



Cite this: *Org. Biomol. Chem.*, 2014, **12**, 8031

Conformational effects due to stereochemistry and C3-substituents in xylopyranoside derivatives as studied by NMR spectroscopy

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Glycosaminoglycans contain a β -D-xylopyranose residue at its reducing end, which links the polysaccharide to the protein in proteoglycans. 2-Naphthyl β -D-xylopyranosides have shown inhibition of tumor growth and we herein investigate conformation and dynamics of compounds structurally and stereochemically modified at the C3 position as well as the influence of solvent. The 3-deoxygenated compound, the 3-C-methyl-substituted β -D-xylopyranoside, β -D-ribofuranoside, the 3-C-methyl-substituted β -D-ribofuranoside as well as 2-naphthyl β -D-xylopyranoside were analyzed by NMR spectroscopy. Conformational equilibria were dependent on the solvent of choice, either methanol- d_4 or chloroform- d , with mainly 4C_1 and 1C_4 conformations present but also skew conformations to some extent. Intramolecular hydrogen bonding was concluded to be important for the 3-C-methyl-substituted β -D-xylopyranosides in the non-polar solvent. Dynamic NMR (DNMR) spectroscopy was carried out for the 3-deoxygenated compound, which at 25 °C in methanol- d_4 exists with equally populated states of the 4C_1 and the 1C_4 conformations, but at -100 °C only a few percent is present of the latter. Using ${}^{13}C$ NMR detection for DNMR, resonance lines were shown to broaden at -40 °C and to sharpen again below -90 °C, without the emergence of a second set of NMR resonances, a typical behavior for an unequally populated equilibrium. The enthalpy and entropy activation barriers were calculated and resulted in $\Delta H^\ddagger = 47.3 \text{ kJ mol}^{-1}$ and $\Delta S^\ddagger = 54 \text{ J mol}^{-1} \text{ K}^{-1}$.

Received 8th July 2014,
Accepted 26th August 2014
DOI: 10.1039/c4ob01422g

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Introduction

The three-dimensional structure of carbohydrates and their interactions with proteins¹ play important roles in regulation of biochemical processes. One class of highly complex carbohydrates is glycosaminoglycans (GAGs) being constituents of proteoglycans.² Xylopyranosides, bearing a hydrophobic aglycone, can act as an acceptor in the biosynthesis of GAGs in cells, with different results depending on the aglycone, cell-type, and the substitution pattern of the xyloside.³ We have previously reported on the conformational properties of XylNap (1) (Fig. 1), with a 2-naphthyl aglycone, in methanol- d_4 (ref. 3) and a wide range of other deuterated solvents,⁴ where it displayed a conformational dependence on the polarity and hydrogen bond accepting ability of the solvents. Solvents of low polarity and low hydrogen bond accepting ability induced conformational transformations from the otherwise preferred 4C_1 conformation to the 2S_0 and 1C_4 conformations, with a maximum of ~20% of the 1C_4 conformation in chloroform,

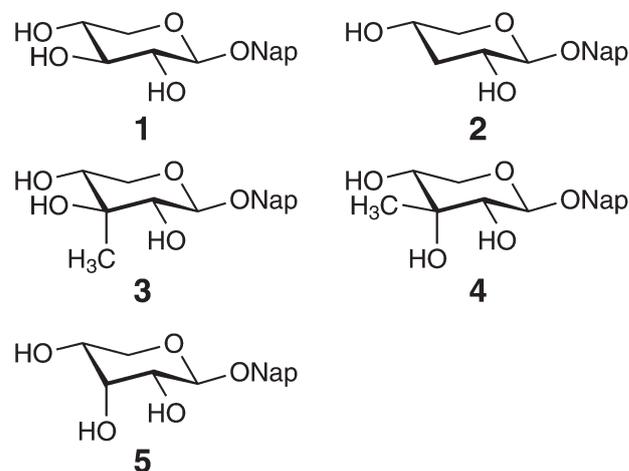


Fig. 1 Schematic of compounds 1–5.

benzene, and toluene. An intramolecular hydrogen bond was detected with the HO2 hydroxyl proton as the donor and an electronegative substituent (F or OH) on C4 as an acceptor; this interaction was suggested to stabilize the 1C_4 conformation.

