resonances of the alcohol mixture consistent with this is to have peaks 1 and 4 correspond to the alcohols with *cis*-methyl groups and peaks 2 and 3 to those with *trans*-methyl groups. To a first approximation, the conformations of these molecules will be favored wherein two or three of the substituents are equatorial, and further, as suggested earlier, methyl groups will be expected to have a greater preference for equatorial locations than hydroxyl groups. Now, a 3-axial methyl group is expected to shift C-1 upfield by 5 ppm relative to the corresponding equatorial isomer. This means that peak 1 corresponds to **5** and peak 4 to **6**. An axial hydroxyl shifts the α-carbon upfield by 5 ppm relative to its equatorial isomer, which permits peak 2 to be assigned to **7** and peak 3 to **8**.

Conclusions as to the quantities of each form are on shakier grounds. If the chemical shifts of the protons directly bonded to the carbinyl carbon in all four isomers are not within about 4 Hz of each other, the efficiency of the decoupling will be different for each isomer. Because significant nuclear Overhauser effects are expected, the relative intensities of the peaks will depend on the offset from the optimum decoupling frequency.

To demonstrate the general quality of spectra obtained as described above for a simpler case, a spectrum of a mixture of *cis*- and *trans*-2-methylcyclohexanol is shown in Figure 7. With one "aliphatic decoupling frequency" and a sweep rate of 10 Hz/sec the resonances are *ca.* 5-Hz wide. Decoupling of the methyl protons is less efficient than of the ring protons and therefore the methyl ^{13}C resonances are broader. Slower sweep rates and optimization of the individual decoupling frequencies results in line widths less than 1 Hz. However, the proton noise-decoupling technique mentioned earlier is more efficient of spectrometer time.[15]

C. Other Cyclic Alcohols. In the continuous-chain alcohols and cyclohexanols, the important conformations are usually those which have groups on adjacent carbon atoms staggered. With many ring systems, more or less eclipsed interactions become unavoidable, and the number of possible favorable conformations of the basic ring system, to say nothing of the possible sites for the substituent groups to reside, become larger. For this reason, the elucidation of the conformations of ring systems other than cyclohexane is difficult and challenging. To see if new light could be shed on such problems, the ^{13}C spectra of the cyclic alcohols with $n = 5, 6, 7$, and 8 have been obtained and the chemical shifts and substituent parameters are summarized in Table VI. The chemical shifts of the cyclic hydrocarbons were those of Lauterbur and Burke.[29]

Cyclopentane is not planar[30] but pseudorotation rapidly equilibrates all of the reasonably possible conformers. No one conformation appears to dominate and thus the observed nmr effects will represent the weighted average of the various conformations. In most conformations of cyclopentanol, the dihedral angle between the hydroxyl group and the *cis*-2-proton is likely to be small and it seems a reasonable first approximation to take cyclopentanol as representing an eclipsed type of structure. It is interesting in this connection, that the downfield β-carbon shift is larger than it is for equatorial substitution of hydroxyl in cyclohexane, indicating that whatever produces the β-carbon substituent effect, operates more efficiently in cyclopentane than in cyclohexane. The effect of hydroxyl on the 3-carbon of cyclopentanol is +1.9 ppm which is comparable to the corresponding value of +1.3 ppm found for equatorial hydroxyl in cyclohexanol and similarly cannot be due to a simple steric effect.

Figure 7. Proton-decoupled ^{13}C spectrum of a mixture of *cis*- and *trans*-2-methylcyclohexanol. The carbinyl carbons come at much lower field and are not shown. The six more intense peaks in the spectrum arise from the *trans* isomer and the six weaker resonances from the *cis* isomer.

Table VI. Carbon-13 Chemical Shifts in Cyclic Alcohols[a]

Compound	C-1	C-2	C-3	C-4	C-5
Cyclopentanol	119.2	157.5	169.1		
	−48.0	−9.7	1.9		
Cyclohexanol	123.0	157.0	168.1	166.6	
	−42.5	−8.5	2.6	1.1	
Cycloheptanol	120.1	154.8	169.2	163.9	
	−44.2	−9.5	4.9	−0.4	
Cyclooctanol	121.2	157.8	169.5	167.0	164.7
	−44.7	−8.1	3.6	1.1	−1.2

[a] The upper line of figures for each alcohol are the experimentally determined chemical shifts in parts per million upfield from carbon disulfide while the lower line gives the substituent effects obtained by subtracting the chemical shifts in parts per million of the corresponding cycloalkanes.[29]

It is expected for cyclopentanol that no single conformation will give a wholly adequate description of the average properties of the molecules. The situation with medium-size ring compounds is still more difficult and the experimental evidence available is not always sufficient to distinguish between a single favored conformation involved in a pseudorotation itinerary or a mixture of nearly equally favored conformations.

