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THE APPLICATION OF *ab initio* MOLECULAR ORBITAL THEORY TO STRUCTURAL MOIETIES OF CARBOHYDRATES*

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ABSTRACT

Ab initio molecular orbital calculations were made on methoxymethanol, a model for the hemiacetal and acetal moieties in aldopyranoses and methyl aldopyranosides, thereby improving on the previous calculations using methanediol. The new calculations confirmed the favored conformations already deduced, and gave, for the conformational-energy differences and C–O bond-length variations, values more appropriate to the carbohydrate systems, as confirmed by a re-examination of the experimental data from crystal-structure determinations. From the results, it was predicted that the O–CH_3 bond in methyl aldopyranosides is lengthened; this is supported by the experimental data. An examination of the angles and bond-lengths in the pyranoid ring and of the linkage bonds of oligosaccharides indicated that similar electronic effects involving the oxygen lone-pair electrons apply to oligo- and poly-saccharides.

INTRODUCTION

In a previous paper[1], we used methanediol, $CH_2(OH)_2$, as a model compound for extrapolating from *ab initio* (Hartree Fock/4-31G basis set) molecular orbital calculations[2] to effects associated with the hemiacetal and acetal bond-sequences that occur in aldopyranosides and methyl aldopyranoses. By examining energies and bond-lengths as a function of torsion angles, we were able to "predict" certain conformational tendencies and bond-shortening effects that had been observed experimentally[3,4]. We have now extended these quantum-mechanical calculations to a larger molecule, namely, methoxymethanol, H_3C–O–CH_2–OH, which is a closer analog of the structural moieties that actually occur in carbohydrates.

*Part II. For Part I of this series, see ref. 1.
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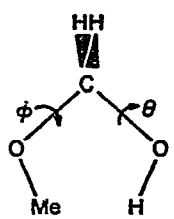
Methoxymethanol can be considered as a model for the aldopyranoses and methyl aldopyranosides in two ways. Firstly, it is a close model for the hemiacetal bond-sequence HC–O–CH–OH in aldopyranoses, with hydrogen atoms replacing C-2, C-4, and C-6 of an aldohexose, for example. Secondly, it is a more approximate model for the acetal bond-sequence HC–O–CH–O–CH_3 in methyl aldopyranosides, with hydrogen atoms replacing C-2 and C-5; here, dimethoxymethane would be a better model, but use of methoxymethanol is a step forward from methanediol*. Similar applications are possible by use of methoxymethanol, with appropriate values of the torsion angles, as a model for aldofuranoses and aldofuranosides.

A further possible application of theoretical studies on these model compounds is to the stereochemistry of such systems of alternating, bonded carbon and oxygen atoms (C–O–C–O–C and C–O–C–O–C–O–C) as occur in the linkage and ring bonds of oligosaccharides. Again, larger "fragment" models would be desirable, but results on methoxymethanol can serve as a preliminary basis for extrapolation to such systems.

Presented first are the theoretical results on methoxymethanol, particularly the energy variation with internal rotation involving the O–C–O bonds and associated bond-length changes. These results are then used, in the way already indicated, in a re-examination of our previous interpretation[1] of data on aldopyranoses and methyl aldopyranosides. Finally, some experimental evidence from the X-ray crystal-structure determination of oligosaccharides is considered from this point of view.

MOLECULAR ORBITAL CALCULATIONS ON METHOXYMETHANOL

Potential-energy surface for internal rotation. — The molecular orbital studies closely paralleled those already reported[1] for methanediol. Closed-shell, self-consistent, molecular orbital theory with the 4-31G basis set[2] was used throughout. In the first set of calculations, a study of the rotational-potential surface was made by

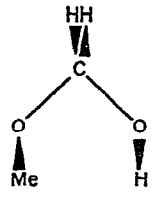


I

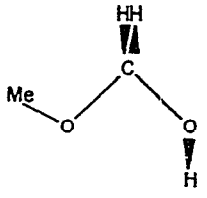
*The computing involved in these *ab initio* calculations increases by more than the third power of the number of electrons in the system. Each energy calculation for methoxymethanol required 30 minutes of UNIVAC 1108 time. It is prudent, if only for the conservation of energy, to proceed cautiously, matching the theory with experiment at each stage of additional complexity in the model compound.

using fixed, standard values for all bond-lengths and angles ($R_{CO} = 143$ pm, $R_{CH} = 109$ pm, $R_{OH} = 96$ pm; all bond angles tetrahedral). The staggered conformation was assumed throughout for the H_3C–O–C group, and the energy was studied as a function of the remaining torsion-angles ϕ and θ (I).

