Preferred Conformation of *C*-Glycosides. 6. Conformational Similarity of Glycosides and Corresponding *C*-Glycosides[†,‡]

Peter G. Goekjian, Tse-Chong Wu, and Yoshito Kishi*

Department of Chemistry, Harvard University, 12 Oxford St., Cambridge, Massachusetts 02138

Received March 11, 1991

The conformation of the α-(axial)-*C*-glycosides **1–3** and the β-(equatorial)-*C*-glycosides **4–6** were studied by ^{1}H NMR. Their preferred solution conformation was found to match that of the corresponding parent glycosides. The study of 2-deoxy compounds **13–16** shows that the preference is due primarily to gauche interactions around the glycosidic bond. Solvent studies indicate that electrostatic interactions and hydrogen bonds do not significantly alter the overall conformation. Temperature studies suggest that these compounds exist as an equilibrium mixture of conformers.

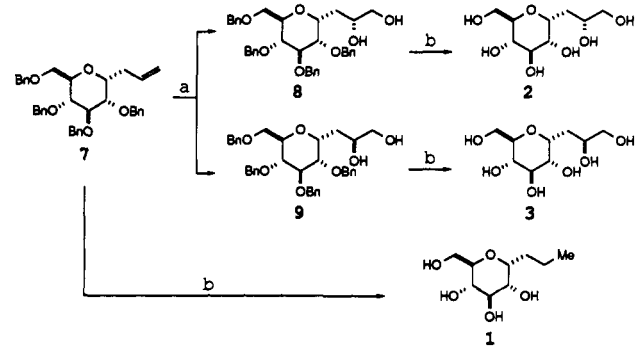
The regulatory role of glycoconjugates in controlling functions such as cell recognition, signal transduction, and membrane transport is a central issue in molecular biology.[1] The study of carbohydrates has become important to issues as diverse as immune response,[2] tumor growth,[3] and viral[4] infection. The possibility that many of these biological functions depend on the recognition of the three-dimensional structure of oligosaccharides has placed the conformational analysis of this class of compounds at the forefront of these studies.[5]

The modern era of carbohydrate conformational analysis began with the discovery of the anomeric[6] and the exo-anomeric[7] effects. The term exo-anomeric effect was introduced by Lemieux in 1969[8] to describe the observed preferred glycosidic conformation of sugars. Of the three staggered rotamers around the glycosidic bond of an α-(axial)-carbohydrate (Figure 1), the conformation **I-A** is preferred over **I-B** and **I-C**. This holds true for both oligosaccharides and simple *O*-alkyl glycosides. The conformational preference has been attributed to a combination of (a) steric preference (**I-A** > **I-B** > **I-C**) and (b) electronic stabilization (**I-A** = **I-C** > **I-B**). The electronic effect is a result of the interaction between the p orbital of the glycosidic oxygen and the antibonding σ* orbital of the polarized C.1–O.5 bond of the pyranose ring. This interaction is directly analogous to the stereoelectronic interaction invoked to account for the anomeric effect.[9]

Substantial controversy remains as to the relative importance of steric and electronic factors in aqueous or methanolic solution.[10] Ab initio calculations have been used to confirm the existence of an exo-anomeric electronic effect.[11] Experimental evidence[12] shows that the anomeric effect is weak in water and indicates the same for the exo-anomeric effect. To our knowledge, no experiment has been run to address directly the relative importance of the steric and electronic components of the exo-anomeric effect.

The carbon analogues of carbohydrates (Figure 1, **II-A,B,C**) represent a possible model for investigating the steric interactions around the glycosidic bonds of carbohydrates in the absence of electronic stabilization. In connection with the stereochemistry assignment and total synthesis of palytoxin,[13–15] we had the opportunity to synthesize a variety of C.1 carbon-substituted glycosides (carbon glycosides).[16] The difference in behavior between the carbon- and oxygen-linked glycosides can be used as an experimental measure of the net effect of the electronic stabilization on the glycosidic conformation of carbohydrates.

Scheme I[a]



[a] OsO_4, NMMO, acetone/water; (b) H_2, $Pd(OH)_2/C$, methanol.

[†] Preliminary results of this work have been published: Wu, T.-C.; Goekjian, P. G.; Kishi, Y. *J. Org. Chem.* **1987**, *52*, 4819. For part 5 of this series, see: Miller, W. H.; Ryckman, D. M.; Goekjian, P. G.; Wang, Y.; Kishi, Y. *J. Org. Chem.* **1988**, *53*, 5580.

[‡] Taken in part from Goekjian, P. G. Ph.D. Dissertation, Harvard University, 1990.

(1) For recent monographs on this subject, for example, see: (a) Weigandt, H. *Glycolipids*; Elsevier: New York, 1985. (b) Jowarski, E. *Glycobiology*; Weiley-Liss: New York, 1990. (c) Hughes, R. C. The Complex Carbohydrates of Mammalian Cell Surfaces and Their Biological Roles. *Essays Biochem.* **1976**, *11*, 1.

(2) For example, see: Montgomery, R. Glycoproteins. In *The Carbohydrates: Chemistry and Biochemistry*; Pigman, W. W., Horton, D., Eds.; Academic Press: New York, 1970.

(3) For example, see: Warren, L.; Fuhrer, J. P.; Tuszynski, G. P.; Buck, C. A. *Biochem. Soc. Symp.* **1974**, *40*, 147.

(4) For example, see: (a) Gottschalk, A.; Fazekas de St. Groth, S. *J. Gen. Microbiol.* **1960**, *22*, 690. (b) Warren, L.; Fuhrer, J. P.; Tuszynski, G. P.; Buck, C. A. *Biochem. Soc. Symp.* **1974**, *40*, 147.

(5) For example, see: (a) Lemieux, R. U. *Chem. Soc. Rev.* **1978**, *7*, 423. (b) Lemieux, R. U. *Frontiers of Chemistry*; Laidler, K. J., Ed.; Pergamon: New York, 1982 and references cited therein.

(6) For recent reviews, see: (a) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon: Oxford, 1983. (b) Kirby, A. J. *The Anomeric Effect and Related Stereoelectronic Effects at Oxygen*; Springer-Verlag: Berlin, 1983. (c) Tvaroska, I.; Bleha, T. *Adv. Carbohydr. Chem. Biochem.* **1989**, *47*, 45.

(7) (a) Lemieux, R. U.; Pavia, A. A.; Martin, J. C.; Watanabe, K. A. *Can. J. Chem.* **1969**, *47*, 4427. (b) Lemieux, R. U.; Koto, S. *Tetrahedron* **1974**, *30*, 1933. (c) Deslongchamps, P.; Pothier, N. *Can. J. Chem.* **1990**, *68*, 597. For a review, see: (d) Wolfe, S.; Whangbo, M.-H.; Mitchell, D. J. *Carbohydr. Res.* **1979**, *69*, 1.

(8) There is some ambiguity in the use of the term "exo-anomeric effect" in the literature. In some cases, it has been used to describe the conformational preference of glycosides for the gauche orientation. In other cases, it has been used to describe the stereoelectronic interaction between the p orbital of the interannular oxygen and the σ* orbital of the pyranose C.1–O.5 bond. In this paper, the former definition will be used for exo-anomeric effect, while the latter interaction will be referred to as the stereoelectronic stabilization.

(9) Radom, L.; Hehre, W. J.; Pople, J. A. *J. Am. Chem. Soc.* **1972**, *94*, 2371.

(10) Thøgersen, H.; Lemieux, R. U.; Bock, K.; Meyer, B. *Can. J. Chem.* **1982**, *60*, 44: "The objective was to provide firm evidence in support of the exo-anomeric effect by showing that the HSEA calculations are in good accord with [experimental parameters]." Lipkind, G. M.; Verovsky, V. E.; Kochetkov, N. K. *Carbohydr. Res.* **1984**, *133*, 1: "Thus, if the exo-anomeric effect for carbohydrates in aqueous media were important, the allowance for the effect would give satisfactory results for both methyl-β-maltoside and methyl-β-cellobioside, which does not correspond with reality. Therefore ... it is unnecessary to take this effect into account."

0022-3263/91/1956-6412$02.50/0

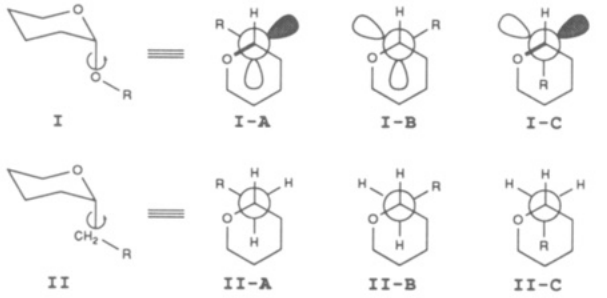
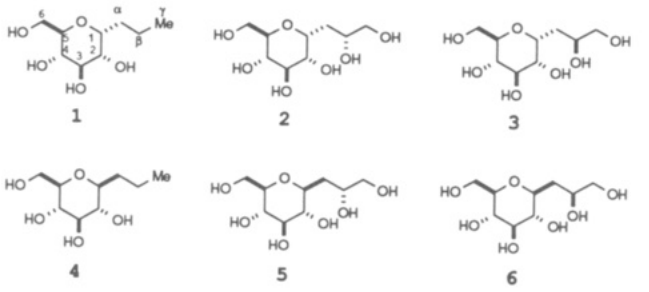


Figure 1. Anomeric rotamers of α-(axial)-glycosides.

The conformations of the carbon analogues can be determined experimentally by taking advantage of the vicinal coupling constants between the C.1 and the C.α protons. The Karplus equation[17] can be used to correlate the magnitude of these couplings to the dihedral angle around the C-glycosidic bond. This conformation can be compared to that of the parent oxygen compound, and the importance of the electronic interaction can be estimated on that basis. Since the C–O bond (1.43 Å) is shorter than the C–C bond (1.54 Å), the steric interactions observed in the carbon glycosides should be less pronounced than in the oxygen case. We therefore feel that this approach will slightly overestimate the effect of the stereoelectronic factor.

The axial propyl *C*-glycoside **1**, the axial dihydroxyl compounds **2** and **3**, and their equatorial isomers **4**, **5**, and **6** were chosen for the preliminary study. The primary



objectives were (a) to evaluate the use of ^{1}H NMR coupling constants in establishing the conformational preference of carbon glycosides, (b) to investigate the factors responsible for their conformational behavior, and (c) to compare the glycosidic conformation of the carbon and oxygen glycosides as an experimental measure of the influence of stereoelectronic factors on the solution conformation of carbohydrates.

Table I. ^{1}H NMR Data (500 MHz, Methanol-d_4) for Compounds 1, 2, and 3 at Room Temperature

proton	chemical shift (ppm), coupling pattern (Hz)
1	
H.6	3.62 (dd, J = 5.7, 11.7)
H.6	3.77 (dd, J = 2.5, 11.7)
H.5	3.37 (ddd, J = 2.5, 5.7, 9.6)
H.4	3.23 (dd, J = 88.4, 9.6)
H.3	3.50 (dd, J – 8.4, 9.5)
H.2	3.47 (dd, J = 5.7, 9.5)
H.1	3.88 (ddd, J = 3.1, 5.7, 11.4)
H.α	1.53 (m, 3.1)[a]
H.α	1.66 (m, 11.4)[a]
H.β	1.32 (m)
H.β	1.57 (m)
H.γ	0.95 (t, J = 7.1)
2	
H.6	3.62 (dd, J = 6.1, 11.7)
H.6	3.79 (dd, J = 2.5, 11.7)
H.5	3.42 (ddd, J = 2.5, 6.1, 9.4)
H.4	3.24 (dd, J = 8.7, 9.4)
H.3	3.52 (dd, J = 8.7, 9.4)
H.2	3.61 (dd, J = 5.9, 9.4)
H.1	4.19 (ddd, J = 3.3, 5.9, 11.3)
H.α	1.66 (ddd, J = 3.3, 10.1, 14.8)
H.α	1.90 (ddd, J = 2.9, 11.3, 14.8)
H.β	3.78 (dddd, J = 2.9, 5.8, 5.8, 10.1)
H.γ	3.49 (dd, J = 5.8, *b*)
H.γ	3.51 (dd, J = 5.8, *b*)
3	
H.6	3.62 (dd, J = 6.4, 11.5)
H.6	3.79 (dd, J = 2.4, 11.5)
H.5	3.55 (ddd, J = 2.4, 6.4, 9.3)
H.4	3.24 (dd, J = 8.5, 9.3)
H.3	3.53 (dd, J = 8.5, 9.4)
H.2	3.60 (dd, J = 5.8, 9.4)
H.1	4.12 (ddd, J = 4.1, 5.8, 10.1)
H.α	1.90 (ddd, J = 4.1, 6.0, 14.7)
H.α	1.84 (ddd, J = 6.4, 10.1, 14.7)
H.β	3.85 (dddd, J = 4.5, 6.0, 6.1, 6.4)
H.γ	3.50 (dd, J = 6.1, 11.4)
H.γ	3.58 (dd, J = 4.5, 11.4)

[a] The listing of a coupling constant associated with a multiplet indicates that the value was measured at a remote proton, but attributed to this signal by homonuclear decoupling. [b] Coupling constant could not be determined.

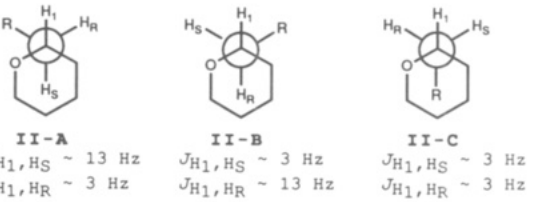


Figure 2. Staggered C.1–C.α rotamers and predicted coupling constants.

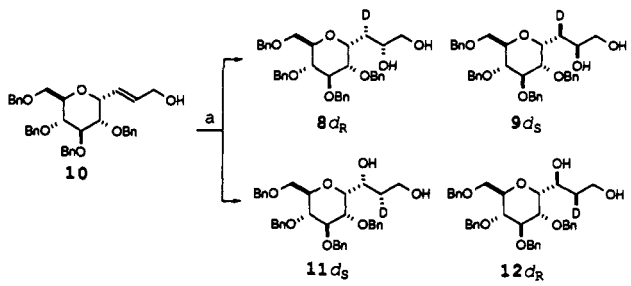
Results and Discussion

Axial *C*-Glycosides. The axial carbon monoglycosides were readily derived from allyl *C*-glycoside **7**[16] (Scheme I). Osmylation yielded the known[18] diols **8** and **9**. Deprotection gave the polyols **2** and **3**. Direct hydrogenolysis of **7** yielded the axial propyl-*C*-glycoside **1**.

