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^{13}C NUCLEAR MAGNETIC RESONANCE SPECTRA OF ETHERS AND GLYCOLS

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Abstract—The ^{13}C NMR spectra of 21 linear and branched ethers together with the corresponding alcohols have been determined in an attempt to correlate the shieldings in both series. It has been found that the shielding of a carbon in an acyclic ether can be given by the summation of additive shift parameters for substituents and correction parameters for the substitution patterns based on the shielding of the parent alcohol. On examination of solvent-induced shifts for α- and β-carbons in ethers and alcohols, significant ones have been noted in carbon tetrachloride → dimethylsulfoxide and carbon tetrachloride → trifluoroacetic acid. No appreciable concentration-dependent shifts of the shieldings have been observed in both ethers and alcohols. For the shieldings of α-carbons in acyclic glycols, it has been noticed that the observed and predicted values are in accord in 1,3-, 1,4- and 1,5-glycols but deviate in 1,2-glycols. The latter has been examined in a polycyclic system, where the deviations ($>3{\cdot}5$ ppm) in a *cis* (gauche) 1,2-glycol are larger than those ($<2{\cdot}5$ ppm) in a *trans* (anti-parallel) 1,2-glycol.

Although ^{13}C spectroscopy has proved useful in the structural studies of naturally occurring substances, its application in this area is still limited. We have been interested in the ^{13}C spectra of aliphatic ethers, for which Lippmaa and Pehk[1] reported some ^{13}C shielding data. However, in their work carbon disulfide was employed as the reference, and the line positions which were converted to the tetramethylsilane scale[2] are slightly different from our values. Christle *et al.*[3] also measured the alkyl carbon shieldings in some branched acyclic ethers and discussed their shift values in relation to steric effects of the substituents. In order to estimate the shielding values for this group of compounds in connection with those for alcohols, a systematic set of results have been obtained and analysed in the present work.

Those first examined were symmetrical di-n-alkyl ethers ROR. As listed in Table 1, the α-carbons of the ethers are deshielded by 4·5–10·7 ppm, the β-carbons shielded by 2·3–2·8 ppm, the γ-carbons deshielded by 0·3–0·5 ppm, and the δ-carbons deshielded by 0·1 ppm relative to the corresponding signals for the parent alcohols ROH. Secondly the various shieldings of asymmetrical ethers ROR' (including methyl ethers) were compared with the alcohols ROH or R'OH to reveal that, as shown in Table 2, the shieldings of the α-, β- and γ-carbons in the alkyl chains of the asymmetrical ethers were found to differ by −0·4 to +10·8 ppm, −2·9 to −4·6 ppm, and −0·6 to +0·4 ppm, respectively.†

On the other hand, the shieldings of the Me carbons in the methyl ethers showed the variation depending upon the substitution patterns of the other alkyl groups. Thus, the shielding changes are +10·7 ppm for dimethyl ether, +8·2 to +8·6 ppm for methyl n-alkyl ethers, +5·8 to +6·1 ppm for methyl sec-alkyl ethers, and −0·4 ppm for the methyl t-alkyl ether as compared with that in methanol.

A comparison of the shieldings in the di-n-alkyl ethers ROR' with those for the corresponding alcohols ROH or R'OH, reveal that the shieldings of carbons in the ethers can be correlated with those of the corresponding carbons

†Increasing positive values are in the direction of increasing frequency, i.e. towards lower field.

Table 1. ^{13}C shieldings of symmetrical ethers and corresponding alcohols (ppm from TMS)

	α	β	γ	δ		α	β	γ	δ	ε
$(CH_3)_2O$*	61.2				$(CH_3CH_2CH_2CH_2)_2O$	71.8	30.8	29.7	23.7	15.1
CH_3OH	50 5				$CH_3CH_2CH_2CH_2OH$	63.2	33 6	29.4	23.8	15 3
$\Delta^{obs.}$	+10 7				$\Delta^{obs.}$	+8.6	-2 8	+0 3	-0.1	-0.2
$\Delta^{cal.}$	+10.6				$\Delta^{cal.}$	+8.6	-2 7	+0.3		
$(CH_3CH_2)_2O$	66.9	16 4			$((CH_3)_2CH)_2O$	69.2	24.3			
CH_3CH_2OH	58.4	19 2			$(CH_3)_2CHOH$	64.7	26 5			
$\Delta^{obs.}$	+8.5	-2 8			$\Delta^{obs.}$	+4.5	-2.2			
$\Delta^{cal.}$	+8.5	-2.7			$\Delta^{cal.}$	+4.5	-3.5			
$(CH_3CH_2CH_2)_2O$	73.7	24.4	11.8		$((CH_3)_2CHCH_2)_2O$	79.1	29.9	20.8		
$CH_3CH_2CH_2OH$	64.9	26 9	11.5		$(CH_3)_2CHCH_2OH$	70.2	32.0	20.4		
$\Delta^{obs.}$	+8.8	-2.5	+0.3		$\Delta^{obs.}$	+8.9	-2.1	+0.4		
$\Delta^{cal.}$	+8.6	-2.7	+0.3		$\Delta^{cal.}$	+8.7	-2.2	+0.3		
$(CH_3CH_2CH_2CH_2)_2O$	71.7	33.4	20.8	15.1						
$CH_3CH_2CH_2CH_2OH$	62.9	36.0	20.3	15.2						
$\Delta^{obs.}$	+8.8	-2.6	+0.5	-0.1						
$\Delta^{cal.}$	+8.6	-2.7	+0.3							