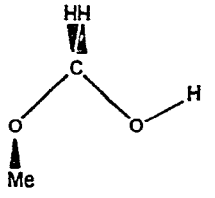
Initially, we considered the five standard conformations (II) (+sc, +sc, $\phi = \theta = +60°$), (III) (ap, +sc, $\phi = 180°$, $\theta = +60°$), (IV) (+sc, ap, $\phi = +60°$, $\theta = 180°$), (V)



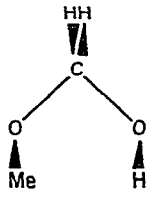
II (+sc, +sc)



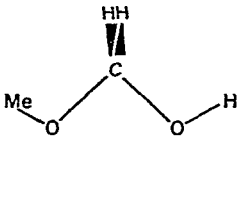
III (ap, +sc)



IV (+sc, ap)



V (+sc, −sc)



VI (ap, ap)

(+sc, −sc, $\phi = +60°$, $\theta = -60°$), and (VI) (ap, ap, $\phi = \theta = 180°$). These are all consistent with a "staggered" arrangement of bonds. The total and relative energies are listed in Table I.

TABLE I

ENERGIES FOR STANDARD CONFORMATIONS OF METHOXYMETHANOL

Conformation	*Formula*	*Total energy (hartrees)*	*Relative energy (kcal. mol^{-1})*
+sc, +sc	II	−228.58756	0.0
ap, +sc	III	−228.58277	3.0
+sc, ap	IV	−228.58073	4.3
+sc, −sc	V	−228.57655	6.9
ap, ap	VI	−228.57260	9.4

These results parallel those for methanediol quite closely. The +sc, +sc conformation is again the most stable. The conformers ap, +sc and +sc, ap have comparable energies that are 3-4 kcal. mol^{-1} above the minimum; this is not quite so far

above it as in methanediol, where the corresponding value is 4.7 kcal. mol^{-1}. The fully extended (ap, ap) conformation is again the least stable, although the energy relative to the minimum (9.4 kcal. mol^{-1}) is less than in methanediol (11.2 kcal. mol^{-1}).

This set of results was then expanded to cover the whole (ϕ, θ) surface with a grid of 60°. The relative energies are listed in Table II and a contour diagram is shown in Fig. 1. Figure 2 shows those sections of this surface on which θ (the OCOH dihedral angle) is varied while ϕ (the COCO dihedral angle) is fixed at 60° (VII), 120° (VIII), and 180° (IX). Figure 3 shows three other sections with variable ϕ, θ being fixed at 60° (X), 120° (XI), and 180° (XII). It will later be seen how these potential-energy sections can be used as models for parts of corresponding surfaces for larger carbohydrate systems.

TABLE II

ENERGIES[a] OF METHOXYMETHANOL RELATIVE TO (+sc, +sc) $\theta = \phi = 60°$

θ	−180	−120	−60	0	+60	+120	+180
ϕ				(degrees)			
(degrees)				(kcal. mol^{-1})			
180	9.4	7.6	3.0	2.7	3.0	7.6	9.4
120	9.8	9.7	5.7	4.3	3.8	8.0	9.8
60	4.3	4.4	6.9	6.9	—	2.9	4.3
0	10.7	10.9	14.7	27.4	14.7	10.9	10.7

[a]The Table can be extended to negative ϕ by using $E(-\phi, -\theta) = E(\phi, \theta)$.

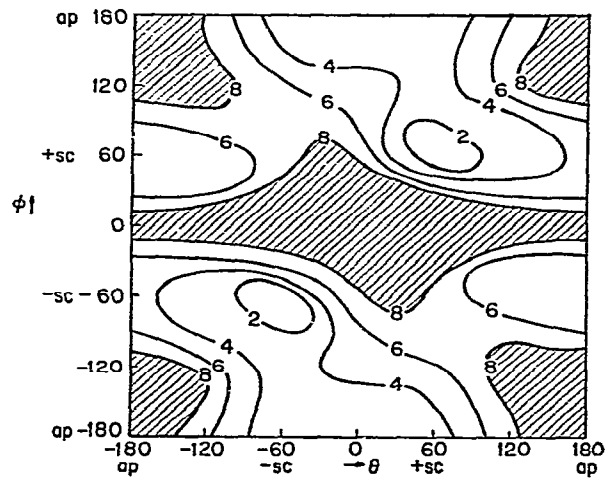


Fig. 1. Energy contours (kcal. mol^{-1}) on the potential surface for internal rotation in methoxymethanol, relative to (+60°, +60°). [Shaded areas are above 8 kcal. mol^{-1}.]