The ^{1}H NMR spectra of compounds **2** and **3** show well-resolved resonances, which were assigned by homonuclear decoupling. All coupling constants were deter-

(11) Jeffrey, G. A.; Pople, J. A.; Binkley, J. S.; Vishveshwara, S. *J. Am. Chem. Soc.* **1978**, *100*, 373.
(12) Lemieux, R. U.; Pavia, A. A.; Martin, J. C.; Watanabe, K. A. *Can. J. Chem.* **1969**, *47*, 4427.
(13) For the gross structure of palytoxin, see: (a) Uemura, D.; Ueda, K.; Hirata, Y.; Naoki, H.; Iwashita, T. *Tetrahedron Lett.* **1981**, *22*, 2781 and references cited therein. For the structure of minor constituents, see: Uemura, D.; Hirata, Y.; Iwashita, T.; Naoki, H. *Tetrahedron* **1985**, *41*, 1007. (b) Moore, R. E.; Bartolini, G. *J. Am. Chem. Soc.* **1981**, *103*, 2491.
(14) For the stereochemistry assignment, see: Cha, J. K.; Christ, W. J.; Finan, J. M.; Fujioka, H.; Kishi, Y.; Klein, L. L.; Ko, S. S.; Leder, J.; McWhorter, W. W., Jr.; Pfaff, K.-P.; Yonaga, M.; Uemura, D.; Hirata, Y. *J. Am. Chem. Soc.* **1982**, *104*, 7369 and preceding papers.
(15) For a total synthesis of palytoxin carboxylic acid and amide, see: Armstrong, R. W.; Beau, J. M.; Cheon, S. H.; Christ, W. J.; Fujioka, H.; Ham, W.-H.; Hawkins, L. D.; Jin, H.; Kang, S. H.; Kishi, Y.; Martinelli, M. J.; McWhorter, W. W., Jr.; Mizuno, M.; Nakata, M.; Stutz, A. E.; Talamas, F. X.; Taniguchi, M.; Tino, J. A.; Ueda, K.; Uenishi, J.; White, J. B.; Yonaga, M. *J. Am. Chem. Soc.* **1989**, *111*, 7530 and references cited therein.
(16) For example, see: Lewis, M. D.; Cha, J. K.; Kishi, Y. *J. Am. Chem. Soc.* **1982**, *104*, 4976.
(17) (a) Karplus, M. *J. Chem. Phys.* **1959**, *30*, 11. (b) Karplus, M. *J. Phys. Chem.* **1960**, *64*, 1793. (c) Karplus, M. *J. Am. Chem. Soc.* **1963**, *85*, 2870. (d) Haasnoot, C. A. G.; de Leeuw, F. A. A. M.; Altona, C. *Tetrahedron* **1980**, *36*, 2783.
(18) Ko, S. S.; Finan, J. M.; Yonaga, M.; Kishi, Y.; Uemura, D.; Hirata, Y. *J. Am. Chem. Soc.* **1982**, *104*, 7364.

Scheme II[a]

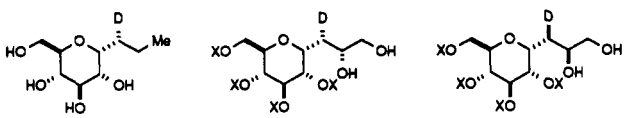


[a] (a) i, BD_3·THF; ii, H_2O_2, NaOH.

mined by first-order analysis (Table I). In the ^1H NMR spectrum of the propyl glycoside 1, most signals are well resolved, and the corresponding coupling constants, including the couplings around the key C-glycosidic C.1–C.α bond, can be measured directly from the spectrum. However, the close chemical shifts of the resonances at δ 1.53 and 1.57 leading to higher order effects, and the large number of couplings among the C.α and C.β methylene protons, lead to patterns whose complexity precludes a first-order analysis. No coupling constants around the C.α–C.β bond can therefore be determined at this stage (vide infra). The vicinal coupling constants around the pyranose rings indicate that they adopt the expected chair conformations.[19]

The three possible staggered rotamers around the C-glycosidic bond of an axial *C*-glycoside are shown in Figure 2. According to the Karplus equation, two antiperiplanar vicinal protons will have a coupling constant of ca. 13 Hz.[20] Two gauche protons will have a coupling of ca. 3 Hz. The observed coupling constants around the C-glycosidic bond for the axial *C*-glycosides 1 (11.4, 3.1 Hz), 2 (11.3, 3.3 Hz), and 3 (10.1, 4.1 Hz) indicate a marked preference for either conformer **II-A** or conformer **II-B**.

In order to differentiate unambiguously between the two possible conformers, it is necessary to assign the absolute stereochemistry of the C.α proton responsible for each methylene signal and corresponding coupling constants in the ^1H NMR spectrum. The stereospecifically C.α-labeled analogues $1d_R$, $2d_R$, and $3d_S$ were therefore synthesized.



Deuteroboration of allylic alcohol **10** yielded a chromatographically separable 4:4:1:1 mixture of the four possible monodeuterated diols (Scheme II). The two C.α deuterated 1,2-diols were identified by comparison of the ^1H NMR spectra to those of the parent unlabeled compounds **8** and **9**. The stereochemistry of the deuterium labels can be deduced from that of the newly installed hydroxyl group. Therefore, the configuration of the C.α deuterium can be assigned as *R* for the deuterated diol corresponding to **8** and *S* for the diol corresponding to **9**. Deprotection

(19) According to the modified Karplus equation,[17d] the coupling constant predicted between two antiperiplanar protons for this functionality is 9.6 Hz.

(20) The magnitude of the coupling constant predicted for a dihedral angle of 180° varies substantially among authors. We arbitrarily chose the value of 13 Hz because values as high as 12.7 Hz were observed in these systems. (a) Reference 17. (b) Bothner-By, A. B. *Adv. Magn. Reson.* **1965**, *1*, 195. (c) Durette, P. L.; Horton, D. *Org. Magn. Reson.* **1971**, *3*, 417. (d) Pachler, K. G. R. *J. Chem. Soc., Perkin Trans II*, **1972**, 1936. (e) Imai, K.; Osawa, E. *Tetrahedron Lett.* **1990**, 4251.

Table II. ^1H NMR Data (500 MHz, Methanol-d_4) for Compounds $1d_R$, $2d_R$, and $3d_S$ at Room Temperature[a]

proton	chemical shift (ppm), coupling pattern (Hz)
$1d_R$	
H.1	3.87 (dd, J = 5.7, 11.6)
H.α (*pro-R*)	no signal observed
H.α (*pro-S*)	1.64 (ddd, J = 4.8, 9.6, 11.6)
H.β	1.53 (dqd, J = 4.8, 7.4, 13.3)
H.β	1.31 (qdd, J = 7.4, 9.6, 13.3)
$2d_R$	
H.1	4.19 (dd, J = 5.9, 11.3)
H.α (*pro-R*)	no signal observed
H.α (*pro-S*)	1.88 (dd, J = 2.7, 11.3)
H.β	3.78 (dt, J = 2.7, 5.5)
$3d_S$	
H.1	4.11 (dd, J = 3.8, 5.4)
H.α (*pro-R*)	1.87 (dd, J = 3.8, 5.7)
H.α (*pro-S*)	no signal observed
H.β	3.83 (ddd, J = 4.4, 5.7, 6.1)

[a] A complete listing can be found in the Experimental Section.

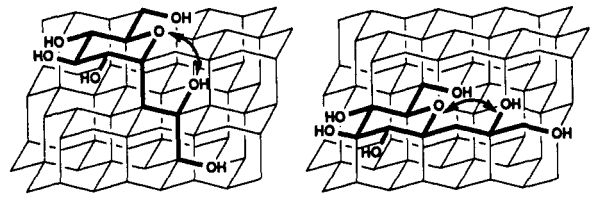


Figure 3. 1,3-Diaxial-like interactions in the extended conformations of compounds **3** and **5**.

of $8d_R$ and $9d_S$ yielded the deuterated polyols $2d_R$ and $3d_S$.

The synthesis of the labeled propyl *C*-glycoside was achieved by deoxygenation of the deuterated diol $8d_R$. Corey–Winter olefination[21] of $8d_R$ yielded the corresponding deuterated allyl *C*-glycoside $7d_R$. Hydrogenation yielded the monodeuterated polyol $1d_R$.

A comparison of the ^1H NMR spectrum of 1 and $1d_R$ reveals the absence of the resonance at δ 1.57 in $1d_R$. The missing signal can be assigned unambiguously to the *pro-R* proton. The remaining C.α methylene resonance at δ 1.64 bearing the large coupling to the C.1 proton therefore corresponds to the *pro-S* proton. In addition, this substitution leads to a dramatic simplification of the spectrum, allowing first-order analysis of the couplings between the *pro-S* C.α proton and the C.β protons (Table II).

Comparison of the ^1H NMR spectra of 2 and $2d_R$ correlates the missing resonance at δ 1.66 to the *pro-R* proton. The remaining methylene signal at δ 1.88 and the large coupling to the C.1 proton therefore correspond to the *pro-S* proton. Similarly, comparison of 3 and $3d_S$ assigns the resonance at δ 1.84, and the large coupling constant to the C.1 proton, to the *pro-S* proton.

The axial-*C*-glycosides 1, 2, and 3 therefore exhibit a strong preference for the conformation around the C-glycosidic C.1–C.α bond with the C.α–C.β bond antiperiplanar to the C.2–C.1 bond (conformer **II-A**). The assignment of the absolute stereochemistry of the proton with the large coupling as *pro-S* in all three cases rules out conformer **II-B**. The magnitude of the coupling constants [1 (11.4, 3.1 Hz), 2 (11.3, 3.3 Hz), and 3 (10.1, 4.1 Hz)] excludes a substantial contribution from other conformers.

The conformation around the C-aglyconic C.α–C.β bond can also be determined, based on the coupling constants observed between the C.α and C.β protons. The conformation for compounds 1 and 2 is predominantly extended. This is shown by the magnitude of the coupling constants

(21) Corey, E. J.; Winter, R. A. E. *J. Am. Chem. Soc.* **1963**, *85*, 2677.

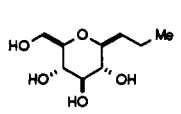
Table III. ^{1}H NMR Data (500 MHz, Methanol-d_4) for Compounds 4, 5, 5d_R, 6, and 6d_S at Room Temperature[a]

proton	chemical shift (ppm), coupling pattern (Hz)
4	
H.1	3.11 (ddd, J = 2.4, 8.5, 9.3)
H.α	1.39 (m, J = 8.5)[b]
H.α	1.78 (m, J = 2.4)[b]
H.β	1.39 (m)
H.β	1.59 (m)
5	
H.1	3.32 (ddd, J = 2.8, 8.9, 9.3)
H.α	1.59 (ddd, J - 6.9, 8.9, 14.6)
H.α	2.09 (ddd, J = 2.8, 5.3, 14.6)
H.β	3.89 (dddd, J = 4.6, 5.3, 5.6, 6.9)
5d_R	
H.1	3.32 (dd, J = 2.7, 9.5)
H.α (*pro-R*)	no signal observed
H.α (*pro-S*)	2.06 (dd, J = 2.7, 5.1)
H.β	3.89 (ddd, J = 4.6, 5.1, 6.2)
6	
H.1	3.39 (ddd, J = 2.5, 9.6, 9.7)
H.α	1.53 (ddd, J - 3.1, 9.7, 14.4)
H.α	1.91 (ddd, J = 2.5, 9.7, 14.4)
H.β	3.88 (dddd, J = 3.1, 4.8, 6.2, 9.7)
6d_S	
H.1	3.38 (dd, J = 9.5, 9.7)
H.α (*pro-R*)	1.52 (dd, J = 3.0, 9.7)
H.α (*pro-S*)	no signal observed
H.β	3.88 (ddd, J = 3.0, 4.9, 6.2)

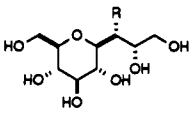
[a] A complete listing can be found in the Experimental Section. [b] The listing of a coupling constant associated with a multiplet indicates that the value was measured at a remote proton, but attributed to this signal by homonuclear dcoupling.

between the C.α and C.β protons for **1** (9.6, 4.8 Hz) and **2** (10.1, 2.9 Hz). In the case of compound **3**, however, the values of 6.0 and 6.4 Hz indicate a sizeable distortion. A 1,3-diaxial-like interaction exists between the C.1–O.5 and C.β–O.β bonds in the extended conformation (Figure 3). The observed distortion may be attributed to the presence of this interaction.[22]

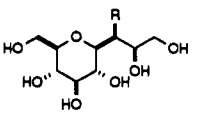
Equatorial *C*-Glycosides. The equatorial isomers **4**, **5**, and **6** and the C.α deuterated compounds 5d_R and 6d_S were prepared by the same procedure as the axial counterparts. The ^{1}H NMR spectrum of compounds **4**, **5**, 5d_R, **6**, and 6d_S were analyzed as above, and the results are summarized in Table III.



4



5: R=H
5d_R: R=D



6: R=H
6d_S: R=D

The conformational behavior of the equatorial carbon glycosides is analogous to that of their axial counterparts. The coupling patterns and stereochemical assignments around the glycosidic C.1–C.α bond for **4** (8.5, 2.4 Hz), **5** (8.9, 2.8 Hz), and **6** (9.7, 2.5 Hz) show a preference for the C-glycosidic conformation with the C.α–C.β bond antiperiplanar to the C.1–C.2 bond (Figure 4, **III-A**). However, the magnitude of the constants indicates that these compounds may be slightly less rigid than the axial compounds.

The C-aglyconic conformation of compounds **5** and **6** is established from the coupling constants around the C.α–C.β bond. It is extended for compound **6** (9.7, 3.1 Hz), but distorted for **5** (6.9, 5.3 Hz), which exhibits a 1,3-diaxial-like interaction in the extended form (Figure 3). This is again parallel to the behavior of the axial isomers.

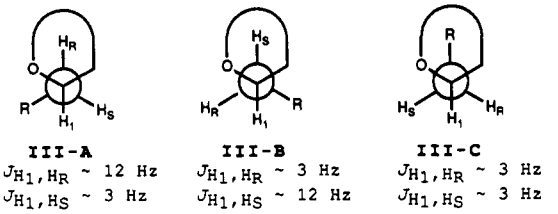


Figure 4. Staggered C.1–C.α rotamers and predicted coupling constants.

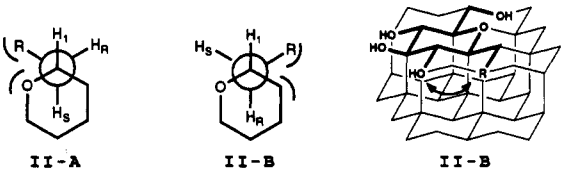


Figure 5. Steric interactions in **II-A** and **II-B**.

