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SHORT INTRAMOLECULAR OH...π - ELECTRON DISTANCES IN RIGID POLYCYCLIC STRUCTURES

Synthesis and IR-spectroscopic study of tetracyclo[5.3.0.0.^{2,5}.0.^{4,8}]dec-9-en-3-ol and the 3-methyl derivative.

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Abstract. Two strained bridgehead cage alcohols with a very short intramolecular OH...π distance, tetracyclo[5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol and its 3-methyl derivative, have been synthesized. The IR spectra have been studied and discussed in relation to the starting ketone tetracyclo[5.3.0.^{2,5}.0.0.^{4,8}] dec-9-en- 3-one.

Considerable attractive OH-proton...π-electron interaction on the one hand and repulsive steric and oxygen-lone-pair...π forces on the other hand lead to a position of the hydroxyl bond, practically parallel to the double bond. Non-bonding proton..proton interaction in the 3-methyl compound causes increased C-H stretching frequencies of the alkyl groups involved. The IR-data of the ketone confirms the presence of non-bonding π-orbital interaction and shows the C=O vibration is subject to Fermi resonance .

INTRODUCTION

The enzymatic hydration of an isolated double bond is a known phenomenon but still not completely understood . The origin of the process is supposed to be induced by the presence of a hydroxyl group in the near vicinity of the double bond [1,2].

Models to study intramolecular olefinic hydration can be found in structures where the hydroxyl group is forced into a position close to an isolated bond by either strong steric hindrance [1] or ring strain [3].

The small intramolecular distance between the OH and the double bond in such molecules is attended with a considerable OH...π interaction.

Infrared spectroscopy has proved to be a valuable tool in the analysis of OH...π interaction [4-7] and in the determination of the orientation of the hydroxyl in the molecule.

In view of the suspected involvement of the hydroxyl group in the mechanism of olefinic hydration a vibrational study of strained cage alcohols with a short OH...double bond distance is of particular interest and may enlarge the insight into this process.

EXPERIMENTAL

Preparation of compounds.

Compound I : tetracyclo[5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-one was prepared by a described procedure [8].
Compound II : endo-tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol.

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A solution of ketone I (0.5 g, 3.4 mmol) in ether (10 ml) was added to a suspension of $LiAlH_4$ (0.15 g, 3.9 mmol) in ether (50 ml). After stirring at room temperature for 30 min., diluted HCl aq. was added until a neutral solution was obtained. The ether phase was washed with H_2O, dried ($MgSO_4$) and concentrated to give alcohol II as a white solid (96%). Recrystallization from hexane or sublimation in vacuo gave analytically pure II, m.p. 130-133^o (closed capillar). δ (CCl_4) 1.65 (s, 2H, H6, H6'), 2.2-2.7 (m, 5H, cage protons), 3.0 (s, 1H, cage proton), 3.4 (s, 1H, OH), 3.9 (s, 1H, H3), 6.4 (s, H9, H10); m/e: 148.0888. Calc. for $C_{10}H_{12}O$: 148.0894 (found: C, 79.5; H, 8.1% ; $C_{10}H_{12}O$ requires : C, 81.04; H, 8.16%).

Compound III : exo-3-methyl tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol.

To a stirred solution of I (0.15 g., 1 mmol) in ether (10 ml) at -78^{o}C, was added MeLi (1.55 M in ether, 2 ml, 3.1 mmol). After stirring for 0.5 h at -78^o, the solution was slowly warmed up to room temperature, concentrated $NaHCO_3$ aq. was added, the organic phase separated and the water layer extracted with ether. The organic layers were dried ($MgSO_4$) and concentrated to give alcohol III as an oil (75%). Purification by destillation in vacuo increased the purity to 92%. GLC showed this alcohol to be contaminated with a minor amount of the starting ketone I. δ ($CDCl_3$) 1.3 (s, 3H, CH_3), 1.6 (s, 2H, H6, H6'), 2.4-3.1 (m. 6H, cage protons), 5.1 (s, 1H, OH), 6.6 (s, 2H, H9, H10); m/e: 162.1046; calc. for $C_{11}H_{14}O$: 162.1045.

Infrared spectra.

Vapour phase : heatable gold-coated gas cell 100^o C, KBr windows pathlength 10 cm. Solid state: KBr pellet Ø 13 mm. Liquid phase: neat film between NaCl-windows. Solutions: 0.2 mm NaCl cells. Separately the OH-stretching region was recorded in dilute solution (CCl_4 and CS_2) in 10 mm "Infrasil" cells.

