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Three related benzoannelated diaza-polyether macrocycles: effects of macrocycle ring size and position of benzo groups on hydrogen bonding of the amine H atoms

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The benzoannelated diazapolyether macrocycles 6,7,9,10,17,-18-hexahydro-5H,11H-8,16,19-trioxa-5,11-diazadibenzo[a,g]-cyclopentadecene, $C_{18}H_{22}N_2O_3$, (I), 6,7,9,10,12,13,20,21-octa-hydro-5H,14H-8,11,19,22-tetraoxa-5,14-diazadibenzo[a,g]-cyclooctadecene, $C_{20}H_{26}N_2O_4$, (II), and 6,7,9,10,17,18,20,21-octahydro-16H,22H-5,8,11,19-tetraoxa-16,22-diazadibenzo-[a,j]cyclooctadecene 0.3-hydrate, $C_{20}H_{26}N_2O_4 \cdot 0.304 H_2O$, (III), show different patterns of hydrogen bonding. In (I), the amine H atoms participate only in intramolecular hydrogen bonds with ether O atoms. In (II), the amine H atoms form intramolecular hydrogen bonds with the phenoxy ether O atoms and intermolecular hydrogen bonds with alkyl ether O atoms in an adjacent molecule, forming a chain linking the macrocycles together *via* an $R_2^2(10)$ motif. Molecules of (II) were found on a crystallographic twofold axis. In (III), the amine H atoms participate in a hydrogen-bond network with adjacent ether O atoms and with a water molecule [having a partial occupancy of 0.304 (6)] that links the molecules together *via* a $C_2^2(7)$ motif.

Comment

Macrocyclic diaminopolyethers, which serve as precursors in the synthesis of cryptands, also are of interest for their potential as receptors for molecules and anions (Kang *et al.*, 2006). In the process of preparing cryptands with aniline-type nitrogen as the bridgehead atoms we have isolated several related benzoannelated macrocyclic diamines, and we report the structures of (I)–(III) here. These closely related compounds reveal the effects of ring size [comparing (I) and (II)] and position of the benzo groups [comparing (II) and (III)] on the orientation of the NH hydrogens, an important consideration for the design of anion and molecular receptors. Among the factors that contribute to the conformation of the

macrocycle, and thus the orientation of the NH hydrogens, are the torsion angles for the X—CH_2—CH_2—O (X = N and O) segments, macrocycle ring size and the position of the benzo groups in the macrocycle backbone. For (I)–(III), the torsion angles for the alkyl X—CH_2—CH_2—O groups lie in the range 54.75 (17)–77.0 (4)°, thus adopting the *gauche* conformation preferred when such subunits contain N or O atoms (Herceg & Weiss, 1970; Wolf *et al.*, 1987). The N—C≡C—O torsion angles for the heteroatoms attached to the benzene ring are geometrically restricted and range from 1.6 (6) to 6.27 (18)°. The N atoms are essentially coplanar with the associated benzo group [with deviations of 0.0055 (13)–0.071 (6) Å], while the amino H atoms show a slightly greater range of deviation [0.0478 (13)–0.193 (6) Å]. Therefore, the orientation of the NH hydrogens will be defined by the associated benzo group and, as shown in Figs. 1–3, the NH hydrogens have an endodentate conformation with respect to the macrocycle cavity.

(I)

(II)