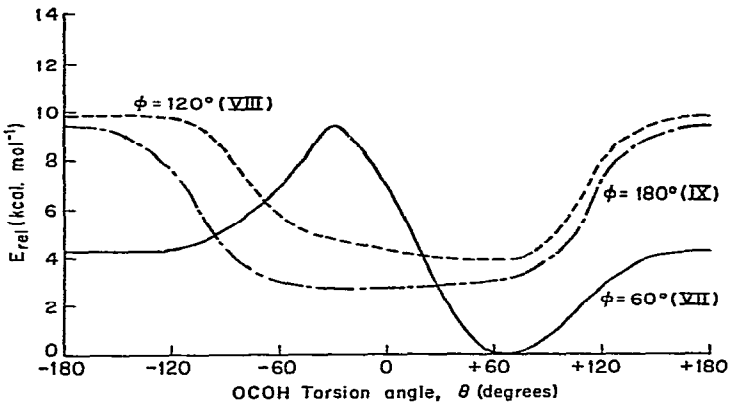


Fig. 2. Sections, V(θ), of the potential surface for internal rotation in methoxymethanol for fixed values of ϕ.

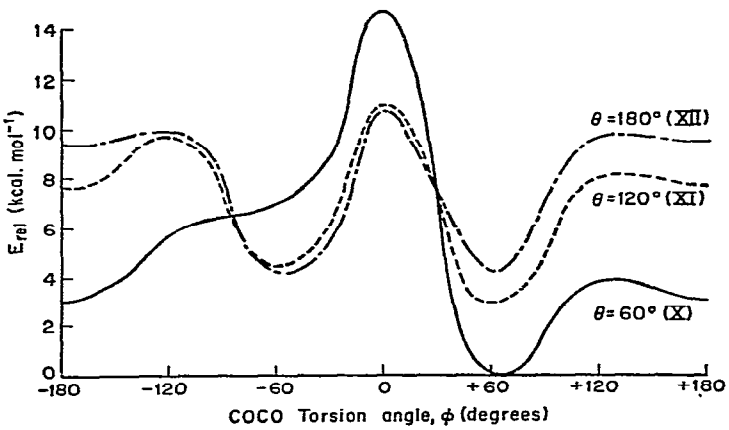
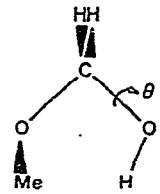
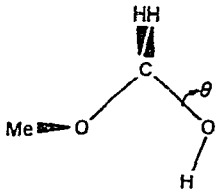


Fig. 3. Sections, V(ϕ), of the potential surface for internal rotation in methoxymethanol for fixed values of θ.

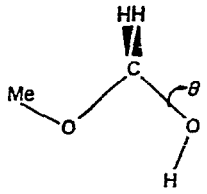
The potential sections may usefully be compared with those for methanediol. Figure 2 (rotation about the OC–OH bond) is similar to that for methanediol (Fig. 2 of ref. 1). When $\phi = 60°$ (VII), there is a single minimum near $\theta = +60°$, and a level region extends from 180 to 120° with no significant maxima or minima. When $\phi = 180°$ (IX), a very flat minimum occurs at $\theta = 0°$; this situation is similar to that for methanediol, where there are two separate minima at $\theta = \pm 30°$, separated by a very small hump. When $\phi = 120°$ (VIII), the potential curve is intermediate in character, with a single, flat minimum near 50°. Comparison of these results with those for methanediol indicated that rotation about the OC–OH bond is not greatly changed by the presence of a methyl group attached to the "left-hand" oxygen atom.