Spectra were recorded on a Perkin-Elmer model 1710 (FT-IR) connected to a Perkin-Elmer 3600 data station. Resolution 1.0 cm^{-1}, accuracy 1.0 cm^{-1}.

MM2-calculations.

Energy minimizations were carried out using Allinger's MM2P program based on QCPE 395 and QCPE 400 (TRIBBLE version). Written by Y.H. Yuh; updated by D.C. Rohrer (1984). The programs were run using CHEMX (Chemical Design Ltd., Oxford, U.K.) as installed at the CAOS/CAMM Center, University of Nijmegen, The Netherlands.

RESULTS AND DISCUSSION

The geometrical structures of the ketone I and the alcohols II and III, calculated by means of MM2, are shown in Fig.1 and the vapour phase IR spectra are presented in Fig.2. The observed frequencies are summarized in Table 1.

The C-H vibrations.

As can be seen from Figure 1 the molecular structure of the compounds is to a large extent the same. The frequencies of the corresponding $-CH_2-$ and six -C-H groups should be almost identical in consequence. In the C-H stretching region the complex band in the vapour phase spectra at 2999-2940 cm^{-1} is assigned to a summation of the overlapping -C-H stretching and the asymmetric $-CH_2-$ stretching vibrations, and the 2874 and 2870 cm^{-1} peaks to the symmetric $-CH_2-$ stretching mode .

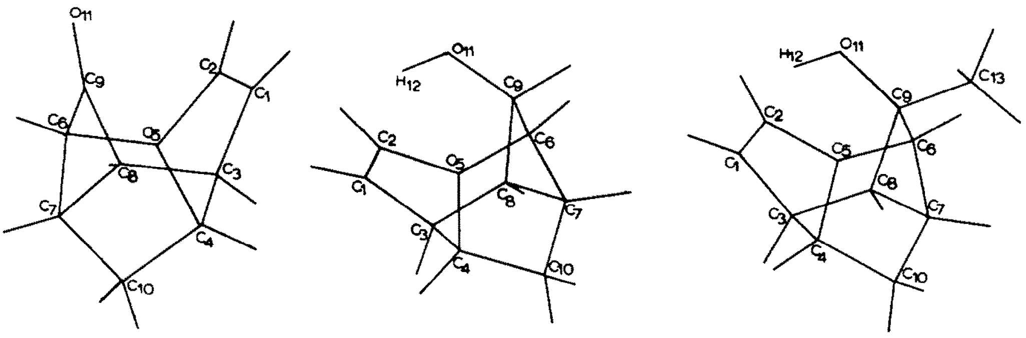
As can be seen from Table 1 some of the -C-H stretching frequencies of the alcohols are slightly lower than those of the parent ketone which points to a (partially) decreased ring strain in the former [9]. In the vapour phase the band maxima at 3019 cm^{-1} and 2955 cm^{-1} are assigned to the asymmetrical and symmetrical CH_3-stretching vibration respectively for the following reasons:

(i) both are absent in the spectra of I and II,

(ii) the frequency of ν_s CH_3 is usually 50-60 cm^{-1} lower than that of ν_{as} CH_3 [10],

(iii) would the 2955 cm^{-1} peak originate from ν_{as}, then ν_s should have been found at about 2900 cm^{-1}.

Indeed the frequencies 3019 and 2955 cm^{-1} are rather high but can be explained, referring to the literature [9,11,12], by a non-bonding interaction of the methyl- and the opposing -C-H proton as result of a short intramolecular H...H distance . The MM2 calculated distance of 2.18 Å endorses this explanation. The stretching frequency of the opposing -C-H group will be increased for the same reason and therefore the



I II III

Figure 1. MM2 calculated geometrical structures of tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-one (I), endo-tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol (II) and exo-3-methyl tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol(III).