It has been shown that the axial carbon glycosides **1**, **2**, and **3** and the equatorial carbon glycosides **4**, **5**, and **6** adopt the "exo-anomeric" conformation **II-A**/**III-A** around the C-glycosidic bond. This conformation can be refined further. The conformational behavior can be treated either in terms of an equilibrium mixture of staggered conformers or in terms of a single conformer deviating slightly from the ideal staggered conformation. In the former case, the observed coupling constants correspond to a room-temperature population of approximately 90% **II-A** for the axial compounds and approximately 75% **III-A** for the equatorial compounds (vide infra). In the latter case, using a modified Karplus equation[17d] and coupling constants of 11.3 and 3.3 Hz for the axial carbon glycosides **1** and **2** yields a dihedral angle of approximately 55° (O.5–C.1–C.α–C.β). Couplings of 9.7 and 2.5 Hz yield approximately −80° for the equatorial cases **4** and **6**.

2-Deoxy Carbon Glycosides. Two alternative explanations may be proposed for the observed conformational preference of the carbon glycosides (Figure 5). The gauche interaction with oxygen (O.5) in **II-A** is favored over the one with carbon (C.2) in **II-B**, or conformer **II-B** is destabilized by a 1,3-diaxial-like interaction between the C.α–C.β bond and the C.2–O.2 bond. The 2-deoxy analogues **13**–**16** were prepared and studied by ^{1}H NMR in order to rule out the latter possibility.

The 2-deoxy compounds and selected deuterated analogues[23] were synthesized in the same manner as the parent compounds. The 500-MHz ^{1}H NMR spectra of **13**–**16** were recorded and analyzed as above (Table IV). A comparison of the coupling constants around the C-glycosidic bond (Table V) shows little effect upon removal of the oxygen at the 2-position of the pyranose ring. The unhindered cases **13** and **16** are virtually unaffected. Slight changes are observed in cases **14** and **15**, which had shown substantial steric interactions in the parent compounds **3** and **5**. The vicinal coupling constants around the C-aglyconic bond also indicate the same behavior as the parent compounds. The C-aglyconic bond of **13** and **16** exist in an

(22) The importance of 1,3-diaxial-like interactions for the conformational preference of carbohydrates was first recognized by Horton and co-workers. El Khadem, H. S.; Horton, D.; Page, T. F., Jr. *J. Org. Chem.* **1968**, *33*, 734. Further experimental investigation into the importance of these effects will be discussed in subsequent publications.

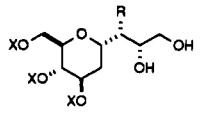
(23) For clarity of presentation, the authors chose not to use the Cahn–Ingold–Prelog nomenclature for the deuterium stereochemistry in these compounds. Instead, the notation was kept consistent with the parent compounds.

Table IV. ^{1}H NMR Data (500 MHz, Methanol-d_4) for 2-Deoxy Compounds 13, 13d_R, 14, 14d_S, 15, and 16 at Room Temperature[a]

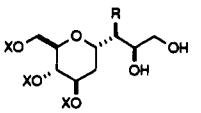
proton	chemical shift (ppm), coupling pattern (Hz)
13	
H.1	4.25 (dddd, J = 2.4, 3.6, 5.7, 11.0)
H.α (*pro-S*)	2.10 (ddd, J = 2.9, 11.0, 14.5)
H.α (*pro-R*)	1.32 (ddd, J = 3.6, 9.8, 14.5)
H.β	3.73 (dtd, J = 2.9, 5.5, 9.8)
13d_R	
H.1	4.24 (ddd, J = 2.3, 5.8, 11.1)
H.α (*pro-S*)	2.08 (dd, J = 2.7, 11.1)
H.α (*pro-R*)	no signal observed
H.β	3.73 (dt, J = 2.7, 5.5)
14	
H.1	4.19 (dddd, J - 2.5, 5.7, 6.0, 8.7)
H.α (*pro-S*)	1.90 (ddd, J = 7.7, 8.7, 14.2)
H.α (*pro-R*)	1.71 (ddd, J = 5.1, 6.0, 14.2)
H.β	3.74 (m, J = 5.1, 7.7)[b]
14d_S	
H.1	4.19 (ddd, J = 2.5, 5.6, 5.6)
H.α (*pro-S*)	no signal observed
H.α (*pro-R*)	1.68 (dd, J = 4.8, 5.6)
H.β	3.74 (m, J = 4.8 Hz)
15	
H.1	3.64 (dddd, J = 1.8, 5.0, 7.5, 11.4)
H.α	1.65 (ddd, J = 5.0, 5.3, 14.1)
H.α	1.70 (ddd, J = 7.5, 7.7, 14.1)
H.β	3.78 (dddd, J = 4.9, 5.3, 5.8, 7.7)
16	
H.1	3.67 (dddd, J = 1.8, 2.8, 9.6, 11.4)
H.α	1.46 (ddd, J = 2.8, 9.6, 14.3)
H.α	1.67 (ddd, J = 3.1, 9.6, 14.3)
H.β	3.86 (dddd, J = 3.1, 4.9, 6.1, 9.6)

[a] A complete listing can be found in the Experimental Section. [b] The listing of a coupling constant associated with a multiplet indicates that the value was measured at a remote proton, but attributed to this signal by homonuclear decoupling.

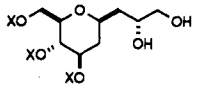
ideal extended conformation. Compound 14 and 15 show significant distortion.[24]



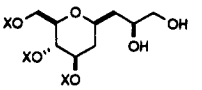
13: R=H
13d_R: R=D



14: R=H
14d_S: R=D



15



16

The experimental observation that the removal of the 2-hydroxyl group does not fundamentally alter the conformation around the C-glycosidic bond rules out the 1,3-diaxial-like interaction between the C.2–O.2 and C.α–C.β bonds as the primary factor in controlling the conformational behavior of these compounds. The preference must be attributed predominantly to gauche interactions. It is therefore independent of the structure and stereochemistry of the substituents of the pyranose ring.[25]

(24) The conformational behavior around the C-aglyconic bond excludes the possibility that a hydrogen bond between the C.β hydroxyl group and the pyranose O.5 oxygen is responsible for the glycosidic conformational preference of these compounds. If such a hydrogen bond were present, 14 and 15 would be expected to exist in an extended conformation, while 13 and 16 would exist in a distorted conformation. Experimentally, the opposite behavior is observed. In addition, the conformational behavior of the polyol, peracetylated, and permethylated forms of 13 and 14 are similar (vide infra). Finally, it was observed that *C*-glycosides with carbon substitution at C.β and *manno* configuration at C.2 show the same glycosidic conformational behavior as these compounds: Babirad, S. A.; Wang, Y.; Goekjian, P. G.; Kishi, Y. *J. Org. Chem.* **1987**, *52*, 4825.

Table V. Comparison of Coupling Data (Hz) between the 2-Hydroxy and Corresponding 2-Deoxy Compounds

compd	J(1,α(R))	J(1,α(S))	J(α(R),β)	J(α(S),β)
2	3.3	11.3	10.1	2.9
13	2.4	11.0	9.8	2.9
3	4.1	10.1	6.0	6.4
14	5.7	8.7	7.7	5.1
5	8.9	2.8	6.9	5.3
15	7.5	5.0	7.7	5.3
6	9.7	2.5	3.1	9.7
16	9.6	2.8	3.1	9.6

Table VI. Solvent Dependence of ^{1}H NMR Coupling Constants (Hz) for Compounds 1, 2, and 4 at Room Temperature[a]

compd	solv	J(1,α(R))	J(1,α(S))	J(α(R),β)	J(α(S),β)
1	D_2O	3.2	11.8		
	CD_3OD	3.1	11.6		
	DMSO	3.2	11.2		
	C_5D_5N	3.9	10.6		
2	D_2O	2.9	11.9	10.5	2.6
	CD_3OD	3.3	11.3	10.1	2.7
	DMSO	2.9	11.5	10.1	2.6
	C_5D_5N	3.8	10.7	9.6	3.5
4	D_2O	8.6	2.5		
	CD_3OD	8.5	2.4		
	DMSO	8.3	2.3		
	C_5D_5N	8.4	2.4		
5	D_2O	9.2	2.8	6.5	6.2
	CD_3OD	8.9	2.8	6.9	5.3
	DMSO	8.9	2.8	6.6	5.8
	C_5D_5N	8.4	3.0	7.1	5.2

[a] Meaningful spectra could not be measured in either $CDCl_3$ or C_6D_6 due to poor solubility.

Table VII. ^{1}H NMR Coupling Constants (Hz) for Polyols and Protected Compounds

compd	XO-	J(1,α(R))	J(1,α(S))	J(α(R),β)	J(α(S),β)
2	HO-[a]	3.3	11.3	10.1	2.7
	AcO-[b]	2.9	11.7	9.7	3.9
	MeO-[b]	2.8	11.8	9.7	3.0
3	HO-[a]	3.8	10.1	6.0	5.7
	AcO-[b]	3.7	11.3	8.2	5.0
	MeO-[c]	4.0	10.0	6.6	4.8
5	HO-[a]	8.9	2.8	6.9	5.3
	AcO-[c]	9.0	2.9	6.0	6.0
	MeO-[b]	9.2	2.7	4.4	7.6
6	HO-[a]	9.7	2.5	3.1	9.7
	AcO-[b]	10.2	2.4	4.1	9.1
	MeO-[b]	10.4	2.1	3.6	9.3
13	HO-[a]	2.4	11.0	9.8	2.9
	AcO-[b]	3.2	10.7	9.5	3.9
	MeO-[b]	3.5	10.5	9.5	2.8
14	HO-[a]	5.7	8.7	7.7	5.1
	AcO-[b]	4.6	9.9	7.4	5.7
	MeO-[b]	4.5	9.0	7.2	5.2

[a] CD_3OD. [b] $CDCl_3$. [c] C_6D_6.

Solvent Effects. The ^{1}H NMR spectra of compounds 1, 2, 4, and 5 were recorded in D_2O, DMSO-d_6, CD_3OD, and pyridine-d_5 in order to determine the influence of the polarity of the medium on the conformational behavior of the simple carbon glycosides (Table VI).

The results indicate that the solvent polarity does not have a significant effect on the conformation of these compounds. The fact that the conformation is similar in protic and aprotic solvents demonstrates that hydrogen bonds and electrostatic interactions do not alter the overall conformational preference of these substrates.[26]

(25) *C*-Glycosides with *manno* and *galacto* configuration as well as with C.2-carbon substitution have been studied. The C-glycosidic conformation was found to be unaffected. These results will be reported in subsequent publications.

Table VIII. Temperature Dependence of the ^{1}H NMR Coupling Constants (Hz) for Compounds 1, 2, 3, 4, 6d_S, 15, and 16

compd	T (K)	solv	J(1,α(R))	J(1,α(S))	J(α(R),β)	J(α(S),β)	II,III-A
1	357	D_2O	3.6	11.1			81
	337	D_2O	3.5	11.3			83
	317	D_2O	3.4	11.6			86
	297	D_2O	3.2	11.8			88
	317	CD_3OD	3.5	11.3			83
	297	CD_3OD	3.1	11.6			86
	273	CD_3OD	2.8	11.8			88
	253	CD_3OD	2.7	12.1			91
	240	CD_3OD	2.6	12.2			92
4	317	CD_3OD	8.1	2.5			60
	297	CD_3OD	8.5	2.2			65
	273	CD_3OD	8.6	2.0			66
	253	CD_3OD	8.7	1.7			67
	237	CD_3OD	8.8	1.5			68
2	357	D_2O	3.2	11.3	9.6	3.3	83
	337	D_2O	3.2	11.5	9.9	3.2	85
	317	D_2O	3.1	11.8	10.2	2.9	88
	297	D_2O	2.9	11.9	10.5	2.6	89
	317	CD_3OD	3.5	11.3	9.8	3.1	83
	297	CD_3OD	3.3	11.3	10.3	2.9	83
	273	CD_3OD	3.2	11.8	10.4	2.7	88
	253	CD_3OD	3.0	12.1	10.7	2.3	91
	237	CD_3OD	2.8	12.2	10.9	2.2	92
3	297	CD_3OD	4.2	10.1	6.4	6.1	71
	273	CD_3OD	4.3	10.1	6.3	6.1	71
	253	CD_3OD	4.7	10.0	6.3	6.2	70
6d_S	317	CD_3OD	9.3		3.0		74
	297	CD_3OD	9.7		3.0		79
	273	CD_3OD	10.2		2.8		85
	225	CD_3OD	10.7		2.3		90
14	317	CD_3OD	5.9	8.8	4.8	7.7	58
	297	CD_3OD	6.0	8.7	5.0	7.7	57
	273	CD_3OD	6.2	8.6	5.2	7.9	56
	253	CD_3OD	6.3	8.6	5.5	7.9	56
	233	CD_3OD	6.4	8.5	5.6	8.0	55
15	317	CD_3OD	7.5	5.0	7.5	5.0	53
	297	CD_3OD	7.6	5.1	7.6	5.1	54
	273	CD_3OD	7.7	5.2	7.7	5.2	55
	253	CD_3OD	7.7	5.2	7.7	5.2	55
	233	CD_3OD	7.7	5.4	7.7	5.4	55

Furthermore, protection of the hydroxyl groups does not dramatically affect the conformation of these compounds (Table VII). Comparison of the coupling constants for the polyol, the permethyl, and the peracetate of compounds **2**, **3**, **5**, **6**, **13**, and **14** shows remarkably little deviation in the experimental conformation of the three cases.[27] This result is pertinent in view of the great difference in the electronic and hydrogen bonding properties of the hydroxy, methoxy, and acetoxy groups. Completely eliminating hydrogen bonding thus does not alter the conformational behavior of these compounds. In addition, the conformation of the polyol in methanol corresponds to the conformation in chloroform in the absence of hydrogen bonding. This is further evidence that hydrogen bonds and electrostatic interactions play little role in the overall glycosidic conformation of the carbon analogues of carbohydrates.

Temperature Effects. Variable-temperature ^{1}H NMR experiments were performed to gain further insight into the conformational behavior of the carbon glycosides. The spectra of compounds **1**, **2**, **3**, **4**, 6d_S, **14**, and **15** were recorded at temperatures ranging from −43 °C to 84 °C (Table VIII). A modest temperature effect was observed in most cases. The population of the major conformer (**II/III-A**) (versus the combined population of conformers **B** and **C**) was approximated from the appropriate coupling constant[28,29] and is listed in Table VIII.