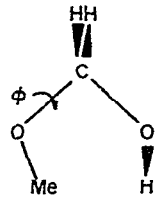
VII



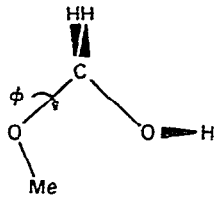
VIII



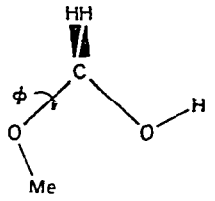
IX



X



XI



XII

The sections shown in Fig. 3 (rotation about the MeO–CO bond) differ more significantly from those for methanediol. When $\theta = 60°$ (X), there is again a single minimum at $\phi = \sim 60°$, but the maximum in the curve (near $\phi = 0°$) is much higher, presumably because of steric overlap. The section with $\theta = 180°$ (XII) now shows two sharply defined minima at $\phi = \pm 60°$, separated by quite a high barrier; in addition, there is a slight minimum at $\phi = 180°$. The curve for $\theta = 120°$ (XI) shows two non-equivalent minima, the one near $\phi = +60°$ giving the lower energy. Thus, the rotational potentials for MeO–CO rotation are considerably different from those for HO–CO, and have higher barriers. This is comparable to the barrier increase found on going[5] from the HO–CH_3 rotation in methanol (1.1 kcal. mol^{-1}) to the MeO–CH_3 rotation in dimethyl ether (2.7 kcal. mol^{-1}).

From the general features of the potential surface (see Fig. 1), it is clear that the +sc, +sc and −sc, −sc conformations are close to the two symmetry-equivalent minima. There is some indication of another, slight, local minimum, ~3 kcal. mol^{-1} higher in energy, that is close to ap, +sc. Near $\phi = 0°$ (MeO–CO, ap), the surface shows a ridge of high energy which is evidently due to steric interactions with the methyl group in this position. The height of this ridge could no doubt be lessened were valence bond-angle flexibility included in the theory.

Bond-length calculations. — In the second set of calculations, the C–O bond-lengths were varied, keeping the torsion angles fixed. Attention was concentrated on the staggered conformations II (+60°, +60°), III (180°, +60°), and IV (+60°, 180°). All lengths and angles were taken as standard, except for the C–O bond-lengths, which were varied to minimize the total energy. Again, this paralleled the procedure previously used for methanediol. The C–O lengths obtained are shown in Fig. 4 (together with those for methanol and methanediol), and the energies in Table III.

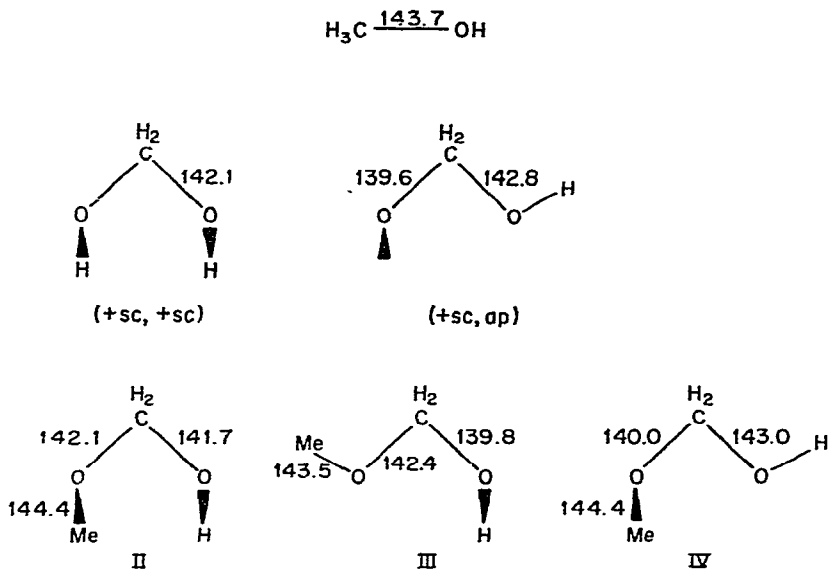


Fig. 4. Calculated bond-lengths (pm) for methanol, methanediol, and methoxymethanol.

TABLE III

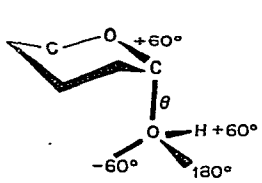
ENERGIES OF METHOXYMETHANOL WITH OPTIMIZED C–O LENGTHS

Conformation	*Formula*	*Total energy (hartrees)*	*Relative energy (kcal. mol^{-1})*
+sc, +sc	II	−228.58786	0.0
ap, +sc	III	−228.58353	2.7
+sc, ap	IV	−228.58149	4.0

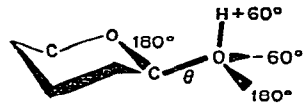
These results indicated that the C–O bonds in the O–C–O segment of methoxymethanol have lengths very close to those in the corresponding conformation of methanediol, *i.e.*, they are shorter than the theoretical value for methanol. However, an important additional effect revealed here is the *lengthening*, relative to methanol, of the additional C–O bond in conformations II (+sc, +sc) and IV (+sc, ap) but not in conformation III (ap, +sc). Evidently, this C–O bond is long in the two cases where the adjacent O–C bond (same oxygen atom) is shortest. This effect can be interpreted as the result of competition for the back donation of oxygen π-type, lone-pair electrons which gives the C–O moiety a partial double-bond character, as illustrated in conformation VI of the previous paper[1]. Increased back-donation from the oxygen lone-pair on the direction of one O–C bond results in less back-donation in the other bond.