For cycloheptane itself, Hendrickson[31] has calculated that the twist-chair conformation should be more stable than the chair, boat, or twist boat by more than 1.4 kcal/mol. As a result, cycloheptane can fairly reasonably be considered as a rapidly pseudorotating mixture of the various possible twist-chair forms. For methylcycloheptane, the situation is not simple. Hendrickson[31b,c] has suggested that there should be four nearly equal energy forms with a single methyl group

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(29) J. J. Burke and P. C. Lauterbur, *J. Amer. Chem. Soc.*, **86**, 1870 (1964).

(30) J. G. Aston, H. L. Fink, and S. C. Schumann, *ibid.*, **65**, 341 (1943).

(31) (a) A detailed theoretical analysis of the energies of many of the possible conformations of methyl-substituted medium-size ring compounds has been very recently published by J. B. Hendrickson, *ibid.*, **89**, 7043 (1967); (b) see also, *ibid.*, **89**, 7036 (1967); somewhat different values were given earlier; (c) *ibid.*, **84**, 3355 (1962); (d) *ibid.*, **83**, 4537 (1961).

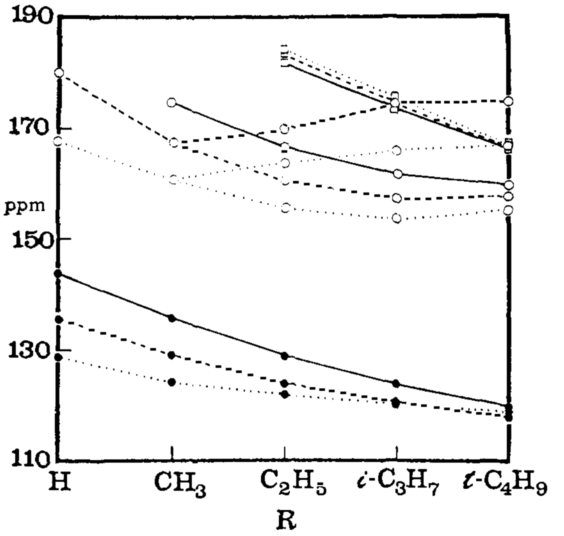


Figure 8. Chemical shifts of ^{13}C in acyclic alcohols relative to CS_2 as a function of R for $HOCH_2R$, $HOCH(CH_3)R$, and $HOC(CH_3)_2R$: ●——●, α, $HOCH_2R$; ●- - -●, α, $HOCH(CH_3)R$; ●· · ·●, α, $HOC(CH_3)_2R$; ○——○, β, $HOCH_2R$; ○- - -○, β, $HOCH(CH_3)R$, upper line = C-1, lower line = C-3; ○· · ·○, β, $HOC(CH_3)_2R$, upper line = C-1, lower line = C-3; □——□, γ, $HOCH_2R$; □- - -□, γ, $HOCH(CH_3)R$; □· · ·□, γ, $HOC(CH_3)_2R$.

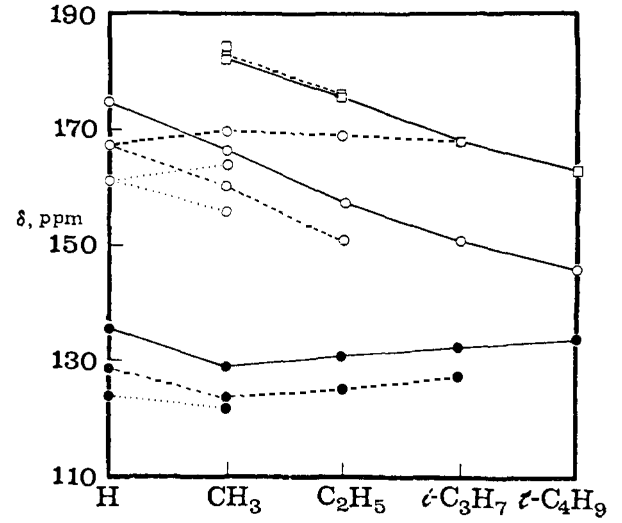
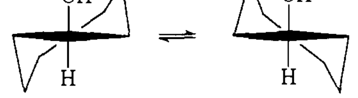