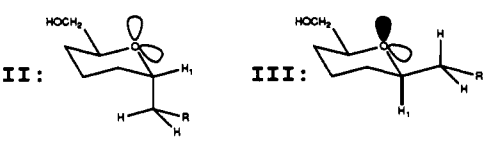
The presence of a temperature effect indicates that these compounds exist as a mixture of staggered conformers rather than as a single twisted conformer. A plot of [ln [Pop(A)/(1 − Pop(A))]] vs [1/temperature] for compounds

(26) Hydrogen bonds may occur in these compounds. These results indicate only that the *net* effect of these interactions is negligible. This is consistent with findings in the parent oxygen case: Spohr, U.; Morishima, N.; Hindsgaul, O.; Lemieux, R. U. *Can. J. Chem.* **1985**, *63*, 2659.

(27) While the conformation around the C-glycosidic and C-aglyconic bonds of the axial 2-deoxy compounds **13** and **14** were not substantially affected, more noticeable changes were observed in the conformational behavior of the pyranose rings. While the pyranose rings showed a clearcut preference for a single chair conformer in the polyol forms (**13**: $J_{H2,H3}$ = 10.9, 4.9 Hz; **14**: $J_{H2,H3}$ = 10.8, 4.8 Hz), a mixture of the two pyranose chair forms was observed for the protected forms (peracetyl **13**: $J_{H2,H3}$ = 7.6, 5.4 Hz; **14**: $J_{H2,H3}$ = 8.5, 4.8 Hz; permethyl **13**: $J_{H2,H3}$ = 8.9, 4.4 Hz; **14**: $J_{H2,H3}$ = 8.9, 4.5 Hz).

(28) The populations were approximated by assuming a 2-conformer system, namely, conformer **II/III-A** (J(A) = 11.7 Hz, from ref 17d) and a combined conformer **B** and **C** (J(B/C) = 3 Hz). Pop(A) = [J(obs) − J(B/C)]/[J(A) − J(B/C)]. For the axial case, it was necessary to use J(A) = 13 Hz since several of the observed couplings were larger than 11.7 Hz.

(29) The value of the coupling constants for conformers **II-A** and **III-A** are not necessarily expected to be the same. Although the dihedral angle and electronegative substituents (α-effect) are identical, differences may arise, for example, from the effect of the substituents on adjacent carbons (β-effect). Schaefer (*Mol. Phys.* **1966**, *10*, 209) observed a substantial increase in observed coupling constants when an electronegative substituent at the β-position is antiperiplanar to one of the coupled protons. Osawa's formulation (*Tetrahedron Lett.* **1989**, 4251, footnote 13) implies that a heteroatom lone pair exerts an electropositive effect, leading to a smaller observed coupling constant. Note that the O.5 lone pair is antiperiplanar to the C.1 proton in the β-(equatorial)-*C*-glycoside **III**, but not in axial isomer **II**.



1, 2, and 6 yields a straight line. The observed temperature-dependent behavior is thus reasonably consistent with a simple two-conformer model. From the slope and intercept of these lines, we can estimate that, roughly, ΔH = −1.8 kcal/mol and ΔS = −2 cal/mol for the axial glycosides, while ΔH = −1.7 kcal/mol and ΔS = −3.6 cal/mol for the equatorial compound.[30]

Conclusions

The conformation of carbon monoglycosides can be derived unambiguously from ^{1}H NMR vicinal coupling constants. In all cases studied, there is a strong preference for the conformation around the C-glycosidic bond which matches that adopted by the parent *O*-alkyl glycosides. In order to compare to the oxygen case, the single conformer obtained from the modified Karplus equation (vide supra) can be regarded as a time-averaged conformation. In this case, the dihedral angles of 55° for the axial cases and −80° for the equatorial cases are in good agreement with the value of 55° cited[31] for methyl α-D-glucopyranoside and −70° cited for methyl β-D-glucopyranoside.[32]

It is also noteworthy that, in cases where 1,3-diaxial-like interactions are present, distortion occurs around the C-aglyconic (C.α–C.β) bond in preference to the C-glycosidic (C.1–C.α) bond. This is consistent with Lemieux's observation in connection with the behavior of the parent carbohydrate compounds.[31]

These results indicate that although the existence of a stereoelectronic stabilization cannot be excluded in the oxygen case, the conformational behavior of glycosides can be accounted for by steric effects as a first approximation. The study of 2-deoxy analogues demonstrates that this preference can be attributed primarily to gauche interactions around the C.1–C.α bond and is relatively independent of interactions with substituents on the pyranose ring. Finally, the solvent studies indicate that electrostatic interactions and hydrogen bonds do not play a major role in the overall conformational behavior of these compounds.

The conformational similarity between the carbon analogues of simple carbohydrates and the corresponding parent glycosides suggests that carbon analogues may provide useful experimental probes for the conformational analysis of more complex oligosaccharides. A variety of experimental techniques have been applied to the conformational analysis of the parent carbohydrates, including nuclear magnetic resonance (T_1, NOE,[5] $^3J_{CH}$,[33] specific deshielding[34]), optical rotation,[35] and single-crystal X-ray. Yet, the ability to systematically derive reliable solution conformations of complex oligosaccharides solely from the experimental data remains elusive.[36,37] Few experimental methods are as well established or as accurate in determining the conformation of organic substrates in solution as the use of the Karplus equation. It may thus be possible to study the solution conformation of oligosaccharides through the use of the carbon-analogue isosteres.

Experimental Section

Only selected analytical data are reported in the Experimental Section. A complete set of data is available in the supplementary material. ^{1}H NMR spectra were recorded at 500 MHz and ^{13}C NMR spectra were recorded at 125 MHz. Chemical shifts are reported in parts per million. The residual solvent peak was used as an internal reference. Fast atom bombardment (FAB) mass spectra were obtained with 3-nitrobenzyl alcohol or glycerol as the matrix. Sodium iodide was added when indicated. Signals below 91 mass units or attributed to the matrix are not reported. Fourier transform infrared spectra were obtained as films on sodium chloride plates. Optical rotations were measured at room temperature, using the sodium D line. All compounds were left open to the air until a constant mass was observed. Elemental analyses were performed by Analytical Laboratory, Meijo University, Nagoya, Japan. Melting points (mp) are uncorrected.

Analytical thin layer chromatography (TLC) was performed with E. Merck pre-coated TLC plates, silica gel 60F-254, layer thickness 0.25 mm. Preparative TLC (PTLC) separations were carried out on E. Merck pre-coated plates, silica gel 60F-254, layer thickness 0.50 mm. Flash chromatography separations were performed on E. Merck kieselgel 60 (230–400 mesh) silica gel. Non-flash silica gel chromatography was conducted with Merck kieselgel 60 (70–230 mesh). Polyols were purified on TSK G3000S polystyrene gel from Toyo Soda Co., Ltd., Tokyo, Japan.

Reagents and solvents are commercial grade and were used as supplied, with the following exceptions. Benzene, ether, and THF were distilled from sodium benzophenone ketyl. Methylene chloride was distilled from phosphorus pentoxide. Toluene was distilled from sodium. Oxalyl chloride was distilled under nitrogen. *p*-Nitrobenzoyl chloride was recrystallized from CCl_4.

All reactions sensitive to air or moisture were conducted under argon or nitrogen. Reaction vessels for moisture-sensitive reactions were flame-dried or oven-dried and allowed to cool under an inert atmosphere.

Methyl 3-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-propenoate (17). A stirred solution of oxalyl chloride (32 μL, 0.37 mmol) in methylene chloride (2 mL) under argon was cooled to −78 °C and treated with a solution of dimethyl sulfoxide (51 μL, 0.72 mmol) in methylene chloride (50 μL). The mixture was stirred at −78 °C for 15 min. A solution of (2,3,4,6-*O*-tetrabenzyl-α-D-glucopyranosyl)methanol[38] (100 mg, 0.180 mmol) in methylene chloride (1 mL) was added dropwise, and the mixture was stirred at −78 °C for 40 min. Triethylamine (130 μL, 0.934 mmol) was added and the reaction mixture was stirred at 0 °C for 10 min. The mixture was diluted with benzene and washed with saturated NH_4Cl and brine. The organic layer was dried over $MgSO_4$, filtered through silica gel, and concentrated in vacuo. The crude aldehyde was used without further purification. A stirred solution of the crude aldehyde (0.18 mmol) in benzene (2 mL) at 0 °C under argon was treated with (carbomethoxymethylene)triphenylphosphorane (100 mg, 0.299 mmol). The

(30) The values of ΔS and ΔH are dependent on our assumptions on the magnitude of the coupling constants of the individual conformers. The values given in the text were determined by using $J_{II\text{-}A}$ = 13 Hz, $J_{II\text{-}B}$ = 3 Hz, $J_{III\text{-}A}$ = 11.7 Hz, and $J_{III\text{-}B}$ = 3 Hz. For the axial case for example, using $J_{II\text{-}A}$ = 13.5 Hz gives ΔH = −1.3 kcal/mol, ΔS = −1.5 cal/mol. Varying $J_{II\text{-}B}$ has a small effect on ΔH (−1.5 kcal/mol with $J_{II\text{-}B}$ = 1 Hz, −1.7 kcal/mol with $J_{II\text{-}B}$ = 4 Hz), but a substantial effect on ΔS (−1.2 cal/mol for $J_{II\text{-}B}$ = 1 Hz, −2.6 cal/mol with $J_{II\text{-}B}$ = 4 Hz).

(31) Lemieux, R. U.; Koto, S. *Tetrahedron* **1974**, *30*, 1933.

(32) The most useful estimate of the free energy stabilization due to the exo-anomeric effect is from the comparison of the relative populations of **II-A** and **II-B** in the carbon cases on one hand with that of **I-A** and **I-B** in the oxygen cases on the other. Unfortunately, no definitive experimental data are available for the relative populations of **I-A** and **I-B** in aqueous or methanolic solution. A direct experimental comparison of the conformational behavior of carbon- and oxygen-linked disaccharides based on T_1 and NOE experiments will be described in a forthcoming full account of a communication: Miller, W. H.; Ryckman, D. M.; Goekjian, P. G.; Wang, Y.; Kishi, Y. *J. Org. Chem.* **1988**, *53*, 5580.

(33) For example, see: (a) Lemieux, R. U.; Nagabhushan, T. L.; Paul, B. *Can. J. Chem.* **1972**, *50*, 773. (b) Schwarcz, J. A.; Perlin, A. S. *Can. J. Chem.* **1972**, *50*, 3667. (c) Gagnaire, D. Y.; Nardin, R.; Taravel, F. R.; Vignon, M. R. *Nouv J. de Chim.* **1977**, *1*, 423. (d) Hamer, G. K.; Balza, F.; Cyr, N.; Perlin, A. S. *Can. J. Chem.* **1978**, *56*, 3109.

(34) Kotowycz, G.; Lemieux, R. U. *Chem. Rev.* **1973**, *73*, 669.

(35) Stevens, E. S.; Sathyanarayana, B. K. *J. Am. Chem. Soc.* **1989**, *111*, 4149.

(36) Thøgersen, H.; Lemieux, R. U.; Bock, K.; Meyer, B. *Can. J. Chem.* **1982**, *60*, 44: "In the absence of molecular models that define the spatial arrangement of the protons in the molecule, even an attempt to assess the significance of NOE, T_1 measurements and other NMR parameters is denied."

(37) For examples of the conformation of carbohydrates from experimental data only, see: (a) Yan, Z.-Y.; Rao, B. N. N.; Bush, C. A. *J. Am. Chem. Soc.* **1987**, *109*, 7663. (b) Gagnaire, D. Y.; Nardin, R.; Taravel, F. R.; Vignon, M. R. *Nouv. J. de Chim.* **1977**, *1*, 423. (c) Carver, J. P.; Brisson, J.-R. The Three-Dimensional Structure of N-Linked Oligosaccharides. In *Biology of Carbohydrates*, Vol. II; Ginsburg, V., Robbins, P. W., Eds.; Wiley: New York, 1984.

(38) (a) Pougny, J. R.; Nassr, M. A. M.; Sinaÿ, P. *Chem. Commun.* **1981**, 375. (b) RajanBabu, T. V.; Reddy, G. S. *J. Org. Chem.* **1986**, *110*, 5458.

