Oxygen-containing Bicyclic Monoterpenes. ^1H, ^{13}C and ^{17}O NMR Spectroscopic and X-Ray Diffraction Studies of Seven Oxidation Products of (+)-3-Carene

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Seven oxidation products of (1*S*,6*R*)-(+)-3,7,7-trimethylbicyclo[4.1.0]hept-3-ene [naturally abundant terpene, (+)-3-carene)] **1**; (1*S*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]hept-3-en-2-one (3-caren-2-one) **2**, (1*S*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]hept-3-en-5-one (3-caren-5-one) **3**, (1*S*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]hept-3-ene-2,5-dione (3-carene-2,5-dione) **4**, (1*S*,3*S*,4*R*,6*R*)-(+)-3,7,7-trimethylbicyclo[4.1.0]heptene 3,4-*trans*-oxide (*trans*-3,4-epoxy-3-carene) **5**, (1*S*,3*R*,4*R*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]heptane-3-*exo*-4-*endo*-diol (carane-3-*exo*-4-*endo*-diol) **6** and (1*S*,2*R*,4*R*,5*R*)-1-methyl-4-*exo*-(1-hydroxy-1-methylethyl)bicyclo[3.1.0]hexan-2-*endo*-ol **7** and (1*S*,6*R*)-3-*endo*-7,7-trimethylbicyclo[4.1.0]heptan-4-one (*trans*-4-caranone) **8** have been obtained by oxidation with *tert*-butylchromate, selenium dioxide, hydrogen peroxide and peracetic acid. The ^1H, ^{13}C and ^{17}O NMR spectra of the purified oxidation products have been recorded and assigned. In addition to C,H-COSY spectra, the ^1J(C,H) coupling constants were especially useful in ^{13}C NMR spectral assignment. The differentiation between isomeric ketones **2** and **3** is based on a clear difference in the ^{13}C NMR shifts of the double bond methyl. The stereochemical structure elucidation of oxide **5** is based on lanthanide shift reagent [Eu(dpm)$_3$] induced effects. For ketone **8**, molecular mechanics (MM) calculations and comparison of experimental and theoretical ^3J(H,H) coupling constants are needed for a final structure elucidation. The assignment of ^{17}O NMR lines of diols **6** and **7** is based on literature values. The crystal structures and absolute configurations of pure enantiomers of diols **6** and **7** have been determined by X-ray diffraction. Crystal data: a = 7.659(2), b = 10.804(3), c = 25.509(4) Å, orthorhombic, space group $C222_1$, Z = 8 (**6**) and a = 8.076(4), b = 8.836(2), c = 12.487(3) Å, orthorhombic, space group $P2_12_12_1$, Z = 4 (**7**).

3-Carene (3,7,7-trimethylbicyclo[4.1.0]hept-3-ene) is a rigid bicyclic monoterpene hydrocarbon, which occurs in nature in three optical forms: as each pure enantiomer, and their racemic mixture.[1] In addition to α- and β-pinene, (+)-3-carene is the main component of turpentine oil obtained from the wood of coniferous trees. The chemistry of 3-carene has been reviewed by Verghese,[2,3] Cocker,[4] Arbuzov and Isaeva,[5] Sadowska and Góra,[6] Grayson[7] and recently by Lajunen.[8]

The preferred conformation of the cyclohexene ring in 3-carene has been shown to be almost planar by ^1H NMR spectroscopy[9,10] and molecular mechanics (MM) calculations.[11] ^{13}C NMR chemical shifts of 3-carene and some related hydrocarbons have been reported by Chernov *et al.*[12] and Denisov *et al.*[13,14] In addition, long-range ^{13}C–^1H coupling constants of 3-carene have been published by Denisov *et al.*[13,14]

^{13}C NMR chemical shifts of some oxygen-containing carene and 3-carene derivatives have been published by Fringuelli *et al.*[15] and Lajunen.[8] Owing to the large scale industrial production of 3-carene, its importance as a starting material in organic syntheses, and the general use of its derivatives in medicine, cosmetics and perfumery, there exists continuous interest in this field of terpenoid chemistry.[1,8] The ^1H NMR spectroscopic data of many oxygen-containing derivatives of 3-carene, such as 3-caren-5-one,[16] isomeric 4-caranones,[17,18] isomeric 3,4-epoxycaranes[18] and 3-carene-2,5-dione[19] are from the period of low field NMR instruments lacking sufficient chemical shift dispersion and/or resolution regarding the requirements of precise computer-aided NMR analyses. Although the ^{13}C NMR chemical shifts have been reported for 3-carene itself and some of its derivatives,[12] generally their ^nJ(C,H) spin–spin coupling constants are not available in the literature. ^1J(C,H) values, however, are sensitive to the bond angles and steric strain in the bicyclic compounds and consequently very useful in assigning their ^{13}C NMR spectra as shown previously for the other bicyclic terpenoids.[20–23] Further, ^{17}O NMR spectroscopic data of the oxidation products of 3-carene are not available. The present study was undertaken as an extension of our investigations dealing with NMR spectroscopic and X-ray structural analysis of the oxidation products of various trimethylbicyclo[2.2.1]- and trimethylbicyclo[3.1.1]-heptane and -heptene compounds.[20–23]

In addition, oxidation products of enantiomerically pure natural (1*S*,6*R*)-(+)-3-carene are interesting from a physiological point of view. For example, (1*S*,3*S*,4*R*,6*R*)-(+)-3-carene 3,4-*trans*-oxide derived from the abundantly available natural (+)-3-carene produces cannabinoids with an acid-catalysed terpenylation reaction of olivetol.[24]

Experimental

Syntheses and Compounds.—95% (1*S*,6*R*)-(+)-3,7,7-trimethylbicyclo[4.1.0]hept-3-ene [(+)-3-carene] **1** from Aldrich (catalogue no. 11,557-6) was used for synthetic purposes and for ^1H and ^{13}C NMR spectroscopy as supplied. Similarly, various cyclopropane derivatives used as model compounds for comparison of ^1J(C,H) coupling constants were analytical grade reagents and used without further purification.

Oxidation of (+)-3-*carene by* tert-*butylchromate.* (1*S*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]hept-3-en-2-one (3-caren-2-one) **2**, (1*S*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]hept-3-en-5-one (3-caren-5-one) **3** and (1*S*,6*R*)-3,7,7-trimethylbicyclo[4.1.0]hept-3-ene-2,5-dione (3-carene-2,5-dione) **4** were identified and purified from the synthesis mixture of *tert*-butylchromate oxidation of (+)-3-carene in benzene solution at 50 °C.[25,26] Relative

amounts of the products were controlled by the reaction time and amount of the oxidant. Using an oxidant/3-carene molar ratio of 2:1 and a reaction time of 48 h the relative yields were 15 for **2**, 42 for **3** and 43% for **4**, respectively. Increasing the molar ratio to 3:1 and the reaction time to 96 h, the relative amounts were 6, 10 and 84%, respectively. The structures of the other oxidation products formed were not fully elucidated and left therefore beyond the scope of this study.

