NMR Spectroscopic, Molecular Mechanics and X-Ray Crystallographic Studies of Performic Acid Oxidation Products of 4-, 5- and 6-Methylbicyclo[2.2.1]hept-5-en-2-ones†

E. Kolehmainen,* K. Laihia, K. Rissanen, J. Korvola and V. Niemi

Department of Chemistry, University of Jyväskylä, P.O. Box 35, SF-40351 Jyväskylä, Finland

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Structures of 5- (**1**) and 8-methyl-2-oxabicyclo[3.3.0]oct-7-en-3-one (**4**), *exo,exo*-7,8-dihydroxy-5-methyl- (**2**), *exo,endo*-7,8-dihydroxy-5-methyl- (**3**), *exo,endo*-7,8-dihydroxy-*exo*-8-methyl- (**5**) and *endo,endo*-7,8-dihydroxy-*exo*-8-methyl-2-oxabicyclo-[3.3.0]octan-3-one (**6**) and of *exo*-5-hydroxy-*endo*-5-methyl- (**7**), *exo,exo*-5,6-dihydroxy-*endo*-5-methyl- (**8**) and *exo,anti*-5,7-dihydroxy-4-methylbicyclo[2.2.1]heptan-2-one (**9**) have been elucidated using ^{1}H and ^{13}C NMR spectroscopy, molecular mechanics (MM) calculations and X-ray diffraction. While 4- and 6-methylbicyclo[2.2.1]hept-5-en-2-ones gave, on treatment with performic acid, rearranged bicyclic lactones **1–6**, the 5-methyl isomer formed bicyclo[2.2.1]heptan-2-one alcohols **7–9**. Comparison of $^3J_{H,H}$ coupling constants and MM results suggests, for compounds **5** and **6**, preferred *exo* and *endo* conformations, respectively. For lactones **2** and **3** both *endo* and *exo* forms should be taken into account in reproducing the experimental NMR data.

Lactone **3** crystallizes in the monoclinic space group $P2_1/c$ (No. 14) with cell dimensions: a = 11.132(2), b = 10.027(1), c = 7.539(1) Å, β = 100.25(1)° and V = 828.0(2) Å^3 with Z = 4. Full-matrix least-squares refinement of 115 parameters gave R = 0.036 for 654 reflections [$I>3\sigma I$]. The cyclopentane ring of lactone **3** in the crystal has an *endo* conformation and there is no O···C=O interaction between the *endo* oxygen O(8) and carbonyl carbon C(3). Lactone **5** crystallizes in the monoclinic space group $P2_1/n$ (No. 14, non-standard) with cell dimensions: a = 12.021(4), b = 10.236(2), c = 6.607(1) Å, β = 98.95(2)° and V = 803.0(4) Å^3 with Z = 4. Full-matrix least-squares refinement of 115 parameters gave R = 0.033 for 634 reflections [$I>3\sigma I$]. The cyclopentane ring of lactone **5** in the crystal has an *exo* conformation and a moderate O···C=O interaction between the *endo* oxygen O(8) and carbonyl carbon C(3) exists, the intermolecular O···C=O distance being 3.089(3) Å.

Our previous work focused on the performic acid oxidation of 1-methylbicyclo[2.2.1]hept-5-en-2-one (1-methylnorborn-5-en-2-one, henceforth abbreviated as 1-MNB).[1] The only reaction products observed were three rearranged bicyclic lactone diols, which could all be classified as Baeyer–Villiger (B–V) type reaction products.[1] Similar lactones were also expected in the present peroxidation reactions of 4-, 5- and 6-MNBs. In contrast with the behavior of 4- and 6-methyl isomers, however, 5-MNB gave bicyclo-[2.2.1]heptanone alcohols as the only reaction products.

In order to clarify these substituent-dependent differences in the reaction mechanism, the stereostructures of all of the reaction products were elucidated as fully as possible. Because the bicyclic lactone diols possess a conformationally non-rigid cyclopentane moiety,[1] NMR spectroscopy alone was not sufficiently reliable to determine the stereochemistry and the conformational preferences of all derivatives obtained. Therefore, molecular mechanics calculations and X-ray crystallographic studies were also performed.

Experimental

Preparation of compounds **1–9**. Racemic mixtures of the starting compounds, 4-, 5- and 6-MNB, were synthesized by a known method[2,3] and oxidized with performic acid as described earlier.[4] The reaction mixtures were separated by flash chromatography: 55 mm × 350 mm Kieselgel 60 (mesh 230–400) column and light petroleum (b.p. 40–60 °C)–acetone (7:5, v:v) as the eluent. The separation of the compounds was monitored by gas chromatography. The relative distribution of compounds **1**, **2** and **3** starting from 4-MNB was 14, 29 and 57 %, compounds **4**, **5** and **6** from 6-MNB 7, 63 and 30 % and compounds **7**, **8** and **9** from 5-MNB 29, 39 and 32 %, respectively. The compounds were recrystallized from ethanol. Their purities were checked by gas chromatography and their structures were verified by mass spectrometry, IR spectrometry, ^{1}H and ^{13}C NMR spectroscopy and for compounds **3** and **5** also by X-ray diffraction analysis.

NMR, IR and mass spectra and molecular mechanics calculations. The ^{1}H and ^{13}C NMR spectra were recorded with a JEOL GSX 270 MHz FT NMR spectrometer at 30 °C for

* To whom correspondence should be addressed.