METHOXYMETHANOL AS A MODEL COMPOUND

Pyranoses. — As already indicated, methoxymethanol can be used as a model for the C-5–O-5–C-1–O-1–H hemiacetal group in an aldopyranose. For an α-aldopyranose, XIII, the angle ϕ is fixed at a value close to 60° (VII). The model then predicts that the most favored conformational angle for θ, O–C–O–H is ~65° (+sc). As shown in Fig. 2, this conformation is the *only minimum*, and it lies at ~4 kcal. below a shoulder that extends from 180° (ap) to −90° (−ac). The maximum energy occurs at $\theta = -30°$, and is almost 10 kcal. mol^{-1} above that of the favored conformation. This result differs from the methanediol calculations (shown in Fig. 2 of the previous paper[1]) in the increase, by ~4 kcal., in the maximum at $\theta = -30°$; this is understandable in terms of the anticipated increase of the $\frac{1}{2}V_3(1-\cos 3\theta)$ type of term in the Fourier decomposition when a hydrogen atom is replaced by a carbon atom [see Equation (*1*) in the previous paper[1]].



XIII

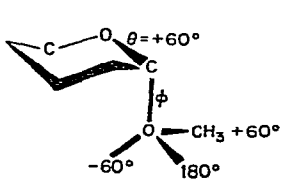


XIV

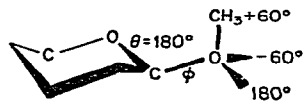
The conformational-energy plot for the β-pyranose, XIV, corresponds to $\phi = 180°$ (IX) in Fig. 2; it shows a broad minimum extending from $\theta = -60$ to +60°, with a small drop at $\theta = 0°$. The maximum at $\theta = 180°$ is about 6 kcal. mol^{-1} higher. These results differ from the methanediol calculation only in a lowering of the minimum energy by ~2 kcal. mol^{-1}, making the minimum energy for the β-pyranose closer to that of the α-pyranose, so that the difference between the most stable α-pyranose model and the most stable β-pyranose model is now ~2.7 kcal. mol^{-1}, a value that would be partly balanced by an entropy difference, because of the broad minimum for the β-pyranose.

Associated with these conformational-energy differences are predicted variations in C–O bond-lengths arising from "back-bonding" of electrons from the oxygen lone-pairs to a depopulated, 2p orbital of the adjacent carbon atom. Again, methoxymethanol can be used as a model, and the corresponding theoretical bond-lengths can be taken from Fig. 4. Relative to the theoretical C–O length in methanol as a standard, the predicted variations in C–O lengths for the C–O$_r$–C–OH hemiacetal sequence in an α-pyranose are +0.7, −1.6, and −2.0 pm. For the β-pyranose, the values are −0.2, −1.3, and −3.9 pm. The predictions as to bond shortening are close to those previously made on using methanediol as a model. In addition, the theory now predicts a small lengthening of the C-5–O-5 ring bond in an α-pyranose.

Methyl pyranosides. — In this application, methoxymethanol is used as a model for the C-5–O-5–C-1–O-1–CH_3 acetal sequence, with C-5 replaced by a hydrogen atom. The angle θ now corresponds to the $+60°$ and $180°$ respectively fixed by the α and β configuration of the methyl pyranosides, as shown in XV and XVI. The energy is then explored as a function of the torsion angle (ϕ), which is now O-5–C-1$\overset{\phi}{-}$O-1–CH_3. The appropriate curves are those given in Fig. 3. As noted earlier, this model is more approximate than that employed previously, because a hydrogen atom now corresponds to C-5 of the pyranoside.



XV



XVI

The theoretical minimum for the α-pyranoside (XV), $\theta = +60°$, occurs at $\phi = \sim +65°$; this value is close to that already predicted for the α-pyranose (XIII). However, the shoulder in the region of $\phi = 180°$ is about 1 kcal. mol^{-1} lower. The maximum near $\phi = 0°$ is also higher than for the α-pyranose; presumably, this is because of steric interaction between the methyl group and the ring-oxygen atom.