*taken from Christl et al.[3]

Table 2. ^{13}C shieldings of asymmetrical ethers and corresponding alcohols (ppm from TMS)

	α	β	βMe	γ	δ	ε	α'	β'	γ'
$CH_3CH_2OCH_3$	69.2	16.1					59.1		
CH_3CH_2OH	58.4	19.2							
$HOCH_3$							50.5		
Δobs.	+10.8	-3.1					+8.6		
Δcal.	+10.6	-3.1					+8.5		
$CH_3CH_2CH_2OCH_3$	75.4	24.0		11.7			59.1		
$CH_3CH_2CH_2OH$	64.9	26.9		11.5					
$HOCH_3$							50.5		
Δobs.	+10.5	-2.9		+0.2			+8.6		
Δcal.	+10.6	-3.1		+0.2			+8.6		
$CH_3CH_2CH_2CH_2OCH_3$	73.4	32.9		20.5	15.0		59.1		
$CH_3CH_2CH_2CH_2OH$	62.9	36.0		20.3	15.2				
$HOCH_3$							50.5		
Δobs.	+10.5	-3.1		+0 2	-0.2		+8.6		
Δcal.	+10.6	-3.1		+0.2			+8.6		
$CH_3CH_2CH_2CH_2CH_2OCH_3$	73.5	30.5		29.5	23.5	14.6	58.7		
$CH_3CH_2CH_2CH_2CH_2OH$	63.2	33.6		29.4	23.8	15.3			
$HOCH_3$							50.5		
Δobs.	+10.3	-3.1		+0.1	-0.3	-0.7	+8.2		
Δcal.	+10.6	-3.1		+0.2			+8.6		
$CH_3CH_2CH_2OCH_2CH_3$	73.3	24.3		11.8			66.9	16.4	
$CH_3CH_2CH_2OH$	64.9	26.9		11.5					
$HOCH_2CH_3$							58.4	19.2	
Δobs.	+8.4	-2.6		+0.3			+8.5	-2.8	
Δcal.	+8.5	-2.7		+0.3			+8.6	-2.7	
$CH_3CH_2CH_2CH_2OCH_2CH_2CH_3$	71.5	33.1		20.7	15.0		73.5	24.2	11.8
$CH_3CH_2CH_2CH_2OH$	62.9	36.0		20.3	15.2				
$HOCH_2CH_2CH_3$							64.9	26.9	11 5
Δobs.	+8.6	-2.9		+0.4	-0.2		+8.6	-2.7	+0 3
Δcal.	+8.6	-2.7		+0.3			+8.6	-2.7	+0.3
$(CH_3)_2CHOCH_3$	74.1		22.9				56.4		
$(CH_3)_2CHOH$	64.7		26.5						
$HOCH_3$							50.5		
Δobs.	+9.4		-3.6				+5.9		
Δcal.	+9.2		-4.3				+5.9		
$CH_3CH_2(CH_3)CHOCH_3$	78.8	30.1	19.6	10.7			56.6		
$CH_3CH_2(CH_3)CHOH$	69.8	33.2	24.0	11.3					
$HOCH_3$							50.5		
Δobs.	+9.0	-3.1	-4.4	-0.6			+6.1		
Δcal.	+9.2	-3.1	-4.3	-0.5			+6.0		
$CH_3CH_2CH_2(CH_3)CHOCH_3$	77.3	39.9	20.0	19.7	15.2		56.5		
$CH_3CH_2CH_2(CH_3)CHOH$	68.1	42.8	24.6	20.2	15.4				
$HOCH_3$							50.5		
Δobs.	+9.2	-2.9	-4.6	-0.5	-0.2		+6.0		
Δcal.	+9.2	-3.1	-4.3	-0.5			+6.0		
$(CH_3)_3COCH_3$	73 6		28.2				50.1		
$(CH_3)_3COH$	69.9		32.7						
$HOCH_3$							50.5		
Δobs.	+3.7		-4.5				-0.4		
Δcal.	+3.7		-4.3				-0.4		
$(CH_3)_2CHOCH_2CH_2CH_3$	72.0		23.9				70.6	24.5	11.8
$(CH_3)_2CHOH$	64.7		26.5						
$HOCH_2CH_2CH_3$							64.9	26.9	11.5
Δobs.	+7.3		-2.6				+5.7	-2.4	+0.3
Δcal.	+7.2		-3 9				+5.9	-2.3	+0.4
[illegible]	78.9	29.8		20.6			73.7	24.1	11.8
[illegible]	70.2	32.0		20.4					
[illegible]							64.9	26.9	11.5
Δobs.	+8.7	-2.2		+0.2			+8.8	-2.8	+0.3
Δcal.	+8.6	-2.2		+0.3			+8.7	-2.7	+0 3
[illegible]	82.5	33 2		27.9			74.0	24.1	11.8
[illegible]	73.8	33.9		27.5					
[illegible]							64.9	26 9	11.5
Δobs.	+8.7	-0.7		+0.4			+9.1	-2.8	+0.3
Δcal.	+8.6	-0.7		+0.3			+8.8	-2.7	+0.3
$(CH_3)_2CHCH_2CH_2OCH_2CH_2CH_3$	70.2	39.9		26.3	23.8		73.5	24.2	11.9
$(CH_3)_2CHCH_2CH_2OH$	61.5	42.9		26.0	24.0				
$HOCH_2CH_2CH_3$							64.9	26.9	11.5
Δobs.	+8.7	-3.0		+0.3	-0.2		+8.6	-2.7	+0.4
Δcal.	+8.6	-2.7		+0.3			+8.6	-2.7	+0.3
$(CH_3)_2CHOCH_2CH(CH_3)_2$	72.2		23.1				76.0	30.0	20.4
$(CH_3)_2CHOH$	64.7		26.5						
$HOCH_2CH(CH_3)_2$							70.2	32.0	20 4
Δobs.	+7.5		-3.4				+5.8	-2.0	0
Δcal.	+7.3		-3.9				+5 7	-1.8	+0.4