mixture was stirred at room temperature overnight. The crude reaction mixture was applied to a flash silica gel column and eluted with 5%, 10% ether/carbon tetrachloride to yield the trans-α,β-unsaturated ester **17** as a clear colorless oil (80.2 mg, 0.132 mmol, 73% yield). IR (neat): 1725 cm^{-1}. ^1H NMR ($CDCl_3$): δ 3.62–3.71 (4 H); 3.71 (1 H, m); 3.76 (3 H, s); 3.82 (1 H, dd, J = 4.2, 9.1 Hz); 4.66 (1 H, m); 6.18 (1 H, dd, J = 2.3, 16.2 Hz); 7.21 (1 H, dd, J = 3.7, 16.2 Hz). ^{13}C NMR ($CDCl_3$): δ 51.68, 68.65, 72.74, 73.01, 73.52, 75.06, 75.61, 77.91, 79.40, 83.00, 124.11, 127.65, 127.71, 127.77, 127.84, 127.89, 127.94, 128.22, 128.37, 128.40, 128.45, 128.49, 137.81, 137.84, 138.04, 138.53, 142.41, 166.33. MS (FAB, NaI): m/z 631 (M + Na). HRMS (FAB, NaI): calcd for $C_{38}H_{40}O_7$ (M + Na) 631.2672; found 631.2672. $[\alpha]_D$: +58.0° (c 1.88, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-1-propen-3-ol (10). A stirred solution of the unsaturated ester **17** (61.4 mg, 0.101 mmol) in methylene chloride (5 mL) at 0 °C under argon was treated with DIBAL (20% w/w in hexanes, 275 μL, 0.261 mmol). The mixture was stirred at 0 °C for 30 min. The reaction was quenched with methanol (50 μL) and distilled water (75 μL) and diluted with methylene chloride (25 mL). The reaction mixture was stirred for 2 h, treated with NaOH (10% aqueous, 2 drops), and dried over Na_2SO_4 for 1 h. The mixture was filtered through silica gel and concentrated in vacuo. Silica gel chromatography (flash silica, 25% ethyl acetate/hexanes) yielded the trans allylic alcohol **10** as a white crystalline solid (52.0 mg, 0.0895 mmol, 89% yield). An analytical sample was obtained by recrystallization from ethyl acetate/hexanes; white needles, mp 99–100 °C. IR (neat): 3451 cm^{-1}. ^1H NMR ($CDCl_3$): δ 3.61–3.67 (2 H); 3.69 (1 H, dd, J = 3.7, 10.6 Hz); 3.74–3.81 (3 H); 4.20 (2 H, m); 4.62 (1 H, m); 6.04 (2 H, m). ^{13}C NMR ($CDCl_3$): δ 63.23, 68.93, 72.02, 72.97, 73.38, 73.51, 75.08, 75.52, 78.23, 79.90, 82.76, 124.74, 127.58, 127.65, 127.69, 127.82, 127.90, 127.93, 128.34, 128.36, 128.41, 134.64, 137.94, 138.04, 138.13, 138.70. MS (FAB, NaI): m/z 603 (M + Na). Anal. Calcd for $C_{37}H_{40}O_6$: C, 76.52; H, 6.94. Found: C, 76.36; H, 6.89. $[\alpha]_D$: +68.0° (c 2.37, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-2,3-propanediol (8, 9). The diols **8** and **9** were prepared according to the procedure of Kishi (*Pure Appl. Chem.* **1989**, *61*, 313). Analytical samples were obtained by recrystallization from ethyl acetate:hexanes; white needles, mp **8** 158–160 °C, mp **9** 126.5–128.5 °C. **2*R* Isomer 8.** IR (neat): 3272 cm^{-1}. ^1H NMR ($CDCl_3$): δ 1.84 (1 H, ddd, J = 4.1, 8.4, 14.9 Hz); 1.89 (1 H, ddd, J = 4.3, 10.1, 14.9 Hz); 2.22 (1 H, dd, J = 5.8, 6.2 Hz); 2.75 (1 H, d, J = 5.1 Hz); 3.50 (1 H, dd, J = 7.8, 9.5 Hz); 3.55 (1 H, ddd, J = 6.2, 6.6, 11.1 Hz); 3.58–3.64 (3 H); 3.68 (1 H, m); 3.72 (1 H, dd, J = 5.3, 9.1 Hz); 3.76 (1 H, dd, J = 8.0, 9.1 Hz); 3.83 (1 H, m); 4.24 (1 H, ddd, J = 4.1, 5.3, 10.1 Hz). ^{13}C NMR ($CDCl_3$): δ 28.89, 66.50, 69.04, 69.49, 71.09, 71.80, 73.38, 73.48, 74.87, 75.32, 77.94, 79.41, 81.97, 127.66, 127.77, 127.86, 127.89, 127.92, 128.00, 128.40, 128.48, 137.71, 137.85, 138.01, 138.51. MS (FAB, NaI): m/z 621 (M + Na). Anal. Calcd for $C_{37}H_{42}O_7 \cdot {}^1/_5H_2O$: C, 73.78; H, 7.09. Found: C, 73.80; H, 7.06. $[\alpha]_D$: +26.8° (c 0.82, $CHCl_3$). **2*S* Isomer 9.** IR (neat): 3245 cm^{-1}. ^1H NMR ($CDCl_3$): δ 1.76 (1 H, br d, J = 15.2 Hz); 2.00 (1 H, ddd, J = 8.5, 11.8, 15.2 Hz); 2.31 (1 H, dd, J = 5.5, 7.0 Hz); 3.41 (1 H, dd, J = 8.5, 9.8 Hz); 3.41 (1 H, m); 3.48 (1 H, dd, J = 6.7, 10.1 Hz); 3.52 (1 H, ddd, J = 5.5, 6.3, 11.2 Hz); 3.61 (1 H, ddd, J = 3.6, 7.0, 11.2 Hz); 3.64 (1 H, dd, J = 2.1, 10.1 Hz); 3.69 (1 H, dd, J = 5.8, 9.3 Hz); 3.76 (1 H, dd, J = 9.1, 9.3 Hz); 3.87–3.93 (2 H); 4.23 (1 H, ddd, J = 2.2, 5.8, 11.8 Hz). ^{13}C NMR ($CDCl_3$): δ 27.85, 66.35, 69.37, 71.46, 71.99, 73.36, 73.47, 74.39, 74.87, 75.42, 78.28, 79.64, 82.01, 127.67, 127.73, 127.77, 127.82, 127.88, 127.91, 128.39, 128.47, 137.59, 137.92, 138.00, 138.47. MS (FAB, NaI): m/z 621 (M + Na). Anal. Calcd for $C_{37}H_{42}O_7$: C, 74.22; H, 7.07. Found: C, 73.95; H, 7.03. $[\alpha]_D$: +27.9° (c 1.81, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-1-deuteriopropane-2,3-diol (8d_R, 9d_S). A stirred solution of the allylic alcohol **10** (96.8 mg, 0.167 mmol) in THF (2.5 mL) at 0 °C under argon was treated with borane-d_3 (0.75 mL, 0.64 mmol). The reaction mixture was allowed to warm to room temperature slowly. After 7 h, the reaction was cooled to 0 °C and quenched with NaOH (10% aqueous, 0.5 mL) followed by hydrogen peroxide (30%, 0.4 mL) and the mixture was stirred for 1 h. Aqueous workup and HPLC (20% acetonitrile/methylene chloride) yielded the deuterated diols as white crystalline solids (8d_R: 36.4 mg, 0.0607 mmol, 36% yield; 9d_S: 7.9 mg, 0.0132 mmol, 8% yield). **1*R*,2*R* Isomer 8d_R.** ^1H NMR ($CDCl_3$): δ 1.87 (1 H, dd, J = 4.0, 10.5 Hz); 3.49 (1 H, dd, J = 8.5, 9.0 Hz); 3.54 (1 H, dd, J = 6.6, 11.1 Hz); 3.58–3.64 (3 H); 3.68 (1 H, m); 3.72 (1 H, dd, J = 5.3, 9.2 Hz); 3.75 (1 H, dd, J = 8.0, 9.2 Hz); 3.80 (1 H, m); 4.23 (1 H, dd, J = 5.3, 10.5 Hz). MS (FAB, NaI): m/z 622 ($C_{37}H_{41}DO_7$ + Na). **1*S*,2*S* Isomer 9d_S.** ^1H NMR ($CDCl_3$): δ 1.73 (1 H, dd, J = 2.3, 2.4 Hz); 3.39 (1 H, dd, J = 8.5, 9.8 Hz); 3.47 (1 H, dd, J = 6.8, 10.1 Hz); 3.51 (1 H, dd, J = 6.3, 11.2 Hz); 3.61 (1 H, dd, J = 3.8, 11.2 Hz); 3.63 (1 H, dd, J = 2.1, 10.0 Hz); 3.68 (1 H, dd, J = 5.8, 9.4 Hz); 3.74 (1 H, dd, J = 8.6, 9.2 Hz); 3.87–3.93 (2 H); 4.21 (1 H, dd, J = 2.4, 5.7 Hz). MS (FAB, NaI): m/z 622 ($C_{37}H_{41}DO_7$ + Na).

1-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-2-propene (7). The allyl glucose **7** was prepared according to the procedure of Lewis, Cha, and Kishi (*J. Am. Chem. Soc.* **1982**, *104*, 4976). An analytical sample was obtained by recrystallization from methanol/water; white needles, mp 64–65 °C. IR (neat): 1641 cm^{-1}. ^1H NMR ($CDCl_3$): δ 2.51 (2 H, m); 3.61–3.68 (3 H); 3.72 (1 H, dd, J = 3.3, 10.5 Hz); 3.77 (1 H, dd, J = 5.5, 9.4 Hz); 3.82 (1 H, dd, J = 7.5, 9.4 Hz); 4.16 (1 H, ddd, J = 5.0, 5.1, 10.5 Hz); 5.09 (1 H, br d, J = 10.2 Hz); 5.13 (1 H, dd, J = 1.3, 17.2 Hz); 5.83 (1 H, dddd, J = 6.7, 7.1, 10.2, 17.2 Hz). ^{13}C NMR ($CDCl_3$): δ 29.81, 69.01, 71.18, 73.06, 73.46, 73.71, 75.03, 75.38, 78.15, 80.08, 82.41, 116.81, 127.53, 127.56, 127.67, 127.74, 127.79, 127.83, 127.87, 127.93, 128.29, 128.35, 128.39, 134.75, 138.13, 138.25, 138.78. MS (FAB, NaI): m/z 587 (M + Na). Anal. Calcd for $C_{37}H_{40}O_5$: C, 78.69; H, 7.13. Found: C, 78.58; H, 7.17. $[\alpha]_D$: +36.5° (c 2.19, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-1(*R*)-deuteriopropane-2,3-(2*R*)-diol 2,3-Thionocarbonate (18d_R). A stirred solution of the monodeuterated diol 8d_R (5.7 mg, 9.5 μmol) in benzene (1.5 mL) at room temperature under argon was treated with 1,1-(thiocarbonyl)diimidazole (10 mg, 0.056 mmol) in benzene (1 mL). The mixture was stirred at 70 °C for 12 h. The crude reaction mixture was cooled to room temperature and applied directly to a flash silica gel column and eluted with 10%, 20% ethyl acetate/hexanes to yield the cyclic thionocarbonate 18d_R as a clear colorless oil (5.0 mg, 7.8 μmol, 82% yield). IR (neat): 1295 cm^{-1}. ^1H NMR ($CDCl_3$): δ 2.13 (1 H, dd, J = 6.4, 11.6 Hz); 3.49 (1 H, br dd, J = 8.0, 8.1 Hz); 3.59–3.70 (5 H); 4.11 (1 H, dd, J = 4.8, 11.6 Hz); 4.29 (1 H, dd, J = 8.5, 8.9 Hz); 4.48 (2 H, d, J = 11.5 Hz); 4.66 (1 H, dd, J = 7.9, 9.0 Hz); 4.91 (1 H, ddd, J = 6.4, 8.0, 8.0 Hz). MS (FAB, NaI): m/z 664 ($C_{38}H_{39}DO_7S$ + Na).

1-(2,3,4,6-*O*-Tetrabenzyl-α-D-glucopyranosyl)-1(*R*)-deuterio-2-propene (7d_R). A stirred solution of the cyclic thionocarbonate 18d_R (5.0 mg, 7.8 μmol) in trimethyl phosphite (2 mL) was stirred at 100 °C for 24 h. The reaction was concentrated in vacuo and applied to a short silica column, which was eluted with toluene and 10% ethyl acetate/hexanes. Preparative TLC (0.25 mm, 10% ethyl acetate/hexanes) yielded the monodeuterated allyl glucose 7d_R as a white crystalline solid (2.8 mg, 4.95 μmol, 63% yield). ^1H NMR ($CDCl_3$): δ 2.48 (1 H, dd, J = 7.5, 11.5 Hz); 3.59–3.67 (3 H); 3.71 (1 H, dd, J = 3.3, 10.6 Hz); 3.75 (1 H, dd, J = 5.5, 9.4 Hz); 3.79 (1 H, dd, J = 7.7, 9.4 Hz); 4.12 (1 H, dd, J = 5.4, 11.5 Hz); 5.07 (1 H, ddd, J = 0.7, 1.0, 10.2 Hz); 5.11 (1 H, ddd, J = 1.2, 1.7, 17.1 Hz); 5.81 (1 H, ddd, J = 7.5, 10.2, 17.1 Hz). MS (FAB, NaI): m/z 588 ($C_{37}H_{39}DO_5$ + Na).

1-(α-D-Glucopyranosyl)-2,3-(2*R*)-propanediol (2). A stirred solution of the unlabeled tetrabenzyl diol **8** (48 mg, 0.087 mmol) in methanol (7 mL) was hydrogenated over Pearlman's catalyst for 43 h. The reaction was filtered through Celite and concentrated in vacuo to yield the polyol **2** as a clear colorless oil (22 mg). An analytical sample was obtained by chromatography on TSK G3000S polystyrene gel. IR (neat): 3342 cm^{-1}, 2927, 1075. ^1H NMR (CD_3OD): δ 1.66 (1 H, ddd, J = 3.3, 10.1, 14.8 Hz); 1.90 (1 H, ddd, J = 2.9, 11.3, 14.8 Hz); 3.24 (1 H, dd, J = 8.7, 9.4 Hz); 3.42 (1 H, ddd, J = 2.5, 6.1, 9.4 Hz); 3.50 (2 H, m); 3.50 (1 H, dd, J = 8.7, 9.4 Hz); 3.61 (1 H, dd, J = 5.9, 9.4 Hz); 3.62 (1 H, dd, J = 6.1, 11.7 Hz); 3.78 (1 H, dtd, J = 2.9, 5.8, 10.1 Hz); 3.79 (1 H, dd, J = 2.5, 11.7 Hz); 4.19 (1 H, ddd, J = 3.3, 5.9, 11.3 Hz). ^{13}C NMR (CD_3OD): δ 29.53, 63.23, 67.69, 69.52, 72.44, 72.79, 73.64, 74.76, 75.29. MS (FAB): m/z 239 (M + H). HRMS (FAB, neg): calcd for $C_9H_{18}O_7$ (M − H) 237.0974, found 237.0979. $[\alpha]_D$: +60.0° (c 0.51, CH_3OH).

1-(α-D-Glucopyranosyl)-1(*R*)-deuteriopropane-2,3-(2*R*)-diol (2d_R). The monodeuterated tetrabenzyl diol 8d_R (10 mg,

0.0167 mmol) was deprotected by the same procedure as 8, to yield the polyol $2d_R$ as a clear colorless oil (4.0 mg). ^{1}H NMR (CD_3OD): 1.88 (1 H, dd, J = 2.7, 11.3 Hz); 3.23 (1 H, dd, J = 8.6, 9.4 Hz); 3.42 (1 H, ddd, J = 2.5, 6.1, 9.4 Hz); 3.46–3.53 (3 H); 3.60 (1 H, dd, J = 5.9, 9.4 Hz); 3.62 (1 H, dd, J = 6.1, 10.9 Hz); 3.78 (1 H, dt, J = 2.7, 5.5 Hz); 3.79 (1 H, dd, J = 2.5, 11.7 Hz); 4.19 (1 H, dd, J = 5.9, 11.3 Hz). MS (FAB, NaI): m/z 262 ($C_9H_{17}DO_7$ + Na).