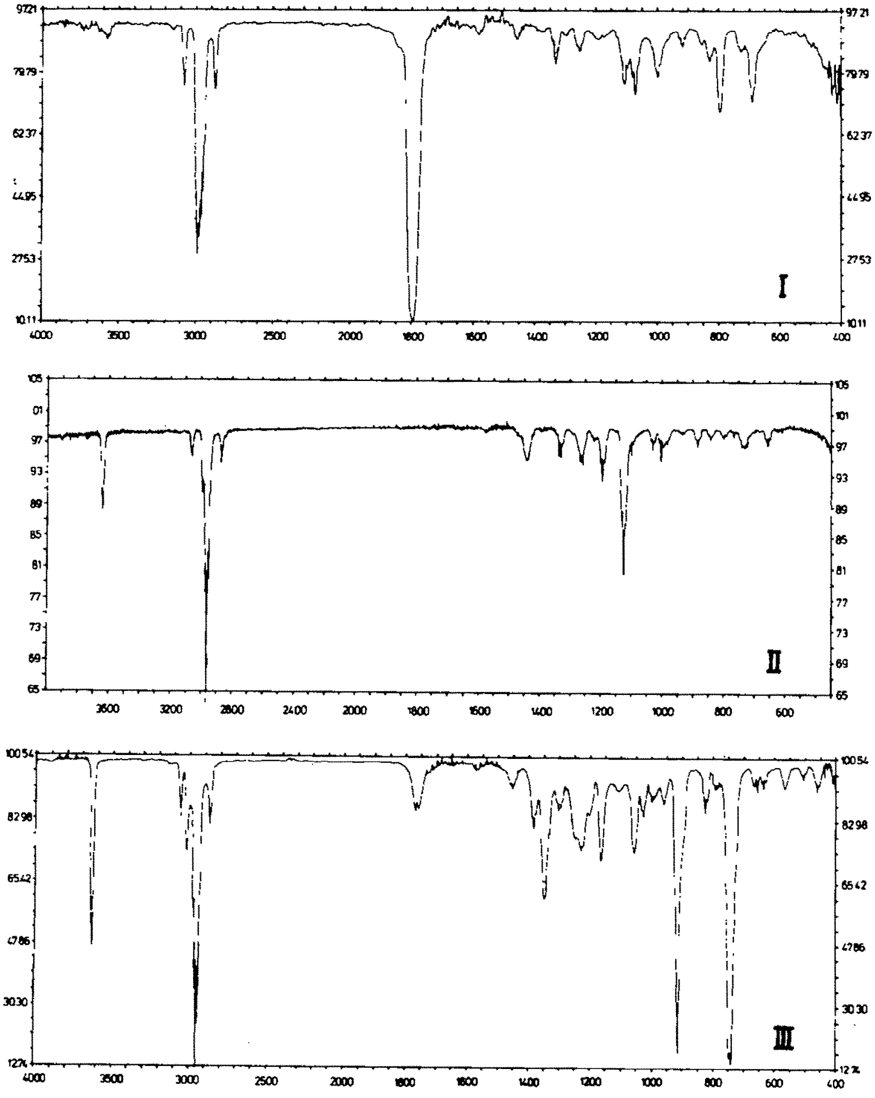


Figure 2. IR vapour phase spectra of tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-one(I), endo-tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol (II) and exo-3-methyl tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}] dec-9-en-3-ol(III).

peak at vapour phase frequency of 2975 cm^{-1} ,which is absent in the spectrum of II, is assigned accordingly. In the bending region the -CH$_2$- scissor deformation is assigned to the bands around 1450 cm^{-1} and the -C-H bendings to the maxima around 1335 cm^{-1} .

According to the vibrational analysis of cyclobutanol by Durig and Green [13], the α-C-H in plane deformation absorbs in the same region which explains the presence of a second peak in the spectrum of II.

The same study revealed the α-C-H out-of-plane at about 927 cm^{-1}. In the vapour phase spectrum of the secondary alcohol no peak is discernable in this region. However in CCl$_4$ solution a weak band is present at 930 cm^{-1} which we assign to this bending vibration.

The peak at 1383 cm^{-1} in the IR spectrum of the tertiary alcohol III is assigned to the characteristic symmetric CH$_3$ deformation.

ketone I		alcohol II		alcohol III	
gas	CCl$_4$	gas	CCl$_4$	gas	CCl$_4$
		3639	3598	3632	3589
3075	3067	3059	3053	3059	3052
				3019	3012
2999					
2988		2990		2975	
2977	2972	2969		2969	
2963		2963	2957	2962	
				2955	2949
		2949		2947	
		2940		2940	
2874	2866	2870	2861	2870	2861
1796	1794				
	1769				
	1576		1570		1570
	1452	1443	1435	1454	1450
				1383	1380
				1349	1347
1333	1328	1337	1335	1335	1330
		1330	1328		
	1293		1288	1304	1302
			1263		
1252	1250	1258	1255		1256
			1217	1229	1219
	1184	1193	1190		1197
				1164	1158
1107	1110	1124	1115	1109	1101
			1111		
		1098			
1070	1072		1079	1056	1055
		1030	1026	1026	1025
998	997	1003	1001	1000	998
	978		990		982
	961		980	959	956
920	921		930	913	908
	856	884	883		
	831		841	826	826
	816		722	793	
794			748		
690				742	
		655		655	
				635	

Table 1. Observed IR-frequencies for tetracyclo[5.3.3.0.0^{2,5}.0^{4,8}] dec-9-en-3-one (I), endo-tetracyclo [5.3.0.0.^{2,5}.0.^{4,8}]dec-9-en-3-ol (II), and exo-methyl- tetracyclo[5.3.0.0^{2,5}.0^{4,8}]dec-9-en-3-ol 3-methyl (III) . Dimensions in cm^{-1}.