in the alcohols as shown in the following empirical linear equation:

$$\delta_i = B_i + \sum_j n_j A_j \qquad (1)$$

where δ_i is the shielding of the ith carbon of an alkyl chain R or R' in an ether, B_i is the shielding of the ith carbon of the same alkyl group R or R' in the corresponding alcohol, n_j is the population factor at the jth position, and A_j is the additive substituent parameter for the jth carbon of the other introduced alkyl group R' or R. For the α-carbons of the ethers, $A_{\alpha'}$, $A_{\beta'}$, $A_{\gamma'}$, and $A_{\delta'}$ were found by a least-squares regressional analysis to be +10·6, −2·1, +0·1 and −0·1 ppm, respectively. The calculated values obtained from the eqn (1) using these parameters were in good correlation with the observed values ($\gamma = 0{\cdot}987$, n = 17). For the β-carbons, the calculated values obtained by using the calculated parameters $A_{\alpha'} = -3{\cdot}1$, $A_{\beta'} = +0{\cdot}4$ and $A_{\gamma'} = 0$ ppm, are in accord with reasonable accuracy with the observed ones ($\gamma = 0{\cdot}923$, n = 11). For the γ-carbons, a similar calculation led to the deduction of the $A_{\alpha'}$ and $A_{\beta'}$ as +0·2

and +0·1 ppm, respectively. However, the values were too small to obtain a good correlation coefficient (γ = 0·767, n = 8). It was clarified that the shieldings of the γ-carbons are practically predicted to appear upfield by 0·2–0·3 ppm as compared with those in the corresponding alcohols.

Branching of the alkyl chains appears to cause the deviation of the predicted values calculated using eqn (1) from the observed values for the α- and β-carbons. The reason for the failure of eqn (1) to predict the shieldings in the branched systems was considered to be due to differences of the substitution patterns of the introduced alkyls and of the observed carbons. As shown in Table 3, there is a definite trend to smaller substituent effects upon increasing alkyl substitution at a carbon in an ether, as has been found for the alkanes[4] and the alcohols.[5] For extension of this approach to the branched ethers, we derived a general expression of the following form:

$$\delta_i = B_i + \sum_j n_j A_j + \sum C_i \qquad (2)$$

where C_i is the additional correction parameter for the ith carbon due to special structural features (substitution patterns). The parameter C_i must be understood as the differences between the calculated shieldings obtained using eqn (1) and the observed shieldings. The result of the analysis of n-alkyl branched-alkyl ethers gave the parameters for α- and β-carbons as follows: C_α (when α-carbon is *tert.*) = −1·4, C_α (when α-carbon is *quat.*) = −6·9, C_α (when α'-carbon is *tert.*) = −0·5,† C_α (when α'-carbon is *quat.*) = −4·7, $C_{\beta CH_3}$ (when α-carbon is *tert.* or *quat.*) = −1·2, C_β (when β-carbon is *tert.*) = +0·5, C_β (when β-carbon is *quat.*) = +2·0, and $C_{\alpha \text{ or } \beta}$ (in other cases) = 0 ppm. In this way, the predicted carbon shieldings for the α- and β-carbons agree with the experimental data (γ = 0·998, n = 16 and γ = 0·969, n = 14, respectively). It should be noted that the large values are allotted for C_α when the α- and/or α'-carbons are tertiary or quaternary, and C_β gives the large values when the β-carbon is tertiary or quaternary and the β-carbon is primary and when the α-carbon is tertiary or quaternary. The discrepancy between the calculated value derived from eqn (2) and the observed value was found in the chemical shift of the β-carbon of methyl isopropyl ether. This is considered to originate from the less steric repulsion between a Me group in the isopropyl and the other alkyl (the Me in this case) since the β-carbons are both primary in the isopropyl, resulting in less displacement than the parameter (C_β = −1·2 ppm) for the primary β-carbon when the α-carbon is tertiary. In order to examine the validity of eqn (2) for dibranched alkyl ethers, the spectra of diisopropyl ether, isopropyl isobutyl ether, and diisobutyl ether were analysed and, it was found that the calculated values are in accord with the observed ones except for the shielding for the β-carbon of diisopropyl ether. This discrepancy must be due to the same reason as that for the β-carbon of methyl isopropyl ether (*vide supra*). The parameters C_γ, C_δ, etc. are negligible with the exception that C_γ is −0·7 ppm when the α-carbon is secondary.