For the β-pyranoside (XVI), $\theta = 180°$, the potential section leads to separate minima near $\theta = \pm 60°$ ($\pm$sc). These minima correspond to the same energy in the methoxymethanol model-compound, but will clearly become non-equivalent in the larger molecule. The two minima are separated by a high maximum (at $\phi = 0°$) not found for the corresponding α-pyranose; again, this is probably associated with steric interaction between the methyl group and the ring-oxygen atom. The potential predicts a slight minimum at $\phi = 180°$, but at a much higher energy. From a comparison with the corresponding, β-pyranose section, it is clear that replacement of a hydrogen atom by a methyl group has so changed the potential curve that it has more ethane-like, three-fold character.

Again, these calculations predict that the energy of the methyl α-pyranoside in the favored +sc, +sc conformation is about 4 kcal. mol^{-1} lower than that for either of the two favored methyl β-pyranoside conformations (ap, $\pm$sc).

The predicted variations in bond length given in Fig. 4 can now be applied, with the hydrogen atom representing C-5 of the pyranose ring, and the hydroxyl oxygen atom representing the ring-oxygen atom. The prediction for the C–O bond-length differences (relative to methanol) in the acetal-bond sequence O_r–C–O–CH_3 in a methyl pyranoside are then -2.0, -1.6, $+0.7$ pm in the favored +sc, +sc conformation of the methyl α-pyranoside, and -0.7, -3.7, $+0.7$ pm in the favored ap, +sc conformation of the methyl β-pyranoside.

COMPARISON WITH CRYSTAL-STRUCTURE DATA

The relevant, crystal-structure data were given in Table II of the previous publication[1]. As these data show definite, systematic trends that can be averaged, they have been summarized in Table IV, with the notation used in the present paper. The bond-length differences are reported relative to the C–O length in methanol, with 142.8 for the experimental standard and 143.7 for the theoretical standard. The discrepancy between the experimental and theoretical results for the methanol molecule arises from deficiencies in this *ab initio* method for calculating the absolute values of bond lengths.

TABLE IV

EXPERIMENTAL TORSION ANGLES AND BOND-LENGTH VARIATIONS IN ALDOPYRANOSES AND METHYL ALDOPYRANOSIDES, WITH THEORETICAL BOND-LENGTH VARIATIONS FOR METHOXYMETHANOL

Compounds	*Torsion angles (degrees)*		*Relative bond-lengths*[a] *(pm)*		
	ϕ	θ	C-5———O-5	$\overset{\phi}{}$ C-1	$\overset{\theta}{}$ ———O-1–H
α-Pyranoses					
Mean of 7 structures[b]	+61	+78	+1.3	+0.2	−3.4
Theoretical[c]	+60	+60	+0.7	−1.6	−2.0
β-Pyranoses					
Mean of 3 structures	−177	−95	+0.3	+0.3	−5.2
Theoretical[c]	+180	−60	−0.2	−1.3	−3.9
	θ	ϕ	O-5———C-1	———O-1	———CH_3
Methyl α-pyranosides					
Mean of 4 structures	+61	+63	−1.1	−2.1	+0.6
Theoretical[c]	+60	+60	−2.0	−1.6	+0.7
Methyl β-pyranosides					
Mean of 3 structures	+178	−73	−1.0	−4.5	+1.7
Theoretical[c]	+180	±60	−0.7	−3.7	+0.7

[a]The numbers under the bonds are bond-length differences. The crystallographic lengths were measured relative to the experimental length for methanol of 142.8 pm, and the theoretical values are relative to the 4-31G length for methanol of 143.7 pm. [b]Those given in Table II of ref. 1, plus those for α-D-glucose monohydrate[6]. [c]The theoretical torsion-angles are not those which correspond exactly to minima in the potential-surface sections. Instead, θ and ϕ correspond to the conformation closest to that which was experimentally observed, and for which theoretical bond-lengths were evaluated.

The first notable feature of the α-pyranoses is the tendency for θ to be greater than the ideal +sc value of 60°. With one exception, α-lactose, the individual values range from 75 to 97°; this is consistent with the potential-energy curve for $\phi = 60°$ (VII) in Fig. 2, which has its minimum at ~65° and rises less steeply for the values of θ greater than 60°.