The oxidation products **2–4** were separated by column chromatography (40 × 400 mm, silica gel 0.032–0.063 mm from Friedel-deHaen) using ethyl acetate–hexane 1:10 (v/v) as eluent. The relative amount of ethyl acetate was increased during the elution to 1:5. Some characteristic *m/z* values and their relative intensities were for **2**: 150 (M^+, 58%), 135 (31), 107 (64) and 39 (100); for **3**: 150 (M^+, 63), 135 (45) and 107 (100); and for **4**: 164 (M^+, 46), 149 (100) and 136 (40). Chromatographic purity of compounds **2–4** used in NMR experiments was >95%. M.p. of **4** was 91.2–92.0 °C.

Oxidation of (+)-3-*carene by hydrogen peroxide.* (1*S*,3*S*,4*R*,6*R*)-3-Carene 3,4-*trans*-oxide [(1*S*,3*S*,4*R*,6*R*)-epoxycarane] **5** and (1*S*,3*R*,4*R*,6*R*)-carane-3-*exo*-4-*endo*-diol **6** were identified and purified after treatment of 3-carene in ethereal solution at 23 °C with 30% hydrogen peroxide as described by Schmidt *et al.*[27] By using a 24 h reaction time 3-carene was transformed in 93.5% overall yield to its 3,4-oxide. In addition, the synthesis mixture contained 3.0% of carane-3-*exo*-4-*endo*-diol **6**. Continuing the reaction time to 240 h increased the relative amount of **6** up to 54.8% and the amount of remaining oxide **5** was only 1.1%.

The oxidation products **5** and **6** were separated by column chromatography (40 × 400 mm, silica gel 0.032–0.063 mm from Friedel-deHaen) using light petroleum (b.p. 40–60 °C)–ethyl acetate 10:1 (v/v) as eluent. The relative amount of ethyl acetate was increased during the elution up to 1:1 (v/v). Some characteristic *m/z* values and their relative intensities were for **5**: 152 (M^+, 12%), 137 (66) and 109 (100), and for **6**: 152 ($M^+ - H_2O$, 47), 137 (13) and 81 (100). M.p. of **6** was 86.3–87.3 °C. The gas chromatographic purity of compounds **5** and **6** used in NMR experiments was >95%.

Oxidation of (+)-*carene by* SeO_2. Because the yield of 3-caren-2-one **2** was small in the *tert*-butylchromate oxidation, selenium dioxide was used as an oxidant, as described by Isaeva *et al.*[28–30] Two solvents, hexane and absolute ethanol, and two oxidant/3-carene molar ratios 1:1 and 2:1 have been tested at 23 °C, keeping the reaction time at 168 h. Hexane proved to be superior to ethanol, giving a 28.8% overall yield, when a molar ratio of 2:1 was used. In ethanol the yield was only 10.9%. Reducing the molar ratio to 1:1 decreased the amount of **2** formed in both solvents.

3-Caren-2-one **2** was separated by column chromatography (40 × 400 mm, silica gel 0.032–0.063 mm from Friedel-deHaen) using light petroleum (b.p. 40–60 °C)–ethyl acetate–ethanol 10:5:1 (v/v/v) as eluent. The other mainly aromatic reaction products, which eluted before compound **2**, were not analysed. The gas chromatographic purity of **2** used in NMR experiments was >95%.

Oxidation of (+)-3-*carene by peracetic acid.* A peracetic acid oxidation[31,32] was performed at 23 °C in CD_2Cl_2 with the molar ratio of oxidant/3-carene, 7:10, in 6 h. The compounds **5**, **6**, **7**, **8** and an easily rearrangeable compound **9** were found in percentage yields of 4, 46, 12, 26 and 12% in the reaction mixture. Changing the oxidant/3-carene molar ratio to 10:1 produced a mixture with the percentage yields of 0, 48, 4, 8 and 40%, respectively. The structure elucidation of the compound **9** failed because it was not stable enough in solution and changed very soon to the other compounds. Some characteristic *m/z* values and their relative intensities were for **7**: 152 ($M^+ - H_2O$, 19%), 137 (28) and 59 (100) and for **8**: 150 (M^+, 16), 135 (37) and 43 (100). M.p. of **7** was 115.8–117.0 °C. Gas chromatographic purity of the compounds **7** and **8** used in NMR experiments was >95%.

The peracetic acid oxidation products were separated by column chromatography (40 × 400 mm, silica gel 0.032–0.063 mm from Friedel-deHaen) using light petroleum (b.p. 40–60 °C)–acetone–hexane–ethanol 6:2:4:1 (v/v/v/v) as eluent. Based on the gas chromatographic determinations of all reaction mixtures, *trans*-4-caranone **8** was formed only in the peracetic acid oxidation.

NMR Spectroscopy.—The ^1H NMR spectra of all compounds **1–8** have been recorded on a JEOL GSX 270 NMR spectrometer operating at 270.2 MHz. ^{13}C and ^{17}O spectra have been recorded on a JEOL GSX 270 NMR spectrometer operating at 67.8 and 36.6 MHz, respectively. The ^1H and ^{13}C measurements were performed using a 5 mm C/H dual probehead and ^{17}O measurements using a 10 mm diameter tunable multinuclear probehead at 30 °C for $CDCl_3$ solutions. The concentrations of the samples were 0.1 mol dm^{-3} in ^1H and 0.5 mol dm^{-3} in ^{13}C, C,H-COSY and ^{17}O NMR measurements, respectively.

In ^1H measurements all chemical shifts are referenced to internal tetramethylsilane (TMS). The digital resolution was <0.1 Hz. All FIDs are windowed by an exponential line broadening factor of the digital resolution prior to FT to improve S/N in the frequency spectra. The number of scans was eight.

In ^{13}C measurements all chemical shifts are referenced to internal TMS. The spectral width was 15 kHz and the number of data points 64 K giving a digital resolution of 0.5 Hz. The FID accumulation time was 2.7 s, pulse delay 2.0 s and flip angle 90°. In proton coupled ^{13}C NMR spectra, the spectral area was limited in carbons bearing hydrogens and the number of data points was increased to improve the digital resolution to better than 0.2 Hz. The number of scans was 100–400 for proton broad band decoupled and 10 000–18 000 for fully coupled spectra, respectively. All FIDs are windowed by an exponential line broadening factor of digital resolution prior to FT to improve S/N in the frequency spectra.

The carbon–proton chemical shift correlated spectra (C,H-COSY) were obtained by using a standard pulse sequence VCHSCF available in the software of the spectrometer. In these experiments the spectral widths were <9000 Hz (^{13}C axis) and <1700 Hz (^1H axis), respectively. The size of the data matrix was 2048 × 1024. Exponential window functions of digital resolutions in both frequency axes were used prior to FT.