The carbon shieldings in cyclic ethers next attracted our interest. The chemical shifts of the α-carbons of the cyclic ethers have been examined by Maciel and Savitsky[6] who found that the shielding of the α-carbon appearing at the highest region in the 3-membered ring ether and progressively moving towards lower field in the order of the 5-membered ring, 6-membered ring, and 4-membered ring ethers. A comparison of the ^{13}C shifts for the cyclic ethers with those for the corresponding glycols was now carried out. The data are listed in Table 4, from which it can be seen that, although no generality was found between the two sets of values, the α-, β- and γ-carbons in the cyclic ethers occur at lower, higher, and lower field, respectively, relative to the corresponding carbons in the

†α'-Carbon: it is present next to oxygen in the other alkyl R′ when an observed carbon is located in the alkyl R in the ethers ROR′.

Table 4. ^{13}C shieldings in cyclic ethers and corresponding glycols (ppm from TMS)

	α	β	γ
ethylene oxide	41.4		
ethylene glycol	64.6		
Δδ	-23.2		
triethylene oxide	72.9	23.7	
triethylene glycol	60.2	36.4	
Δδ	+12.7	-12.7	
tetrahydrofuran	68.7	27.0	
1,4-butanediol	63.0	30.3	
Δδ	+5.7	-3.3	
tetrahydropyran	69 5	28.1	25.1
1,5-pentanediol	63.1	33.7	23.5
Δδ	+6.4	-5.6	+1 6
dioxane	68.3		
ethylene glycol	64 6		
Δδ	+3.7		

Table 3. Methyl substituent effects on ^{13}C shieldings of ethers (ppm)

original subst.	substituted deriv.	Δδ α	Δδ β	Δδ γ
α-substitution				
CH_3OCH_3	$CH_3CH_2OCH_3$	+8.0		
$CH_3CH_2OCH_3$	$(CH_3)_2CHOCH_3$	+4.9		
$(CH_3)_2CHOCH_3$	$(CH_3)_3COCH_3$	-0.5		
β-substitution				
$CH_3CH_2OCH_2CH_2CH_3$	$CH_3CH_2CH_2OCH_2CH_2CH_3$	+6.8	+8.0	
$CH_3CH_2CH_2OCH_2CH_2CH_3$	$(CH_3)_2CHCH_2OCH_2CH_2CH_3$	+5.2	+5 4	
$(CH_3)_2CHCH_2OCH_2CH_2CH_3$	$(CH_3)_3CCH_2OCH_2CH_2CH_3$	+3.6	+3.8	
γ-substitution				
$CH_3CH_2CH_2OCH_2CH_2CH_3$	$CH_3CH_2CH_2CH_2OCH_2CH_2CH_3$	-2.2	+8.7	+8 9
$CH_3CH_2CH_2CH_2OCH_2CH_2CH_3$	$(CH_3)_2CHCH_2CH_2OCH_2CH_2CH_3$	-1.3	+6.8	+5.3

glycols as observed in the pairs of the acyclic ethers and the corresponding alcohols. The exception is the set of ethylene oxide and ethylene glycol, where the carbon resonance for the former appears at the abnormally higher field than that for the latter.

The effects of solute-solvent interactions on the ^{13}C shieldings in some ethers were next investigated in comparison with those in the corresponding alcohols. The results are collected in Table 5. In the following discussion the shifts in a solvent are relative to the shieldings in carbon tetrachloride. In pyridine, acetone, and dimethylsulfoxide, the upfield shifts of the α-carbons in the alcohols were found. There is a trend to greater the shifts upon increasing substitution at the carbinyl carbons. The β-carbons in the alcohols showed the upfield shifts in acetone, while those exhibited the downfield shifts by 0·3–0·9 ppm in dimethylsulfoxide and no or little shifts in pyridine. In contrast, a general trend was found that pyridine and acetone bring about the upfield shifts on both α- and β-carbons in the ethers. The solvent shifts for the α- and β-carbons in the ethers on passing to dimethylsulfoxide were small. From the above data it appears that a study of ^{13}C solvent shifts (in particular, that of the behaviors (shift differences) of the α- and β-carbons induced by dimethylsulfoxide) is a potentially informative approach to distinguish between alcohols and ethers. Another solvent tried, trifluoroacetic acid, causes large deshielding effects and large shielding effects on the signals for the α- and β-carbons in the alcohols, respectively, while it gives rise to less deshielding effects and less shielding effects on the signals for α- and β-carbons in the ethers, respectively. These shifts towards lower field induced by trifluoroacetic acid can be used to identify the resonances of β-carbons in alcohols and ethers.