† Part 2: for Part 1. see Ref. 1.

0.1–0.5 M solutions in pyridine-d_5. In all ^{1}H NMR measurements the digital resolution was < 0.1 Hz, the number of scans was 8 and the flip angle was 90°. In addition, the spectra of compounds **2** and **7** were measured at 400 MHz with a Bruker WB 400 FT NMR spectrometer, because their ^{1}H NMR resonances at 270 MHz overlapped too strongly to be analyzed reliably. In ^{13}C NMR experiments, the digital resolution of the proton-noise-decoupled ^{13}C NMR spectra was < 1.0 Hz and the number of scans was 400–800 (for compound **1** ca. 5000 scans were needed for a reliable spectrum owing to its low concentration). For fully coupled ^{13}C NMR spectra the digital resolution was < 0.3 Hz and number of scans was ca. 10000 (for compound **1**, 30000 scans were needed to obtain the $^1J_{C,H}$ coupling constants reliably). To improve the signal-to-noise ratio in the frequency spectra all FIDs were exponentially windowed by a factor of the digital resolution. All chemical shifts are referenced to internal tetramethylsilane (TMS). IR spectra were recorded with a Perkin–Elmer 283 IR spectrometer as KBr wafers (1:200 mg). The mass spectra were recorded with a Varian MAT 212 spectrometer working at an ionization potential of 70 eV.

The second-order ^{1}H NMR spectra were analyzed by means of the iterative programs MAOCON[5] and MLDC8[6] using a VAX 8650 computer at the Computer Center of the University of Jyväskylä. Molecular mechanics (MM) calculations were performed using the program PCMODEL[7] with default force constants on a Hewlett-Packard Vectra QS/16S personal computer.

Table 1. Experimental crystallographic data for **3** and **5**.

Compound	**3**	**5**
Formula	$C_8H_{12}O_4$	$C_8H_{12}O_4$
M_r	172.18	172.18
a/Å	11.132(2)	12.021(4)
b/Å	10.027(1)	10.236(2)
c/Å	7.539(1)	6.607(1)
α/°	90	90
β/°	100.25(1)	98.95(2)
γ/°	90	90(1)
V/Å^3	828.0(2)	803.04(4)
Z	4	4
d_{calc}/Mg m^{-3}	1.381	1.424
μ/mm^{-1}	0.104	0.107
λ/Mo K_α	0.71073	0.71073
F(000)	368	368
Space group	$P2_1/c$ (No. 14)	$P2_1/n$ (No. 14, non-std.)
T/K	296±1	296±1
Crystal size/mm	0.20×0.22×0.24	0.15×0.20×0.20
Refl. for latt. meas.	25	25
θ range for latt. meas./°	5–12	4–17
Scan method	ω/2θ	ω/2θ
Scan speed/° min^{-1}	1–6	1–7
Scan width (ω)/°	0.5 + 0.34 tanθ	0.8 + 0.34 tanθ
θ range/°	2–20	2–20
h range	−1 → 7	−1 → 11
k range	−1 → 9	−1 → 9
l range	−10 → 10	−6 → 6
Variation of std. refl.	None	None
Refl. measured	1140	1040
Number of unique refl.	767	750
Condition of obs. refl.	I>3.0σ(I)	I>3.0σ(I)
Refl. used in refinement	654	634
Max. shift/error	<0.01	<0.01
No. of param.	115	115
Max. in final Δρ/e Å^{-3}	0.16	0.25
R_{int}	0.030	0.019
R	0.036	0.033
R_w	0.047	0.043
Chebychev coefficients	1.93, 1.15, 1.16	8.68, −0.859, 6.83

$w = w' \cdot [1.0 - (\Delta F/6\,\sigma F)^2]^2$, where w' = Chebychev polynomial for F_c.

Crystal structure analysis of lactones **3** *and* **5**. The crystal data and experimental parameters for the data collections are given in Table 1.* The lattice parameters were determined by measuring 25 reflections using Mo K_α (λ = 0.71073 Å) radiation at room temperature (296 K). Intensity data were collected on an Enraf–Nonius CAD4 diffractometer using Mo K_α radiation and ω/2θ scan mode. The intensity data were corrected for Lorentz and polarization effects but not for extinction. An empirical absorption correction was applied according to Walker and Stuart[8] for both data sets, the maximum and minimum correction coefficients being 1.184 and 0.946 for lactone **3** and 1.225 and 0.776 for lactone **5**, respectively. The structures were solved by direct methods using the SHELXS program.[9] The final refinements were carried out by full-matrix least-squares using the CRYSTALS program,[10] anisotropically for all non H-atoms. The hydroxylic hydrogen atoms were located from a ΔF map and refined with a fixed isotropic temperature factor (U = 0.08 Å^2) whilst the residual H-atoms were calculated to their idealized positions and refined as riding atoms with a fixed isotropic temperature factor (U = 0.08 Å^2). The atomic scattering factors were taken from Ref. 11. The final coordinates are quoted in Table 2.* In addition to quoted programs the PLUTO[12] program was used. The crystallographic calculations were performed on a micro-VAX 3100 computer at the Department of Chemistry, University of Jyväskylä.