In ^{17}O NMR measurements all chemical shifts are referenced to the resonance of D_2O (2 mm diameter capillary inserted coaxially inside the 10 mm sample tube). The ^{17}O chemical shifts are uncorrected for the ^2H isotope shift (in comparison with H_2O) of −3 ppm.[33] The spectral width was 36 kHz, number of data points 8 K, accumulation time 100 ms without any pulse delay, flip angle 90° and number of scans *ca.* 300 000. All FIDs are windowed by an exponential line broadening factor of digital resolution (9 Hz) prior to FT to improve S/N in the frequency spectra.

Mass Spectrometry.—The high-resolution mass spectra of all oxidation products were recorded with VG AutoSpec mass spectrometer equipped with Hewlett-Packard 5890 gas chromatograph.

Computations.—The second-order ^1H NMR spectra have been analysed by means of iterative computer programs MAOCON[34] and MLDC8[35] in a VAX 4000 computer at the Computer Center of the University of Jyväskylä. Molecular mechanics calculations were performed with a MM2[36] based program PCMODEL[37] with default force constants in PC.

Table 1 Experimental crystallographic data for **6** and **7**

	6	**7**
Formula	$C_{10}H_{18}O_2 \cdot H_2O$	$C_{10}H_{18}O_2$
M_r	188.27	170.25
a/Å	7.659(2)	8.076(4)
b/Å	10.804(3)	8.836(2)
c/Å	25.509(4)	12.487(3)
α/°	90	90
β/°	90	90
γ/°	90	90
V/Å^3	2110.6(9)	991.9(5)
Z	8	4
d_{calc}/Mg m^{-3}	1.185	1.140
μ/mm^{-1}	0.080	0.073
λ/Mo-Kα	0.710 73	0.710 73
$F(000)$	832	376
Space group	$C222_1$	$P2_12_12_1$
T/K	296 ± 1	296 ± 1
Crystal size/mm	0.20 × 0.30 × 0.35	0.15 × 0.20 × 0.45
Reflections for latt. meas.	25	25
θ range for latt. meas./°	8–12	8–11
Scan method	$\omega/2\theta$	$\omega/2\theta$
Scan speed/° min^{-1}	1–7	1–7
Scan width (ω)/°	0.54 + 0.34 tanθ	1.10 + 0.34 tanθ
θ range/°	2–25	2–23
h range	0 ⟶ 9	0 ⟶ 8
k range	0 ⟶ 12	0 ⟶ 10
l range	0 ⟶ 30	0 ⟶ 13
Variation of standard reflections	none	none
Reflections measured	1072	821
Number of unique reflections	1072	821
Condition of observed reflections	$I > 3.0\sigma(I)$	$I > 3.0\sigma(I)$
Reflections used in refinement	951	660
Max. shift/error	< 0.01	< 0.01
No. of param.	118	109
Max. in final $\Delta\rho$/e Å^{-3}	0.42	0.45
R_{int}	—	—
R	0.053	0.059
R_w	0.066	0.056
Chebychev coefficients	7.87, 2.35, 6.18	3.34, −3.64, 1.16, −1.73, −0.473

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

X-Ray Crystal Structure Analysis of **6** *and* **7**.—Table 1 summarises the crystal data and refinement parameters. The data were collected from colourless crystals with an Enraf–Nonius CAD4 diffractometer using graphite monochromatized Mo-Kα radiation. Lp correction and empirical absorption correction[38] were applied to the data with minimum and maximum correction coefficients 0.539 and 1.373 for compound **6** and 0.756 and 1.161 for compound **7**, respectively. The structures were solved by direct methods[39] and subjected to full-matrix refinement.[40] All non-H atoms were refined anisotropically. The hydrogen atoms were calculated to their idealized positions (C–H distance 1.00 Å) and refined as riding atoms with fixed isotropic temperature factors (U = 0.08 Å^2). The hydrogens of the water molecule (compound **6**) and in the hydroxy groups could not be located from difference Fourier map owing to the rather poor crystal quality, nor could they be calculated, and they were therefore ignored during the refinements.

Results and Discussion

The structures of the compounds **1**–**8** and the numbering of carbons and protons in the 3,7,7-trimethylbicyclo[4.1.0]-hept-3-ene, -heptane and bicyclo[3.1.0]hexane skeletons are presented in Fig. 1.

The ^{1}H NMR chemical shifts and ^nJ(H,H) coupling constants for compounds **1**–**8** are given in Tables 2 and 3. The ^{13}C NMR chemical shifts and ^1J(C,H) coupling constants are given in Tables 4 and 5, respectively. The ^{17}O NMR chemical shifts are collected in Table 6.

^{1}H *NMR Spectra*.—The ^{1}H NMR chemical shifts (Table 2) of 3-carene itself have been published by several research groups.[9–11] The protons 1 and 6 in the cyclopropyl moiety in 3-carene show typically strongly shielded values at δ = 0.711 and 0.610,[11] respectively. Introducing one or two C=O groups at the adjacent positions to the cyclopropyl ring (as in compounds **2**, **3** and **4**) causes a clear deshielding effect on the cyclopropyl protons, their chemical shifts being located at δ = 1.62/1.44, 1.46/1.55 and 2.35/2.33, respectively. A C=O group located at a longer distance at carbon 4 (**8**) clearly causes smaller effects on the ^{1}H NMR chemical shifts of cyclopropyl protons than for 2- and 5-monoketones.

In the epoxy derivative **5**, the protons 1 and 6 show the most shielded chemical shifts in this series of compounds. The methyl carbon 10 also shows an exceptionally shielded value when compared with other compounds studied. Proton 4 of **5** possesses a clearly deshielded value of 2.82 ppm due to the proximity of the electronegative epoxy group.

All ^{1}H NMR spectral analyses are performed by computerized iterations. The guess values needed for this approach have been obtained by C,H-COSY experiments, first-order analysis of splitting patterns, molecular mechanical calculations providing dihedral angles and corresponding vicinal coupling constants[41] and finally by X-ray crystallographic analysis, in cases

Table 2 ^{1}H NMR chemical shifts of 3-carene and its oxidation products **2–8**, in $CDCl_3$ in ppm from TMS

	δ(^{1}H)							
Proton	**1**[a]	**2**	**3**	**4**	**5**	**6**	**7**	**8**
H-1	0.711	1.62	1.46	2.35	0.45	0.70	—	0.84
H-2n	2.164	—	2.64	—	2.10	1.95	—	2.03
H-2x	1.801	—	2.34	—	1.49	1.20	4.14	1.73
H-3n	—	—	—	—		—	1.56	—
H-3x	—	—	—	—		—	1.52	2.23
H-4	5.232	6.41	5.82	6.51		—	—	—
H-4n	—	—	—	—		—	2.59	—
H-4x	—	—	—	—	2.82	3.23	—	—
H-5	—	—	—	—		—	1.19	—
H-5n	2.343	2.71	—	—	2.28	1.64	—	2.57
H-5x	1.948	2.46	—	—	1.63	2.06	—	2.09
H-6	0.610	1.44	1.55	2.33	0.52	0.67	—	1.04
H-6n	—	—	—	—	—	—	0.36	—
H-6x	—	—	—	—	—	—	0.66	—
CH_3-8	0.760	1.08	1.04	1.34	0.73	0.96	1.32	0.93
CH_3-9	1.020	1.18	1.19	1.34	1.01	1.18	1.29	1.07
CH_3-10	1.595	1.75	1.88	1.98	1.25	0.98	1.21	1.23

[a] Ref. 11.

