Conformation of 6-Morpholino-3-azabicyclo[3.1.0]hexane Derivatives

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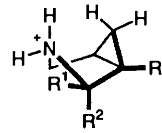
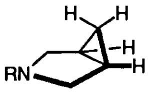
^{1}H NMR spectroscopic studies established the presence of a chair conformation for *endo*-3-methyl-6-morpholino-3-azabicyclo[3.1.0]hexane derivatives **8a** and **b**. This was additionally confirmed by an X-ray structural analysis of **8b**. The diastereomers **10a,b** and the *N*-demethyl-*endo*-morpholino compounds **9a,b**, however, were found to prefer a boat conformation. The correlation between dihedral angles and ring buckle of 3-azabicyclo[3.1.0]hexane **4** was determined by MNDOC semiempirical calculations. Further structural information about this bicyclic system was obtained by HF/6-31 G* calculations for the 3-azabicyclo[3.1.0]hexane parent compounds **4** and **5**.

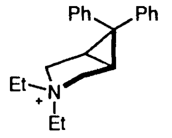
X-Ray structural analyses of some 3-azoniabicyclohexane derivatives **1**,[1] **2**[1] and **3**[2] showed that this type of compound adopts mainly a boat conformation in the solid state. 3-Azoniabicyclo[3.1.0]hexane derivatives **6**[3] and **7**,[4] however, possessing two additional substituents at the N(3)-atom, prefer a chair conformation as the most favourable structure.



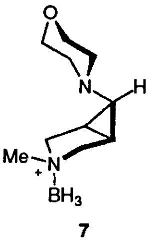
1 $R^1 = R^3 = H, R^2 = COO^-$
2 $R^2 = R^3 = H, R^1 = COO^-$
3 $R^1 = R^2 = H, R^3 = 4\text{-}CH_3C_6H_4$—



4 R = H
5 $R = CH_3$

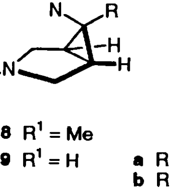


6

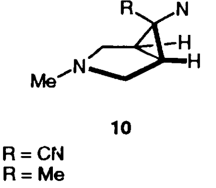


7

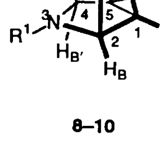
A half chair conformation[5] and a slightly boat shaped conformation[6] were postulated for compounds **4** and **2** due to detailed ^{1}H NMR spectroscopic investigations (LAOCN 3), respectively. Within our work on stereoselective syntheses, we found an access to two pairs of 6-morpholino-3-azabicyclo-[3.1.0]hexane diastereomers **8a,b**[7,8] and **10a,b**.[9]



8 R^1 = Me
9 R^1 = H



10
a R = CN
b R = Me

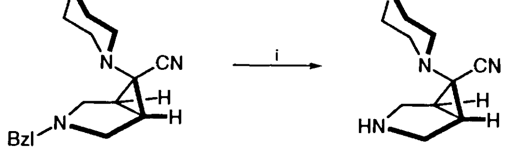


8–10

Conformational properties of these aminoazabicyclo[3.1.0]-hexanes **8a,b** and **10a,b** and of the *N*-demethyl species **9a,b** were studied by ^{1}H NMR spectroscopy. An X-ray structural analysis gave further insight in the conformation of derivative **8b**. General information about the structural properties of the 3-azabicyclo[3.1.0]hexane skeleton were expected from HF/6-31 G* calculations which were done for the parent compounds **4** and **5**. The results of these conformational investigations are described in this paper.

Results and Discussion

The syntheses of diastereomeric compounds **8a**/**10a**[7,8] and **8b**/**10b**[9] were described in the literature. N-Demethyl compound **9a** could be obtained in analogy to **9b**[9] by hydrogenolysis of the corresponding *N*-benzylbicyclic nitrile **11** (Scheme 1).