1-(α-D-Glucopyranosyl)-2,3-(2*S*)-propanediol (3). The unlabeled tetrabenzyl diol **9** (50 mg, 0.091 mmol) was deprotected according the same procedure as 8, to yield the polyol **3** as a clear colorless oil (21.7 mg). An analytical sample was obtained by chromatography on TSK G3000S polystyrene gel. IR (neat): 3333 cm^{-1}, 2930, 1077. ^{1}H NMR (CD_3OD): δ 1.84 (1 H, ddd, J = 6.4, 10.1, 14.7 Hz); 1.90 (1 H, ddd, J = 4.1, 6.0, 14.7 Hz); 3.24 (1 H, dd, J = 8.5, 9.3 Hz); 3.50 (1 H, dd, J = 6.1, 11.4 Hz); 3.51 (1 H, dd, J = 8.5, 9.4 Hz); 3.55 (1 H, ddd, J = 2.4, 6.4, 9.3 Hz); 3.58 (1 H, dd, J = 4.5, 11.4 Hz); 3.60 (1 H, dd, J = 5.8, 9.4 Hz); 3.62 (1 H, dd, J = 6.4, 11.5 Hz); 3.79 (1 H, dd, J = 2.4, 11.5 Hz); 3.85 (1 H, dddd, J = 4.5, 6.0, 6.1, 6.4 Hz); 4.12 (1 H, ddd, J = 4.1, 5.8, 10.1 Hz). ^{13}C NMR (CD_3OD): δ 29.87, 63.12, 66.64, 71.81, 72.34, 72.92, 75.09, 75.12. MS (FAB, NaI): m/z 261 (M + Na). HRMS (FAB, neg): calcd for $C_9H_{18}O_7$ (M − H) 237.0974, found 237.0976. $[\alpha]_D$: +50.1° (c 0.36, CH_3OH).

1-(α-D-Glucopyranosyl)-1(*S*)-deuteriopropane-2,3-(2*S*)-diol ($3d_S$). The monodeuterated tetrabenzyl diol $9d_S$ (8.7 mg, 0.0145 mmol) was deprotected by the same procedure as 8, to yield the polyol $3d_S$ as a clear colorless oil (3.5 mg). ^{1}H NMR (CD_3OD): δ 1.87 (1 H, dd, J = 3.8, 5.7 Hz); 3.22 (1 H, dd, J = 8.5, 9.2 Hz); 3.51 (1 H, dd, J = 6.1, 11.4 Hz); 3.51 (1 H, dd, J = 8.5, 9.4 Hz); 3.50–3.60 (3 H); 3.62 (1 H, dd, J = 6.4, 11.5 Hz); 3.79 (1 H, dd, J = 2.4, 11.5 Hz); 3.83 (1 H, ddd, J = 4.5, 5.7, 6.1 Hz); 4.11 (1 H, dd, J = 3.8, 5.4 Hz). MS (FAB, NaI): m/z 262 ($C_9H_{17}DO_7$ + Na).

1-(α-D-Glucopyranosyl)propane (1). The allyl glucose **7** (50 mg, 0.105 mmol) was hydrogenated by the same procedure as 8, to yield the polyol **1** as a white solid (22 mg). An analytical sample was obtained by chromatography on TSK G3000S polystyrene gel. IR (neat): 3348 cm^{-1}, 2957, 2934, 2873, 1070. ^{1}H NMR (CD_3OD): δ 0.95 (3 H, t, J = 7.1 Hz); 1.31 (1 H, m); 1.48–1.70 (3 H); 3.23 (1 H, dd, J = 8.4, 9.6 Hz); 3.37 (1 H, ddd, J = 2.5, 5.7, 9.6 Hz); 3.50 (1 H, dd, J = 8.4, 9.5 Hz); 3.57 (1 H, dd, J = 5.7, 9.5 Hz); 3.62 (1 H, dd, J = 5.6, 11.7 Hz); 3.77 (1 H, dd, J = 2.5, 11.7 Hz); 3.88 (1 H, ddd, J = 3.1, 5.7, 11.4 Hz). ^{13}C NMR (CD_3OD): δ 14.30, 19.81, 27.66, 63.21, 72.50, 73.16, 74.36, 75.33, 76.98. MS (FAB, NaI): m/z 229 (M + Na). HRMS (FAB, neg): calcd for $C_9H_{18}O_5$ (M − H) 205.1076 found 205.1089. $[\alpha]_D$: +84.1° (c 0.34, CH_3OH).

1-(α-D-Glucopyranosyl)-1(*R*)-deuteriopropane ($1d_R$). The monodeuterated allyl glucose $7d_R$ (8 mg, 0.014 mmol) was deprotected by the same procedure as 8, to yield the polyol $1d_R$ as a clear colorless oil (2.9 mg). ^{1}H NMR (CD_3OD): δ 0.96 (3 H, t, J = 7.4 Hz); 1.31 (1 H, qdd, J = 7.4, 9.5, 13.3 Hz); 1.53 (1 H, dqd, J = 4.8, 7.4, 13.3 Hz); 1.64 (1 H, ddd, J = 4.8, 9.6, 11.6 Hz); 3.23 (1 H, dd, J = 8.4, 9.6 Hz); 3.38 (1 H, ddd, J = 2.5, 5.7, 9.6 Hz); 3.51 (1 H, dd, J = 8.4, 9.5 Hz); 3.57 (1 H, dd, J = 5.7, 9.5 Hz); 3.62 (1 H, dd, J = 5.7, 11.7 Hz); 3.76 (1 H, dd, J = 2.5, 11.7 Hz); 3.87 (1 H, dd, J = 5.7, 11.6 Hz). MS (FAB, NaI): m/z 230 ($C_9H_{17}DO_5$ + Na).

Methyl 3-(2,3,4,6-*O*-Tetrabenzyl-β-D-glucopyranosyl)-propenoate (19). (2,3,4,6-*O*-Tetrabenzyl-β-D-glucopyranosyl)-methanol[38] (252.5 mg, 0.455 mmol) was converted to the α,β-unsaturated ester **19** (228.3 mg, 0.375 mmol, 82% yield) by the same procedure as the axial isomer. An analytical sample was obtained by recrystallization from ethyl acetate/hexanes; white needles, mp 92–93.5 °C. IR (neat): 1725 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 3.34 (1 H, dd, J = 9.2, 9.4 Hz); 3.52 (1 H, ddd, J = 2.9, 3.0, 9.7 Hz); 3.67 (1 H, dd, J = 9.3, 9.4 Hz); 3.71–3.78 (4 H); 3.78 (3 H, s); 3.96 (1 H, ddd, J = 1.3, 4.6, 9.7 Hz); 6.21 (1 H, ddd, J = 0.6, 1.3, 15.8 Hz); 7.09 (1 H, dd, J = 4.6, 15.8 Hz). ^{13}C NMR ($CDCl_3$): δ 51.60, 68.83, 73.49, 75.06, 75.37, 75.65, 77.70, 78.01, 78.89, 81.97, 86.85, 121.97, 127.63, 127.66, 127.69, 127.75, 127.91, 127.93, 128.20, 128.37, 128.39, 128.43, 128.48, 137.48, 138.00, 138.07, 138.41, 144.05, 166.62. MS (FAB, NaI): m/z 631 (M + Na). Anal. Calcd for $C_{38}H_{40}O_7$: C, 74.97; H, 6.62. Found: C, 74.81; H, 6.63. $[\alpha]_D$: −22.4° (c 1.81, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-β-D-glucopyranosyl)-1-propen-3-ol (20). The unsaturated ester **19** (192.0 mg, 0.315 mmol) was converted to the allylic alcohol **20** (150.6 mg, 0.259 mmol, 82% yield) by the same procedure as the axial isomer. An analytical sample was obtained by recrystallization from ethyl acetate/hexanes; white needles, mp 88–90 °C. IR (neat): 3502 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 3.33 (1 H, dd, J = 9.0, 9.3 Hz); 3.48 (1 H, ddd, J = 2.6, 3.0, 9.6 Hz); 3.64 (1 H, dd, J = 9.2, 9.4 Hz); 3.67–3.75 (3 H); 3.79 (1 H, dd, J = 6.8, 9.3 Hz); 4.11 (2 H, m); 5.73 (1 H, br dd, J = 6.6, 15.6 Hz); 5.99 (1 H, ddd, J = 5.2, 5.2, 15.6 Hz). ^{13}C NMR ($CDCl_3$): δ 63.02, 68.97, 73.52, 75.02, 75.08, 75.65, 78.17, 78.71, 79.39, 82.31, 86.84, 127.63, 127.73, 127.78, 127.85, 127.92, 128.08, 128.26, 128.35, 128.38, 128.42, 133.08, 138.09, 138.12, 138.59. MS (FAB, NaI): m/z 603 (M + Na). Anal. Calcd for $C_{37}H_{40}O_6 \cdot {}^1/_5H_2O$: C, 76.05; H, 6.96. Found: C, 76.03; H, 6.84. $[\alpha]_D$: −3.2° (c 1.06, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-β-D-glucopyranosyl)-2,3-propanediol (21, 22). The diols **21** and **22** were prepared according to the procedure of Kishi (*Pure Appl. Chem.* **1989**, *61*, 313). Analytical samples were obtained by recrystallization from ethyl acetate/hexanes; white needles, mp **21** 117–118 °C, mp **22** 109–110 °C. **2*R* Isomer 21.** IR (neat): 3261 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.61 (1 H, ddd, J = 9.6, 10.5, 14.5 Hz); 1.96 (1 H, ddd, J = 2.2, 2.3, 14.5 Hz); 2.22 (1 H, dd, J = 5.8, 6.7 Hz); 3.29 (1 H, dd, J = 9.1, 9.2 Hz); 3.47 (1 H, ddd, J = 5.8, 5.8, 11.0 Hz); 3.49–3.55 (4 H); 3.47 (1 H, ddd, J = 3.6, 6.7, 11.0 Hz); 3.64–3.72 (3 H); 3.94 (1 H, br s). ^{13}C NMR ($CDCl_3$): δ 34.71, 66.55, 69.21, 71.69, 73.49, 75.07, 75.40, 75.65, 78.47, 78.53, 79.55, 82.19, 86.85, 127.71, 127.75, 127.83, 127.87, 127.97, 128.44, 128.49, 137.75, 137.82, 138.36. MS (FAB, NaI): m/z 621 (M + Na). Anal. Calcd for $C_{37}H_{42}O_7$: C, 74.22; H, 7.07. Found: C, 73.89; H, 7.04. $[\alpha]_D$: +6.0° (c 0.96, $CHCl_3$). **2*S* Isomer 22.** IR (neat): 3406 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.63 (1 H, ddd, J = 3.7, 7.9, 14.5 Hz); 1.97 (1 H, ddd, J = 3.0, 8.5, 14.5 Hz); 2.17 (1 H, dd, J = 6.4, 6.8 Hz); 2.99 (1 H, d, J = 4.6 Hz); 3.37 (1 H, dd, J = 9.2, 9.3 Hz); 3.41–3.47 (2 H); 3.51–3.57 (2 H); 3.58 (1 H, dd, J = 9.0, 9.7 Hz); 3.58 (1 H, dd, J = 4.8, 10.5 Hz); 3.67 (1 H, dd, J = 2.1, 10.5 Hz); 3.71 (1 H, dd, J = 9.0, 9.2 Hz); 3.86 (1 H, m). ^{13}C NMR ($CDCl_3$): δ 34.33, 66.71, 68.93, 69.35, 73.44, 75.00, 75.16, 75.57, 76.86, 78.38, 78.60, 81.07, 87.16, 127.65, 127.68, 127.72, 127.80, 127.91, 128.08, 128.40, 128.47, 137.87, 137.98, 138.44. MS (FAB, NaI): m/z 621 (M + Na). Anal. Calcd for $C_{37}H_{42}O_7 \cdot {}^1/_4H_2O$: C, 73.67; H, 7.10. Found: C, 73.66; H, 7.07. $[\alpha]_D$: −2.2° (c 1.46, $CHCl_3$).

1-(2,3,4,6-*O*-Tetrabenzyl-β-D-glucopyranosyl)-1-deuteriopropane-2,3-diol ($21d_R$, $22d_S$). The allylic alcohol **20** (101.8 mg, 0.175 mmol) was converted to the deuterated diols ($21d_R$: 14.0 mg, 0.0233 mmol, 13% yield; $22d_S$: 12.5 mg, 0.0208 mmol, 12% yield) by the same procedure as the axial isomers. **1*R*,2*R* Isomer $21d_R$.** ^{1}H NMR ($CDCl_3$): δ 1.93 (1 H, dd, J = 2.3, 2.7 Hz); 3.28 (1 H, dd, J = 9.2, 9.2 Hz); 3.46 (1 H, dd, J = 5.6, 11.1 Hz); 3.48–3.54 (4 H); 3.59 (1 H, dd, J = 3.6, 11.1 Hz); 3.63–3.71 (2 H); 3.94 (1 H, ddd, J = 2.7, 3.6, 5.5 Hz). MS (FAB, NaI): m/z 622 ($C_{37}H_{41}DO_7$ + Na). **1*S*,2*S* Isomer $22d_S$.** ^{1}H NMR ($CDCl_3$): δ 1.62 (1 H, dd, J = 3.6, 7.9 Hz); 3.36 (1 H, dd, J = 9.2, 9.3 Hz); 3.44 (1 H, m, J = 1.9, 4.8, 9.7 Hz); 3.44 (1 H, dd, J = 6.3, 11.2 Hz); 3.54 (1 H, dd, J = 7.9, 9.7 Hz); 3.55 (1 H, dd, J = 3.6, 11.2 Hz); 3.58 (1 H, dd, J = 9.0, 9.7 Hz); 3.59 (1 H, dd, J = 4.8, 10.5 Hz); 3.66 (1 H, dd, J = 1.9, 10.5 Hz); 3.69 (1 H, dd, J = 9.0, 9.0 Hz); 3.86 (1 H, ddd, J = 3.6, 3.7, 6.3 Hz). MS (FAB, NaI): m/z 622 ($C_{37}H_{41}DO_7$ + Na).

1-(β-D-Glucopyranosyl)-2,3-(2*R*)-propanediol (5). The unlabeled tetrabenzyl diol **21** (25 mg, 0.0418 mmol) was deprotected by the same procedure as the axial isomer to yield the polyol **5** as a clear colorless oil (10.0 mg). IR (neat): 3337 cm^{-1}, 2917, 1093. ^{1}H NMR (CD_3OD): δ 1.59 (1 H, ddd, J = 6.9, 8.9, 14.6 Hz); 2.09 (1 H, ddd, J = 2.8, 5.3, 14.6 Hz); 3.08 (1 H, dd, J = 8.9, 9.3 Hz); 3.19–3.27 (2 H); 3.30 (1 H, dd, J = 8.3, 8.9 Hz); 3.32 (1 H, ddd, J = 2.8, 8.9, 9.3 Hz); 3.47 (1 H, dd, J = 6.1, 11.3 Hz); 3.53 (1 H, dd, J = 4.6, 11.3 Hz); 3.59 (1 H, m); 3.83 (1 H, dd, J = 1.7, 11.8 Hz); 3.89 (1 H, dddd, J = 4.6, 5.3, 6.1, 6.9 Hz). ^{13}C NMR (CD_3OD): δ 36.73, 63.10, 66.94, 71.70, 71.96, 75.72, 79.34, 79.69, 81.70. MS (FAB, neg): m/z 237 (M − H). HRMS (FAB, neg): calcd for $C_9H_{18}O_7$ (M − H) 237.0974, found 237.0966. $[\alpha]_D$: −2.1° (c 1.08, CH_3OH).

