organic compounds

Two polycyclic compounds derived from a Diels–Alder reaction

J. Zukerman-Schpector,[a,b]* I. Caracelli,[a] Mauricio Vega,[a] Mauricio Gomes Constantino,[c] Adilson Beatriz[c] and Gil Valdo da Silva[c]

[a]Laboratório de Cristalografia, Estereodinâmica e Modelagem Molecular, Departamento Química, Universidade Federal de São Carlos, Caixa Postal 676, 13565-905 São Carlos, SP, Brazil, [b]Instituto de Química, Universidade de São Paulo, São Paulo, SP, Brazil, and [c]Departamento de Química, Faculdade de Filosofia, Ciências e Letras de Ribeirão Preto, USP, Ribeirão Preto, SP, Brazil
Correspondence e-mail: julio@power.ufscar.br

In both 9,10-dimethoxy-11-oxatricyclo[6.2.1.0^{2,7}]undeca-4,9-diene-3,6-diol, $C_{12}H_{16}O_5$, (I), and 5,6-dimethoxy-3,7-dioxatetracyclo[6.4.0.0^{2,6}.0^{4,12}]dodec-9-en-11-ol, $C_{12}H_{16}O_5$, (II), the hetero-oxygen-containing five-membered rings have an envelope conformation. The six-membered rings are in a boat conformation in compound (I), and in (II), one is in a half-boat and the other is in a slightly distorted boat conformation. The molecules in both compounds interact through classical hydrogen bonds and C—H···O contacts.

Comment

Heliangolides are interesting natural products containing a polymacrocyclic structure (da Costa *et al.*, 1993). Our investigation, aimed at the synthesis of these macrocyclic structures, started with the Diels–Alder reaction between 3,4-dimethoxyfuran and benzoquinone in benzene. The product, (III), was further reduced with sodium borohydride in the presence of ceric chloride to give (I). Due to the cage-like structure of (III), which should prevent the approach of the reagent to the concave face of the substrate, a very high stereoselectivity is expected. In fact, only one product was isolated. We noticed that compound (I) was converted into a different crystalline product, which could be (II) or (IV), within a few hours when kept in chloroform at room temperature. This unexpected result prompted us to proceed with detailed X-ray crystal structure determinations of (I) and the other product, which was identified as (II).

In order to establish possible changes in the conformations of and distances between the functional groups in the molecules, when released from interactions with surrounding molecules in the crystalline state, a series of semi-empirical (*AM*1 and *PM*3) and *ab initio* quantum chemical calculations were performed. This study should help in postulating a mechanism for the transformation of (I) into (II). The calcu-

lations were carried out using the 6-31G** basis set of the *MOPAC* 7.01 (Stewart, 1990; Csern, 2000) and *GAMESS* 98 (Schmidt *et al.*, 1993) packages.
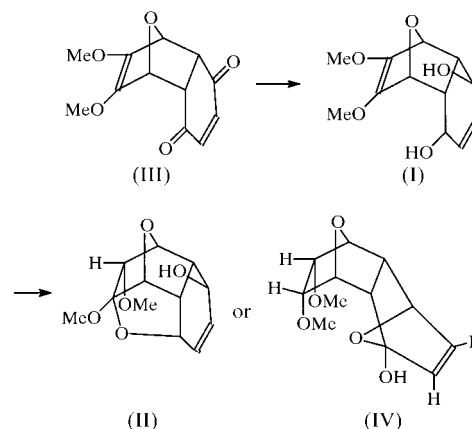
The molecular structure of (I) is shown in Fig. 1. Table 3 gives the Cremer & Pople (1975) puckering parameters. As in other norbornenes (Zukerman-Schpector *et al.*, 1999), the six-membered ring (C1, C2 and C7–C10) is in a boat conformation. The 'boat' is almost symmetric, with a dihedral angle between the planes defined by C1/O1/C8 and C2/C7/C9/C10 of 86.4 (1)°, and with equal deviations of C8 and C1 from the C2/C7/C9/C10 plane of 0.794 (3) Å; the deviations of O4 and O5 from the C2/C7/C9/C10 plane are 0.598 (3) and 0.812 (3) Å, respectively. The two hetero-oxygen-containing five-membered rings have envelope conformations, with O1 displaced 0.867 (2) Å from the C1/C2/C7/C8 plane and 0.787 (3) Å displaced from the C1/C8/C9/C10 plane. The C2–C7 six-membered ring is also in a boat conformation, and makes dihedral angles of 11.1 (1)° with the C1—O1—C8 bridge and 75.29 (8)° with the C2/C7/C9/C10 plane.