The C=C and =C-H vibrations.

Referring to Bellamy [6] the C=C stretching frequency of endocyclic double bonds falls on increasing ring strain and on fusion with additional rings, predominantly due to the increased p-character of the carbon-carbon orbits of the ring whereas $\nu_{=C\text{-}H}$ often increases as the olefinic protons take proportionally more s-character. Therefore the observed low C=C frequencies (1576 and 1570 cm^{-1}) confirm a considerable ring strain in all molecules but the frequency shifts of the C=C and =C-H stretching vibrations seem contradictory in determining which molecule has the largerst ring strain. On the one hand the C=C frequency of the ketone is 6 cm^{-1} higher than those of the alcohols thus pointing to a smaller strain in the former, on the other hand the =C-H stretching frequencies of the alcohols are decreased thus indicating the opposite.

The MM2-calculated molecular energies also suggest ketone I to be somewhat more relaxed (67.4 Kcal/mole against 69.5 Kcal/mole for compound II and 72.3 Kcal/mole for III). But, it must be noted that (i) the calculated differences are too small to be decisive, and (ii) these energies count for the complete molecule while the observed frequency shifts represent local differences in ring strain.

A decreased C=C frequency in the alcohols as result of intramolecular OH..π interaction is rejected as such effect is presumed to be very small [9].

However, as recently has been demonstrated [14], the spatial proximity of the olefinic and the carbonyl π-system in the ketone, is attended with a considerable orbital interaction. Obviously this interaction also affects the C=C (and C=O) vibration , and therefore the higher C=C frequency in the ketone may as well be the result of this interaction and not of a smaller ring strain.

The apparently affected C=O stretching vibration agrees with this . Due to the lack of vapour phase C=O references solution-data had to be used. The individual gas phase band (1796 cm^{-1}) appears to be a solvent sensitive doublet in solution (band maxima in CCl_4 : 1794 and 1769 cm^{-1}).

Referring to Bellamy and Williams [15] the solvent sensitivity of the intensity ratio and the frequencies, point to Fermi resonance. Only the lower frequency band showed the regular shift and pattern of carbonyl compounds [15] (see Table 2) and so we conclude that this one is the C=O fundamental and that the high frequency component is the result of Fermi resonance.

	ν_1	ν_2	A_1/A_2	$\Delta\nu$
gas	1796			
hexane	1794	1777	3	17
CCl_4	1794	1769	7	25
CS_2	1793	1768	8	25
CH_3CN	1795	1762	14	33

Table 2. Solvent sensitivity in the C=O stretching region: ν_1 and ν_2 are the bandmaxima, A_1/A_2 is the intensity ratio difference and wavenumber difference as result of Fermi resonance. Dimensions in cm^{-1} except A_1/A_2 which is dimensionless.

The 1796 cm^{-1} value is low for a fused cyclobutanone [16] and the decrease can only to a small extent be attributed to a smaller ring strain or to the effect of Fermi resonance. Thus another factor also decreases the C=O frequency , in our opinion the earlier mentioned π-orbital interaction .

Little is known about the =C-H out-of-plane vibration of this type of double bond. Potts and Nyquist [17] reported the absence of this mode in many spectra of cis-double bond compounds because of a small changing of the dipole moment. The weak band(s) in the region around 700 cm^{-1} most likely originate from this fundamental .

The C-O vibrations.

The strong band at 1124 cm^{-1} in the spectrum of II is assigned, in accordance with the vibrational analysis of cyclobutanol [13], to the C-O stretching vibration. In tertiary alcohols this fundamental usually increases in frequency and decreases in intensity and for that reason the 1349 cm^{-1} band in the spectrum of III is assigned to this mode.

The C-O bending vibrations are found in the region 700-400 cm^{-1} but these have not been studied.

The O-H vibrations.

The OH-deformation is often strongly coupled with the C-O stretching vibration and thus less suitable to study the orientation of the hydroxyl.