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It was observed that the 3-deoxy-compound (2) resides in equal amounts of the 4C_1 and 1C_4 conformations in methanol solution at 37 °C, in stark contrast to the other substances in the study.³ In a subsequent study of the 3-*C*-methylated compounds 3 and 4 in methanol- d_4 solution, an increased conformational flexibility was observed, compared to 1.⁵ Compound 3 was the most flexible of the two, due to the larger 1,3-diaxial interactions arising from the methyl group in the 4C_1 conformation of 3 compared to that of the hydroxyl group in 4. Herein, we elaborate further on the effects of the stereochemistry and substituents at C3 on the conformation of xylopyranoside derivatives (Fig. 1).

Results and discussion

1H NMR spectra of compounds 1–5 in chloroform- d solution at 37 °C were recorded and resonances assigned; NMR assignments were also carried out for compound 5 in methanol- d_4 solution. Scalar couplings were extracted through NMR spin simulation⁶ and ${}^{13}C$ NMR data were also acquired for some of the compounds (Table 1). The resulting coupling constants were fitted to coupling constants calculated from the Haasnoot–Altona equation⁷ and molecular models of the canonical ring conformations 4C_1 , 1C_4 , 1S_3 , 1S_5 , 0S_2 , 3S_1 , 5S_1 and 2S_0 in accordance with the previously devised methodology.^{3,4} The resulting equilibrium populations and those previously reported for compounds 1–4 in methanol- d_4 (ref. 2 and 4) and of 1 in chloroform- d solution² are listed in Table 2. In chloroform- d solution, compounds 2 and 3 were observed to occupy the 1C_4 conformation to a large extent, ~90%, supported by the long-range ${}^4J_{H2,H4}$ coupling in the latter, whereas the 4C_1 and 1C_4 conformations are close to equally populated for compound 4. The intermediate ${}^3J_{H1,H2}$ coupling for compound 5 in methanol- d_4 solution suggests a large population of the 1C_4 conformation, >50%, and in the non-polar chloroform- d solu-

tion, ${}^3J_{H1,H2} = 2.2$ Hz is consistent with a large population of the 1C_4 conformation, ~90%.

Compounds 2–4 were also investigated by 1D 1H , 1H -NOESY experiments.^{5,8} In methanol- d_4 solution, NOE correlations were observed for compound 2 from H1 to H3_{pro-R} and H5_{pro-S} (Fig. 2a), which are significant in the 4C_1 conformation (α -face of the ring), and between H3_{pro-S} and H5_{pro-R} (Fig. 2b), which is significant only in the 1C_4 conformation (β -face of the ring), consistent with approximately equally populated 4C_1 and 1C_4 conformations. In chloroform- d solution, correlations between H1 and H3_{pro-R} and H5_{pro-S} were not observed, while a strong NOE correlation between H3_{pro-S} and H5_{pro-R} was present, thus verifying the strong prevalence for the 1C_4 conformation in the non-polar solvent. NOE experiments were pursued for compounds 3 and 4 in chloroform- d solution, with selective excitation of the respective methyl groups. Strong NOEs were detected for compound 3 from the methyl group to the H2 and H4 atoms (Fig. 2c), indicating a preference for the 1C_4 conformation. In methanol- d_4 solution, where the 4C_1 conformation is highly favored, strong inter-nuclear correlations were observed from the methyl group to the H1 and H5_{pro-S} atoms⁵ (Fig. 2d), none of which were observed in chloroform- d solution, further underlining the conformational dependence on solvent properties. In compound 4, NOE correlations from the methyl group to the H2 and H4 atoms (Fig. 2e) were observed both in methanol- d_4 solution⁵ and chloroform- d solution, consistent with a 4C_1 conformation. In chloroform- d , an NOE correlation to the H5_{pro-R} resonance was also observed, which indicates a large population of the 1C_4 conformation (Fig. 2f).