Figure 9. Chemical shifts of ^{13}C in acyclic alcohols relative to CS_2 as a function of R for $HOCH_2CH_2R$, $HOCH(CH_3)CH_2R$, and $HOC(CH_3)_2CH_2R$: ●——●, α, $HOCH_2CH_2R$; ●- - -●, α, $HOCH(CH_3)CH_2R$; ●· · ·●, α, $HOC(CH_3)_2CH_2R$; ○——○, β, $HOCH_2CH_2R$; ○- - -○, β, $HOCH(CH_3)CH_2R$, upper line = C-1, lower line = C-3; ○· · ·○, β, $HOC(CH_3)_2CH_2R$, upper line = C-1, lower line = C-3; □——□, γ, $HOCH_2CH_2R$; □- - -□, γ, $HOCH(CH_3)CH_2R$.

substituted on a twist-chair conformation. These have the methyl at the isoclinal[31] or "axis" position (1) and the 2, 3, and 4 equatorial positions. All axial-type positions are calculated to be less favorable by 1.3 kcal/mol or more. If these predictions are valid, and there is no *a priori* reason to expect they are not, cycloheptanol which has a substituent with a smaller steric effect than methyl, is likely to be a mixture of the several equatorial and isoclinial (and possibly even axial) conformations.

The chemical shift of the ^{13}C carbons in cycloheptane is expected to be the statistically weighted average of the chemical shifts of the four different carbons of a twist-chair form. Therefore, the observed chemical shift is $\nu = (\nu_1 + 2\nu_2 + 2\nu_3 + 2\nu_4)/7$ where the subscripts refer to the position numbers of the twist-chair conformation as defined by Hendrickson.[31d] It is, of course, not known at present how different the various ν_n values are.

For cycloheptanol, the ^{13}C chemical-shift parameter which appears to be most useful for conformational analysis is the 3-carbon shift which amounts to +4.9 ppm. Judging from cyclohexanols (Table V) this is somewhat intermediate between what would be expected for a pure axial or pure equatorial orientation of the hydroxyl on a cyclohexane. However, before embracing the notion that cycloheptanol is a complex mixture of conformations with axial and equatorial hydroxyl it is well to point out that the optimized positions for equatorial methyl on the twist-chair form have some larger interactions than those for equatorial methyl on cyclohexane and, furthermore, the axial positions generally have very much greater interactions. As a result, some upfield shift is expected for the carbons γ to the hydroxyl, even if the hydroxyl is very largely equatorial. The shift data of the γ carbons by no means rule out a substantial contribution of the conformation with the hydroxyl at the isoclinal carbon.



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The two enantiomeric conformations with isoclinal hydroxyl **9** and **10** (which are expected to be in rapid equilibrium) have the hydroxyl intermediate in character between axial and equatorial—for either **9** or **10** the 3,6-carbons have one essentially *trans* and one essentially *gauche* hydroxyl interaction. If we take +1.3 ppm to be the intrinsic effect of an equatorial hydroxyl on the shift of the 3-carbon and about +6.6 ppm to be the effect of a corresponding axial hydroxyl, then the average of 4 ppm is not greatly different from the observed shift of 4.9 ppm. Clearly, what is needed is more information on substituted cycloheptanols with favored and known or predictable conformations. The ^{13}C chemical shifts of the α- and β-carbons of cycloheptanol are consonant with those of the γ-carbons in showing sizable steric interactions relative to cyclohexane. Nothing in the data so far obtained is in other than general accord with expectations based on Hendrickson's calculations.[31]

For cyclooctanol, because of the large number of possible conformations, it is not really practical to attempt a detailed analysis. Hendrickson[31a,b] has reviewed the recent literature and has made rather refined calculations of the energies of a variety of conformations of cyclooctane and monomethylcyclooctane. Although the recent low-temperature nmr studies of Anet and St. Jacques[32] on cyclooctane suggest that the boat-chair conformation is favored (a result also supported by Hendrickson's calculations[31]) it is very likely that there are several other conformations which are very

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(32) F. A. L. Anet and M. St. Jacques, *J. Amer. Chem. Soc.*, **88**, 2586 (1966).

close in energy and may contribute substantially to the equilibrium at room temperature.[33] The pattern of ^{13}C chemical shifts of cyclooctanol at room temperature is rather similar to that of cycloheptanol. The only positive conclusion seems to be that cyclooctanol is, on the average, rather congested judging from the general upfield shift of all of the ^{13}C resonances, but from the shift of the γ carbons, the hydroxyl is on the average in a more equatorial-like environment than for cycloheptanol. Obviously, more work also needs to be done on substituted cyclooctanols with reasonably predictable conformations.