·0.304 H_2O

(III)
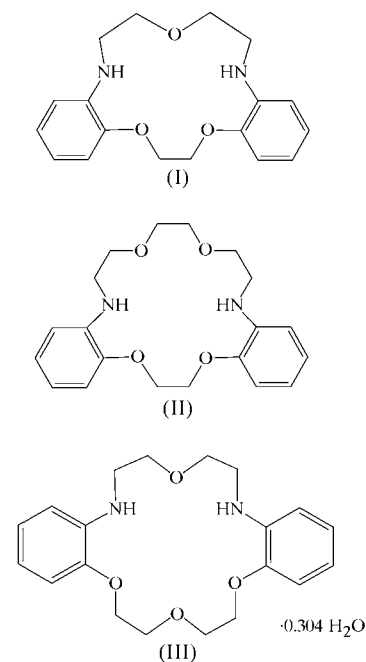
For (I), the *gauche* conformation of the X—CH_2—CH_2—O subunits, the smaller ring size and the short five-atom bridge (CCOCC) connecting atoms N5 and N11 result in the molecule adopting a relatively flat conformation (Fig. 1), although the least-squares plane defined by atoms N5, O8, N11, O16 and O19 [the mean deviation is 0.4288 (14) Å] is the least well defined among the three compounds. Benzene rings *A* and *B* have dihedral angles of 28.5 (2) and 137.7 (2)°, respectively, with the plane defined by the heteroatoms and 166.2 (2)° with one another. Atom H5 forms hydrogen bonds with atoms O8 and O19, while atom H11 has reasonable hydrogen-bond geometry only with atom O16 (Fig. 1 and Table 1).
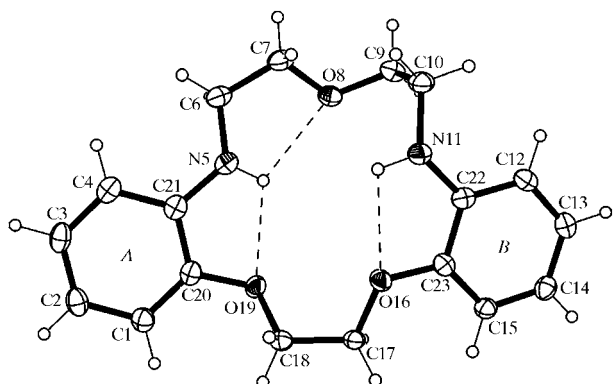
Molecule (II) lies on a twofold rotation axis. The eight-atom chain (CCOCCOCC) between the N atoms allows the benzo groups to rotate out the plane defined by atoms N5, O8 and O22 [the mean deviation is 0.2513 (12) Å] to a much greater extent than for (I). The resulting conformation has the benzo

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groups on opposite sides of the heteroatom plane (Fig. 4), forming a dihedral angle of 72.9 (2)° with one another and 112.1 (2)° with the heteroatom plane. As a result, one NH hydrogen is oriented above and the other below the heteroatom plane. Each forms an intramolecular hydrogen bond with the proximal phenoxy ether O atom (Fig. 2 and Table 2). In addition, each NH hydrogen forms a hydrogen bond to ether atom O8($-x + 1$, $-y + 1$, $-z + 1$) in an adjacent molecule, linking the macrocycles together in a chain-like fashion via an $R_2^2(10)$ motif (Bernstein et al., 1995) along the c axis (Fig. 4).
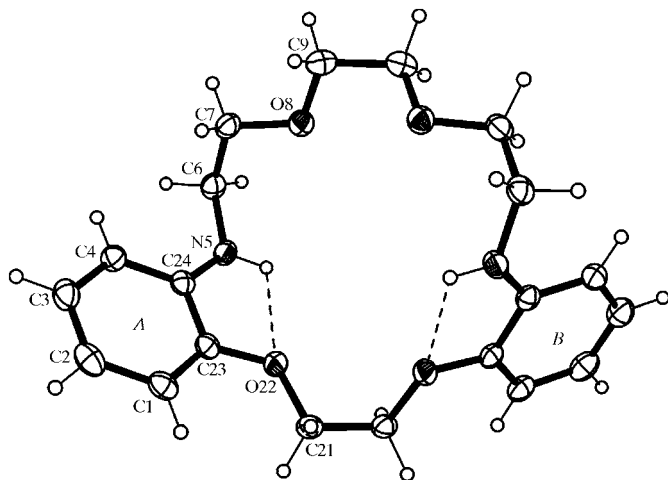
The macrocycle ring size of (III) is the same as that of (II) but the positions of the benzo groups and N atoms in the ring differ, and a molecule of water [with a fractional occupancy of 0.304 (6)] is present above the center of the macrocycle cavity. The positions of the benzo groups and gauche conformation of all the $X-CH_2-CH_2-O$ subunits allow the molecule to adopt a folded conformation defined by an axis passing through atoms O8 and O19 (Fig. 5). The benzo groups are located on the same side of the plane defined by atoms O5, O8, O11, N16, O19 and N22 [the mean deviation is