11
Bzl = benzyl

9a

Scheme 1 *Reagents:* i, H_2/Pd–C, MeOH

Conformational Analysis of the Compounds **8a,b**, **9a,b** *and* **10a,b** *on the Basis of* ^{1}H *NMR Coupling Constants.*—The ^{1}H NMR signals of the 3-azabicyclo[3.1.0]hexane skeleton of the two diastereomeric bicyclic nitriles **8a** and **b** were treated as AA'BB'XX'-spin systems. The experimentally detectable couplings ($J_{AB} = J_{A'B'}$, $J_{AX} = J_{A'X'}$, $J_{BX} = J_{B'X'}$) were taken from the spectra; values of 8.5 Hz (for **8a**) and 6.5 Hz (for **10a**) were taken for the $J_{XX'}$-coupling due to a report on this coupling for 3,5-dioxabicyclo[5.1.0]octane diastereomeric compounds.[10] All other couplings ($J_{AA'}$, $J_{BB'}$, $J_{AB'}$, $J_{AX'}$, $J_{BX'}$) were zero. $H(2)_A$ and $H(4)_{A'}$ are in the *endo*-position, $H(2)_B$ and $H(4)_{B'}$ are in the *exo*-position of the bicyclic system; assignment was made by coupling with $H(1)_X/H(5)_{X'}$ which is larger for *exo*-H atoms (H_B, $H_{B'}$) in all cases.

Simulation with the LAOKOON III program[11] and variation of the coupling constants to a small extent showed that the originally used values already gave sufficient correspondence between the experimental and the simulated ^{1}H NMR spectra. Subsequent iterative simulation with the PANIC

Table 1 ^1H NMR data of the 3-azabicyclo[3.1.0]hexane skeleton of diastereomeric compounds **8a**/**10a** and **8b**/**10b** and of *N*-demethyl species **9a** and **9b** (200 MHz, *J* in Hz)[a,b]

	$H(1)_X$ $H(5)_{X'}$	$H(2)_B$ $H(4)_{B'}$	$H(2)_A$ $H(4)_{A'}$	$J_{1.2B}$ $J_{5.4B'}$	$J_{1.2A}$ $J_{5.4A'}$	$J_{2A.2B}$ $J_{4A'.4B'}$	$J_{1.5}$
8a[c,d]	1.69	2.87	1.83	5.94	1.96	9.76	8.69
10a[d,e]	1.33	2.17	2.83	3.55	0	9.29	7.64
8b[f,g]	1.58	3.13	2.10	6.9	2.8	10.1	8.5
10b[f,g]	1.46	2.63	2.75	4.8	0	9.6	7.5
9a[h,g]	2.15	2.94	3.14	3.3	0	12.8	7.6
9b[d,g]	0.98	2.94	2.82	3.7	0	12.3	7.5

[a] Coupling constants *J* were taken from the spectra and optimized by simulation of the ^1H NMR spectra by the LAOKOON III program[11] (for **8a**, **9a**, **10a**) or by the PANIC 81 program[12] (for **8b**, **9b** and **10b**). The coupling between $H(1)_X$ and $H(5)_{X'}$ (XX'-coupling of the AA'BB'XX'-system) is essential for a correct simulation of the spectra; $^3J_{HH} = 8.5$ Hz (for **8a**) and $^3J_{HH} = 6.8$ Hz (for **10a**) were used as starting values for the coupling of the two *syn*-H-atoms $H(1)_X$ and $H(5)_{X'}$ at the cyclopropane. All other couplings ($J_{AA'}$, $J_{BB'}$, $J_{AB'}$, $J_{AX'}$, $J_{BX'}$) were zero. [b] Numbers of atoms correspond to the usual counting in a 3-azabicyclo[3.1.0]hexane system; $H(2)_A$ and $H(4)_{A'}$ are in the *endo*-position and $H(2)_B$ and $H(4)_{B'}$ are in the *exo*-position of the bicyclic skeleton. Assignment was made by coupling with $H(1)_X/H(5)_{X'}$ which is larger for *exo*-hydrogen atoms (H_B, $H_{B'}$) in all cases. [c] Additional iterative adaption of the spectrum by the PANIC 81 program;[12] two iterative steps, RMS-error at the end of the 2nd step: 0.098; error of $J \pm 0.04$ Hz. [d] $C_6D_5CD_3$. [e] Additional iterative adaption of the spectrum by the PANIC 81 program;[12] four iterative steps, RMS-error at the end of the 3rd and the 4th step: 0.067; error of $J \pm 0.02$ Hz. [f] $CDCl_3$. [g] *J*-values are given with only one decimal digit if iterative simulation was not performed. [h] CD_3CN.