Complementary to the NOE-based information for compound 3 in chloroform- d solution, chemical shift information and scalar coupling data are also illustrative. The 1H NMR chemical shift for the hydroxyl proton HO3 is unusually high, δ_H 3.63, which may be compared to that of the 4-fluoro-4-deoxy- β -D-Xylp-Nap derivative, having δ_H 2.92 being present to 26% in the 1C_4 conformation.⁵ In this compound, an F4...HO2 hydrogen bond was proven by $J_{F4,HO2} = 2$ Hz;

Table 1 δ_H , ${}^nJ_{HH}$ in parenthesis and δ_C in square brackets of xyloside analogs 1–5 in chloroform- d and 5 in methanol- d_4 at 37 °C. For methylene groups, the 1H NMR chemical shift of the pro-*R* proton is given prior to that of the pro-*S* proton. n.d. = not determined

Compound	1	2	3	4	5	Me	HO2	HO3	HO4
1	5.109 (6.224) [100.91]	3.709 (7.786) [74.64]	3.675 (7.634) [74.56]	3.809 (4.501, 8.268) [69.42]	4.112, 3.468 (−11.880) [64.54]		2.704 (4.198)	2.768 (3.736)	2.266 (3.447)
2	5.513 (2.050) [98.07]	3.888 (3.092, 3.556) [66.92]	2.050, 2.267 (3.570, 3.156, −14.733) [30.82]	3.940 (1.575, 2.125) [65.77]	3.988, 3.635 (−12.427) [65.38]		3.461 (8.279)		2.452 (4.963)
3	5.590 (2.559)	3.625 (1.441) ^b		3.608 (1.937, 3.117)	4.265, 3.641 (−12.753)	1.438	3.172 (8.678)	3.631	2.282 (5.091)
4	5.555 (4.443)	3.666		3.632 (3.268, 6.124)	4.037, 3.814 (−11.956)	1.531	n.d.	n.d.	n.d.
5	5.759 (2.185)	4.067 (1.295)	4.134 (3.009)	4.012 (1.655, 2.624)	4.012, 3.905 (−12.527)		3.433 (4.544)	3.159 (3.826)	3.095 (3.815)
5 ^a	5.592 (3.881) [100.65]	3.860 (3.197) [72.37]	4.074 (3.184) [68.26]	3.874 (2.662, 4.825) [70.46]	3.900, 3.815 (−11.852) [65.57]				

^a In methanol- d_4 . ^b ${}^4J_{H2,H4}$.



Table 2 Populations of ring conformations of compounds 1–5 in methanol-*d*₄ (upper) and chloroform-*d* (lower), at 37 °C, in percent (%)

Compound	⁴ C ₁	^x S _y	¹ C ₄
1	94	6 ^a	0
2	48	0	52
3	70	15 ^b	15
4	90	5 ^b	5
5	25	20 ^b	55
1	71	22 ^a	7
2	0	9 ^a	91
3	5	5 ^b	90
4	45	5 ^b	50
5	5	5 ^b	90

^a *x* = 2, *y* = 0. ^b At least two skew conformations are possible.

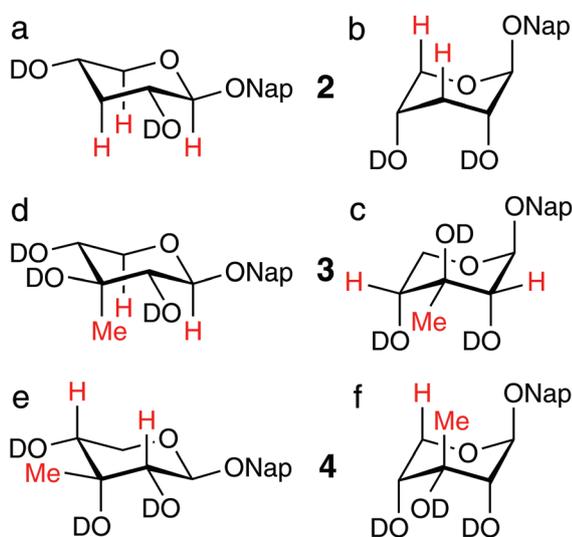


Fig. 2 ¹H,¹H-NOE correlations between atoms (colored red), observed from selective excitations of, *inter alia*, H1 or CH₃. Compound 2 in ⁴C₁ conformation (a) and in ¹C₄ conformation (b); 3 in ¹C₄ (c) and in ⁴C₁ (d); 4 in ⁴C₁ (e) and in ¹C₄ (f).