The molecular diagram of (II) is shown in Fig. 2. Table 6 gives the Cremer & Pople (1975) puckering parameters. The ring formed by atoms C1, C2, C6, C5, C4 and C12 adopts a slightly distorted boat (towards a half-boat) conformation, which is imposed by O1 bridging C2 and C4. Atoms C2 and C4 deviate from the plane defined by C1/C6/C5/C12 [planar to within 0.015 (1) Å] by 0.971 (3) and 0.712 (3) Å, respectively. The C1/C8–C12 ring is in a half-boat conformation and makes dihedral angles of 18.51 (8), 88.78 (7) and 71.94 (8)° with the C2/O1/C4, C1/C6/C5/C12 and C1/C2/C6/O2/C8 planes, respectively. The three hetero-oxygen-containing five-
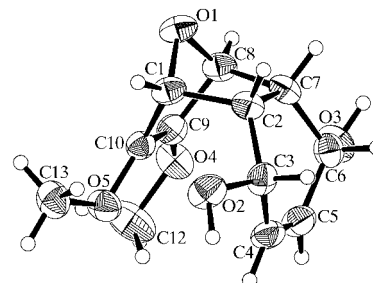

Figure 1
The molecular structure of (I) showing the atom-labelling scheme. Displacement ellipsoids are drawn at the 50% probability level and H atoms are shown as small spheres of arbitrary radii.

Figure 2
The molecular structure of (II) showing the atom-labelling scheme. Displacement ellipsoids are drawn at the 50% probability level and H atoms are shown as small spheres of arbitrary radii.
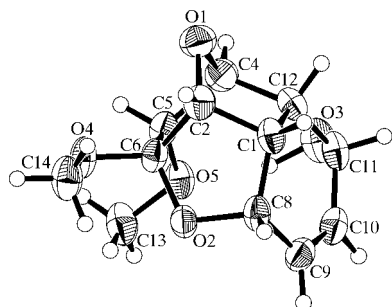
membered rings have envelope conformations, as shown in Table 3, with O1 displaced 0.804 (3) Å from the C1/C2/C4/C12 plane and 0.771 (3) Å from the C2/C4/C5/C6 plane, and C2 displaced 0.564 (3) Å from the C1/C8/O2/C6 plane.

In Tables 2 and 5 it is shown that in (I), molecules are linked by several classical hydrogen bonds and a short C—H···O interaction, while in (II), the molecules are linked only by C—H···O short interactions. In both cases, these might be described as hydrogen-bonding interactions. However, as pointed out by Cotton *et al.* (1997), 'the field is getting muddier and muddier as the definition of a hydrogen bond is relaxed'. Therefore, we only choose those with a C—H···O angle greater than 100° and an H···O distance of up to 2.73 Å, which corresponds to the sum of the van der Waals radii of O and H, as given by Pauling (1960), plus 5%.