0.0557 (6) Å]. Benzene rings A and B form dihedral angles of 33.5 (2) and 148.0 (2)°, respectively, with the heteroatom plane and 114.6 (2)° with one another. Both NH hydrogens are on the same side of the macrocycle plane and are oriented toward, but above, the center of the cavity. Each NH hydrogen forms an intramolecular hydrogen bond with the adjacent phenoxy ether O atom (Fig. 3 and Table 3). In addition, both NH hydrogens interact with atom O1S of the water molecule. Atom H1S1 forms a hydrogen bond with O8, while H1S2 forms a hydrogen bond with atom O19(x, $y + 1$, z) in an adjacent molecule, linking the crown ether units in a chain via a $C_2^2(7)$ motif (Bernstein et al., 1995) along the b axis (Fig. 5).
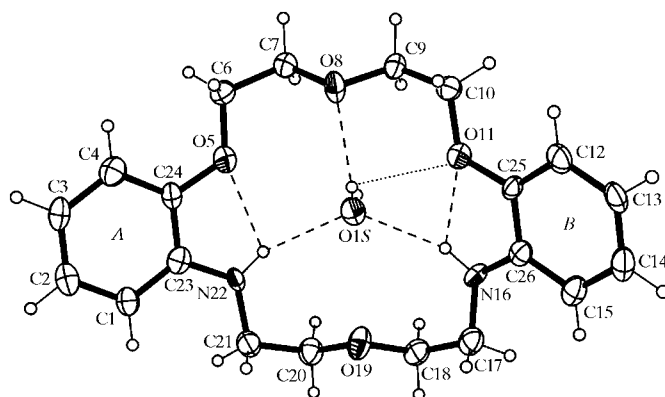
The NH hydrogens for (I)–(III) all form weak intramolecular hydrogen bonds with one or more ether O atoms in the macrocycle; however, the N—H···O angles [106.0 (14)– 116 (3)°] cannot achieve optimal geometry owing to confor-

Figure 3
The molecular structure of (III), showing the atom-numbering scheme. Displacement ellipsoids are drawn at the 50% probability level.
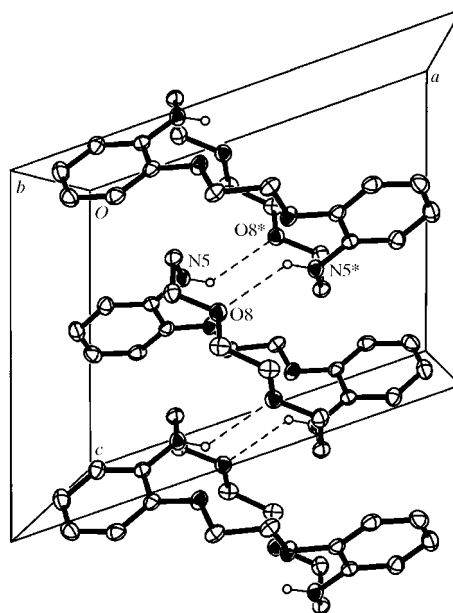

Figure 1
The molecular structure of (I), showing the atom-numbering scheme. Displacement ellipsoids are drawn at the 50% probability level.

Figure 4
Part of the crystal structure of (II), showing the formation of a chain of hydrogen-bonded $R_2^2(10)$ rings along the c axis. H atoms attached to C atoms have been omitted for clarity. Atoms marked with an asterisk (*) are related by the symmetry operation $(1 - x, 1 - y, 1 - z)$. Displacement ellipsoids are drawn at the 50% probability level.

Figure 2
The molecular structure of (II), showing the atom-numbering scheme. Displacement ellipsoids are drawn at the 50% probability level.

organic compounds

mational restrictions imposed by the ring structure and the presence of the benzo groups in the macrocycle backbone. The intermolecular N—H···O angles for (III) [152 (4)–173 (13)°] fall in the conventional range, except for O1S—H1S···O11 [117 (11)°], while those for (II) [134.9 (11)°] are somewhat lower. Comparison of the structural characteristics of (I)–(III) suggests that a macrocycle with NH groups separated by a five-atom bridge and a ring size of 18 atoms, as in (III), provides hydrogen-bond donors with the spacing and orientation suitable to interact preferably with an external hydrogen-bond acceptor guest.
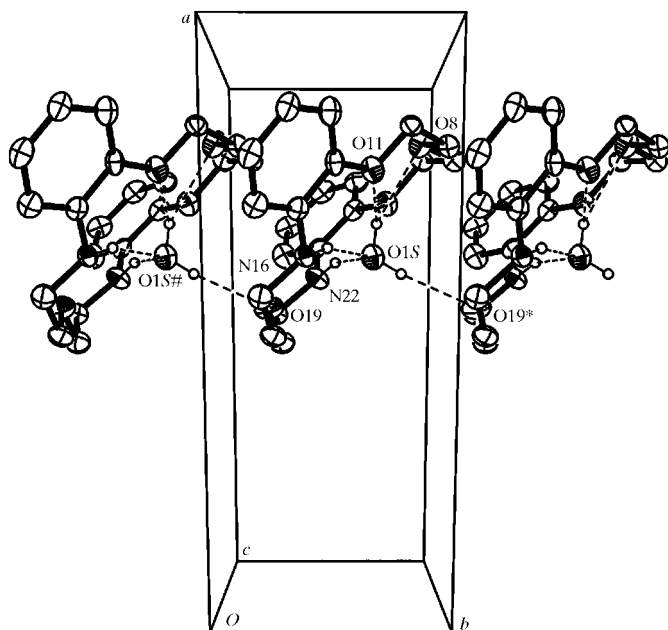
Figure 5
Part of the crystal structure of (III), showing the formation of a hydrogen-bonded $C_2^2(7)$ chain along the b axis involving the amine H atoms, water molecules and ether O atoms. Atoms marked with an asterisk (*) or a hash (#) are related by the symmetry operations $(x, y + 1, z)$ and $(x, -y + 1, z)$, respectively. H atoms attached to carbon have been omitted for clarity. Displacement ellipsoids are drawn at the 50% probability level.