Results and discussion

The structures of the starting compounds and their performic acid oxidation products **1–9** are illustrated in Schemes 1–3. The reaction mechanisms leading to these different groups of compound are presented for compounds **1–6** in our previous paper[1] and for compounds **7–9** in Scheme 3. In the case of 4- and 6-MNB the reaction mechanism is very similar with that of the performic acid oxidation of the 1-methyl isomer.[1] The 4- and 6- isomers both include a B–V type reaction,[13] with a regioselective oxygen insertion and migration of the allylic bridgehead

* Lists of structure factors, calculated H-atom coordinates and anisotropic temperature factors may be obtained from one of the authors (K.R.) on request.

Table 2. Fractional coordinates and equivalent isotopic temperature factors[a] for compounds **3** and **5** with e.s.d.s in parentheses.

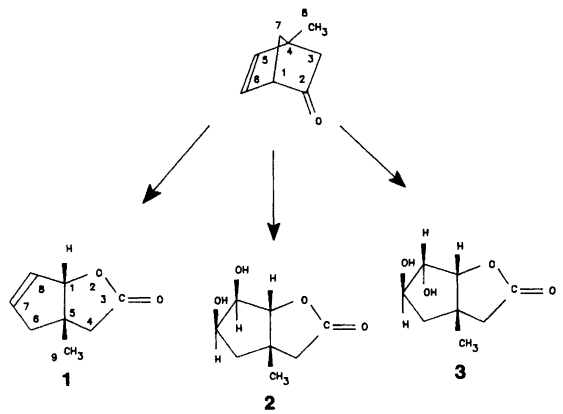
Atom	*x/a*	*y/b*	*z/c*	*U*(iso)
Compound **3**				
O(2)	0.6984(2)	0.1825(2)	0.1640(3)	0.0427
O(3)	0.5012(2)	0.1782(3)	0.0473(4)	0.0674
O(7)	0.9399(2)	−0.1501(2)	0.1439(3)	0.0470
O(8)	0.9490(2)	0.1535(2)	0.1447(3)	0.0410
C(1)	0.7803(3)	0.1257(3)	0.3182(4)	0.0343
C(3)	0.5833(3)	0.1369(3)	0.1597(5)	0.0439
C(4)	0.5802(3)	0.0404(3)	0.3072(4)	0.0403
C(5)	0.7135(2)	0.0045(3)	0.3792(4)	0.0316
C(6)	0.7595(3)	−0.1149(3)	0.2788(4)	0.0420
C(7)	0.8448(3)	−0.0583(3)	0.1597(4)	0.0352
C(8)	0.8905(2)	0.0693(3)	0.2543(4)	0.0318
C(9)	0.7386(3)	−0.0165(3)	0.5830(4)	0.0458
H(7)	0.970(4)	−0.128(4)	0.060(5)	0.08
H(8)	0.979(3)	0.211(4)	0.195(5)	0.08
Compound **5**				
O(2)	0.0165(2)	0.3264(2)	−0.1175(3)	0.0348
O(3)	0.0570(2)	0.5132(2)	−0.2585(3)	0.0467
O(7)	0.1670(2)	−0.0085(2)	0.1997(4)	0.0439
O(8)	0.1357(2)	0.3384(2)	0.2640(3)	0.0331
C(1)	0.0739(2)	0.2084(3)	−0.0381(4)	0.0314
C(3)	0.0868(3)	0.4054(3)	−0.1960(4)	0.0317
C(4)	0.1993(3)	0.3440(3)	−0.1954(4)	0.0370
C(5)	0.1890(2)	0.2069(3)	−0.1120(4)	0.0316
C(6)	0.2752(2)	0.1687(3)	0.0780(4)	0.0331
C(7)	0.2039(2)	0.1237(3)	0.2355(4)	0.0328
C(8)	0.0993(2)	0.2089(3)	0.1976(4)	0.0279
C(9)	0.0015(3)	0.1667(3)	0.3000(5)	0.0448
H(7)	0.227(3)	−0.060(3)	0.207(5)	0.08
H(8)	0.076(3)	0.388(4)	0.258(5)	0.08

[a] $U(\text{iso}) = [U(11) \times U(22) \times U(33)]^{1/3}$.

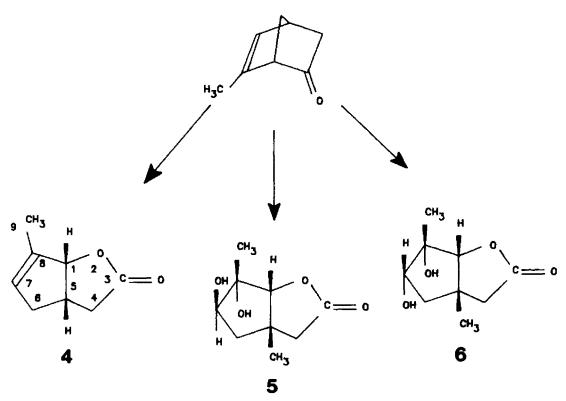
position. This gives first a rearranged, unsaturated lactone, **1** or **4**, depending on the starting ketone. The carbon–carbon double bond is, however, oxidized further and the reaction products are lactone diol monoformates, which on saponification give the lactone diols **2** and **3** from 4-MNB and **5** and **6** from the 6-MNB. Secondary *exo*-7-hydroxy 8-carbocation (the 7-hydroxy group is on the same side of the cyclopentane ring as the methyl group) would give both lactones **2** and **3** from the unsaturated lactone **1**, while other cations or epoxy intermediates would give only one of the two reaction products. When the unsaturated lactone **4** is further oxidized, a tertiary *exo*-7-hydroxy-8-methyl 8-carbocation would give lactone **5** and *endo*-7-hydroxy-8-methyl 8-carbocation would give lactone **6** as reaction products.