1-(β-D-Glucopyranosyl)-1(*R*)-deuteriopropane-2,3-(2*R*)-diol ($5d_R$). The monodeuterated tetrabenzyl diol $21d_R$ (6.0 mg,

0.010 mmol) was deprotected by the same procedure as the axial isomer to yield the monodeuterated polyol $5d_R$ as a clear colorless oil (2.4 mg). ^{1}H NMR (CD_3OD): δ 2.06 (1 H, dd, J = 2.7, 5.1 Hz); 3.08 (1 H, dd, J = 8.8, 9.4 Hz); 3.20–3.27 (2 H); 3.30 (1 H); 3.32 (1 H, dd, J = 2.7, 9.5 Hz); 3.47 (1 H, dd, J = 6.2, 11.3 Hz); 3.53 (1 H, dd, J = 4.6, 11.3 Hz); 3.59 (1 H, m); 3.83 (1 H, dd, J = 1.7, 11.9 Hz); 3.89 (1 H, ddd, J = 4.6, 5.1, 6.2 Hz). MS (FAB, NaI): m/z 262 ($C_9H_{17}DO_7$ + Na).

1-(β-D-Glucopyranosyl)-2,3-(2*S*)-propanediol (6). The unlabeled tetrabenzyl diol **22** (25.1 mg, 0.0419 mmol) was deprotected by the same procedure as the axial isomer to yield the polyol **6** as a clear colorless oil (10.3 mg). IR (neat): 3340 cm^{-1}, 2920, 1086. ^{1}H NMR (CD_3OD): δ 1.53 (1 H, ddd, J = 3.1, 9.7, 14.4 Hz); 1.91 (1 H, ddd, J = 2.5, 9.7, 14.4 Hz); 3.04 (1 H, dd, J = 9.0, 9.6 Hz); 3.22 (1 H, ddd, J = 2.0, 5.6, 9.5 Hz); 3.24 (1 H, dd, J = 8.8, 9.5 Hz); 3.33 (1 H, dd, J = 8.8, 9.0 Hz); 3.39 (1 H, ddd, J = 2.5, 9.6, 9.7 Hz); 3.46 (1 H, dd, J = 6.2, 11.1 Hz); 3.50 (1 H, dd, J = 4.8, 11.1 Hz); 3.61 (1 H, dd, J = 5.6, 11.8 Hz); 3.84 (1 H, dd, J = 2.0, 11.8 Hz); 3.88 (1 H, dddd, J = 3.1, 4.8, 6.2, 9.7 Hz). ^{13}C NMR (CD_3OD): δ 37.18, 63.17, 67.76, 69.78, 72.09, 75.79, 77.66, 79.87, 81.52. MS (FAB, neg): m/z 237 (M − H). HRMS (FAB, neg): calcd for $C_9H_{18}O_7$ (M − H) 237.0974, found 237.0986. $[\alpha]_D$: −20.0° (c 1.09, CH_3OH).

1-(β-D-Glucopyranosyl)-1(*S*)-deuteriopropane-2,3-(2*S*)-diol ($6d_S$). The monodeuterated tetrabenzyl diol $22d_S$ (5 mg, 8.3 μmol) was deprotected by the same procedure as the axial isomer to yield the monodeuterated polyol $6d_S$ as a clear colorless oil (2.0 mg). ^{1}H NMR (CD_3OD): δ 1.52 (1 H, dd, J = 3.0, 9.7 Hz); 3.04 (1 H, dd, J = 8.8, 9.5 Hz); 3.21 (1 H, ddd, J = 1.9, 5.6, 9.5 Hz); 3.24 (1 H, dd, J = 8.5, 9.5 Hz); 3.32 (1 H, dd, J = 8.5, 8.8 Hz); 3.38 (1 H, dd, J = 9.5, 9.7 Hz); 3.46 (1 H, dd, J = 6.2, 11.2 Hz); 3.50 (1 H, dd, J = 4.9, 11.2 Hz); 3.61 (1 H, dd, J = 5.6, 11.7 Hz); 3.83 (1 H, dd, J = 1.9, 11.7 Hz); 3.88 (1 H, ddd, J = 3.0, 4.9, 6.2 Hz). MS (FAB, NaI): m/z 262 ($C_9H_{17}DO_7$ + Na).

1-(β-D-Glucopyranosyl)propane (4). 1-(2,3,4,6-*O*-Tetrabenzyl-β-D-glucopyranosyl)-2-propene (13 mg, 0.027 mmol) was deprotected by the same procedure as the axial isomer to yield the polyol **4** as a clear colorless oil (5.6 mg). IR (neat): 3324 cm^{-1}, 2960, 2874, 1090. ^{1}H NMR (CD_3OD): δ 0.92 (3 H, t, J = 7.3 Hz); 1.35–1.45 (2 H); 1.59 (1 H, m); 1.78 (1 H, br ddd, J = 2.5, 7.7, 10.2 Hz); 3.03 (1 H, dd, J = 8.6, 9.3 Hz); 3.11 (1 H, ddd, J = 2.4, 8.5, 9.3 Hz); 3.16 (1 H, ddd, J = 2.4, 5.7, 9.4 Hz); 3.23 (1 H, dd, J = 8.8, 9.3 Hz); 3.29 (1 H, dd, J = 8.7, 8.9 Hz); 3.61 (1 H, dd, J = 5.7, 11.8 Hz); 3.81 (1 H, dd, J = 2.4, 11.8 Hz). ^{13}C NMR (CD_3OD): δ 14.47, 19.61, 35.09, 63.20, 72.13, 75.53, 79.95, 80.64, 81.58. MS (FAB, NaI): m/z 229 (M + Na). HRMS (FAB, neg): calcd for $C_9H_{18}O_5$ (M − H) 205.1076, found 205.1078. $[\alpha]_D$: −14.3° (c 0.32, CH_3OH).

Methyl 3-(2-Deoxy-3,4,6-*O*-tribenzyl-α-D-glucopyranosyl)propenoate (23). (2-Deoxy-3,4,6-*O*-tribenzyl-α-D-glucopyranosyl)methanol (92.5 mg, 0.206 mmol) was converted to the trans-α,β-unsaturated ester **23** (colorless, opaque oil, 65.5 mg, 0.130 mmol, 63% yield; cis isomer: 21.5 mg, 0.043 mmol, 21% yield) by the same procedure as the parent 2-benzyloxy compound. IR (neat): 1724 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.86 (1 H, ddd, J = 5.5, 10.1, 13.4 Hz); 2.07 (1 H, ddd, J = 3.9, 4.0, 13.4 Hz); 3.51 (1 H, dd, J = 7.8, 7.9 Hz); 3.59–3.71 (4 H); 3.67 (3 H, s); 4.63 (1 H, m); 5.90 (1 H, dd, J = 2.1, 16.1 Hz); 6.85 (1 H, dd, J = 3.6, 16.1 Hz). ^{13}C NMR ($CDCl_3$): δ 33.04, 51.65, 68.79, 70.35, 71.78, 73.41, 73.80, 74.30, 76.79, 77.13, 122.21, 127.61, 127.64, 127.67, 127.72, 127.84, 128.33, 128.43, 138.02, 138.20, 147.10, 166.34. MS (FAB, NaI): m/z 525 (M + Na). HRMS (FAB, NaI): calcd for $C_{31}H_{34}O_6$ (M + Na) 525.2253, found 525.2279. $[\alpha]_D$: +54.9° (c 1.05, $CHCl_3$).

1-(2-Deoxy-3,4,6-*O*-tribenzyl-α-D-glucopyranosyl)-2-propen-3-ol (24). The unsaturated ester **23** (132.7 mg, 0.264 mmol) was converted to the trans-allylic alcohol **24** (clear, colorless oil 108.5 mg, 0.229 mmol, 87% yield) by the same procedure as the parent 2-benzyloxy compound. IR (neat): 3435 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.88 (1 H, ddd, J = 5.4, 10.4, 13.3 Hz); 2.17 (1 H, ddd, J = 3.4, 4.1, 13.3 Hz); 3.56 (1 H, dd, J = 8.0, 8.0 Hz); 3.67–3.83 (4 H); 4.12 (2 H, m); 4.60 (1 H, m); 5.76 (2 H, m). ^{13}C NMR ($CDCl_3$): δ 33.14, 62.91, 69.14, 71.09, 71.56, 73.10, 73.42, 74.45, 76.84, 77.79, 127.56, 127.62, 127.70, 127.85, 127.92, 128.30, 128.37, 130.06, 131.83, 138.13, 138.31, 138.44. MS (FAB, NaI): m/z 497 (M + Na). HRMS (FAB, NaI): calcd for $C_{30}H_{34}O_5$ (M + Na) 497.2304, found 497.2335. $[\alpha]_D$: +51.7° (c 2.23, $CHCl_3$).

1-(2-Deoxy-3,4,6-*O*-tribenzyl-α-D-glucopyranosyl)-2,3-propanediol (25, 26). The diols **25** and **26** were prepared according to the procedure of Kishi (*Pure Appl. Chem.* **1989**, *61*, 313). An analytical sample of **25** was obtained by recrystallization from ethyl acetate/hexanes; white needles, mp 95–97 °C. **2*R* Isomer 25.** IR (neat): 3258 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.50 (1 H, ddd, J = 3.1, 8.7, 14.3 Hz); 1.78 (1 H, ddd, J = 4.0, 6.9, 13.6 Hz); 1.82 (1 H, ddd, J = 4.3, 10.8, 14.3 Hz); 1.95 (1 H, ddd, J = 3.9, 7.0, 13.6 Hz); 2.24 (1 H, dd, J = 5.3, 6.8 Hz); 2.95 (1 H, d, J = 5.1 Hz); 3.37 (1 H, dd, J = 5.3, 5.4 Hz); 3.49–3.57 (2 H); 3.60 (1 H, ddd, J = 3.4, 6.8, 11.2 Hz); 3.77 (1 H, m); 3.89 (1 H, dd, J = 7.7, 10.2 Hz); 3.92 (1 H, m); 3.96 (1 H, ddd, J = 3.6, 5.2, 7.8 Hz); 4.23 (1 H, dddd, J = 3.1, 4.0, 7.0, 10.8 Hz). ^{13}C NMR ($CDCl_3$): δ 32.94, 35.76, 65.54, 66.42, 68.15, 69.32, 71.29, 73.10, 73.19, 74.97, 75.23, 127.52, 127.69, 127.74, 127.83, 127.87, 128.40, 137.84, 138.08, 138.21. MS (FAB, NaI): m/z 515 (M + Na). Anal. Calcd for $C_{30}H_{36}O_6$: C, 73.14; H, 7.36. Found: C, 73.02; H, 7.39. $[\alpha]_D$: +17.8° (c 0.92, $CHCl_3$). **2*S* Isomer 26.** IR (neat): 3430 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.39 (1 H, ddd, J = 2.6, 2.6, 14.7 Hz); 1.79 (1 H, ddd, J = 4.5, 7.7, 13.6 Hz); 1.93 (1 H, ddd, J = 4.0, 6.2, 13.6 Hz); 1.98 (1 H, ddd, J = 8.8, 11.2, 14.7 Hz); 2.34 (1 H, dd, J = 5.6, 6.9 Hz); 3.37 (1 H, dd, J = 6.1, 6.1 Hz); 3.49 (1 H, ddd, J = 5.5, 5.6, 11.1 Hz); 3.60 (1 H, ddd, J = 3.7, 6.9, 11.1 Hz); 3.63 (1 H, dd, J = 3.6, 10.1 Hz); 3.71 (1 H, dd, J = 7.7, 10.1 Hz); 3.72–3.80 (2 H); 3.92 (1 H, m); 4.01 (1 H, ddd, J = 3.6, 6.4, 7.6 Hz); 4.23 (1 H, m). ^{13}C NMR ($CDCl_3$): δ 33.49, 35.74, 66.39, 68.79, 69.75, 71.41, 71:82, 72.95, 73.32, 75.47, 75.70, 127.54, 127.68, 127.72, 127.74, 127.79, 127.82, 128.39, 128.43, 137.85, 138.04, 138.18. MS (FAB, NaI): m/z 515 (M + Na). HRMS (FAB, NaI): calcd for $C_{30}H_{36}O_6$ (M + Na) 515.2410, found 515.2416. $[\alpha]_D$: +22.0° (c 1.56, $CHCl_3$).

1-(2-Deoxy-3,4,6-*O*-tribenzyl-α-D-glucopyranosyl)-1-deuteriopropane-2,3-diol ($25d_R$, $26d_S$). The allylic alcohol **24** (96.8 mg, 0.167 mmol) was converted to the deuterated diols ($25d_R$: clear colorless oil, 7.9 mg, 0.0132 mmol, 8% yield; $26d_S$: white crystalline solid, 36.4 mg, 0.0607 mmol, 36% yield) by the same procedure as the parent 2-benzyloxy compounds. **1*R*,2*R* Isomer $25d_R$.** ^{1}H NMR ($CDCl_3$): δ 1.76 (1 H, ddd, J = 4.0, 6.8, 13.6 Hz); 1.79 (1 H, dd, J = 4.3, 10.8 Hz); 1.93 (1 H, ddd, J = 3.7, 7.2, 13.6 Hz); 3.36 (1 H, dd, J = 5.2, 5.3 Hz); 3.50–3.55 (2 H); 3.60 (1 H, dd, J = 3.1, 11.2 Hz); 3.75 (1 H, m); 3.89 (1 H, dd, J = 7.7, 10.2 Hz); 3.91 (1 H, m, J = 3.4, 4.3, 6.3 Hz); 3.96 (1 H, ddd, J = 3.6, 5.2, 7.8 Hz); 4.23 (1 H, ddd, J = 4.0, 7.2, 10.8 Hz). MS (FAB, NaI): m/z 516 ($C_{30}H_{35}DO_6$ + Na). **1*S*,2*S* Isomer $26d_S$.** ^{1}H NMR ($CDCl_3$): δ 1.39 (1 H, dd, J = 2.5, 2.5 Hz); 1.79 (1 H, ddd, J = 4.6, 7.8, 13.6 Hz); 1.94 (1 H, ddd, J = 4.0, 6.2, 13.6 Hz); 3.37 (1 H, dd, J = 6.1, 6.4 Hz); 3.49 (1 H, dd, J = 5.8, 11.1 Hz); 3.60 (1 H, dd, J = 3.7, 11.1 Hz); 3.63 (1 H, dd, J = 3.6, 10.1 Hz); 3.71 (1 H, dd, J = 7.7, 10.1 Hz); 3.76 (1 H, ddd, J = 4.0, 6.1, 7.8 Hz); 3.93 (1 H, m); 4.02 (1 H, ddd, J = 3.6, 6.4, 7.6 Hz); 4.23 (1 H, m, J = 2.5, 4.6, 6.2 Hz). MS (FAB, NaI): m/z 516 ($C_{30}H_{35}DO_6$ + Na).