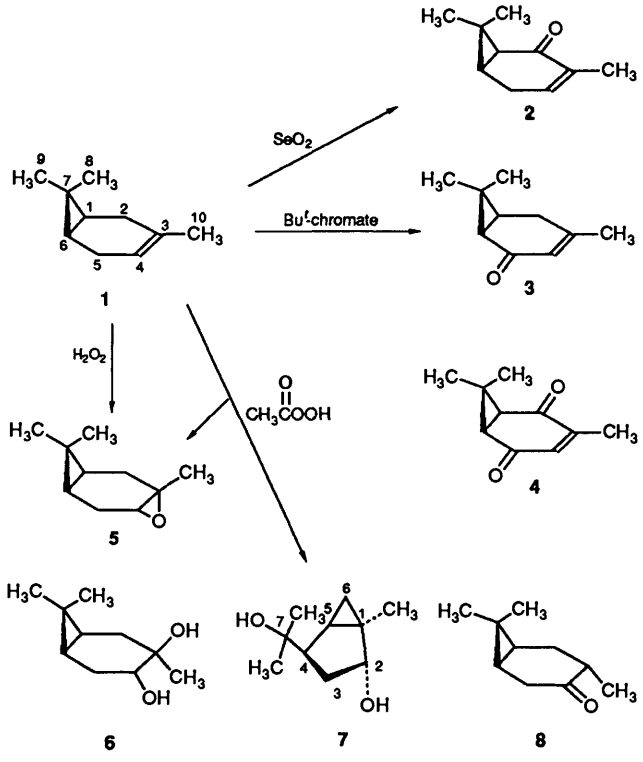

Fig. 1 Oxidation products of 3-carene

where the products formed crystals regular enough for X-ray structural analysis.

The ^nJ(H,H) spin-spin coupling constants (Table 3) of 3-carene are well documented in the literature.[9–11] These values were useful only to some extent in analysing the present spectra of oxygen-containing derivatives of 3-carene. This is due to the fact that the conformational characteristics and many structural parameters are varied within this series of compounds. For example, the geminal couplings ^2J(H-2$_{endo}$,H-2$_{exo}$) and ^2J(H-5$_{endo}$,H-5$_{exo}$) vary from −14.44 to −20.84 Hz and from −14.36 to −21.44 Hz, respectively. The variation of the geminal couplings of methylene protons next to sp^2 centres has been explained by M. Barfield *et al.*[42]

Structure elucidation of 3-*carene*-3,4-*oxide* **5** *by* Eu(dpm)$_3$-*induced* ^{1}H *NMR chemical shift changes.* In order to elucidate the stereochemistry (*cis–trans* isomerism) of compound **5**, the effects induced by a lanthanide shift reagent, Eu(dpm)$_3$ were detected.* The greatest influences are found on protons 4 and methyl 10, which are adjacent to the epoxy ring. The other signals are shifted markedly less than those of H-4 and the methyl 10. At the saturation concentration of Eu(dpm)$_3$, the signals of methyls 8, 9 and 10 are deshielded by 0.26, 0.11 and 0.53 ppm, respectively. Further, the protons 2$_{endo}$ and 5$_{endo}$ are deshielded significantly more than the protons 2$_{exo}$ and 5$_{exo}$. This suggests that the attack of lanthanide occurs at the *endo*-side of the 3-carene. Consequently, the epoxy ring must be located at the *trans*-position to the cyclopropane ring. This deduction is also supported by the relatively small effect experienced by the methyl 8. In a *cis*-epoxy group, the methyl 8 should become deshielded more strongly by the complexing lanthanide than in its *trans*-isomer.

Structure elucidation of compound **8** *by comparing the molecular mechanics (MM) calculated and experimental* ^{3}J(H,H) *coupling constants.* 4-Caranone, with a saturated ring system, can exhibit four possible conformations as proposed by H. C. Brown *et al.*,[18] and illustrated in Fig. 2.

According to MM calculations, in *trans*-4-caranone conformers **I–IV** (numbering in Fig. 2 is the same as in ref. 18) may exist. In *cis*-4-caranone only two conformers **I** and **IV** were stable, because in forms **II** and **III** there exists strong steric repulsion between methyls 3 and 8. The experimental ^3J(H-2$_{endo}$,3) = 2.55 Hz, and ^3J(H-2$_{exo}$,3) = 5.08 Hz, in **8** are in accord with the stereochemistry of *trans*-4-caranone.

^{13}C *NMR Spectra.*—The resonances of 3-carene itself and 4-caranone have been reported in the literature.[12–15,43] The present ^{13}C NMR spectral assignments are based on the C,H-COSY experiments and fully coupled ^{13}C NMR spectra.

For the correct ^{13}C NMR chemical shift assignment of the methyls 8 and 9 in 3-carene and its derivatives, a reliable ^{1}H NMR chemical shift assignment is useful. This has been published by Lassak and Southwell[44] based on an Eu(dpm)$_3$ shift study of (−)-3-caren-2-one derived from natural (+)-3-carene. This knowledge can be used in assigning the ^{13}C NMR chemical shifts based on C,H-COSY experiments. Generally, the methyl 8 is strongly shielded in comparison with methyl 9.

* Eu(dpm)$_3$ = Tris(dipivaloylmethanato)europium(III).