In the case of 5-MNB, the peroxidation reaction proceeds via mechanisms presented in Scheme 3. If the reaction starts with an electrophilic attack of a proton at the carbon–carbon double bond, the reaction will continue with an attack of formate anion on the tertiary 5-carbocation. After saponification the reaction product will be compound **7**. If the attacking electrophile is, however, the hydroxylium ion (HO^+) as is usual in the performic acid oxidations,[4] the reaction product would be a tertiary *exo*-6-hydroxy 5-carbocation. This intermediate can react as such with the formate anion to give (after saponification) compound **8** or, after Wagner–Meerwein (W–M) rearrangement compound, **9**. The W–M rearrangement is a fast and well known reaction of the bicyclo[2.2.1]heptyl cation. The contrasting behavior of 5-MNB compared with 1-, 4- and 6-MNBs in these peroxidation reactions can, at least partly, be explained by the greater stability of the tertiary carbocation intermediate. The reaction can be considered as kinetically controlled by the rapid cation formation before the oxygen insertion reaction happens, which would give the bicyclic lactone diols as end products.

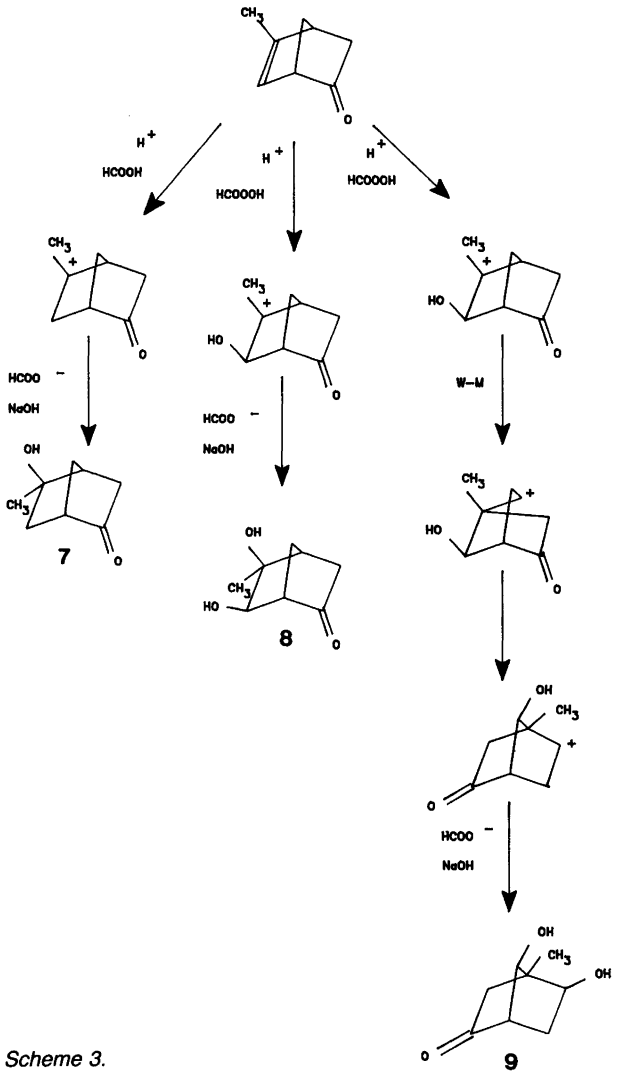
^1H and ^{13}C NMR spectroscopy and molecular mechanics calculations. The ^1H NMR chemical shifts and $^nJ_{H,H}$ coupling constants for the lactones **1–6** are presented in Tables 3 and 4. The ^1H NMR chemical shifts and $^nJ_{H,H}$ coupling constants for bicyclo[2.2.1]heptanone alcohols **7–9** are presented in Tables 5 and 6. The ^{13}C NMR chemical shifts and $^1J_{C,H}$ coupling constants for the lactones **1–6** are presented in Tables 7 and 8. The ^{13}C NMR chemical shifts and $^1J_{C,H}$ coupling constants for bicyclo[2.2.1]heptanone alcohols **7–9** are presented in Tables 9 and 10.



Scheme 1.



Scheme 2.



Scheme 3.

The ^{1}H and ^{13}C NMR data of two groups of compounds **1–6** and **7–9** immediately reveal their structural differences. For example the ^{13}C NMR chemical shifts of the carbonyl carbons in compounds **1–6** vary from 176.5 to 178.9 ppm and in compounds **7–9** from 212.4 to 216.1 ppm, respectively. The former range is characteristic of carboxylic acids, their esters and lactones and the latter of aldehydes and ketones.

The well-known relationship between vicinal coupling constants $^{3}J_{H,H}$ and the inter-proton dihedral angles[14] was used in order to clarify the stereostructures of the isomeric lactone diols **2**, **3**, **5** and **6**. In Table 11 are collected the dihedral angles between vicinal protons in the MM-optimized structures of the lactone diols **2**, **3**, **5** and **6**, the calculated[14] and experimental $^{3}J_{H,H}$ coupling constants together with the corresponding X-ray crystallographic dihedral angles for compounds **3** and **5**.