On the basis of the foregoing results it might be reasonable to assume that a possible contribution to the solvent-induced shifts arise from H-bonding between the solutes and the solvents. It was then thought that solute-solute interactions through H-bonding might affect the ^{13}C shieldings if the solute were an alcohol. In order to examine this effect, the concentration dependencies of the ^{13}C shieldings in the alcohols and ethers were determined; the results are collected in Table 6. The variation of the ^{13}C shieldings in the alcohols and the ethers with the change of the concentrations in each of the solutes was found to be insignificant.

Next the ^{13}C shieldings in some glycols were examined in relation to those in the corresponding ethers. The chemical shifts of the carbons in glycols have already been reported by Brown[7] who showed that in $HO(CH_2)_nOH$ (n = 2–5) the observed values were in agreement with the calculated values within the deviation of 1 ppm. We have now calculated the ^{13}C shieldings in the glycols considering those as the ω-hydroxylated n-alcohols and using the substituent parameters proposed by Roberts *et al.*[5] The results are shown in Table 7. As is evident from Table 1, the observed values are in good accord with the calculated values in these glycols except for ethylene glycol in which, different from the result of Brown, the observed value is found to deviate by 2·8 ppm from the calculated value. This discrepancy for ethylene glycol is apparently due to the difference of the reference compounds, n-alkanes and n-alcohols, in both works. In order to confirm the abnormality of the ^{13}C shielding in 1,2-glycols, those in hexane-2,3-diols were investigated.

Table 6. Concentration effects on ^{13}C shieldings of ethers and alcohols (ppm from TMS)

	α	β		α	β
diethyl ether			ethanol		
0.3 M	66.9	16.7	0.3 M	58.9	19.8
1.0 M	66.9	16.7	1.0 M	58.6	19.5
3.0 M	66.9	16.6	3.0 M	58.5	19.4
diisopropyl ether			isopropanol		
0.3 M	69.2	24.4	0.3 M	64.9	26.6
1.0 M	69.1	24.3	1.0 M	64.9	26.7
3.0 M	69.0	24.0	3.0 M	64.7	26.6
tetrahydrofuran			tert.-butanol		
0.3 M	68.7	27.1	0.3 M	70.0	32.9
1.0 M	68.7	27.1	1.0 M	69.7	32.6
3.0 M	68.7	27.0	3.0 M	69.9	32.7

Table 5. Solvent effects on ^{13}C shieldings of ethers and alcohols (ppm)

	α		β			α		β	
	δ	Δδ	δ	Δδ		δ	Δδ	δ	Δδ
diethyl ether					ethanol				
carbon tetrachloride	66.9		16.4		carbon tetrachloride	58.4		19.2	
pyridine	66.4	-0.5	16.0	-0.4	pyridine	57.8	-0.6	19.4	+0.2
acetone	66.1	-0.8	15.7	-0.7	acetone	57.8	-0.6	18.7	-0.5
dimethylsulfoxide	66.7	-0.2	16.7	+0.3	dimethylsulfoxide	57.9	-0.5	20.1	+0.9
trifluoroacetic acid	66.9	0	13.7	-2.7	trifluoroacetic acid	65.8	+7.4	12.7	-6.5
diisopropyl ether					isopropanol				
carbon tetrachloride	69.2		24.3		carbon tetrachloride	64.7		26.5	
pyridine	68.7	-0.5	23.7	-0.6	pyridine	63.8	-0.9	26.5	0
acetone	68.7	-0.5	23.4	-0.9	acetone	63.8	-0.9	25.7	-0.8
dimethylsulfoxide*					dimethylsulfoxide	63.8	-0.9	27.0	+0.5
trifluoroacetic acid	72.6	+3.4	21 8	-2.5	trifluoroacetic acid	68.0	+3.3	23.2	-3.3
tetrahydrofuran					tert.-butanol				
carbon tetrachloride	68.7		27.0		carbon tetrachloride	69.9		32.7	
pyridine	68.4	-0.3	26.5	-0.5	pyridine	68.3	-1.6	32.3	-0.4
acetone	68.2	-0.5	26.3	-0.7	acetone	68.4	-1.5	30.8	-1.9
dimethylsulfoxide	68.9	+0.2	26.9	-0.1	dimethylsulfoxide	68.8	-1.1	33.0	+0.3
trifluoroacetic acid	68.7	0	25.5	-1.5	trifluoroacetic acid	74.5	+4.6	27 1	-5.6

*undeterminable since the solute and the solvent are not miscible.