Table 3 ^nJ(H,H)s (in Hz) of 3-carene and its oxidation products **2–8**

	^nJ(H,H)							
Protons	**1**[a]	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1,2n	7.8	—	8.24	—	8.96	9.56	—	8.97
1,2x	0.5	—	1.02	—	2.47	5.33	—	5.90
1,4x	—	—	—	—	—	0.68	—	—
1,5n	—	—	—	—	−0.24	−0.25	—	—
1,5x	—	1.87	—	—	−0.10	−0.89	—	−0.33
1,6	9.0	7.93	7.84	6.54	8.94	8.77	—	8.74
2n,2x	18.4	—	−20.84	—	−16.23	−14.44	—	−14.95
2n,3x	—	—	—	—	—	—	—	2.55
2n,4	2.0	—	2.04	—	—	—	—	—
2n,4x	—	—	—	—	—	−0.15	—	—
2n,5n	2.2	—	—	—	—	0.22	—	−0.19
2n,5x	2.3	—	—	—	—	−0.35	—	0.90
2n,6	—	—	1.16	—	−0.31	0.72	—	—
2n,10	1.0	—	1.05	—	—	—	—	—
2x,3x	—	—	—	—	—	—	5.22	5.08
2x,4	2.0	—	3.24	—	—	—	—	—
2x,4x	—	—	—	—	−0.12	0.49	—	—
2x,5n	2.3	—	—	—	—	—	—	0.18
2x,5x	4.5	—	—	—	−0.11	0.88	—	−0.16
2x,6	—	—	−1.32	—	−0.36	−1.71	—	—
2x,10	1.0	—	0.88	—	—	—	—	—
3n,3x	—	—	—	—	—	—	−14.05	—
3n,4n	—	—	—	—	—	—	7.35	—
3x,5n	—	—	—	—	—	—	—	−0.26
3x,5x	—	—	—	—	—	—	—	0.33
3x,4n	—	—	—	—	—	—	11.82	—
4,5n	3.6	3.29	—	—	—	—	—	—
4,5x	3.6	4.44	—	—	—	—	—	—
4,6	0.6	1.29	—	1.74	—	—	—	—
4,10	1.4	1.51	1.30	1.50	—	—	—	—
4n,5	—	—	—	—	—	—	3.86	—
4x,5n	—	—	—	—	1.96	10.49	—	—
4x,5x	—	—	—	—	2.36	6.95	—	—
4x,6	—	—	—	—	—	−0.27	—	—
5,6n	—	—	—	—	—	—	7.51	—
5,6x	—	—	—	—	—	—	3.79	—
5n,5x	19.0	−21.44	—	—	−16.37	14.36	—	−18.00
5n,6	7.8	8.37	—	—	9.12	8.17	—	8.69
5n,10	2.2	2.64	—	—	—	—	—	—
5x,6	0.5	1.01	—	—	2.33	1.35	—	3.46
5x,10	2.2	1.82	—	—	—	—	—	—
6n,6x	—	—	—	—	—	—	−5.15	—

[a] Ref. 11.

Table 4 ^{13}C NMR chemical shifts of 3-carene and its derivatives **2–8** in ppm from TMS

	$\delta(^{13}C)$								
Carbon	**1**[a]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**[b]
C-1	19.36	18.6	34.3	24.7	38.9	13.8	19.9	25.8	22.4
C-2	25.47	24.9	196.2	26.7	194.2	23.2	33.6	76.0	27.5
C-3	131.54	131.3	135.0	158.0	149.9	55.6	73.3	31.8	42.2
C-4	120.17	119.6	142.5	125.1	137.6	57.9	74.3	47.5	218.4
C-5	21.46	20.9	23.0	195.1	194.8	19.1	27.8	23.4	34.7
C-6	17.55	16.8	26.4	31.7	39.8	15.9	21.0	12.4	17.4
C-7	17.25	16.8	21.7	21.3	33.3	15.8	17.6	71.8	20.1
CH_3-8	13.64	13.2	14.3	13.3	15.4	14.4	15.7	27.1	15.3
CH_3-9	28.88	28.4	28.5	27.3	29.0	27.6	28.6	28.8	28.7
CH_3-10	24.02	23.7	16.0	22.5	16.1	22.9	18.9	15.8	17.6

[a] Ref. 13. [b] Ref. 15.

An exception is compound **7**, in which the structure is totally changed *via* a rearrangement of the carene skeleton.

Differentiation of the isomeric ketones **2** *and* **3**. Ketones **2** and **3** did not show any clear differences in their mass spectra and also possess quite similar ^{1}H NMR characteristics. Therefore their differentiation is based on an inspection of the ^{13}C NMR chemical shifts of methyl 10. In 3-carene-2,5-dione the methyl 10 (δ = 16.1) is strongly shielded by the influence of the adjacent carbonyl at position 2. In compounds **2** and **3** the corresponding values for methyl 10 are 16.0 and 22.5 ppm. Now it is concluded that **2** is 3-caren-2-one, because in this isomer the methyl 10 experiences the same anisotropic effect as in diketone **4**. The ^{1}H

Table 5 ^1J(C,H)s (in Hz) of (*a*) 3-carene and its oxidation products **2**–**8** and (*b*) cyclopropane derivatives

(*a*)	^1J(C,H)/Hz							
Coupling	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
C-1,H-1	159.2	165.9	164.0	169.5	147.2	160.9	—	161.3
C-2,H-2	123.5	—	126.5	—	125.7	127.2	147.7	128.1
C-3,H-3	—		—	—	—	—	129.4	132.0
C-4,H-4	152.9	154.9	160.6	163.1	170.7	139.0	125.4	—
C-5,H-5	125.1	126.8	—	—	126.4	127.0	166.3	126.7
C-6,H-6	159.2	164.0	165.9	170.0	149.1	161.8	158.1	160.2
C-8,H-8	124.8	126.2	126.0	127.4	124.8	124.4	125.4	125.3
C-9,H-9	124.6	126.0	126.0	127.9	124.8	125.9	124.5	125.1
C-10,H-10	124.8	127.7	127.0	129.1	126.0	125.2	126.0	127.8

(*b*)	^1J(C,H)/Hz	
Compound	C-1	C-2,3
Cyclopropane	161[a]	161[a]
Cyclopropylamine	170.2 (C-NH_2)	161.4
Cyclopropylbenzene	159.4 (C-Ph)	162.6
Cyclopropyl bromide	192.5 (C-Br)	164.9
Cyclopropylmethanol	159.9	161.6
Cyclopropanecarboxylic acid	169.9	165.6
1,1-Cyclopropanedicarb. acid	—	170.0[b]
	—	169.3[c]
Cyclopropyl methyl ketone	165.5	165.5
Diphenylcyclopropylmethanol	158.0	161.8

[a] Ref. 48, p. 139. [b] In $CDCl_3$. [c] In [$^2H_6$]acetone.

Table 6 ^{17}O NMR chemical shifts of the oxidation products **2**–**8** in ppm from ext. D_2O

Compound	δ
2	520.5
3	518.8
4	571.7
5	22.9
6	51.0 and 17.6
7	53.4 and 29.2
8	546.8

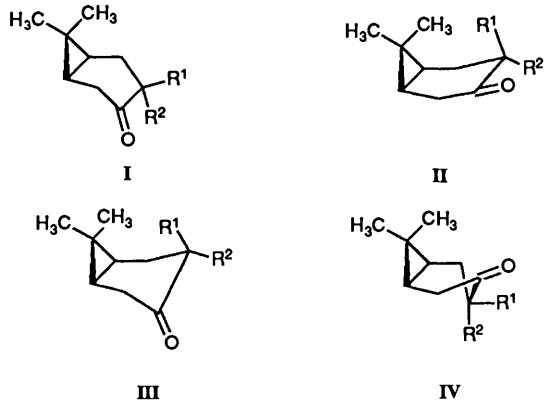

Fig. 2 Possible conformations of isomeric 4-caranones[18]

NMR parameters of compound **2** (Tables 2 and 3) also agree very well with the values for 3-caren-2-one, whose structure has been verified previously by inspecting the effect of Eu(dpm)$_3$ on its ^{1}H NMR spectrum.[44]