Experimental

Monocyclic diamines (I), (II) and (III) were prepared by condensation of the appropriate α,ω-polyoxadianiline with the corresponding diacid chloride ether under high-dilution conditions (Dietrich *et al.*, 1973) according to reported methods (Lockhart & Thompson, 1977; Aguilar *et al.*, 2001; Formanovskii & Murakhovskaya, 1985; Formanovskii *et al.*, 1988; Crossley *et al.*, 1994). The resulting dilactams were purified by recrystallization from ethanol [for (I) and (II)] or benzene/toluene [for (III)] (Smith *et al.*, 2006). Reduction of the dilactams using BH$_3$ in THF and subsequent work-up (Smith *et al.*, 1986, 1988) gave the title compounds. Compound (I) was obtained in 58% overall yield; ESI–MS: m/z = 315.2 (M+H$^+$), 337.2 (M+Na$^+$), 651.4 ($2M$+Na$^+$). Compound (II) was obtained in 51% overall yield; ESI–MS: m/z = 359.2 (M+H$^+$), 381.2 (M+Na$^+$). Compound (III) was obtained in 70% overall yield; ESI–MS: m/z = 359.2 (M+H$^+$), 381.2 (M+Na$^+$). ^{1}H NMR spectra were consistent with previously reported values for (I) (Formanovskii & Murakhovskaya, 1985) and (III) (Aguilar *et al.*, 2001). Crystals suitable for X-ray crystallographic

analysis were grown by vapor diffusion of heptane into a solution of (I) in benzene, by vapor diffusion of water into a solution of (II) in benzene, and by slow evaporation of a solution of (III) in methanol.

Compound (I)

Crystal data

C$_{18}$H$_{22}$N$_2$O$_3$	$V = 1586.7$ (3) Å^3
$M_r = 314.38$	$Z = 4$
Orthorhombic, $P2_12_12_1$	Mo $K\alpha$ radiation
$a = 7.8995$ (8) Å	$\mu = 0.09$ mm^{-1}
$b = 9.5228$ (10) Å	$T = 100$ (2) K
$c = 21.093$ (2) Å	$0.32 \times 0.26 \times 0.20$ mm

Data collection

Bruker APEX CCD diffractometer	16397 measured reflections
Absorption correction: multi-scan	1809 independent reflections
(*SADABS*; Sheldrick, 2002)	1788 reflections with $I > 2\sigma(I)$
$T_{min} = 0.971$, $T_{max} = 0.984$	$R_{int} = 0.014$

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.026$	H atoms treated by a mixture of
$wR(F^2) = 0.071$	independent and constrained
$S = 1.07$	refinement
1809 reflections	$\Delta\rho_{max} = 0.17$ e Å^{-3}
215 parameters	$\Delta\rho_{min} = -0.18$ e Å^{-3}

Table 1
Hydrogen-bond geometry (Å, °) for (I).

D—H···A	D—H	H···A	D···A	D—H···A
N5—H5···O8	0.887 (19)	2.349 (18)	2.7310 (16)	106.0 (14)
N5—H5···O19	0.887 (19)	2.220 (19)	2.6699 (17)	111.0 (14)
N11—H11···O16	0.893 (17)	2.246 (18)	2.6655 (16)	108.3 (14)

Compound (II)

Crystal data

C$_{20}$H$_{26}$N$_2$O$_4$	$V = 1871.3$ (6) Å^3
$M_r = 358.43$	$Z = 4$
Monoclinic, $C2/c$	Mo $K\alpha$ radiation
$a = 11.837$ (2) Å	$\mu = 0.09$ mm^{-1}
$b = 18.116$ (3) Å	$T = 120$ (2) K
$c = 9.2565$ (18) Å	$0.28 \times 0.18 \times 0.14$ mm
$\beta = 109.485$ (5)°	

Data collection

Bruker APEX CCD diffractometer	9314 measured reflections
Absorption correction: multi-scan	1839 independent reflections
(*SADABS*; Sheldrick, 2002)	1726 reflections with $I > 2\sigma(I)$
$T_{min} = 0.973$, $T_{max} = 0.989$	$R_{int} = 0.018$

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.033$	H atoms treated by a mixture of
$wR(F^2) = 0.091$	independent and constrained
$S = 1.00$	refinement
1839 reflections	$\Delta\rho_{max} = 0.24$ e Å^{-3}
122 parameters	$\Delta\rho_{min} = -0.21$ e Å^{-3}

Table 2
Hydrogen-bond geometry (Å, °) for (II).