The OH stretching vibration however has proved to be a sensitive probe for local molecular interactions [4-7] and a useful tool to determine the position of the OH in the molecule. Would there be no ring strain effects nor any steric and electric interactions then two different OH-positions can be discerned (Figure 3);

(a) staggered with respect to the α- C-H (II) or α- C-CH_3 axis (III) and/or

(b) 120° rotated

Taking into account van der Waals and Coulomb interactions, the MM2 program calculates two other positions ;

(c) anti to the double bond (Figure 3c) as the most favourable for both II and III, (molecular energies 69.5 Kcal/mole and 72.3 Kcal/mole respectively), and

(d) virtually parallel to the C=C (Figure 4d) as a local minimum (energy 71.1 Kcal/mole for II and 73.1 Kcal/mole for III).

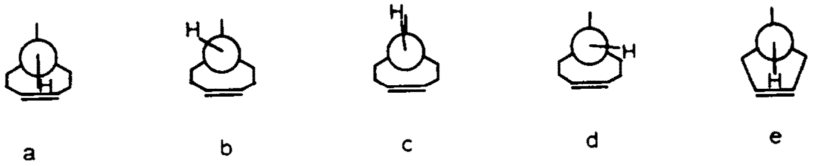


Figure 3. Newman projection of the possible OH-positions in endo-tetracyclo $[5.3.0.0.^{2,5}.0.^{4,8}]$ dec-9-en-3-ol and exo-3-methyl tetracyclo $[5.3.0.0.^{2,5}.0.^{4,8}]$ dec-9-en-3-ol (a,b,c,d) and the OH-orientation in norbornadienol-7 (e).

The bandshape, the symmetry and the halfbandwidth of the observed OH-stretching band of II and III, in the vapour phase as well as in solution clearly point to the presence of only one OH-position. The observed OH-streching frequencies of 3598 and 3589 cm^{-1} (CCl_4-solution) are clearly decreased compared to the data of saturated cyclobutanols (a range of 3625.5-3615.0 cm^{-1} for primary, secondary and tertiary compounds [18]) whereas the intensities of 34.1 (alcohol II) and 42.0 km/mol (alcohol III) are considerably increased (13.7-17.8 km/mol for saturated cyclobutanols [18].). This definitely indicates that OH...π interaction is involved and thus excludes the positions (b) and (c). This is endorsed by the very small solvent induced frequency shift $\nu_d(=\nu CCl_4-\nu CS_2)$ of 1.0 cm^{-1}(II) and 0 cm^{-1} (III) [4], and also by the OH-band in the spectra of the pure samples which is to a large extent "free" and not intermolecularly bridged .

Both point to an orientation where the OH is shielded from intermolecular interactions by its local environment i.e. positions (a) or (d).

MM2-calculations on the conformers (a) and (d) reveal a substantially higher molecular energy for (a) (alcohol II : 78.5 Kcal/mole, alcohol III : 82.7 Kcal/mole) and an extremely short distance between the hydroxyl proton and the double bond C-atoms (alcohol II : 1.866 Å , alcohol III : 1.817 Å) making position (a) highly improbable therefore.

This is endorsed by the OH-frequencies of 3639 cm^{-1} (alcohol II) and 3632 cm^{-1} (III) which are dramatically higher than for norbornadien-7-ol (frequency 3586.5 cm^{-1}[19]) and the unsaturated polycyclic alcohol as described by Ganter et al [3] (frequency 3555 cm^{-1}). In the latter the OH is in a position as drawn in Figure 3e, comparable to position (a) but with a larger OH-proton...π distance. However in these molecules the considerably decreased OH-frequencies confirm the presence of strong OH...π interaction.

All together we conclude that the OH is not in position (a) but in (d) or one very much alike.

The precise position of the hydroxyl bond (exactly parallel to C=C or slightly rotated) is difficult to define as the effect of the OH...π interaction on the OH-vibration depends on the angle O-H...π and the distribution of the negative charge over the double bond. Therefore we propose that the O-H bond in the alcohols II and III is oriented either parallel to the C=C axis, or slightly twisted in that direction.

CONCLUSIONS

Summarizing the results for these strained cage alcohols we conclude:

(i) a considerable ring strain is present in all compounds,

(ii) the ring strain in the ketone is somewhat larger than in the corresponding alcohols ,

(iii) the non-bonding π-orbital interaction in the ketone is confirmed by the IR-spectroscopic data,

(iv) the C=O stretching band in the ketone is subject to Fermi resonance,

(v) a considerable non-bonding proton...proton interaction in alcohol III causes an increase of the C-H stretching frequencies of the $-CH_3$ and -C-H groups involved,

(vi) the position of the OH in the alcohols II and III is almost parallel to the double bond.

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