^{1}J(C,H) *Values for compounds* **1**–**8**. These are collected in Table 5. From these coupling constants, ^1J(C-1,H-1) varying from 147.2 (**5**) to 169.5 Hz (**4**) and ^1J(C-6,H-6) varying from 149.1 (**5**) to 170.0 Hz (**4**) of the cyclopropane ring are significantly greater than those of the cyclohexane ring, characterized by a clearly smaller steric strain. The ^1J(C,H)s in the cyclopropane ring of the rearranged reaction product **7** show values of 166.3 (C-5) and 158.1 (C-6) Hz, respectively. A corresponding relation between the steric strain and the magnitude of the ^1J(C,H) coupling constants is also observed in bicyclo[3.1.1]heptanes.[22] ^1J(C,H)s of the cyclobutane ring in the bicyclo[3.1.1]heptane moiety are generally > 135 Hz, which is clearly greater than those of sp^3-carbons in unstrained ring systems.^1J(C,H)s of the cyclobutane ring in bicyclo[3.1.1]-heptanes are clearly smaller than the direct couplings of the cyclopropane ring in bicyclo[4.1.0]heptane or bicyclo[3.1.0]-hexane. These findings are in agreement with a generalization, that the one bond carbon–proton coupling constant is known to correlate with the ring size.[45]

In Table 5 can be seen, that the structural variation in molecular framework has a clear influence on the ^1J(C,H) coupling of the cyclopropyl moiety. Therefore the ^1J(C,H) data of some simple cyclopropane derivatives have also been studied. These ^1J(C,H) values are collected in Table 5(b).

The ^1J(C,H)s in cyclopropane system vary from 158.0 Hz from diphenylcyclopropylmethanol to 192.5 Hz in cyclopropyl bromide. Adding an electronegative substituent such as bromine or an amino group in the cyclopropane ring seems to increase strongly the direct coupling constant in the substituent attached carbon. Among the model compounds, cyclopropyl methyl ketone contains a structural unit similar to those of ketones **2** and **3**. Therefore it is not surprising, that ^1J(C-1,H-1) = 165.5 Hz of cyclopropyl methyl ketone is very similar with the values of ^1J(C-1,H-1) = 164.0 Hz and ^1J(C-6,H-6) = 165.9 Hz of **2** as well as with ^1J(C-1,H-1) = 165.9 Hz and ^1J(C-6,H-6) = 164.0 Hz of **3**, respectivley. On the other hand, cyclopropylmethanol showing values ^1J(C-1,H-1) = 159.9 Hz and ^1J(C-2,H-2) = 161.6 Hz can be thought to mimic the diols **6** and **7**. Especially the values of ^1J(C-1,H-1) = 160.9 Hz and ^1J(C-6,H-6) = 161.8 Hz of **6** agree very well with those of the model compound.

Based on these comparisons one can suggest that even simple oxygen-containing cyclopropane derivatives such as cyclo-

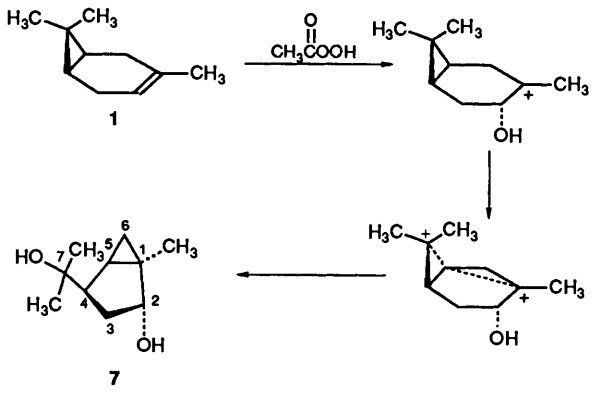

Fig. 3 Formation of diol 7 from 3-carene

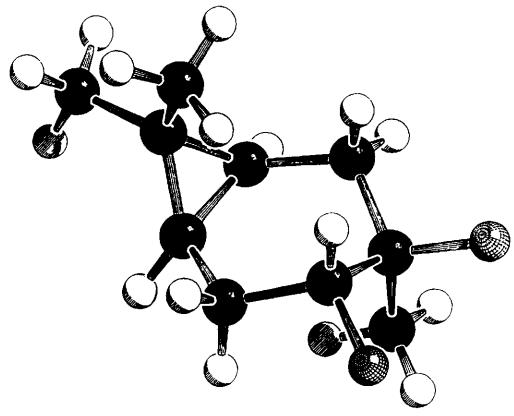

Fig. 4 SCHAKAL plot of 6

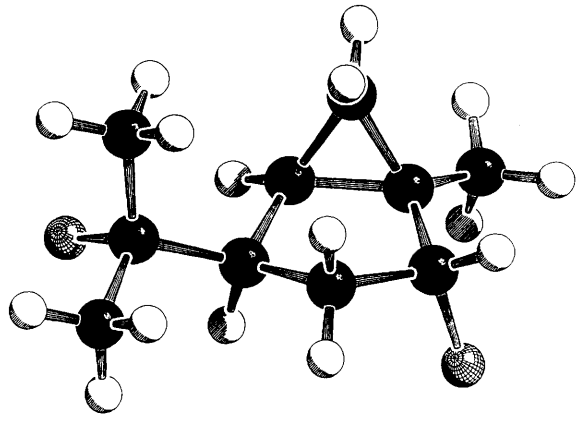

Fig. 5 SCHAKAL plot of 7

Table 7 Bond distances (Å) and angles (°) for compounds 6 and 7

Compound 6		Compound 7	
O(3)–C(3)	1.445(3)	O(2)–C(2)	1.436(7)
O(4)–C(4)	1.431(3)	O(6)–C(7)	1.459(7)
C(1)–C(2)	1.529(4)	C(1)–C(2)	1.484(8)
C(1)–C(6)	1.511(4)	C(1)–C(5)	1.520(7)
C(1)–C(7)	1.515(4)	C(1)–C(6)	1.511(8)
C(2)–C(3)	1.542(4)	C(1)–C(10)	1.513(8)
C(3)–C(4)	1.528(4)	C(2)–C(3)	1.536(8)
C(3)–C(10)	1.522(4)	C(3)–C(4)	1.531(7)
C(4)–C(5)	1.525(4)	C(4)–C(5)	1.504(7)
C(5)–C(6)	1.514(4)	C(4)–C(7)	1.563(7)
C(6)–C(7)	1.507(4)	C(5)–C(6)	1.511(8)
C(7)–C(8)	1.506(4)	C(7)–C(8)	1.526(7)
C(7)–C(9)	1.521(4)	C(7)–C(9)	1.512(8)
C(6)–C(1)–C(2)	117.7(3)	C(5)–C(1)–C(2)	108.0(5)
C(7)–C(1)–C(2)	122.6(3)	C(6)–C(1)–C(2)	116.1(4)
C(7)–C(1)–C(6)	59.7(2)	C(6)–C(1)–C(5)	59.8(4)
C(3)–C(2)–C(1)	112.2(2)	C(10)–C(1)–C(2)	119.8(5)
C(2)–C(3)–O(3)	109.7(2)	C(10)–C(1)–C(5)	122.1(5)
C(4)–C(3)–O(3)	108.2(2)	C(10)–C(1)–C(6)	116.8(5)
C(4)–C(3)–C(2)	107.0(2)	C(1)–C(2)–O(2)	110.0(4)
C(10–C(3)–O(3)	107.1(2)	C(3)–C(2)–O(2)	111.0(5)
C(10)–C(3)–C(2)	111.5(3)	C(3)–C(2)–C(1)	104.8(4)
C(10)–C(3)–C(4)	113.3(3)	C(4)–C(3)–C(2)	104.4(4)
C(3)–C(4)–O(4)	110.7(2)	C(5)–C(4)–C(3)	104.2(4)
C(5)–C(4)–O(4)	109.6(2)	C(7)–C(4)–C(3)	114.9(4)
C(5)–C(4)–C(3)	111.9(2)	C(7)–C(4)–C(5)	116.7(4)
C(6)–C(5)–C(4)	116.0(2)	C(4)–C(5)–C(1)	107.1(5)
C(5)–C(6)–C(1)	120.3(3)	C(6)–C(5)–C(1)	59.8(4)
C(7)–C(6)–C(1)	60.3(2)	C(6)–C(5)–C(4)	118.0(5)
C(7)–C(6)–C(5)	125.2(3)	C(5)–C(6)–C(1)	60.4(3)
C(6)–C(7)–C(1)	60.0(2)	C(4)–C(7)–O(6)	103.1(4)
C(8)–C(7)–C(1)	122.0(3)	C(8)–C(7)–O(6)	108.1(5)
C(8)–C(7)–C(6)	120.6(3)	C(8)–C(7)–C(4)	113.4(5)
C(9)–C(7)–C(1)	115.9(3)	C(9)–C(7)–O(6)	109.9(5)
C(9)–C(7)–C(6)	116.8(3)	C(9)–C(7)–C(4)	111.7(5)
C(9)–C(7)–C(8)	112.3(2)	C(9)–C(7)–C(8)	110.3(5)