In addition to NMR spectroscopy, molecular mechanics (MM) calculations were utilized in the determination of the stereochemistry and conformational preferences of the lactone diols **2**, **3**, **5** and **6**. Because the cyclopentane ring can

Table 3. ^{1}H NMR chemical shifts for lactones **1–6**.

Proton	δ (ppm)					
	1	**2**	**3**	**4**[a]	**5**	**6**
H(1)	4.94	4.67	4.78	5.1	5.00	4.87
H(4A)	2.46	2.58	2.54	2.8	2.81	2.90
H(4B)	2.56	3.04	2.77	2.2	2.54	2.70
H(5)	–	–	–	2.9	3.07	3.18
H(6A)	2.31	2.30	2.35	2.5	2.25	2.73
H(6B)	2.13	2.16	1.89	2.0	2.23	1.86
H(7)	5.87	4.64	4.61	5.4	4.44	4.35
H(8)	5.72	4.65	4.48	–	–	–
CH_3	1.09	1.35	1.31	1.7	1.70	1.85

[a]Not iterated because of 10 coupled spins.

Table 4. $^{n}J_{H,H}$ coupling constants for lactones **1–6**.

Coupling	$^{n}J_{H,H}$/Hz					
	1	**2**	**3**	**4**[a]	**5**	**6**
1,5	–	–	–	7.5	8.55	7.59
1,6a	2.32	–	–	–	–	–
1,6b	1.21	–	–	–	–	–
1,7	0.55	1.17	–	–	–	1.31
1,8	2.09	1.38	4.29	–	–	–
4a,4b	−17.95	−18.07	17.90	17.9	−18.02	−18.14
4a,5	–	–	–	10.6	11.23	11.58
4b,5	–	–	–	5.6	6.39	3.66
5,6a	–	–	–	–	10.25	9.26
5,6b	–	–	–	8.0	4.84	1.72
5,7	–	–	–	2.4	–	0.30
6a,6b	−17.29	−13.34	−13.51	17.0	−13.40	−13.51
6a,7	2.33	4.83	5.86	2.4	2.62	4.37
6a,8	2.24	–	–	–	–	–
6b,7	2.27	3.56	4.88	–	5.13	1.36
6b,8	2.25	1.12	–	–	–	–
7,8	5.86	2.84	4.85	–	–	–

[a]Not iterated because of 10 coupled spins.

Table 5. ^{1}H NMR chemical shifts for alcohols **7–9**.

Proton	δ (ppm)		
	7[a]	**8**	**9**
H(1)	2.6	2.69	2.68
H(3*n*)	2.0	2.76	1.90
H(3)	2.0	1.91	1.95
H(4)	2.4	2.45	–
H(5*n*)	–	–	3.82
H(6*n*)	1.6	4.00	2.18
H(6*x*)	2.0	–	2.31
H(7*a*)	2.3	2.33	–
H(7*s*)	1.7	1.73	4.04
CH_3	1.4	1.60	1.39

[a]Not iterated because of eight coupled spins.

Table 6. $^{n}J_{H,H}$ coupling constants for alcohols **7–9**.

Coupling	$^{n}J_{H,H}$/Hz		
	7[a]	**8**	**9**
1,3*n*	–	0.58	–
1,3*x*	–	1.29	1.06
1,4	1.6	2.06	–
1,6*n*	–	0.78	0.56
1,6*x*	5.3	–	5.35
1,7*a*	1.6	0.81	–
1,7*s*	1.6	1.51	0.80
3*n*,3*x*	–	−17.60	−18.61
3*n*,7*a*	–	4.38	–
3*n*,4	–	0.55	–
3*x*,4	4.7	4.67	–
4,7*a*	1.6	2.08	–
4,7*s*	1.6	1.50	–
5*n*,6*n*	–	–	7.16
5*n*,6*x*	–	–	2.64
5*n*,7*s*	–	–	1.71
6*n*,6*x*	−13.8	–	−14.27
6*n*,7*s*	2.4	2.39	0.75
7*a*,7*s*	−10.5	−10.76	–

[a]Not iterated because of eight coupled spins.

exist in both *endo* and *exo* conformations,[1] eight different structures need to be optimized for both pairs of isomeric diols. MM calculations reveal two predominant structures from the eight possible forms of the isomer pair **5** and **6**, in which the calculated $^{3}J_{H,H}$ coupling constants are in reasonable agreement with the experimental $^{3}J_{H,H}$ coupling constants. These structures are an *exo* conformer of *exo,endo*-7,8-dihydroxy-*exo*-8-methyl-2-oxabicyclo[3.3.0]octan-3-one **5** (also present in crystalline state) and an *endo* conformer of *endo,endo*-7,8-dihydroxy-*exo*-8-methyl-2-oxabicyclo-[3.3.0]octan-3-one **6**, respectively. For the isomer pair **2** and **3**, the situation is more complex and any single conformer alone does not correspond unambiguously to the experimental NMR data. In these cases, a statistical mean value of the calculated $^{3}J_{H,H}$ coupling constants for an *endo–exo* conformer pair should be used instead of that of

Table 7. ^{13}C NMR chemical shifts for lactones **1–6**.