1-(2-Deoxy-α-D-glucopyranosyl)-2,3-(2*R*)-propanediol (13). The unlabeled tribenzyl diol **25** (19 mg, 0.039 mmol) was deprotected by the same procedure as the parent 2-benzyloxy compound to yield the polyol **13** as a clear colorless oil (8.9 mg). IR (neat): 3319 cm^{-1}, 2935, 1065. ^{1}H NMR (CD_3OD): δ 1.32 (1 H, ddd, J = 3.6, 9.8, 14.5 Hz); 1.75 (1 H, ddd, J = 5.7, 10.9, 13.1 Hz); 1.87 (1 H, ddd, J = 2.4, 4.9, 13.1 Hz); 2.10 (1 H, ddd, J = 2.9, 11.0, 14.5 Hz); 3.17 (1 H, dd, J = 8.3, 8.8 Hz); 3.41 (1 H, ddd, J = 2.7, 6.2, 8.8 Hz); 3.48 (2 H, d, J = 5.5 Hz); 3.67 (1 H, dd, J = 6.2, 11.6 Hz); 3.70–3.77 (2 H); 3.79 (1 H, dd, J = 2.7, 11.6 Hz); 4.25 (1 H, dddd, J = 2.4, 3.6, 5.7, 11.0 Hz). ^{13}C NMR (CD_3OD): δ 35.62, 37.85, 63.24, 67.56, 69.81, 69.92, 70.30, 73.66, 75.42. MS (FAB, NaI): m/z 245 (M + Na). HRMS (FAB, neg): calcd for $C_9H_{18}O_6$ (M − H) 221.1025, found 221.1013. $[\alpha]_D$: +54.1° (c 0.76, CH_3OH).

1-(2-Deoxy-α-D-glucopyranosyl)-1(*S*)-deuteriopropane-2,3-(2*R*)-diol ($13d_R$). The monodeuterated tribenzyl diol $25d_R$ (6 mg, 0.012 mmol) was deprotected by the same procedure as the parent 2-benzyloxy compound to yield the polyol $13d_R$ as a clear colorless oil (2.9 mg). ^{1}H NMR (CD_3OD): δ 1.74 (1 H, ddd, J = 5.8, 10.9, 13.1 Hz); 1.86 (1 H, ddd, J = 2.3, 4.9, 13.1 Hz); 2.08 (1 H, dd, J = 2.7, 11.1 Hz); 3.17 (1 H, dd, J = 8.1, 8.7 Hz); 3.41 (1 H, ddd, J = 2.6, 6.4, 8.7 Hz); 3.47 (2 H, d, J = 5.5 Hz); 3.67 (1 H, dd, J = 6.4, 11.6 Hz); 3.70–3.77 (2 H); 3.78 (1 H, dd, J = 2.6, 11.6 Hz); 4.24 (1 H, ddd, J = 2.3, 5.8, 11.1 Hz). MS (FAB,

NaI): m/z 246 ($C_9H_{17}DO_6$ + Na).

1-(2-Deoxy-α-D-glucopyranosyl)-2,3-(2*S*)-propanediol (14). The unlabeled tribenzyl diol **26** (14 mg, 0.028 mmol) was deprotected by the same procedure as the parent 2-benzyloxy compound to yield the polyol **14** as a clear colorless oil (6 mg). IR (neat): 3329 cm^{-1}, 2930, 1061. ^1H NMR (CD_3OD): δ 1.71 (1 H, ddd, J = 5.7, 10.8, 13.3 Hz); 1.71 (1 H, ddd, J = 5.1, 6.0, 14.2 Hz); 1.90 (1 H, ddd, J = 7.7, 8.7, 14.2 Hz); 1.91 (1 H, ddd, J = 2.5, 4.6, 13.3 Hz); 3.18 (1 H, dd, J = 8.5, 8.6 Hz); 3.51 (1 H, ddd, J = 2.7, 6.4, 8.5 Hz); 3.50–3.55 (2 H, m); 3.66 (1 H, dd, J = 6.4, 11.6 Hz); 3.70–3.76 (2 H); 3.79 (1 H, dd, J = 2.7, 11.6 Hz); 4.19 (1 H, dddd, J = 2.5, 5.7, 6.0, 8.7 Hz). ^{13}C NMR (CD_3OD): δ 35.77, 37.01, 63.16, 66.82, 70.14, 71.15, 71.43, 73.56, 75.87. MS (FAB, neg): m/z 221 (M − H). HRMS (FAB, neg): calcd for $C_9H_{18}O_6$ (M − H) 221.1025, found 221.1022. $[\alpha]_D$: +33.3° (c 0.55, CH_3OH).

1-(2-Deoxy-α-D-glucopyranosyl)-1(*R*)-deuteriopropane-2,3-(2*S*)-diol (15d_S). The monodeuterated tribenzyl diol **26**d_S (2.5 mg, 5.1 μmol) was deprotected by the same procedure as the parent 2-benzyloxy compound to yield the polyol **14**d_S as a clear colorless oil (1.2 mg). ^1H NMR (CD_3OD): δ 1.68 (1 H, dd, J = 4.8, 5.6 Hz); 1.70 (1 H, ddd, J = 5.6, 10.8, 13.2 Hz); 1.90 (1 H, ddd, J = 2.5, 4.8, 13.2 Hz); 3.18 (1 H, dd, J = 8.2, 8.7 Hz); 3.49 (1 H, ddd, J = 2.7, 6.4, 8.7 Hz); 3.50–3.55 (2 H, m); 3.66 (1 H, dd, J = 6.4, 11.6 Hz); 3.70–3.76 (2 H); 3.79 (1 H, dd, J = 2.7, 11.6 Hz); 4.19 (1 H, ddd, J = 2.5, 5.6, 5.6 Hz). MS (FAB, NaI): m/z 246 ($C_9H_{17}DO_6$ + Na).

1-(2-Deoxy-β-D-glucopyranosyl)-2,3-(2*R*)-propanediol (15). 1-(2-Deoxy-3,4,6-*O*-tribenzyl-β-D-glucopyranosyl)-2,3-(2*R*)-propanediol (9 mg, 0.018 mmol) was deprotected by the same procedure as the parent 2-benzyloxy compound to yield the polyol **15** as a clear colorless oil (4.1 mg). IR (neat): 3330 cm^{-1}, 2920, 2873, 1063. ^1H NMR (CD_3OD): δ 1.32 (1 H, ddd, J = 11.4, 11.4, 12.7 Hz); 1.65 (1 H, ddd, J = 5.0, 5.3, 14.1 Hz); 1.70 (1 H, ddd, J = 7.5, 7.7, 14.1 Hz); 2.01 (1 H, ddd, J = 1.8, 5.1, 12.7 Hz); 3.14 (1 H, dd, J = 8.4, 9.6 Hz); 3.18 (1 H, ddd, J = 2.4, 5.9, 9.6 Hz); 3.46 (1 H, dd, J = 5.8, 11.2 Hz); 3.49 (1 H, dd, J = 4.9, 11.2 Hz); 3.54 (1 H, ddd, J = 5.1, 8.4, 11.4 Hz); 3.62 (1 H, dd, J = 5.9, 11.8 Hz); 3.64 (1 H, dddd, J = 1.8, 5.0, 7.5, 11.4 Hz); 3.78 (1 H, dddd, J = 4.9, 5.3, 5.8, 7.7 Hz); 3.84 (1 H, dd, J = 2.4, 11.8 Hz). ^{13}C NMR (CD_3OD): δ 40.06, 40.65, 63.27, 67.07, 71.12, 73.55, 73.91, 74.89, 81.78. MS (FAB): m/z 223 (M + H). HRMS (FAB, neg): calcd for $C_9H_{18}O_6$ (M − H) 221.1025, found 221.1035. $[\alpha]_D$: +2.6° (c 0.43, CH_3OH).

1-(2-Deoxy-β-D-glucopyranosyl)-2,3-(2*S*)-propanediol (16). 1-(2-Deoxy-3,4,6-*O*-tribenzyl-β-D-glucopyranosyl)-2,3-(2*S*)-propanediol (8 mg, 0.016 mmol) was deprotected by the same procedure as the parent 2-benzyloxy compound to yield the polyol **16** as a clear colorless oil (3.6 mg). IR (neat): 3327 cm^{-1}, 2920, 2870, 1064. ^1H NMR (CD_3OD): δ 1.35 (1 H, ddd, J = 11.4, 11.4, 12.7 Hz); 1.46 (1 H, ddd, J = 2.8, 9.6, 14.3 Hz); 1.67 (1 H, ddd, J = 3.1, 9.6, 14.3 Hz); 1.93 (1 H, ddd, J = 1.9, 5.1, 12.7 Hz); 3.14 (1 H, dd, J = 8.3, 9.5 Hz); 3.18 (1 H, ddd, J = 2.3, 5.8, 9.5 Hz); 3.43 (1 H, dd, J = 6.1, 11.2 Hz); 3.49 (1 H, dd, J = 4.9, 11.2 Hz); 3.55 (1 H, ddd, J = 5.1, 8.3, 11.4 Hz); 3.63 (1 H, dd, J = 5.8, 11.7 Hz); 3.67 (1 H, dddd, J = 1.9, 2.8, 9.6, 11.4 Hz); 3.85 (1 H, dd, J = 2.3, 11.7 Hz); 3.86 (1 H, dddd, J = 3.1, 4.9, 6.1, 9.6 Hz). ^{13}C NMR (CD_3OD): δ 40.53, 41.25, 63.32, 67.63, 69.79, 73.31, 73.61, 74.05, 81.60. MS (FAB): m/z 223 (M + H). HRMS (FAB, neg): calcd for $C_9H_{18}O_6$ (M − H) 221.1025, found 221.1034. $[\alpha]_D$: −2.5° (c 0.39, CH_3OH).

Acknowledgment. Financial support from the National Institutes of Health (NS 12108) and the National Science Foundation (CHE 89-09762) is gratefully acknowledged.

Registry No. **1**, 110352-30-2; **1d$_R$**, 110316-51-3; **2**, 110352-31-3; **2d$_R$**, 110316-52-4; **3**, 110352-32-4; **3d$_S$**, 110352-33-5; **4**, 3736-73-0; **5**, 54548-38-8; **5d$_R$**, 110352-38-0; **6**, 54503-51-4; **6d$_S$**, 110352-36-8; **7**, 82659-52-7; **7d$_R$**, 136089-03-7; **β-7**, 81972-19-2; **8**, 136088-95-4; **8d$_R$**, 136089-04-8; **9**, 136172-66-2; **9d$_S$**, 136172-71-9; **10**, 136088-96-5; **11d$_S$**, 136089-05-9; **12d$_R$**, 136172-73-1; **13**, 110316-53-5; **13d$_R$**, 110316-54-6; **14**, 110352-34-6; **14d$_S$**, 110352-35-7; **15**, 110352-39-1; **15** 3,4,6-tri-*O*-benzyl derivative, 136172-72-0; **16**, 110352-37-9; **16** 3,4,6-tri-*O*-benzyl derivative, 136172-74-2; **17**, 136088-97-6; **18d$_R$**, 136089-06-0; **19**, 136088-98-7; **20**, 136172-67-3; **21**, 136172-68-4; **21d$_R$**, 136172-75-3; **22**, 136172-69-5; **22d$_S$**, 136172-76-4; **23**, 136088-99-8; **24**, 136089-00-4; **25**, 136089-01-5; **25d$_R$**, 136089-07-1; **26**, 136172-70-8; **26d$_S$**, 136172-77-5; (2,3,4,6-*O*-tetrabenzyl-α-D-glucopyranosyl)methanol, 79258-16-5; (2,3,4,6-*O*-tetrabenzyl-α-D-glucopyranosyl)carboxaldehyde, 113019-43-5; (2-deoxy-3,4,6-*O*-tribenzyl-α-D-glucopyranosyl)methanol, 136089-02-6; (2,3,4,6-*O*-tetrabenzyl-β-D-glucopyranosyl)methanol, 89064-71-1.

Supplementary Material Available: Complete spectroscopic data (IR, ^1H NMR, ^{13}C NMR, MS, HRMS/analysis, and copies of ^1H NMR spectra) for all compounds (58 pages). Ordering information is given on any current masthead page.

Preferred Conformation of *C*-Glycosides. 7. Preferred Conformation of Carbon Analogues of Isomaltose and Gentiobiose†,‡

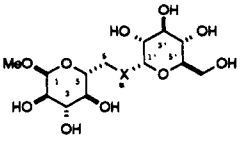
Peter G. Goekjian, Tse-Chong Wu, Han-Young Kang, and Yoshito Kishi*

Department of Chemistry, Harvard University, 12 Oxford St., Cambridge, Massachusetts 02138

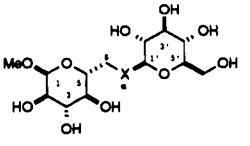
Received March 20, 1991

The preferred solution conformation of the 1,6-linked *C*-disaccharides **3** and **4**, carbon analogues of methyl isomaltoside and methyl gentiobioside, was shown to be **3-A** and **4-A**, respectively, by ^1H NMR spectroscopy.

We have shown that the preferred solution conformation of *C*-monoglycosides can be determined on the basis of vicinal coupling constants measured from the ^1H NMR and that the carbon analogues mirror the glycosidic conformation of the parent *O*-glycosides.[1] We sought to extend our analysis to the case of the 1,6-linked disaccharides, methyl isomaltoside (**1**) and methyl gentiobioside (**2**).[2]



1: X = O
3: X = CH_2



2: X = O
4: X = CH_2

The conformation of the 1,6-disaccharides can be analyzed in terms of two independent monoglycosidic systems.

† Preliminary results of this work have been published: Goekjian, P. G.; Wu, T.-C.; Kang, H.-Y.; Kishi, Y. *J. Org. Chem.* **1987**, *52*, 4823. For part 6 of this series, see: Goekjian, P. G.; Wu, T.-C.; Kishi, Y. *J. Org. Chem.*, previous article in this issue.

‡ Taken in part from Goekjian, P. G. Ph.D. Dissertation, Harvard University, 1990.

(1) Wu, T.-C.; Goekjian, P. G.; Kishi, Y. *J. Org. Chem.* **1987**, *52*, 4819. Goekjian, P. G.; Wu, T.-C.; Kishi, Y. *J. Org. Chem.*, previous paper in this issue.

0022-3263/91/1956-6422$02.50/0