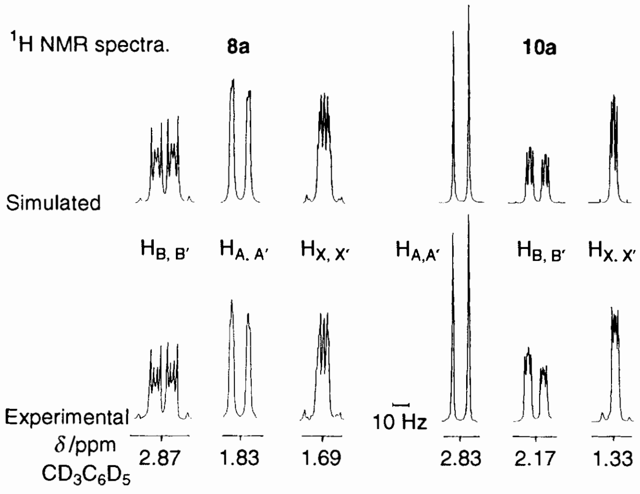


Fig. 1 Signals of the 3-azabicyclo[3.1.0]hexane skeleton of **8a** and **10a** of the simulated and the experimental ^1H NMR spectrum

Table 2 Correlation between the angle of ring buckle (α) and some dihedral angles in 3-azabicyclo[3.1.0]hexane **4** obtained by MNDOC calculations[a]

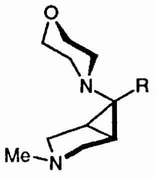
		Dihedral angles (°)[b]	
Conformation	α (°)	$H(1)C(1)C(2)H(2)_B$ $H(5)C(5)C(4)H(4)_{B'}$	$H(1)C(1)C(2)H(2)_A$ $H(5)C(5)C(4)H(4)_{A'}$
Boat	30	−38.5	80.0
Boat	25	−35.9	83.1
Boat	20	−33.2	85.6
Boat	15	−30.4	88.1
Boat	10	−27.6	90.7
Boat	5	−24.9	93.4
Chair	5	−19.5	98.7
Chair	10	−16.7	101.6
Chair	15	−14.0	104.4
Chair	20	−11.3	107.3
Chair	25	−8.7	110.2
Chair	30	−6.1	113.1

[a] MNDOC parameters taken from ref. 13. [b] Values of dihedral angles directed to $H(2)_{A.B}$ and $H(4)_{A'.B'}$ are identical due to C_s-symmetry.

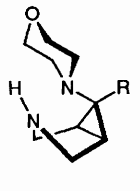
81 program[12] led to an almost identical reproduction of the experimental spectra of **8a** and **10a**. *J*-Values from the iterative simulation are given in Table 1; Fig. 1 shows the signals of the 3-azabicyclo[3.1.0]hexane skeleton of **8a** and **10a** of the simulated and the experimental ^1H NMR spectrum.

Simulation without iterative proceeding was performed in the case of **8b**/**10b** and **9a**/**9b**. Iterative calculated XX'-coupling constants of **8a** and **10a** were used for the simulation of the spectra of **8b**/**10b** and **9a**/**9b**. The other experimentally detectable coupling constants were varied to some extent until an optimal agreement between experimental and simulated ^1H NMR spectra was obtained (Table 1).