Carbon	δ (ppm)					
	1	**2**	**3**	**4**	**5**	**6**
C(1)	95.0	96.5	91.2	91.6	89.2	91.7
C(3)	176.5	177.6	178.0	177.1	178.9	178.2
C(4)	43.0[a]	44.9	45.4	36.3	37.6	37.7
C(5)	44.1	43.7	41.6	35.7	34.4	36.2
C(6)	46.3[a]	47.0	46.3	38.8	40.4	40.6
C(7)	137.4[a]	82.0	76.2	129.9	79.2	80.1
C(8)	129.0[a]	78.2	77.8	138.2	79.8	81.4
CH_3	25.0	28.3	28.5	13.9	20.3	19.9

[a]Assignment not unambiguous.

Table 8. $^{1}J_{C,H}$ for lactones **1–6**.

Coupling	$^{1}J_{C,H}$/Hz					
	1	**2**	**3**	**4**	**5**	**6**
C(1),H(1)	158.0	156.3	155.7	158.1	156.8	158.4
C(4),H(4)	129.9	135.2	132.7	133.8	132.8	133.5
C(5),H(5)	–	–	–	139.6	134.8	137.2
C(6),H(6)	130.2	128.5	129.1	131.1	130.5	130.0
C(7),H(7)	167.6	146.6	144.6	161.3	146.9	147.1
C(8),H(8)	165.9	146.2	145.2	–	–	–
C(9),H(9)	127.2	126.2	125.8	126.5	125.9	126.2

one conformer to reproduce the experimental NMR coupling constants. The present MM calculations predict, that, in compounds **2** and **3**, the *endo* form is somewhat preferred over the *exo* form in solution as well as in the crystalline state of compound **3**.

Based on the fact that the approach of peroxy acids to norbornanes takes place predominantly from the less hindered *exo* side,[15] the stereochemistry of the compounds **7–9** should be as illustrated in Scheme 3. In order to ascertain their stereochemistry, the fully coupled ^{13}C NMR spectra of both diastereoisomers of 2-methylbicyclo[2.2.1]heptan-2-ols (2-methylnorborneols)[16,17] have been measured. The coupled methyl signal (characterized by two couplings of 124.5 and 4.4 Hz) of *endo*-2-methylnorborneol shows a very similar pattern to the compounds **7** (124.5 and 3.7 Hz)

Table 9. ^{13}C NMR chemical shifts for alcohols **7–9**.

Carbon	δ (ppm)		
	7	**8**	**9**
C(1)	51.5	62.0	56.7
C(2)	216.0	216.1	212.4
C(3)	40.5	40.3	47.6
C(4)	48.7	48.3	48.9
C(5)	75.5	79.9	76.1
C(6)	42.9	80.5	35.3
C(7)	36.7	35.0	80.4
CH_3	25.9	24.5	13.7

Table 10. $^{1}J_{C,H}$ in Hz for alcohols **7–9**.

Coupling	$^{1}J_{C,H}$/Hz		
	7	**8**	**9**
C(1),H(1)	148.9	148.9	148.9
C(3),H(3)	136.2	133.1	130.0
C(4),H(4)	142.3	144.0	–
C(5),H(5)	–	–	150.8
C(6),H(6)	131.9	148.9	134.9
C(7),H(7)	133.1	136.1	148.9
C(8),H(8)	124.5	126.4	125.7

Table 11. X-Ray crystallographic dihedral angles for compounds **3** and **5**, MM dihedral angles for compounds **2**, **3**, **5** and **6** and their calculated and experimental $^3J_{H,H}$ NMR coupling constants.

Lactone	Dihedral angle/° and $^3J_{H,H}$/Hz between protons								
	1,5	1,8	4A,5	4B,5	5,6A	5,6B	6A,7	6B,7	7,8
2									
MM (*endo*)	–	88	–	–	–	–	165	45	42
^3J/MM (*endo*)	–	−0.3	–	–	–	–	10.4	6.3	2.9
MM (*exo*)	–	149	–	–	–	–	77	40	45
^3J/MM (*exo*)	–	3.6	–	–	–	–	0.7	4.6	4.0
^3J/NMR	–	1.4	–	–	–	–	4.8	3.6	2.8
3									
X-Ray	–	39	–	–	–	–	142	21	−150
MM (*endo*)	–	31	–	–	–	–	165	45	163
^3J/MM (*endo*)	–	5.5	–	–	–	–	10.4	6.3	6.1
MM (*exo*)	–	36	–	–	–	–	84	32	74
^3J/MM (*exo*)	–	4.7	–	–	–	–	0.9	5.9	−0.9
^3J/NMR	–	4.3	–	–	–	–	5.9	4.9	4.9
5									
X-Ray	10	–	−2	−123	4	125	80	−42	–
MM	15	–	19	142	11	130	84	34	–
^3J/MM	9.4	–	9.2	8.2	10.1	6.2	0.9	5.6	–
^3J/NMR	8.6	–	11.2	6.4	10.3	4.8	2.6	5.1	–
6									
MM	4	–	3	118	27	91	43	75	–
^3J/MM	9.0	–	10.4	4.2	8.1	1.1	4.6	0.8	–
^3J/NMR	7.6	–	11.6	3.7	9.3	1.7	4.4	1.4	–

and **8** (216.4 and 3.2 Hz), as in fenchones,[18] while *exo*-2-methylnorborneol shows a more complex coupling pattern characterized with coupling constants of 124.5, 6.2 and 2.8 Hz and some additional small couplings.

Crystal structure analysis of lactones **3** *and* **5**. Bond distances and angles for **3** and **5** are given in Table 12. A view of the molecules **3** and **5** with numbering schemes are presented in Fig. 1 and 2.