D. Acyclic Alcohols. Detailed interpretation of the resonance line positions for ^{13}C atoms in acyclic alcohols is rendered difficult, if not impossible, by our lack of knowledge of the conformations assumed by these substances in the liquid phase. As already mentioned,[27] the substituent effects are especially hard to interpret because of possible conformational differences between the hydrocarbons and the alcohols. Nonetheless, inspection of Table IV shows many regularities which indicate that if conformational differences are important, they remain constant for alcohols of similar structure.

There are also some striking regularities of the ^{13}C shifts in compounds of the type $HOCH_2R$, $CH_3CH(OH)R$, $(CH_3)_2C(OH)R$, $HOCH_2CH_2R$, $CH_3CH(OH)CH_2R$, and $(CH_3)_2C(OH)CH_2R$ with R = H, methyl ethyl, isopropyl, and *t*-butyl which can be seen in Figures 8 and 9. We have no explanations of these regularities at the present time.

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[33] Further evidence on cyclooctane conformations as gained from nmr studies of fluorinated cyclooctanes is available elsewhere: J. E. Anderson, E. S. Glazer, D. L. Griffith, R. Knorr, and J. D. Roberts, *J. Amer. Chem. Soc.*, **91**, 1386 (1969).

Nuclear Magnetic Resonance Spectroscopy. Carbon-13 Chemical Shifts in Cycloalkanones[1]

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Abstract: High-resolution ^{13}C nuclear magnetic resonance spectra have been obtained of a number of cycloalkanones. Simple additivity relationships were found which enable reasonable prediction of the chemical shifts of alkyl-substituted cyclohexanones. Attempts have been made to assign conformations to the higher cycloalkanones on the basis of their ^{13}C chemical shifts.

The ^{13}C chemical shifts of the carbonyl carbons in cyclic ketones have been measured by several groups.[3–5] The unexpectedly low-field shift in cyclopentanone has been correlated with the red shift of the $n \rightarrow \pi^*$ electronic transition.[4] Grant and Cheney[6] have measured substituent effects on ^{13}C chemical shifts of methyl ketones relative to the corresponding alkanes.

Cyclohexanones

The ^{13}C chemical shifts measured for a number of substituted cyclohexanones as previously described[7] are shown in Table I while the corresponding substituent effects[7] are given in Table II. In order to determine the value of these data for qualitative and conformational analysis, simple additivity relations have been investigated for the nonketonic carbons of methyl-, dimethyl-, and *t*-butylcyclohexanones. The procedure involved summing the shifts of the corresponding carbons of alkylcyclohexanes[8] and cyclohexanone and then subtracting twice the shift of cyclohexane. Thus for the carbon-3 of 2-methylcyclohexanone, the predicted shift is $156.6 + 166.0 - 2 \times 165.5 = -8.4$ ppm. The results are given in Table II and the degree of correlation between calculated and observed shifts can be judged from Figure 1. In general, the deviations from additivity turn out to be small over a shift range of more

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[2] National Science Foundation Predoctoral Fellow, 1965–1968.

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

[4] G. B. Savitsky, K. Namikawa, and G. Zweifel, *J. Phys. Chem.*, **69**, 3105 (1965).

[5] D. H. Marr and J. B. Stothers, *Can. J. Chem.*, **43**, 596 (1965).

[6] See B. V. Cheney, Ph.D. Thesis, University of Utah, Salt Lake City, Utah, 1967.

[7] J. D. Roberts, F. J. Weigert, J. I. Kroschwitz, and H. J. Reich, *J. Amer. Chem. Soc.*, **92**, 1338 (1970). The ketones were commercial materials used without purification. The *cis–trans* pairs were measured as mixtures.

[8] The ^{13}C shift data for methyl- and *t*-butylcyclohexanes were taken from ref 7, while those for dimethylcyclohexanes are from D. K. Dalling and D. M. Grant, *ibid.*, **89**, 6612 (1967).