additionally, the ³J_{H₂,H_{O2}} = 6.1 Hz. In compound 3, the latter coupling constant was also large being ³J_{H₂,H_{O2}} = 8.7 Hz, indicating hindered rotation. In order to obtain information on the conformational preference (if any) of the hydroxyl proton HO₃, we rely on the heteronuclear ¹H,¹³C spin-spin coupling constant to the methyl group on C₃, since the compound is devoid of a hydrogen atom in this position. Employing a J-HMBC experiment⁹ and detecting the interaction between the methyl ¹³C group and the HO₃ group, we obtained ³J_{C(Me),H_{O3}} = 6.5 Hz, consistent with an *antiperiplanar* arrangement (*cf.* eqn (10) in ref. 10). Taken together, these results support that the ¹C₄ conformation for compound 3 in chloroform-*d* solution is stabilized by the intramolecular hydrogen bonds O₄...HO₂ and O₁...HO₃.

To elaborate on the dynamics of the 3-deoxygenated compound (2), ¹H NMR spectra were recorded at a ¹H resonance frequency of 500 MHz in a temperature range from 50 °C to

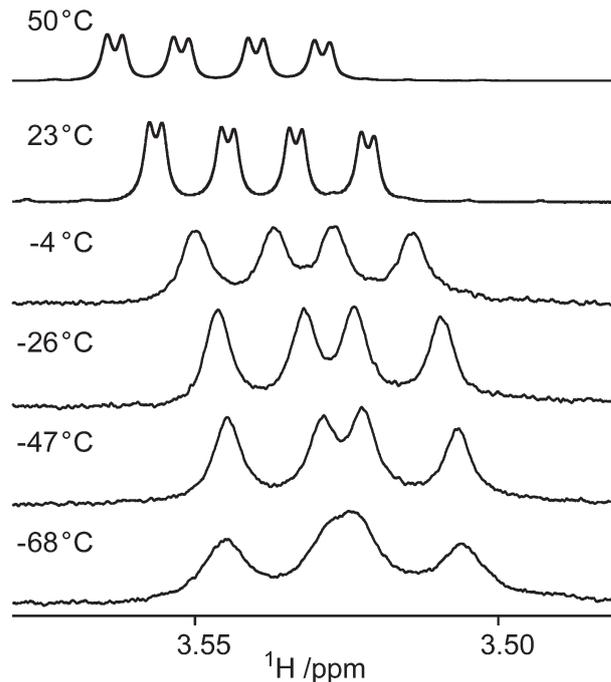


Fig. 3 The ¹H NMR resonance at 500 MHz of H₅_{pro-S} of compound 2 in methanol-*d*₄ solution as a function of temperature.

Table 3 Experimental data and extrapolated data (italicized) of compound 2 in methanol-*d*₄ at different temperatures. Exchange rates (s⁻¹) were obtained as described in ref. 15

Temp/°C	⁴ C ₁ /%	¹ C ₄	δ _{H1} /ppm	J _{H1,H2} /Hz	k _{ex} /s ⁻¹
50	46	54	5.279	4.416	100 000 000
39	48	52	5.271	4.513	52 000 000
23	51	49	5.255	4.717	19 000 000
-4	59	41	5.225	5.015	2 500 000
-26	65	35	5.193	5.452	340 000
-47	73	27	5.158	5.850	37 000
-66	80	20	5.13	6.42	2800
-68	80	20	5.127	6.580	2500
-76	85	15	5.10	6.73	840
-86	90	10	5.04	7.03	180
-95	92	8	5.02	7.15	44
-101	93	7	5.02	7.21	9.7