An intramolecular interaction between the *endo* oxygen and the carbonyl carbon is often present in *cis*-2-oxabicyclo[3.3.0]octan-3-one derivatives. This type of incipient nucleophilic attack on the electrophilic carbon atom is defined as an O···C=O interaction and occurs readily when sterically possible. This type of interaction has been observed in other similar *cis*-2-oxabicyclo[3.3.0]octan-3-one derivatives.[1] In lactone **3**, the interaction is not present owing to the unfavourable stereochemistry (Fig. 1), the intramolecular O···C=O distance being > 3.50 Å. The *endo* conformation of the cyclopentane moiety in lactone **3** makes it sterically unfavourable for an O···C=O interaction to occur, whereas the *exo* conformation of the cyclo-

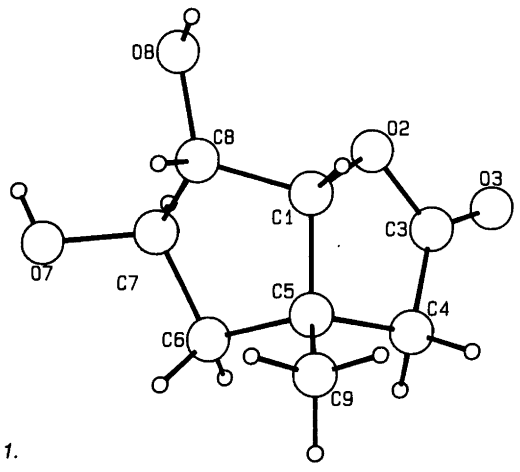


Fig. 1.

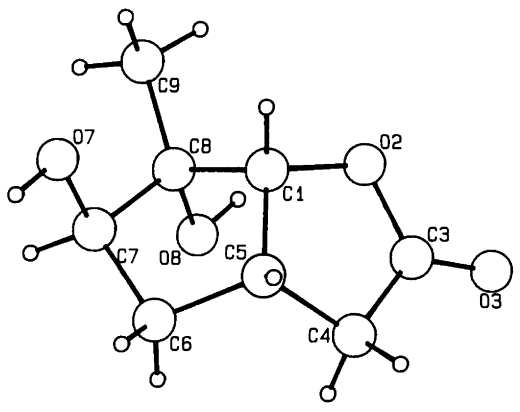


Fig. 2.

Table 12. Bond distances (Å) and angles (°) for compounds **3** and **5** with e.s.d.s in parentheses.

	3	**5**
O(2)–C(1)	1.459(4)	1.449(3)
O(2)–C(3)	1.355(4)	1.331(4)
O(3)–C(3)	1.204(4)	1.212(4)
O(7)–C(7)	1.424(3)	1.432(4)
O(7)–H(7)	0.81(4)	0.89(4)
O(8)–C(8)	1.417(3)	1.443(3)
H(8)–C(8)	0.75(4)	0.89(4)
C(1)–C(5)	1.536(4)	1.538(4)
C(1)–C(8)	1.506(4)	1.539(4)
C(3)–C(4)	1.479(5)	1.429(4)
C(4)–C(5)	1.530(4)	1.520(4)
C(5)–C(6)	1.551(4)	1.548(4)
C(5)–C(9)	1.527(4)	–
C(6)–C(7)	1.527(4)	1.518(4)
C(7)–C(8)	1.509(4)	1.519(4)
C(8)–C(9)	–	1.508(4)
C(3)–O(2)–C(1)	110.0(2)	110.7(2)
C(7)–O(7)–H(7)	108(3)	109(2)
C(8)–O(8)–H(8)	112(3)	108(2)
C(5)–C(1)–O(2)	106.3(2)	107.1(2)
C(8)–C(1)–O(2)	108.7(2)	111.9(2)
C(8)–C(1)–C(5)	105.3(2)	105.9(2)
O(3)–C(3)–O(2)	119.8(3)	120.9(3)
C(4)–C(3)–O(2)	110.5(3)	111.9(3)
C(4)–C(3)–O(3)	129.6(3)	127.2(3)
C(5)–C(4)–C(3)	105.6(2)	105.4(3)
C(4)–C(5)–C(1)	101.5(2)	103.5(2)
C(6)–C(5)–C(1)	104.2(2)	105.4(2)
C(6)–C(5)–C(4)	113.1(2)	116.4(2)
C(9)–C(5)–C(1)	113.5(2)	–
C(9)–C(5)–C(4)	112.4(3)	–
C(9)–C(5)–C(6)	111.5(2)	–
C(7)–C(6)–C(5)	107.1(2)	104.8(2)
C(6)–C(7)–O(7)	111.0(2)	111.5(2)
C(8)–C(7)–O(7)	113.3(2)	106.7(2)
C(8)–C(7)–C(6)	103.3(2)	104.7(2)
C(1)–C(8)–O(8)	116.6(2)	108.3(2)
C(7)–C(8)–O(8)	112.4(2)	105.9(2)
C(7)–C(8)–C(1)	104.1(2)	101.2(2)
C(9)–C(8)–O(8)	–	110.3(2)
C(9)–C(8)–C(1)	–	114.0(3)
C(9)–C(8)–C(7)	–	116.4(2)

pentane ring in lactone **5** allows a moderate interaction (Fig. 2), the intermolecular O···C=O distance being 3.089(3) Å. The bicyclo[3.3.0] skeleton is structurally similar in **3** and **5** and to other similar *cis*-2-oxabicyclo-[3.3.0]octan-3-one derivatives[1] (Table 12).