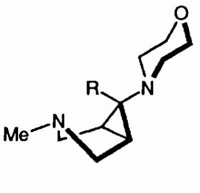
The ^1H NMR signals of the azabicyclo[3.1.0]hexane skeleton of **8a** and **b** on the one hand and of **9a,b** and **10a,b** on the other hand differ both in shape and in chemical shifts. The most important fact is the coupling $J_{1.2A}$ and $J_{5.4A'}$. It indicates the presence of a chair conformation **C** for **8a,b** ($J_{1.2A}$, $J_{5.4A'}$ = 0 Hz) and a boat conformation **B** for **9a,b** and **10a,b** ($J_{1,2A}$, $J_{5.4A'}$ = 2–3 Hz).



8C



9B
a R = CN
b R = Me



10B

HC(1)C(2)H/HC(5)C(4)H-dihedral angles of the 3-azabicyclo[3.1.0]hexane system, dependent upon the ring buckling, were determined by MNDOC semiempirical calculations (see Table 2). For example, a boat conformation with α = 20° leads to a dihedral angle of 85.6° for $H(1)C(1)C(2)H(2)_A/H(5)C(5)C(4)H(4)_{A'}$. This agrees well with the missing coupling $J_{1.2A}$ and $J_{5.4A'}$ in the boat conformation of **9a,b** and **10a,b**. A value of 30° for a chair conformation on the other hand corresponds with a dihedral angle of 113.1° and with coupling constants of 1.96 Hz and 2.8 Hz for **8a** and **b**, respectively. The MNDOC semiempirical calculations[13] were done for compound **4**. The ring buckle was varied between −30° and −5° (chair) and between +30° and +5° (boat) in steps of 5°; each conformation was fully optimized with exception of the value α of the ring buckle.

The ^1H NMR results of **9a,b** and **10a,b** indicating a boat conformation correspond quite well with those which were reported for the boat conformation of methanoproline derivative **1** ['zero coupling'[1,6] between H(1) or H(5) and the *endo*-H-atom of the adjacent methylene moiety; *J* values of 2.3 and 4.6 Hz[1,6] for the analogous coupling of H(1) and H(5) with the *exo*-H-atom of the adjacent methylene group, respectively].

Conformational Analysis of the Compounds **8a**/**9a** *and* **8b**/**9b** *on the Basis of Temperature Dependent* ^1H *NMR Spectroscopy.*—^1H NMR spectroscopy of the morpholine moiety in the compounds **8a**/**10a** and **8b**/**10b** could be used for a simple establishment of the configuration: topomerization of the H_A and the H_B signal of a CH_AH_B-group of morpholine is much easier if it is in the *exo*-position of a [*n*.1.0]bicyclic system than in the corresponding *endo*-position.[14,15] It was shown that this topomerization process for hydrogen atoms of a mor-

Table 3 $\Delta G^{\ddagger}$ Values of the dynamics of the morpholine ring of the compounds **8a,b** and **9a,b** in $CD_3C_6D_5$

	$\Delta G^{\ddagger}$/kJ mol^{-1}
8a[a]	58.5,[b] 58.4[c]
8b[e]	58.6,[b] 59.9[c]
9a[d]	68.5,[b] 68.7[c]
9b[e,f]	66.0[b]

[a] Ref. 7. [b] Determined for OCH_2. [c] Determined for NCH_2. [d] OCH_2: H_A:3.43, H_B:2.95, J_{AB}: 10.9 Hz; T_c = 77 °C. NCH_2:H_A:2.48, H_B:1.84, J_{AB}:11.2 Hz; T_c = 82 °C; $\Delta G^{\ddagger}$ calculated according to the approximation formula for the coupled case.[18] [e] Ref. 9. [f] OCH_2:H_A:3.53, H_B:3.11, J_{AB}: 12.0 Hz; T_c = 63 °C. NCH_2:H_A:2.39, H_B:1.90, J_{AB}: 12.0 Hz; T_c = 65 °C; $\Delta G^{\ddagger}$ calculated according to the approximation formula for the coupled case.[18]

Table 4 Selected bond lengths, torsional angles and interplanar angles for **8b**[a]