For the β-pyranoses, there is a greater spread in the three observed θ values, from -72 to $-116°$. Although this is in agreement with the broad minimum for $\phi = 180°$ (IX) in Fig. 3, a range of smaller values is predicted by the theory. It should be noted that, in these pyranoid sugars, the θ values are particularly sensitive to crystal-field effects from adjoining molecules in the crystal lattice. In all the crystal structures, the hydroxyl hydrogen atom is involved in an intermolecular hydrogen-bond that has a favored direction depending upon the molecular packing. This is a less disturbing factor in the methyl pyranosides, where the methyl group is subject only to Van der Waals interactions, which are less directional in character. In consequence, the ϕ values for the methyl pyranosides lie in much narrower ranges, $+61$ to $+64°$ in the α series, and -70 to $-76°$ in the β series. These results may be compared with $\theta = 60°$ (IX) and $\theta = 180°$ (X) in Fig. 3. In both instances, the values observed lie on the less steeply rising side of the 60° minimum. The comparison with the theoretically predicted bond-length variations, given in Table IV, shows an agreement better than might be expected, as the experimental results are the mean of a limited number of individual observations, with standards deviations ranging from 1.0 to 0.5 pm. All of the systematic trends predicted by the theory, including the lengthening of the additional C–O bonds in going from methanediol to methoxymethanol, are reproduced in the experimental data on the carbohydrates studied.

EXTRAPOLATION TO THE LINKAGE BONDS IN OLIGOSACCHARIDES

Sequences of alternating, bonded carbon and oxygen atoms are always present in oligo- and poly-saccharides. They may be five-atom sequences, as in cellulose, or seven-atom sequences, as in sucrose. The trisaccharides raffinose, planteose, 1-kestose, and melezitose have both five- and seven-atom sequences. The experimental data relating to the torsion angles and bond-length variations are given in Table V. As in Table II of the previous paper[1], the ϕ and ϕ' angles are characteristic of the monosaccharide configuration, *i.e.*, ideally 60° and 180° for α- and β-pyranosidic linkages. Where one of the monosaccharide residues is a D-fructofuranosyl group or residue, ϕ' depends on the pseudorotational phase-angle of the furanose ring, and it may depart from the 120° of a planar, five-membered ring, depending upon the degree and type of puckering. Because of their biological importance, these data include those from the most recent and precise carbohydrate structural investigations available. Those for sucrose, for example, combine high-precision X-ray and neutron analyses, to give molecular dimensions with standard deviations of 0.15 pm in C–O bond-lengths, *i.e.*, one tenth the theoretical bond-length differences. The structural data on α,α-trehalose resulted from three, independent X-ray determinations, giving standard deviations of 0.2–0.4 pm in the C–O bond-lengths.

The θ torsion-angle data clearly show the same trend toward the favored $+$sc, $+$sc for α-linkages and ap, $\pm$sc for β-linkages. In fact, the conformations lie in the ap, $-$sc range, because the ap, $+$sc torsion-angles incur steric interference between substituents and ring-oxygen atoms of adjacent monosaccharide units.

TABLE V

CONFORMATIONAL TORSION-ANGLES AND BOND-LENGTH VARIATIONS FOR ACETAL GROUPS IN THE LINKAGE BONDS OF DI- AND TRI-SACCHARIDES

Compound	*5-Atom sequences*						*References*
	Torsion angles (degrees)		*Relative bond-lengths*[a] *(pm)*				
	ϕ	θ	C-5——O-5—$\overset{\phi}{}$—C-1—$\overset{\theta}{}$—O-1——C				
α Linkages[b]							
β-Maltose monohydrate (1→4α, Glc-Glc)	60	123	+4.1	−3.9	+0.6	+1.6	7
Methyl β-maltoside (1→4α, Glc-Glc)	64	110	+1.3	−2.8	−1.3	+1.2	8
Isomaltulose monohydrate (1→6α, Glc-Glc)	58	77	+0.2	−0.2	−3.1	+0.4	9
Raffinose pentahydrate (1→6α, Gal-Glc)	60	72	+0.8	−0.5	−0.0	+1.4	10
Melezitose monohydrate (1→3α, Glc-Fru)	58	92	+0.6	−1.3	−2.2	−0.6	11
Aldotriouronic acid trihydrate (1→2α, Glc-Xyl)	59	79	+0.2	−0.6	−1.8	+0.2	12
Planteose dihydrate (1→6α, Gal-Fru)	60	59	+1.6	−1.0	−1.4	+0.1	13
Cyclohexaamylose, propyl alcoholate, hydrate[c]	57	108	+1.8	−2.2	−2.6	+0.3	14
β-Linkages[d]							
Cellobiose (1→4β, Glc-Glc)	177	−76	+1.4	−0.2	−2.6	+1.7	15
Methyl β-cellobioside methanolate (1→4β, Glc-Glc)	172	−91	−0.0	+0.5	−3.9	+0.8	16
α-Lactose monohydrate (1→4β, Gal-Glc)	−178	−94	+1.9	−0.2	−4.1	+0.7	17