D—H···A	D—H	H···A	D···A	D—H···A
N5—H5···O8^i	0.851 (14)	2.392 (13)	3.0530 (12)	134.9 (11)
N5—H5···O22	0.851 (14)	2.223 (13)	2.6138 (11)	107.9 (10)

Symmetry code: (i) $-x + 1, -y + 1, -z + 1$.

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Compound (III)

Crystal data

$C_{20}H_{26}N_2O_4 \cdot 0.304H_2O$
$M_r = 363.92$
Monoclinic, $P2_1$
$a = 13.507$ (8) Å
$b = 5.133$ (3) Å
$c = 14.644$ (8) Å
$\beta = 112.336$ (9)°

$V = 939.1$ (9) Å^3
$Z = 2$
Mo $K\alpha$ radiation
$\mu = 0.09$ mm^{-1}
$T = 100$ (2) K
$0.22 \times 0.05 \times 0.04$ mm

Data collection

Bruker APEX CCD diffractometer
Absorption correction: multi-scan
(SADABS; Sheldrick, 2002)
$T_{min} = 0.979$, $T_{max} = 0.997$

4546 measured reflections
2037 independent reflections
1223 reflections with $I > 2\sigma(I)$
$R_{int} = 0.064$

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.053$
$wR(F^2) = 0.095$
$S = 1.00$
2037 reflections
257 parameters
6 restraints

H atoms treated by a mixture of independent and constrained refinement
$\Delta\rho_{max} = 0.23$ e Å^{-3}
$\Delta\rho_{min} = -0.20$ e Å^{-3}

Table 3
Hydrogen-bond geometry (Å, °) for (III).

D—H$\cdots A$	D—H	H$\cdots A$	$D\cdots A$	D—H$\cdots A$
N16—H16$\cdots$O11	0.861 (19)	2.17 (4)	2.643 (5)	114 (3)
N16—H16$\cdots$O1S	0.861 (19)	2.25 (5)	3.073 (11)	160 (4)
N22—H22$\cdots$O5	0.842 (19)	2.16 (4)	2.639 (5)	116 (3)
N22—H22$\cdots$O1S	0.842 (19)	2.17 (3)	2.937 (11)	152 (4)
O1S—H1S$\cdots$O8	0.83 (2)	2.30 (6)	3.078 (10)	157 (12)
O1S—H1S$\cdots$O11	0.83 (2)	2.56 (12)	3.021 (10)	117 (11)
O1S—H2S$\cdots$O19^i	0.82 (2)	2.04 (3)	2.859 (12)	173 (13)

Symmetry code: (i) x, $y + 1$, z.

H atoms attached to C atoms were positioned geometrically and refined using a riding model, with C—H distances of 0.95 (phenyl) or 0.99 Å (ethylene). H atoms attached to N or O atoms were located initially in a difference map and refined independently in (I) and (II) and with distance restraints applied in (III). The U_{iso}(H) parameters for all H atoms were set at $1.2U_{eq}$(C,N,O). The water O atom in (III) was located in a difference map. After initial refinements that lead to an implausibly large displacement parameter for this O atom, the occupancy of the atom was refined with a fixed displacement parameter. After a converged refinement with both occupancy and isotropic displacement parameter for the water O atom, a difference map revealed two peaks in chemically reasonable positions for the H atoms. The positional parameters of the water H atoms were restrained to have O—H distances of 0.82 (2) Å and a nearly tetrahedral angle in the molecule. The N—H bonds in (III) were restrained to be 0.85 (2) Å. One polar-axis restraint for (III) was applied in the manner of Flack & Schwarzenbach (1988).

For all compounds, data collection: *SMART* (Bruker, 1998); cell refinement: *SMART*; data reduction: *SAINT* (Bruker, 1998); program(s) used to solve structure: *SHELXTL* (Sheldrick, 2000); program(s) used to refine structure: *SHELXTL*; molecular graphics: *SHELXTL*; software used to prepare material for publication: *SHELXTL*.

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