-68 °C in methanol-*d*₄ solution. The equilibrium populations were altered significantly with temperature, observed through changes in *e.g.* the ³J_{H₁,H₂} and the ³J_{H₄,H₅pro-S} coupling constants (Fig. 3). At temperatures below ~25 °C, the ⁴C₁ conformation is predominantly occupied, reflected by increased values of the ³J_{H₁,H₂} coupling constant (Table 3). At temperatures below -68 °C, where the population of the ⁴C₁ conformation was >80%, some of the signals, *e.g.* H1 and H₃_{pro-R}, were significantly broadened, thus disabling coupling constant analysis. The δ_{H1} and J_{H₁,H₂} for the separate conformers could, however, be extrapolated to give for the ⁴C₁ conformation δ_{H1} 5.02 and J_{H₁,H₂} = 7.64 Hz and for the ¹C₄ conformation δ_{H1} 5.50 and J_{H₁,H₂} = 1.56 Hz.



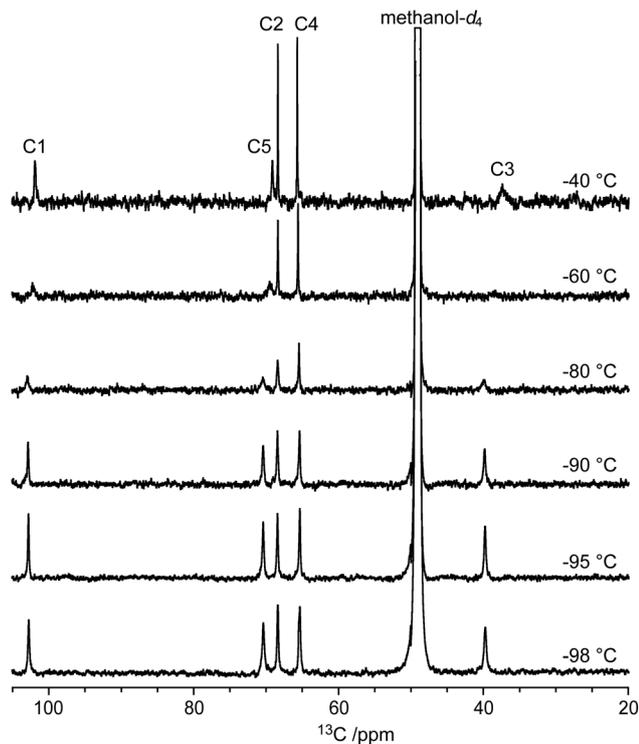


Fig. 4 The ^{13}C NMR resonances at 200 MHz of compound 2 in methanol- d_4 solution as a function of temperature.

At this point, we turned to a higher magnetic field strength of 18.8 T, which enabled extension of the above dynamic NMR (DNMR) measurements.¹¹ Using ^{13}C NMR spectra at 200 MHz spectrometer frequency, we observed a broadening of the resonances corresponding to C1, C3, and C5 at $-40\text{ }^\circ\text{C}$ that were observed to coalesce at $-60\text{ }^\circ\text{C}$ (Fig. 4). Well defined sharp peaks were observed below $-80\text{ }^\circ\text{C}$, corresponding to the $^4\text{C}_1$ conformer, while resonances from the less populated conformer were absent even after prolonged experimental time; a typical behavior for an unequally populated equilibrium.^{12,13} The two H3 resonances of 2 were unequally broadened in ^1H NMR spectra below $-60\text{ }^\circ\text{C}$ at 800 MHz spectrometer frequency. The H3_{pro-R} resonance (axially oriented in the $^4\text{C}_1$ conformation) was significantly broadened and eventually split up at $-95\text{ }^\circ\text{C}$, yielding a major and a minor signal ($\sim 5\%$) at $-101\text{ }^\circ\text{C}$ (Fig. 5). The conformational exchange rates $k_{\text{ex}} = k_1 + k_{-1}$, where k_1 and k_{-1} are the forward and reverse rate constants for the $^4\text{C}_1 \rightleftharpoons ^1\text{C}_4$ conformational equilibrium, respectively, were subsequently investigated by NMR line-shape analysis of the H3 resonances, with emphasis on exchange rates and population distribution, and yielded the data reported in Table 3. The enthalpy and entropy activation barriers were calculated from an Eyring plot¹⁴ resulting in $\Delta H^\ddagger = 47.3\text{ kJ mol}^{-1}$ and $\Delta S^\ddagger = 54\text{ J mol}^{-1}\text{ K}^{-1}$. The free energy of activation barrier ΔG^\ddagger can subsequently be calculated at a given temperature, under the assumption that ΔH^\ddagger and ΔS^\ddagger were not temperature dependent. For example, at $-70\text{ }^\circ\text{C}$ one obtains $\Delta G^\ddagger = 36.3\text{ kJ mol}^{-1}$, which can be compared to protected