TABLE V (*continued*)

Compound	*5-Atom sequences*										*References*
	Torsion angles (degrees)		*Relative bond-lengths[a] (pm)*								
	ϕ	θ	C-5——O-5 $\overset{\phi}{}$ C-1 $\overset{\theta}{}$ O-1——C								
β-Linkages[d] (continued)											
Aldotriouronic acid trihydrate (1→4β, Xyl-Xyl)	175	−82	+1.2	+1.4	−3.5	+2.0					12
β-D-Xylobiose hexaacetate	178	−104	+0.6	−2.9	−3.7	−0.9					18
	7-Atom sequences										
	ϕ	θ	θ'	ϕ'	C-5——O-5 $\overset{\phi}{}$ C-1 $\overset{\theta}{}$ O-1 $\overset{\theta'}{}$ C-2′ $\overset{\phi'}{}$ O-2′——C-5′						
α-Linkages[b]											
α,α-Trehalose dihydrate (1→1α, Glc-Glc)	58	62	75	56	+0.3	−2.4	−0.6	−1.3	−0.7	+0.5[e]	19
Sucrose (1→2α, Glc-Fru)	68	108	−45	−102[f]	+1.3	−1.6	−0.3	+0.3	−2.0	+1.9 (X-ray)	20
					+1.1	−1.7	−0.6	+0.1	−2.0	+1.7 (neutron)	21
Planteose dihydrate (1→2α, Glc-Fru)	60	109	−27	−101[f]	+0.2	−1.2	−1.3	+1.2	−2.1	+3.5	13
Raffinose pentahydrate (1→2α, Glc-Fru)	60	82	11	−110[f]	+0.5	−0.9	−2.5	+1.5	−1.6	+2.6	10
1-Kestose (1→2α, Glc-Fru)	60	85	−66	−121[f]	+1.3	−1.6	−1.1	−1.6	−1.5	+2.6	22
Melezitose monohydrate	64	109	−42	−92[f]	+0.5	−2.4	−0.4	+0.8	−1.5	+2.4	11

[a] *C.f.*, C–O 142.8 pm. [b] ϕ ~60°. [c] Mean of values for six residues. [d] ϕ ~180°. [e] Mean of three independent experiments. [f] Adjacent to D-fructofuranose ring.

As with the pyranoses and methyl pyranosides, the θ values are generally greater than 60° and, indeed, go as high as 123°. However, in all the disaccharides studied, except α,α-trehalose, there is an intramolecular hydrogen-bond linking oxygen atoms in the two monosaccharide units, and the geometrical requirements for strong hydrogen-bond formation constitute an important factor controlling the linkage torsion-angles.

Where ϕ' involves the ring bonds of D-fructofuranose, as in most of the sucrose components of the seven-atom sequences, the angle is constrained to be $-120 \pm 30°$. The corresponding, energy plot is $\phi = 120°$ (VIII) in Fig. 3 With the exception of the θ' value of raffinose, all observed values lie close to the lower theoretical minimum at $-60°$ (−ac, −sc). The result for raffinose may be exceptional. In the crystal structure of its pentahydrate, the molecules form a helical arrangement that is stabilized by hydrogen bonding through the water molecules. The lattice energy of this particular, hydrated structure could overcome an unfavorable conformational energy for one of the linkage bonds.

The most striking feature of the data presented in Table V consists in the systematic trends in bond-length variations. In both the five- and seven-atom sequences, the inner bonds tend to be shortened, and the outer ones lengthened or shortened to a much lesser degree. All of the trends noted for the monosaccharides are also observed, particularly the greater shortening of the C-1–O-1 bond in the β-pyranosidic linkage, accompanied by a tendency for the adjacent C-5–O-5 ring-bonds and the second O-1–C linkage-bonds to be longer; this illustrates the competitive character of the back-bonding discussed earlier.

The inference from these results is that the electronic effects that influence the conformational energy for rotation about the glycoside linkages in aldopyranoses and methyl aldopyranosides should also apply to the linkage bonds in oligo- and poly-saccharides. The results from calculations on methoxymethanol as a model compound indicate that these effects may involve energy factors of the order of several kcal; these are comparable to the Van der Waals and intramolecular hydrogen-bond interactions, and must, therefore, also be included in conformational-energy calculations for the linkage bonds in oligo- and poly-saccharides.

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