The geometry optimization calculations on (I), using the three methods mentioned above (*AM*1, *PM*3 and *ab initio*), showed three main conformational changes. Firstly, the C2—C3—O2—H2O torsion angle changes from 180 to 71°, to give an H2O···O5 distance of 2.28 Å (less than the sum of the van der Waals radii). It should be noted that in the crystal, this OH moiety is involved in an intermolecular hydrogen bond (Table 2). Secondly, the C13—O5—C10—C1 torsion angle changes from 39.9 (3) to 71.1°, to leave space for atom H2O. Thirdly, the H3O—O3—C6—C7 torsion angle changes from 67 to −69°, to give a final H3···O4 distance of 2.33 Å. Recall that in (I), the O3—H3O hydroxyl group is involved in an intermolecular hydrogen bond and in (II), it forms an intramolecular hydrogen bond (Table 5). These results strongly suggest that the transformation of (I) into (II) is by the mechanism shown below.
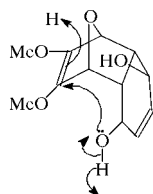
Experimental

Brief details of the preparation of (I) and (II) are given in the *Comment*. In order to prevent transformation into (II), (I) was kept

in and crystallized from ethyl acetate. Suitable crystals of (II) were obtained by slow evaporation from an ethanol solution.

Compound (I)

Crystal data

$C_{12}H_{16}O_5$
$M_r = 240.25$
Orthorhombic, $P2_12_12_1$
$a = 8.0796\ (4)$ Å
$b = 10.1970\ (7)$ Å
$c = 13.7534\ (9)$ Å
$V = 1133.11\ (12)$ Å^3
$Z = 4$
$D_x = 1.408$ Mg m^{-3}

Mo $K\alpha$ radiation
Cell parameters from 25 reflections
$\theta = 10.0–18.4°$
$\mu = 0.11$ mm^{-1}
$T = 293$ K
Irregular, colourless
$0.20 \times 0.10 \times 0.05$ mm

Data collection

Enraf–Nonius CAD-4 diffract-ometer
$\omega/2\theta$ scans
1235 measured reflections
1235 independent reflections
1131 reflections with $F^2 > 2\sigma F^2$
$\theta_{max} = 25.5°$

$h = -9 \rightarrow 0$
$k = -12 \rightarrow 0$
$l = 0 \rightarrow 16$
3 standard reflections
  frequency: 30 min
  intensity decay: 1.0%

Refinement

Refinement on F^2
$R[F^2 > 2\sigma(F^2)] = 0.028$
$wR(F^2) = 0.071$
$S = 1.05$
1235 reflections
156 parameters
H-atom parameters constrained

$w = 1/[\sigma^2(F_o^2) + (0.0386P)^2 + 0.2105P]$
  where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max} < 0.001$
$\Delta\rho_{max} = 0.13$ e Å^{-3}
$\Delta\rho_{min} = -0.12$ e Å^{-3}

Table 1
Selected geometric parameters (Å, °) for (I).

O1—C8	1.448 (2)	O3—C6	1.431 (2)
O1—C1	1.455 (2)	C4—C5	1.321 (3)
O2—C3	1.418 (2)	C9—C10	1.334 (3)
C8—O1—C1	95.09 (13)	C5—C4—C3	121.2 (2)
C9—O4—C11	116.61 (16)	C4—C5—C6	121.6 (2)
C10—O5—C12	116.29 (16)	O1—C8—C9	101.15 (15)
O1—C1—C10	100.82 (14)	O1—C8—C7	100.12 (15)
O1—C1—C2	99.41 (15)	C9—C8—C7	111.22 (16)

Table 2
Hydrogen-bonding geometry (Å, °) for (I).

D—H···A	D—H	H···A	D···A	D—H···A
C12—H12A···O2	0.96	2.55	3.273 (3)	133
O2—H2O···O3^i	0.95	2.03	2.815 (2)	139
O2—H2O···O4^i	0.95	2.36	3.094 (2)	133
O3—H3O···O1^{ii}	0.93	1.87	2.788 (2)	173
C1—H1···O5^{iii}	0.98	2.62	3.383 (2)	135

Symmetry codes: (i) $\frac{1}{2} - x, 2 - y, z - \frac{1}{2}$; (ii) $x - \frac{1}{2}, \frac{3}{2} - y, 2 - z$; (iii) $1 - x, y - \frac{1}{2}, \frac{3}{2} - z$.

Table 3
Cremer & Pople (1975) puckering parameters (Å, °) for (I).