Table 7. ^{13}C shieldings in glycols (ppm from TMS)

		α	β	γ	δ	ε	ζ
$HOCH_2CH_2OH$	obs.	64.6	64.6				
	cal.	68 6	67.5				
$HOCH_2CH_2CH_2OH$	obs.	60.2	36 4	60.2			
	cal.	59.1	37.1	59.8			
$HOCH_2CH_2CH_2CH_2OH$	obs.	63 0	30.3	30.3	63.0		
	cal.	63.2	30 2	30.5	63.5		
$HOCH_2CH_2CH_2CH_2CH_2OH$	obs.	63.1	33.7	23.5	33.7	63.1	
	cal.	63.3	33.9	23.6	34.0	63.6	
erythro-$CH_3(\underset{OH}{CH})_2(CH_2)_2CH_3$	obs.	17.5	72.0	77.0	36.8	20.7	15.5
threo-"	obs.	20 3	71.8	75.9	35.9	20.7	15.5
(from n-hexane)	cal.	19.9	75.1	80.2	36.4	19 4	14.4
(from hexan-2-ol)	cal.	20.9	75.9	80.9	37.2	20.3	15.6
(from hexan-3-ol)	cal.	20.9	74.2	81.1	37.1	20.4	15.7

As shown in Table 7, the abnormality (deviation of the observed values from the calculated ones) of the shieldings of the carbinyl carbons was also found in this case using either n-hexane or n-hexanol as the reference compound.

We next examined the ^{13}C shieldings of cyclic glycols. Perlin and Koch[8] have studied the cyclohexane glycols and noted a large deviation between the observed values and the calculated values. The situation is rather complex, since the conformations of the cyclohexane glycols are flexible and the exact application of the substituent parameters is difficult. In order to clarify the differences between the ^{13}C shieldings in the polycarbocyclic glycols and those in the corresponding alcohols and in order to examine the availability of the substituent parameters, we determined the ^{13}C spectra of cholestane-3β,5α-diol, cholestane-3β,6α-diol, cholestane-3β,6β-diol, cholestane-3β,5α,6α-triol, and cholestane-3β,5α,6β-triol in which the conformations of the carbocycles are rigid and the configurations (axial and equatorial) of the hydroxyls are obvious. The assignments for the carbons in these compounds follow from the result for cholestan-3β-ol.[9] Signals predicted to move by the introduction of a hydroxyl(s) at C-5 and/or C-6 were those for C-1 to C-11 and C-19. Identification of the other carbons was made on the basis of the chemical shift considerations coupled with the results of off-resonance experiments. Although the chemical shifts of the C-11 and C-19 signals varied slightly, the assignments were readily performed because there were no other confusable signals. The assignments for C-3 carbons were easily carried out based on the following prediction that the C-3 resonances occur at lower field region because they are the carbinyl carbons, and when an OH is introduced into C-5 the resonance shows an +3·5 to +3·0 ppm shift. Since it is considered that the shieldings of C-2 carbons remain essentially constant by the introduction of an OH into C-5 or C-6, the methylene signals whose chemical shifts are consistent with the C-2 resonance in cholestan-3β-ol were assigned to C-2 carbons. On the other hand, introduction of an OH into C-5 or C-6 is expected to cause the downfield shifts by approximate 40 ppm and 4–10 ppm of the signals of the carbon in question and the vicinal carbons, respectively. Therefore, the assignments for C-5 and C-6 were readily performed by locating the signals showing such behavior. Next, C-10 is the only quaternary carbon and was easily assigned by off-resonance experiment. Off-resonance decoupling further permitted the allocation of the yet unassigned signals to C-1, C-4 and C-7. Based on the carbon resonances in cholestan-3β-ol, the C-4 signal and the C-1 and C-7 signals are thought to move towards lower-field and higher-field, respectively, when an OH is introduced into C-5, and the C-4 signal and C-7 signal are considered to show an upfield shift and a downfield shift, respectively, if C-6 is hydroxylated. The expected behavior permitted the assignments for the methylene carbons in question. The C-8 and C-9 resonances were easily pointed out by off-resonance experiment since these carbons are tertiary. The distinction between the two methine carbon signals was carried out by their different behavior that the C-8 or C-9 resonance shifts upfield relative to the corresponding resonance in cholestan-3β-ol when an OH is introduced into C-6 or C-5, respectively. The assignments are collected in Table 8. In these five substances, all the C-19 resonances are found to appear at lower field than the C-19 resonance in cholestan-3β-ol. This finding is quite interesting because a shielding usually exhibits an upfield shift when an OH is introduced into either γ- or δ-position.