The packing in the crystalline state is maintained by the strong hydrogen bonds from oxygens O(7) and O(8) for both compounds. The *exo* hydroxy hydrogen H(7) forms a hydrogen bond to the *endo* oxygen O(8) of the adjacent molecule [the O(7)···O(8) distance is 2.701(3) Å and the hydrogen bond angle 156(4)°]. The *endo* hydrogen H(8) is hydrogen bonded to the *exo* oxygen O(7) of one more adjacent molecule [the O(7)···O(8) distance is 2.695(3) Å and the hydrogen bond angle 172(4)°] in lactone **3**. In lactone **5** the *exo* hydroxy hydrogen H(7) forms a hydrogen bond to the *endo* oxygen O(8) of the adjacent molecule [the O(7)···O(8) distance is 2.829(3) Å and the hydrogen bond angle 175(3)°] and the *endo* hydrogen H(8) is hydrogen bonded to the carbonyl oxygen O(3) of one more adjacent molecule [the O(8)···O(3) distance is 2.775(3) Å and the hydrogen bond angle 175(5)°].

Conclusions

The performic acid oxidation reactions of isomeric 4-, 5- and 6-methylbicyclo[2.2.1]hept-5-en-2-ones show a clear structure dependence. While the 4- and 6-methyl isomers form unsaturated bicyclic lactones or conformationally flexible bicyclic lactone diols, the 5-methyl compound gives conformationally rigid bicyclo[2.2.1]heptanone alcohols as the only reaction products. ^{1}H NMR spectroscopy and molecular mechanics calculations suggest that the conformational preferences of bicyclic lactone diols in solution clearly depend on the position of the methyl substituent. For the 8-methyl isomers **5** and **6** a single preferred *exo* or *endo* conformer is proposed, while the 5-methyl isomers **2** and **3** should be interpreted as statistical averages of *endo–exo* conformers. According to molecular mechanics, the cyclopentane moiety in all of the lactone diols is very flexible. Thus, one preferred conformer proposed for compounds **5** and **6** does not rule out their conformational flexibility. Their average conformational state just corresponds to one of two optimized conformers obtained by molecular mechanics calculations. Based on X-ray crystallography, the cyclopentane ring of lactone **5** in the crystalline state has an *exo* conformation. This is in accordance with the results obtained by ^{1}H NMR spectroscopy and molecular mechanics in solution for lactone **5**. The cyclopentane ring of lactone **3** in the crystalline state has an *endo* conformation. This is also in accordance with the present ^{1}H NMR and molecular mechanics results for lactone **3** characterized by a preference for the *endo* conformation in solution.

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References

1. Laihia, K., Rissanen, K., Kolehmainen, E., Korvola, J. and Leskinen, K. *Acta Chem. Scand. 45* (1991) 499 and references cited therein.
2. Masar, S. E. and Krieger, H. *Suom. Kemistil. B 42* (1969) 1.
3. Masar, S. E. and Krieger, H. *Suom. Kemistil. B 43* (1970) 315.
4. Paasivirta, J. and Äyräs, P. *Suom. Kemistil. B 42* (1969) 379 and references cited therein.
5. Laatikainen, R. *J. Magn. Reson. 27* (1977) 169.
6. Laatikainen, R. *J. Magn. Reson. 92* (1991) 1.
7. N. L. Allinger, MM2(85), QCPE (1985). PCMODEL (version 2.0) is a 300-atom version of C. Still's (Columbia University) MODEL program (VAX version 1.1) modified by K. Steliou (University of Montreal) and for IBM-PC (or compatible) by M. M. Midland. Molecular mechanics (MMX) of PCMODEL is based on N. L. Allinger's program MM2(85).
8. Walker, N. and Stuart, D. *Acta Crystallogr., Sect. A 39* (1983) 158.
9. Sheldrick, G. M. In: Sheldrick, G. M., Kruger, C. and Goddard, R., Eds., Crystallographic Computing, Oxford University Press, Oxford, England 1985, Vol. 3, pp. 175–189.
10. Carruthers, B. and Watkin, D. CRYSTALS, Chemical Crystallography Laboratory, Oxford, England 1990.
11. *International Tables for X-Ray Crystallography,* Kynoch Press, Birmingham 1974, Vol. IV.
12. Motherwell, W. D. S. and Clegg, W. PLUTO78, University of Cambridge 1978.
13. Krow, G. R. *Tetrahedron 37* (1981) 2697.
14. Haasnoot, C. A. G., de Leeuw, F. A. A. M. and Altona, C. *Tetrahedron 36* (1980) 2783.
15. Sargent, G. D. In: Carbonium Ions, Vol. III, Olah, G. A. and Schleyer, P. von R., Eds., Wiley, New York, NY 1972, Chap. 24.
16. Toivonen, N. J., Siltanen, E. and Ojala, K. *Ann. Acad. Sci. Fenn. A II* (1955) 64.
17. Lippmaa, E., Pehk, T., Paasivirta, J., Belikova, N. and Platé, A. *Org. Magn. Reson. 2* (1970) 581.
18. Kolehmainen, E., Laihia, K., Korvola, J., Kauppinen, R., Mannila, B. and Mannila, E. *Magn. Reson. Chem. 28* (1990) 812.

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