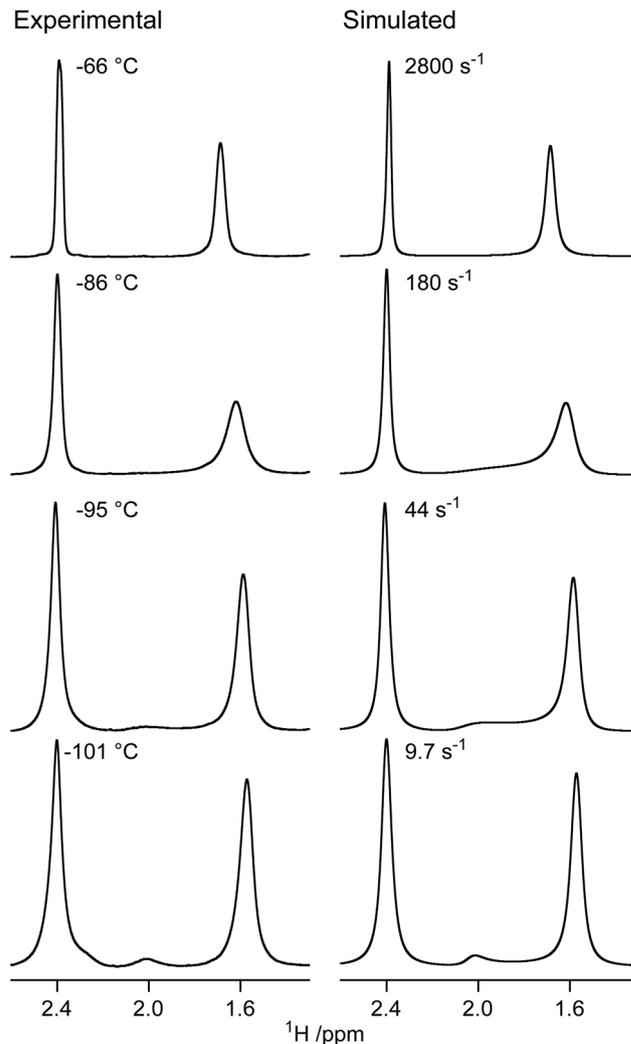


Fig. 5 The ^1H NMR resonances at 800 MHz of H3_{pro-R} ($\sim 1.6\text{ ppm}$) and H3_{pro-S} ($\sim 2.4\text{ ppm}$) of compound 2 in methanol- d_4 solution as a function of temperature and the corresponding simulated spectra. Note the small peak at $\sim 2.0\text{ ppm}$ in the spectrum obtained at the lowest temperature.

O-methyl glycosides of α -D-mannuronic acid esters in CD_2Cl_2 at the same temperature showing $\Delta G^\ddagger \approx 46\text{ kJ mol}^{-1}$ for the $^4\text{C}_1 \rightleftharpoons ^1\text{C}_4$ ring interconversion.¹⁵ Thus, the free energy of activation barrier ΔG^\ddagger for the 3-deoxygenated compound (2), is indeed low, but can be determined by DNMR spectroscopy.