Bond lengths/Å			
C(1)–C(5)	1.512(3)	N(3)–C(2)	1.460(3)
C(1)–C(6)	1.508(3)	N(3)–C(7)	1.433(3)
C(5)–C(6)	1.519(3)	C(4)–N(3)	1.478(3)
Torsional angles (°)			
H(1)–C(1)–C(2)–$H(2)_A$	112.3	$H(4)_A$–C(4)–C(5)–H(5)	−112.5
H(1)–C(1)–C(2)–$H(2)_B$	−11.5	$H(4)_B$–C(4)–C(5)–H(5)	5.1
Interplanar angles (°)			
C(1)C(5)C(6)–C(4)C(5)C(1)C(2)	65		
C(4)C(5)C(1)C(2)–C(2)N(3)C(4)	29.5		

[a] The numbering of the atoms in Fig. 2 and Table 4 in this paper was changed partially with respect to the numbering in the deposited data; it was adjusted to the general numbering in a 3-azabicyclo[3.1.0]hexane system for better comparison with other data.

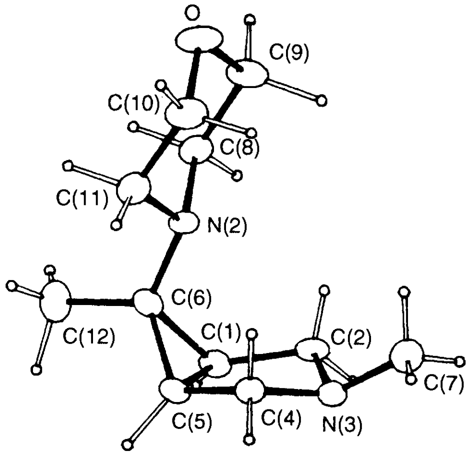


Fig. 2 ORTEP representation of **8b** with the atom-labelling scheme. Elipsoids are scaled to enclose 33% of the electronic density.

pholine moiety in the *endo*-6-position of a bicyclo[3.1.0]hexane skeleton was additionally influenced by the conformation of the latter: the dynamics of morpholine are more hindered by a boat bicyclo[3.1.0]hexyl moiety than by a chair bicyclohexyl group as N-substituent.[16,17]

It may be expected, therefore, that conformational differences of **8a** and **9a** or **8b** and **9b** also are detectable by studying the morpholine dynamics. Thus, the $\Delta G^{\ddagger}$-values of **9a** and **b** were determined and compared with those of **8a** and **b**, respectively (Table 3). The N(3)–H compounds **9a** and **b** indeed gave higher $\Delta G^{\ddagger}$-values for the topomerization of morpholine H-atoms than the N(3)-methyl analogues **8a** and **b**. The obviously higher space requirement of N(3)–H in **9a** and **b** than N(3)–Me in **8a** and **b** can only be understood by the presence of different conformations since H–N is less bulky than N–Me. A boat conformation can be deduced for **9a,b** and a chair conformation follows for **8a,b**. Presumably, the H-atom at N(3) in **9a** and **b** is in the axial position due to lone pair–lone pair repulsion.

X-Ray Structural Analytic Detection of the Conformation of **8b**.—Thus far X-ray structural data are only known for 3-azoniabicyclo[3.1.0]hexane derivatives possessing an ammonium type nitrogen atom. Compound **8b** was selected, therefore, for the X-ray structural analysis to get information about the conformation of a 3-azabicyclo[3.1.0]hexane skeleton as a free base. X-Ray structural analysis was performed at −68 °C. Selected data are given in Table 4. The presence of a chair conformation with an equatorial N-methyl group for **8b** can be clearly seen in the Ortep plot (Fig. 2). A steric inside fixation of the morpholine N-lone pair by the bicyclic system and its repulsive effect on the lone pair of the N(3)-nitrogen atom should be the reason for the chair structure of this type of compounds. MNDOC prediction of the dihedral angles $H(1)C(1)C(2)H(2)_{A/B}/H(5)C(5)C(4)H(4)_{A/B}$ for the found ring buckle a = 29.5° (Table 2) agrees sufficiently with the experimental values from the X-ray structural analysis (Table 4).