After the completion of the assignments for all the carbon resonances in these five substances, comparison of the chemical shifts of the diols with the calculated values derived from the shieldings of cholestan-3β-ol as the reference and the additive substituent parameters for the additional OH ($\alpha = 37{\cdot}8$, $\beta = 5{\cdot}5$, $\gamma = -6{\cdot}8$ and $\delta = -0{\cdot}7$ ppm for an axial OH, and $\alpha = 43{\cdot}3$, $\beta = 7{\cdot}3$, $\gamma = -1{\cdot}3$ and $\delta = -1{\cdot}4$ ppm for an equatorial OH[5]) was first carried out (Table 9). In cholestane-3β,5α-diol, it was found that the observed C-3, C-5 and C-9 resonances deviate to a great extent from the calculated values. For the C-3 resonance, the occurence at a lower field region than the calculated value is expected since the C-3 carbon together with the C-5 carbon constitute a 1,3-glycol system.[8] As for the deviation of the shielding for C-5, the substituent parameter (37·8 ppm) used for the calculation of its resonance is originally alloted for the case when an OH is introduced into a secondary carbon and, therefore, the deviation is due to the introduction of an OH into the tertiary carbon where the parameter is much smaller as mentioned above. The discrepancy between the observed and calculated values for the C-9 resonance may be explained by the much larger steric interaction between the C-5 OH and the C-9 hydrogen than that between an axial OH and the hydrogen on the β-carbon in simple cyclohexanols as the reference substance since the ring system of the parent substance is rigid, causing an upfield shift of the signal. In cholestane-3β,6α-diol, the good agreement between the calculated and observed chemical

Table 8. ^{13}C shieldings in cholestanols (ppm from TMS)

carbon No.	cholest-an-3β-ol	cholestane-3β,5α-diol	cholestane-3β,6α-diol	cholestane-3β,6β-diol	cholestane-3β,5α,6α-triol	cholestane-3β,5α,6β-triol
1	37.5	31.9*	38.8*	39.7	26.7	32.5
2	32.4	32.5*	32.9	33.0	31.1	33.4
3	70.6	67.1	69.5	71.8	67.4	67.6
4	39.2	45.9	37.3*	36.5	43.3	42.1
5	45.3	74.4	53.4	49.0	78.8	76.0
6	29.2	35.5	71.7	71.8	72.0	76.3
7	32.4	26.8	43.5	41.3	36.8	35.8
8	35.8	35.6	35.4	31.5	34.6	31.3
9	54.7	45.9	55.1	55.5	43.8	46.0
10	35.8	39.6	34.2	36.5	41.9	39.2
11	21.6	22.1	22.3	22.0	22.5	22.0
12	40.4	40.9	40.9	40.9	40.6	40.8
13	42.9	43.3	43.3	43.4	43.3	43.2
14	56.7	56.9	57.4	57.2	56.8	56.8
15	24.4	24.8	24.9	25.0	24.6	24.7
16	28.5	28.9	29.1	29.0	28.7	28.7
17	56.7	56.9	57.4	57.2	56.8	56.8
18	12.5	12.7	13.0	12.7	12.6	12.6
19	12.3	16.5	14.4	16.6	18.0	17.3
20	36.1	36.4	36.8	36.5	36.5	36.3
21	19.0	19.2	19.7	19.4	19.2	19.2
22	36.5	36.8	37.3	37.0	36.8	36.6
23	24.2	24.5	24.9	24.8	24.6	24.4
24	39.8	40.0	40.5	40.3	40.1	39.9
25	28.2	28.5	28.5	28.6	28.7	28.4
26	22.7	23.1	23.4	23.3	23.0	22.9
27	22.9	23.1	23.4	23.3	23.3	22.9

* The assignments of the asterisked signals are ambiguous and might have to be reversed.

Table 9. Deviations of ^{13}C shieldings in cholestanediols (ppm)

carbon No.	cholestane-3β,5α-diol cal.	$\Delta^{obs.-cal.}$	cholestane-3β,6α-diol cal.	$\Delta^{obs.-cal.}$	cholestane-3β,6β-diol cal.	$\Delta^{obs.-cal.}$
1	30.7	+1.2	36.1	+2.7	36.8	+2.9
2	31.7	+0.8	32.4	+0.5	32.4	+0.6
3	63.8	+3.3	69.2	+0.3	69.9	+1.9
4	44.7	+1.2	37.9	-0.6	32.4	+4.1
5	83.1	-8.7	52.6	+0.8	50.8	-1.8
6	34.7	+0.8	72.5	-0.8	67.0	+4.8
7	25.6	+1.2	39.7	+3.8	37.9	+3.4
8	35.1	+0.5	34.5	+0.9	29.0	+2.5
9	47.9	-2.0	53.3	+1.8	54.0	+1.5
10	41.3	-1.7	34.5	-0.3	36.4	+0.1

shifts for all the carbons was found with the exception for C-1 and C-7. However, the discrepancy for C-1 and C-7 cannot be reasonably explained at the moment. When a carbon was hydroxylated at the bridgehead position of the *trans* fused rings (5α) or at the other position so as to make the OH be equatorial (6α), the conformation is considered to be essentially invariable, when the observed values and the calculated values appear to be in good accord. The considerable differences between the observed and calculated values of the shieldings for C-1–C-10 in cholestane-3β,6β-diol, may reflect the conformational change of the B-ring due to the steric repulsion between the C-6 OH and the C-19 Me. Here the reason for the occurrence of the C-5 signal at a higher field as compared with the calculated shielding is unknown.