Ring	q_2	q_3	φ_2	θ_2	Q
O1/C1/C2/C7/C8	0.614 (2)		1.0 (2)		
O1/C1/C10/C9/C8	0.533 (3)		179.2 (2)		
C1/C2/C7/C8/C9/C10	0.917 (2)	0.002 (2)	−1.3 (1)	89.9 (1)	0.917 (2)
C2/C3/C4/C5/C6/C7	0.496 (2)	−0.010 (2)	−120.7 (2)	91.1 (3)	0.497 (2)

organic compounds

Compound (II)

Crystal data

$C_{12}H_{16}O_5$
$M_r = 240.25$
Monoclinic, $C2/c$
$a = 7.545 (1)$ Å
$b = 10.750 (1)$ Å
$c = 27.336 (3)$ Å
$\beta = 94.69 (2)°$
$V = 2209.8 (4)$ Å^3
$Z = 8$

$D_x = 1.444$ Mg m^{-3}
Mo $K\alpha$ radiation
Cell parameters from 25
 reflections
$\theta = 9.9–18.2°$
$\mu = 0.11$ mm^{-1}
$T = 293$ K
Irregular, colourless
$0.25 \times 0.20 \times 0.16$ mm

Data collection

Enraf–Nonius CAD-4 diffract-
 ometer
$\omega/2\theta$ scans
4326 measured reflections
2038 independent reflections
1513 reflections with $F^2 > 2\sigma F^2$
$R_{int} = 0.026$

$\theta_{max} = 25.5°$
$h = -7 \rightarrow 9$
$k = -7 \rightarrow 12$
$l = -33 \rightarrow 33$
3 standard reflections
 frequency: 30 min
 intensity decay: 1.1%

Refinement

Refinement on F^2
$R[F^2 > 2\sigma(F^2)] = 0.040$
$wR(F^2) = 0.100$
$S = 1.06$
2038 reflections
156 parameters
H-atom parameters constrained

$w = 1/[\sigma^2(F_o^2) + (0.0465P)^2 + 1.8597P]$
 where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max} < 0.001$
$\Delta\rho_{max} = 0.19$ e Å^{-3}
$\Delta\rho_{min} = -0.21$ e Å^{-3}

Table 4
Selected geometric parameters (Å, °) for (II).

O1—C2	1.435 (3)	O2—C8	1.454 (2)
O1—C4	1.444 (3)	C9—C10	1.319 (3)
O2—C6	1.408 (2)		
C2—O1—C4	96.72 (15)	C1—C2—C6	99.60 (17)
C6—O2—C8	108.91 (15)	O1—C4—C5	99.60 (15)
C6—O4—C14	114.67 (15)	O1—C4—C12	100.40 (16)
C5—O5—C13	112.42 (15)	C5—C4—C12	115.55 (18)
O1—C2—C1	106.58 (16)	C10—C9—C8	123.0 (2)
O1—C2—C6	103.88 (16)	C9—C10—C11	125.9 (2)

Table 5
Hydrogen-bonding geometry (Å, °) for (II).

D—H$\cdots A$	D—H	H$\cdots A$	$D\cdots A$	D—H$\cdots A$
O3—H3O$\cdots$O5	1.06	1.95	2.849 (2)	140
C13—H13$C\cdots$O2	0.96	2.60	3.133 (3)	115
C13—H13$A\cdots$O1^i	0.96	2.61	3.325 (3)	132
C4—H4$\cdots$O2^{ii}	0.98	2.47	3.320 (3)	144
C11—H11$\cdots$O3^{iii}	0.98	2.74	3.648 (3)	154

Symmetry codes: (i) $\frac{1}{2} + x, y - \frac{1}{2}, z$; (ii) $\frac{1}{2} + x, \frac{1}{2} + y, z$; (iii) $2 - x, y, \frac{1}{2} - z$.