propyl methyl ketone and methanol can be used in estimating the ^1J(C,H) values of naturally occurring terpenoids containing fused or nonfused cyclopropane rings.

The rearrangement of the 3-carene skeleton to the bicyclo[3.1.0]hexane ring system can occur by a mechanism described in Fig. 3. A similar type of rearrangement has been proposed for 3-carene 3,4-*trans*-oxide producing a thujone-type alcohol characterized by a similar bicyclic ring system as in the diol 7.[24]

^{17}O NMR Spectra.—The ^{17}O chemical shifts for **2–8** (Table 6) are typical for ketones, ethers (oxides) and alcohols, supporting the given structures.[33]

The ketone **4** possesses a clearly higher chemical shift value than the other ketones **2**, **3** and **8**. Both carbonyl signals of **4** overlap strongly. Both diols **6** and **7** show two well resolved ^{17}O NMR lines. Their assignment is based on the fact that both of the diols have secondary and tertiary alcoholic groups. Chandrasekaran and Boykin[46] have published the ^{17}O NMR chemical shifts for a series of secondary alcohols: pentan-3-ol, 25.4 ppm, cyclopentanol, 33.3 ppm, cyclohexanol, 35.7 ppm and cycloheptanol, 40.8 ppm, respectively. On the other hand, there exists a clear difference in the ^{17}O NMR chemical shifts between *sec*-butyl alcohol (41 ppm) and *tert*-butyl alcohol (70 ppm)[33] (ref. 33, p. 21). Therefore, the shifts of 51.0 and 53.4 can be assigned to the tertiary hydroxy groups at the 3-*exo* (**6**) and 7 (**7**) positions, and the values of 17.6 and 29.2 ppm to the secondary hydroxy groups at the 4-*endo* (**6**) and 2-*endo* (**7**) positions.

X-Ray Structures of **6** *and* **7**.—Fractional coordinates with e.s.d.s in parentheses and temperature factors for **6** and **7** have been deposited at the Cambridge Crystallographic Data Centre.* The bond distances (Å) and angles (°) of **6** and **7** are collected in Table 7. The SCHAKAL[47] plots of **6** and **7** are drawn in Figs. 4 and 5, respectively.

The X-ray structure analysis reveals that the both diols **6** and **7** crystallize as pure enantiomers. Their absolute configurations are assigned based on the known absolute configuration of the starting material (1*S*,6*R*)-(+)-3,7,7-trimethylbicyclo[4.1.0]-hept-3-ene[(+)-3-carene]. Compound **6** proved to be (1*S*, 3*R*,-4*R*,6*R*)-3-*endo*-,7,7-trimethylbicyclo[4.1.0]heptane-3-*exo*-4-*endo*-diol and compound **7** (1*S*,2*R*,4*R*,5*R*)-1-methyl-4-*exo*-(1-hydroxy-1-methylethyl)bicyclo[3.1.0]hexan-2-*endo*-ol.

* For details of the deposition scheme see 'Instructions for Authors,' *J. Chem. Soc., Perkin Trans. 2*, 1993, issue 1.

Conclusions

In spite of the intensive research already carried out, 3-carene and its derivatives still are interesting from *e.g.* NMR spectroscopic, synthetic and physiological points of view, owing to their easy isomerization, large structural variation, stereochemistry and reactivity.

^{1}H NMR parameters reported in the literature have often been measured with low field instruments. Therefore modern high field NMR spectroscopy combined with X-ray crystal structure analysis can provide an improved understanding of the relationship between NMR data and structural parameters. Further, two-dimensional NMR techniques greatly help in verifying the ^{1}H and ^{13}C NMR spectral assignments. ^{17}O NMR gives an interesting new view in the field of structural chemistry of terpenoids.

Owing to the NMR spectral similarities of isomeric 3-caren-2-one and 3-caren-5-one, the ^{13}C NMR chemical shifts of the double bond methyl 10 were of extreme importance. In the case of 3-carene 3,4-*trans*-oxide Eu(dpm)$_3$ studies were needed for the final stereochemical structure elucidation. For a conformationally flexible compound, *trans*-4-caranone, comparisons between the molecular mechanics (MM) derived and experimental ^3J(H,H)s were useful in the final structure elucidation.

Generally, the ^1J(C,H) coupling constants can be used as an aid in assigning the ^{13}C NMR chemical shifts of 3-carene derivatives characterized by strained ring systems. Simple oxygen-containing cyclopropyl derivatives show, ^1J(C,H) values very similar to those they possess when fused in the structures of the 3-carene-type terpenoids.

X-Ray structure analysis reveals that two diols studied crystallize as pure enantiomers. Their absolute configurations are determined based on the known absolute configuration of the starting material, (+)-3-carene. ^{17}O NMR resonances of these isomeric diols are well resolved and can be useful in deriving the ^{17}O NMR and structural correlations.