Complementary spectroscopic techniques include optical rotation, which facilitates additional information about conformational preferences. The technique can be used to differentiate anomeric configuration between methyl glycosides and has been applied in conformational studies of oligosaccharides.^{16,17} Additionally, it has been suggested that the extent of a particular chair conformation can be deduced in this way.¹⁸ For compound 1 in methanol the specific rotation $[\alpha]_{\text{D}}^{20} = -30.04^\circ$ corresponding to a molecular rotation $[M]_{\text{D}}^{20} = -83.0^\circ$, and is similar to that of the corresponding methyl xyloside in water, $[M]_{\text{D}}^{20} = -108^\circ$, but numerically quite different to those



of other methyl pentopyranosides.¹⁸ For β -D-Xylp-OMe in water the calculated molecular rotation for the 1C_4 chair conformation has a value that is more negative than that corresponding to the 4C_1 conformation. In methanol solution compound **3** has $[\alpha]_D^{20} = -44^\circ$ and compound **4** has $[\alpha]_D^{20} = -18^\circ$,⁵ corresponding to $[M]_D^{20} = -128^\circ$, and $[M]_D^{20} = -52^\circ$, respectively. A direct comparison to compound **1**, with conformational preferences determined by NMR spectroscopy (Table 2), is difficult due to the additional 3-C-methyl group in **3** and **4**. However, the significantly more negative value of **3** is consistent with the presence of a larger proportion of a 1C_4 conformation, harmonizing with the NMR-based results (Table 2), where the extent of the 4C_1 conformation is 70% in **3** compared to 90% in **4**. It is anticipated that these types of changes in molecular rotation will be able to report on alterations of conformational equilibria and we foresee that NMR studies in the future may be complemented by determination of the molecular rotation.

We conclude by noting that, in comparison to the 2-naphthyl β -D-xylopyranoside, stereochemical and substituent modifications at C3 lead to large changes in flexibility and/or conformational equilibria being dependent on the solvent. Notably, the flexibility is increased if the hydroxyl group at C3 is removed, leading to lower steric interactions, or if a C-methyl substituent is added, leading to higher steric interactions, or if the stereochemistry is inverted at the C3 position. The conformational equilibrium of the 3-deoxygenated compound was found to be highly temperature dependent with an almost exclusive 4C_1 conformation present at -100°C and only a few percent of the 1C_4 conformation compared to equally populated states at 25°C . Thus, the enthalpy-favored 4C_1 conformer of compound **2** becomes evident at low temperature and only at high temperature is the 1C_4 conformer favored in methanol solution as a result of significant entropic contributions to the conformational state. The importance of sugar puckering¹⁹ and the implications of the herein obtained results for glycosyl transferase activity and antiproliferative properties of these compounds is a challenging area for future research where progress recently has been made.⁵

Experimental section

Experimental procedures and analysis protocols were the same as previously described.^{3–5,15} NMR experiments were performed on a Bruker AVANCE II 500 MHz and AVANCE III 600 MHz spectrometers and a Varian Inova 800 MHz spectrometer. ${}^1\text{H}$ and ${}^{13}\text{C}$ chemical shifts are reported in ppm using residual solvent signals as references, *viz.*, in methanol- d_4 : δ_{H} 3.31 and δ_{C} 49.0; in chloroform- d : δ_{H} 7.26 and δ_{C} 77.16. Two J-HMBC experiments were performed as described^{9,20} using a scaling factor κ of 18.1 and 21.4. For compound **1** the specific rotation was measured on five separate samples with a Perkin-Elmer 341 polarimeter at 589 nm and 20°C in a quartz cuvette of 10 cm length; SD 0.46, c 1.01, MeOH.

Acknowledgements

This work was supported by grants from the Swedish Research Council, The Knut and Alice Wallenberg Foundation, and the Royal Physiographic Society in Lund. The Swedish NMR Centre at Göteborg University is thanked for access to a high field spectrometer.

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