HF/6-31G Calculations of the* 3-*Azabicyclo*[3.1.0]*hexane Parent Compounds* **4** *and* **5**.—Energetic differences of chair and boat conformations of the 3-azabicyclo[3.1.0]hexane skeleton should be best predicted by *ab initio* calculations. The *ab initio* calculations were performed using the Convex and Cray versions of the Gaussian 92 program package.[20] The 6-31 G* basis set[21] was chosen for geometry optimizations. All geometries were fully optimized in C_s symmetry and characterized by diagonalization of the HF/6-31G* force matrix. Four conformations were investigated for each of the two parent compounds **4** and **5**: a boat conformation with an axial (**B**$_{ax}$) or equatorial (**B**$_{eq}$) N-substituent and analogously a chair conformation with an axial (**C**$_{ax}$) or equatorial (**C**$_{eq}$) N-moiety.

HF/6-31G* total energies, zero point energies ZPE, relative energies and interplanar angles of these selected conformations of **4** and **5** are given in Table 5; the missing conformation **4C**$_{eq}$ proved not to be a minimum on the energy hypersurface. Fig. 3 shows the calculated structures of **4** and **5**. The boat conformation turned out to be favoured for both compounds **4** and **5**. In the case of **4**, however, almost identical energies were calculated for both boat conformations **4B**$_{ax}$ and **4B**$_{eq}$. An axial position of the *N*-methyl moiety in **5** was calculated to be unfavourable for boat and for chair conformation **5B**$_{ax}$ and **5C**$_{ax}$, respectively. The lowest energy was found for **5B**$_{eq}$.

The ring buckling (interplanar angles) of the chair conformation **5C**$_{eq}$, predicted by the *ab initio* calculation (67.7° and 28.6°), corresponds quite well with the experimental values of the X-ray structural analysis of **8b** (65° and 29.5°). The presence of a boat or a chair conformation proved to have no influence on the bond-length of C(1)C(6), C(1)C(5) or N(3)C(2) of the compounds **4** and **5** [C(1)C(6): 1.50 Å for all conformations of **4** and **5**; C(1)C(5): 1.53 Å for all conformations of **4** and **5** except **4B**$_{ax}$ (1.52 Å) and **4C**$_{ax}$ (1.52 Å); C(2)N(3): 1.46 Å for all conformations of **4** and **5** except **4B**$_{eq}$ (1.47 Å)].