The substituent parameters of the 5α-, 6α-, and 6β-hydroxyls on C-1–C-10, calculated from the shieldings in cholestane-3β,5α-diol, cholestane-3β,6α-diol, and cholestane-3β,6β-diol using those in cholestan-3β-ol as the reference, are listed in Table 10. The predicted chemical shifts for cholestane-3β,5α,6α-triol and cholestane-3β,5α,6β-triol were calculated using the

Table 10. Hydroxyl substituent effects on ^{13}C shieldings of cholestan-3β-ol (ppm)

carbon No.	5α-effect	6α-effect	6β-effect
1	-5.6	+1.3	+2.2
2	+0.1	+0.5	+0.6
3	-3.5	-1.1	+1.2
4	+6.7	-1.9	-2.7
5	+29.1	+8.1	+3.7
6	+6.3	+42.5	+42.6
7	-5.6	+11.1	+8.9
8	-0.2	-0.4	-4.3
9	-8.8	+0.4	+0.8
10	+3.8	-1.6	+0.7

Table 11. Deviations of ^{13}C shieldings in cholestanetriols (ppm)

carbon No.	cholestane-3β,5α,6α-triol cal	$\Delta^{obs.-cal.}$	cholestane-3β,5α,6β-triol cal.	$\Delta^{obs.-cal.}$
1	33.2	-6.5	34.1	-1.6
2	33.0	-1.9	33.1	+0.3
3	66.0	+1.4	68.3	-0.7
4	44.0	-0.7	43.2	-1.1
5	82.5	-3.7	78.1	-2.1
6	78.0	-6.0	78.1	-1.8
7	37 9	-1.1	35.7	+0.1
8	35.2	-0.6	31.3	0
9	46.3	-2.5	46.7	-0.7
10	38.0	+3.9	40.3	-1.1

shieldings of the reference substance cholestan-3β-ol and the substituent parameters thus obtained which are shown in Table 11. Concerning cholestane-3β,5α,6α-triol, the calculated values are in accord with the observed within 2·5 ppm except for C-1, C-5, C-6 and C-10. The reasons for the discrepancy in C-1 and C-10 are unknown. In C-5 and C-6, the observed values are shifted 3·5 and 6·0 ppm upfield from the calculated ones, respectively. These shifts are comparable with the trend previously noted in some 1,2-glycols, confirming the abnormality of the chemical shifts of the carbinyl carbons in *cis*-1,2-glycols also in a polycarbocyclic system. On the other hand, in cholestane-3β,5α,6β-triol, it was found that the calculated chemical shifts are consistent with the observed ones within 2·1 ppm. Indeed, as for the shieldings of the carbinyl carbons C-5 and C-6 in question, the deviations of the observed values from the calculated ones are less than the corresponding ones in the 3β,5α,6α-triol. From the above results, it may be concluded that, even in 1,2-glycols, those in which the two hydroxyls are situated in the 1,2-*trans*-diaxial relationship show a little abnormality in the chemical shifts of the carbinyl carbons. On the basis of these findings, therefore, the abnormality (deviation of the observed values from the calculated values) of the ^{13}C resonances of the carbinyl carbons in certain 1,2-glycols is significant when the dihedral angles between the two hydroxyls are small, which may be considered to be due to intramolecular H-bonding, steric repulsion, and/or dipolemoment interaction between the hydroxyls.

EXPERIMENTAL

For measurements of ^{13}C resonances, a JEOL PS-100 NMR spectrometer, equipped with a PFT-100 pulsed-Fourier transform spectrometer and ^{13}C accessories (including an SD-HC heteronucleus spin decoupler), was used in combination with a JEC-980A spectrum computer. The operating frequency for ^{13}C resonance was 25 MHz and that for ^{2}H resonance as internal lock 15 MHz. An 8 mmϕ sample tube was used. The samples were dissolved in CCl_4 (50% soln) except for the glycols. The hexane derivatives and the cholestane derivatives were dissolved in C_5D_5N. In the case of solvent-induced shift study, 3 M solution was used. Measurement conditions are as follows: temp. 28°; pulse width, 11 μsec (*ca.* 45°); repetition time, 2 sec; spectral width, 6·25 kHz; data points, 8192; delay time, 120 μsec. Noise modulated proton decoupling was carried out at a normal power level of 30 W. Off resonance spectra were obtained by offsetting the decoupling single frequency using an offset of 0·7-1 kHz at a power level of 5 W. Peak positions were computer-calculated on digitized frequency spectra from the sampling rate of free induction decay. The chemical shifts were expressed in ppm downfield from tetramethyl silane (TMS) as internal reference.

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