In spite of the rather poor diffraction quality of (I), the main aim of the work was achieved, which was to obtain the relevant structural information. H atoms were located on stereochemical grounds, except those of the hydroxyl groups, and were refined as riding, with an isotropic displacement parameter amounting to 1.5 (for methyl H atoms) or 1.2 (for the other H atoms) times the value of the

Table 6
Cremer & Pople (1975) puckering parameters (Å, °) for (II).

Ring	q_2	q_3	φ_2	θ_2	Q
O1/C2/C1/C12/C4	0.549 (2)		164.4 (2)		
O1/C2/C6/C5/C4	0.568 (2)		-10.4 (2)		
C1/C2/C6/O2/C8	0.357 (2)		34.7 (3)		
C1/C2/C6/C5/C4/C12	0.978 (2)	-0.133 (2)	-121.7 (1)	97.8 (1)	0.987 (2)
C1/C8/C9/C10/C11/C12	0.225 (2)	-0.179 (2)	-179.0 (5)	128.6 (4)	0.288 (2)

equivalent isotropic displacement parameter of the parent atom. H atoms bound to O atoms were located in difference maps.

For both compounds, data collection: *CAD*-4 *Software* (Enraf–Nonius, 1989); cell refinement: *CAD*-4 *Software*; data reduction: *XCAD*-4 (Harms & Wocadlo, 1995). For compound (I), program(s) used to solve structure: *SHELXS*86 (Sheldrick, 1985); for compound (II), *SIR*92 (Altomare *et al.*, 1993). For both compounds, program(s) used to refine structure: *SHELXL*97 (Sheldrick, 1997); molecular graphics: *ZORTEP* (Zsolnai, 1995); software used to prepare material for publication: *PARST*95 (Nardelli, 1995), *PLATON* (Spek, 1998) and *WinGX* (Farrugia, 1999).

References

Altomare, A., Cascarano, G., Giacovazzo, C. & Guagliardi, A. (1993). *J. Appl. Cryst.* **26**, 343–350.
Costa, F. B. da, Dias, D. A., Lopes, J. L. C. & Vichnewski, W. (1993). *Phytochemistry*, **34**, 261–265.
Cotton, F. A., Daniels, L. M., Jordan, G. T. IV & Murillo, C. A. (1997). *J. Chem. Soc. Chem. Commun.* pp. 1673–1674.
Cremer, D. & Pople, J. A. (1975). *J. Am. Chem. Soc.* **97**, 1354–1358.
Csern, I. (2000). *MOPAC* 7.01 for LINUX (public domain version). Institute of Nuclear Research, Hungarian Academy of Science, Debrecen, Hungary.
Enraf–Nonius (1989). *CAD-4 Software*. Version 5.0. Enraf–Nonius, Delft, The Netherlands.
Farrugia, L. J. (1999). *J. Appl. Cryst.* **32**, 837–838.
Harms, K. & Wocadlo, S. (1995). *XCAD*-4. University of Marburg, Germany.
Nardelli, M. (1995). *J. Appl. Cryst.* **28**, 659.
Pauling, L. (1960). *The Nature of the Chemical Bond*, 3rd ed. Ithaca: Cornell University Press.
Schmidt, M. W., Baldridge, K. K., Boatz, J. A., Elbert, S. T., Gordon, M. S., Jensen, J. H., Koseki, S., Matsunaga, N., Nguyen, K. A., Su, S. J., Windus, T. S., Dupuis, M. & Montgomery, J. A. (1993). *J. Comput. Chem.* **14**, 1347–1363.
Sheldrick, G. M. (1985). *SHELXS*86. University of Göttingen, Germany.
Sheldrick, G. M. (1997). *SHELXL*97. University of Göttingen, Germany.
Spek, A. L. (1998). *PLATON*. University of Utrecht, The Netherlands.
Stewart, J. J. P. (1990). *J. Comput. Aided Mol. Des.* **4**, 1–105.
Zsolnai, L. (1995). *ZORTEP*. University of Heidelberg, Germany.
Zukerman-Schpector, J., Gruber, J. & Camilo, F. F. (1999). *Acta Cryst.* C**55**, 980–983.