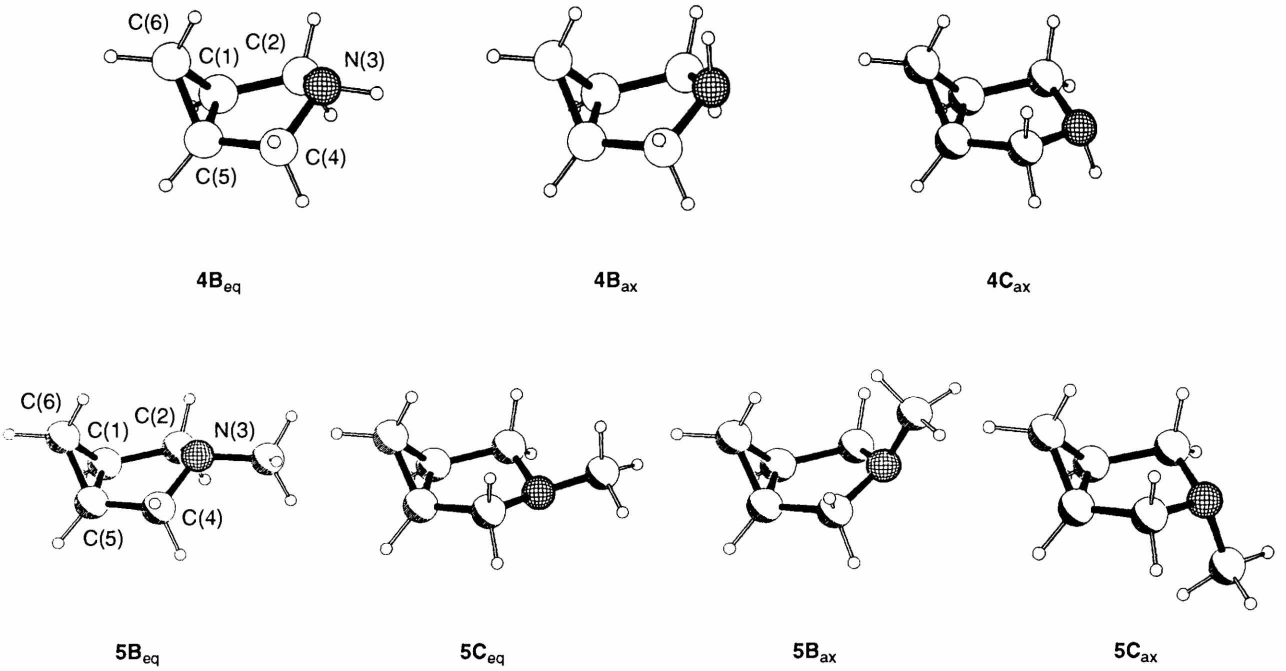
Conclusions

A boat conformation should be most favourable for a 3-azabicyclo[3.1.0]hexane skeleton as indicated by *ab initio* calculations for the parent compounds **4** and **5**. It was shown experimentally that 6-morpholino-3-azabicyclohexane derivatives indeed prefer a boat conformation if the 6-amino moiety is in the *exo*-position as in **10**. Prevention of lone pair–lone pair interactions, however, becomes important in the case

Table 5 HF/6-31 G* Total energies (au), zero point energies (kcal mol^{-1}), relative energies including ZPE correction (kcal mol^{-1}) and interplanar angles of the conformers $\mathbf{4B}_{ax}$, $\mathbf{4B}_{eq}$, $\mathbf{4C}_{ax}$, $\mathbf{5B}_{ax}$, $\mathbf{5B}_{eq}$, $\mathbf{5C}_{ax}$ and $\mathbf{5C}_{eq}$

	Conformation	HF (au) [E_{rel}] kcal mol^{-1}	ZPE/kcal mol^{-1}	Interplanar angle (°)[a] C(1)C(5)C(6) C(4)C(5)C(1)C(2)	Interplanar angle (°)[a] C(4)C(5)C(1)C(2) C(2)N(3)C(4)
$\mathbf{4B}_{eq}$	Boat	−248.982 43 [0]	91.44	68.2	35.0
$\mathbf{4B}_{ax}$	Boat	−248.982 53 [0.1]	91.56	68.3	26.4
$\mathbf{4C}_{ax}$	Chair	−248.974 96 [4.7]	91.43	67.8	25.1
$\mathbf{5B}_{eq}$	Boat	−288.014 33 [0]	110.01	68.0	34.4
$\mathbf{5C}_{eq}$	Chair	−288.007 45 [4.1]	109.84	67.7	28.6
$\mathbf{5B}_{ax}$	Boat	−288.006 59 [4.7]	109.82	68.8	15.5
$\mathbf{5C}_{ax}$	Chair	−288.002 16 [7.8]	110.15	67.5	31.0

[a] The numbering of the atoms corresponds to the general numbering in a 3-azabicyclo[3.1.0]hexane system.



$\mathbf{4B}_{eq}$ $\mathbf{4B}_{ax}$ $\mathbf{4C}_{ax}$

$\mathbf{5B}_{eq}$ $\mathbf{5C}_{eq}$ $\mathbf{5B}_{ax}$ $\mathbf{5C}_{ax}$

Fig. 3 HF/6-31G* Optimized geometries of the 3-azabicyclo[3.1.0]hexane derivatives **4** and **5**

of *endo*-6-morpholino-3-azabicyclohexane compounds **8** and **9**. In this case lone pair–lone pair interactions are circumvented in a boat conformation by arranging the lone pair in an equatorial position. This can be realized by **9** with a hydrogen atom as substituent at N(3). Substituents at N(3) which are larger than a hydrogen atom strongly prefer an equatorial position. Interaction of the resulting axial N(3)-lone pair with the second N-lone pair then can be avoided only by adoption of a chair conformation as in **8**.