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References

1 *CRC Handbook of Terpenoids*, ed. S. Dev, CRC Press, Inc., Boca Raton, 1982, Vol. II.
2 J. Verghese, *Perfum. Essent. Oil. Rec.*, 1965, **56**, 438.
3 J. Verghese, *Perfum. Flavor.*, 1979, **4**, 23.
4 W. Cocker, *J. Soc. Cosmet. Chem.*, 1971, **22**, 249.
5 B. A. Arbuzov and Z. G. Isaeva, *Russ. Chem. Rev.*, 1976, **45**, 673.
6 H. Sadowska and J. Góra, Pollena: *Tluszcze, Srodki Piorace, Kosmet*, 1984, **28**, 21; *Chem. Abstr.*, 1985, **102**, 6826.
7 D. H. Grayson, *Nat. Prod. Rep.*, 1988, **5**, 447.
8 M. Lajunen, Ph.D. Thesis, *Annales Academiae Scientiarum Fennicae, Ser. A, II. Chemica*, no. 232, Helsinki, 1991, Finland. ISSN 0355-0087, ISBN 951-41-0656-3.
9 R. J. Abraham, M. A. Cooper and D. Whittaker, *Org. Magn. Reson.*, 1973, **5**, 515.
10 A. N. Chernov, A. V. Il'yasov, A. A. Nafikova, E. Kh. Kazakova and A. N. Vereshchagin, *Zh. Org. Khim.*, 1988, **24**, 377.
11 A. V. Tkachev and A. Yu. Denisov, *Mendeleev Commun.*, 1991, 98.
12 A. N. Chernov, A. V. Il'yasov, A. A. Nafikova, A. N. Vereshchagin and E. Kh. Kazakova, *Zh. Obsh. Khim.*, 1990, **60**, 376.
13 A. Yu. Denisov, A. V. Tkachev and V. I. Mamatyuk, *Magn. Reson. Chem.*, 1992, **30**, 95.
14 A. Yu. Denisov, E. A. Tyshchishin, A. V. Tkachev and V. I. Mamatyuk, *Magn. Reson. Chem.*, 1992, **30**, 886.
15 F. Fringuelli, H. E. Gottlieb, E. W. Hagaman, A. Taticchi, E. Wenkert and P. M. Wovkulich, *Gazz. Chim. Ital.*, 1975, **105**, 1215.
16 W. D. P. Burns, M. S. Carson, W. Cocker and P. V. R. Shannon, *J. Chem. Soc., C*, 1968, 3073.
17 W. Cocker, P. V. R. Shannon and P. A. Staniland, *J. Chem. Soc., C*, 1967, 485.
18 H. C. Brown and A. Suzuki, *J. Am. Chem. Soc.*, 1967, **89**, 1933.
19 J. Endo and T. Nakamura, *Yakugaku Zasshi*, 1978, **98**, 789.
20 K. Laihia, K. Rissanen, E. Kolehmainen, J. Korvola and K. Leskinen, *Acta Chem. Scand.*, 1991, **45**, 499.
21 E. Kolehmainen, K. Laihia, K. Rissanen, J. Korvola and V. Niemi, *Acta Chem. Scand.*, 1992, **46**, 290.
22 K. Laihia, E. Kolehmainen, P. Malkavaara, J. Korvola, P. Mänttäri and R. Kauppinen, *Magn. Reson. Chem.*, 1992, **30**, 754.
23 E. Kolehmainen, K. Rissanen, K. Laihia, P. Malkavaara, J. Korvola and R. Kauppinen, *J. Chem. Soc., Perkin Trans. 2*, 1993, 437.
24 L. Crombie, W. M. L. Crombie, S. V. Jamieson and C. J. Palmer, *J. Chem. Soc., Perkin Trans. 1*, 1988, 1243 and references cited therein.
25 T. Matsuura, K. Saito and Y. Shimakawa, *Bull. Chem. Soc. Jpn.*, 1960, **33**, 1151.
26 T. Suga, T. Shishibori and T. Matsuura, *Bull. Chem. Soc. Jpn.*, 1972, **45**, 1873.
27 H. Schmidt, P. Richter and M. Muehlstaedt, *Ber.*, 1963, **96**, 2636.
28 Z. G. Isaeva, B. A. Arbuzov and V. V. Ratner, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1965, 475 [*Chem. Abstr.*, 1965, **63**, 633f].
29 B. A. Arbuzov, Z. G. Isaeva and V. V. Ratner, *Dokl. Akad. Nauk, SSSR*, 1965, **164**, 1289 [*Chem. Abstr.*, 1966, **64**, 3608f].
30 B. A. Arbuzov, Z. G. Isaeva and V. V. Ratner, *Zh. Org. Khim.*, 1966, **2**, 1401 [*Chem. Abstr.*, 1967, **66**, 46491b].
31 B. A. Arbuzov and B. M. Mikhailov, *J. Prakt. Chem.*, 1930, **127**, 1 [*Chem. Abstr.*, 1930, **24**, 4285].
32 B. A. Arbuzov and B. M. Mikhailov, *J. Russ. Phys. Chem.*, 1930, **62**, 607 [*Chem. Abstr.*, 1930, **24**, 4775].
33 J.-P. Kintzinger, in *NMR-Basic Principles and Progress, Oxygen-17 and Silicon-29, Oxygen NMR. Characteristic Paramaters and Applications*, ed. P. Diehl, E. Fluck and R. Kosfeld, Springer Verlag, Berlin, 1981, vol. 17, p. 21–25.
34 R. Laatikainen, *J. Magn. Reson.*, 1977, **27**, 169.
35 R. Laatikainen, *J. Magn. Reson.*, 1991, **92**, 1.
36 N. L. Allinger, MM2(85), QCPE(1985).
37 Program PCMODEL (Serena Software) (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) computers by M. M. Midland. Molecular mechanics (MMX) of PCMODEL is based on N. L. Allinger's MM2(85).
38 DIFABS: N. Walker and D. Stuart, *Acta Crystallogr., Sect. A*, 1983, **39**, 158.
39 SHELXS: G. M. Sheldrick, in *Crystallographic Computing 3*, eds. G. M. Sheldrick, C. Kruger and R. Goddard, Oxford University Press, Oxford, England, 1985, pp. 175–189.
40 CRYSTALS: D. Watkin, J. R. Carruthers and P. W. Betteridge, Chemical Crystallography Laboratory, Oxford, England, 1990.
41 C. A. G. Haasnoot, F. A. A. M. deLeeuw and C. Altona, *Tetrahedron*, 1980, **36**, 2783.
42 M. Barfield, V. J. Hruby and J.-P. Meraldi, *J. Am. Chem. Soc.*, 1976, **98**, 1308.
43 F. Bohlman, R. Zeisberg and E. Klein, *Org. Magn. Reson.*, 1975, **7**, 426.
44 E. V. Lassak and I. A. Southwell, *Aust. J. Chem.*, 1974, **27**, 2061.
45 J. J. Burke and P. C. Lauterbur, *J. Am. Chem. Soc.*, 1964, **86**, 1870.
46 S. Chandrasekaran and D. W. Boykin, *Heteroatom Chem.*, 1992, **3**, 1.
47 E. Keller, SCHAKAL88. Kristallographisches Institut für Universität Freiburg, Deutschland.
48 E. Breitmaier and W. Voelter, *Carbon-13 NMR Spectroscopy*, Third completely revised edition, VCH, Weinheim, 1987.

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