Experimental

^{1}H NMR and ^{13}C NMR spectra were measured with a Bruker WP 200 and an AMX 400 spectrometer (Me_4Si as internal standard). *Ab initio* calculations were done with a Convex C220 and a Cray YMP supercomputer. MNDOC semiempirical molecular orbital calculations were performed on a 486 Personal Computer.

(1α,5α,6β)-6-*Morpholino*-3-*azabicyclo*[3.1.0]*hexane*-6-*carbonitrile* **9a**.—Pd-catalyst (10% Pd–C, 710 mg) was added to a solution of *N*-benzyl compound **11**[9] (2.0 g, 7.06 mmol) in methanol (80 cm^3). The solution was saturated with hydrogen and stored over hydrogen until the theoretical amount of hydrogen (157 cm^3, 7.06 mmol) was consumed. Removal of the catalyst by filtration, evaporation of the solvent and recrystallization of the residue from ether gave **9a** as colourless crystals (0.75 g, 55%); m.p. 81 °C (Found: C, 62.2; H, 8.0; N, 21.8. $C_{10}H_{15}N_3O$ requires C, 62.15; H, 7.82; N, 21.74%); ν_{max}(KBr)/cm^{-1} 3380 (N–H) and 2200 (C–N); δ_H(CD_3CN) 1.90 (1 H, br s, NH), 2.15 (2 H, H_{X1}, $H_{X'1}$), 2.94 (2 H, H_{B1}, $H_{B'1}$), 3.14 (2 H, H_{A1}, $H_{A'1}$) (AA'BB'XX'-system, 3-azabicyclohexane system), 2.51 (2 H, H_Y), 2.60 (2 H, H_{X2}), 3.48 (2 H, H_{B2}) and 3.74 (2 H, H_{A2}) (ABXY-system, morpholine); δ_C($CDCl_3$) 32.5 (d), 41.5 (s), 48.0 (t), 51.3 (t), 66.8 (t) and 116.1 (s).

X-*Ray Crystal Structure Analysis of* **8b**.—Single crystals of **8b**[9] were obtained by crystallization from ether.

Crystal data. $C_{11}H_{20}N_2O$, M = 196.3. Monoclinic, a = 8.447(4), b = 8.825(3), c = 15.420(6) Å; β = 105.66(3)°, V = 1106.8(15) Å^3; space group $P2_1/n$, Z = 4, D_X = 1.18 g cm^{-3}.

Colourless crystal. Crystal dimensions 0.6 × 0.5 × 0.3 mm, μ(Mo-Kα) = 0.71 cm^{-1}.

Data collection and processing. Enraf-Nonius CAD4 diffractometer, temperature: 205 K; $\omega/2\theta$ mode with ω scan width = $1.00 + 0.35 \tan\theta$, ω scan speed 1.21–4.02 deg min^{-1}, graphite-monochromated Mo-Kα radiation; 1235 reflections measured ($4.00 < 2\theta < 42.00°$), 1182 unique [merging R = 0.036], giving 988 with $I > 2.50\sigma(I)$.

Structure analysis and refinement. The structure was solved by direct methods. Refined was performed by a full-matrix least-squares program. Hydrogen atoms were localized in a ΔF map and refined with isotropic temperature factors. Refinement converged at $R = 0.0064$ and $R_w = 0.069$, weighting scheme: $w = 4F_o^2/[\sigma(I)^2 + (PF_o^2)^2]$ ($P = 0.015$). The largest shift/error ratio at this stage was 0.62. The residual electron density was <0.23.[19]

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