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Quantitative description of six-membered ring conformations following the IUPAC conformational nomenclature

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Abstract—Although several methods of quantitative conformational characterization exist in the literature, all these methods use a spherical polar coordinate representation which is in contrast to the qualitative description based on the IUPAC nomenclature. To bridge this gap this paper introduces a method to characterize six-membered ring conformations as a linear combination of ideal basic conformations. The linear combination coefficients are derived by projection of the vector of torsion angles onto those of ideal basic conformations. As the IUPAC nomenclature uses subscripts and superscripts to indicate atoms below and above the reference plane, the linear combination coefficients combined with the IUPAC name provide an instant visual image of the conformation. The method introduced here is based on endocyclic dihedral angles and requires only three dihedral angles for a full characterization, which is often available by NMR measurements for rigid conformations. We provide a table of equations to determine the missing dihedral angles based on redundancy conditions. The relationship between linear combinations and spherical representation similar to the well-known Cremer–Pople parameters is presented. In deriving the spherical conformational parameters we solved an inconsistency of previous definitions for spherical representation, namely that none of previous definitions place the intermediate halfchair or twistboat conformations exactly halfway between the pole (chair) and the equator (boat and twistboat) of the sphere as expected based on intuitive stereochemistry. To make our method generally available we provide an interface on the Internet that carries out all calculations described in the paper and allows the user to visualize, rotate and manipulate the ring (http://www.nrc.ca/ibs/6ring.html). By simplifying both the concepts and the access to carry out the calculations more experimental chemists can benefit from the description of ring conformation.

1. Introduction

Ring conformation plays an important role in the function and reactivity of carbohydrates.[1] This role is manifested in the mechanisms of oligosaccharide synthesis by chemical glycosylations[2] or glycosyl transferases[3] as well as in the solvolysis of the glycosidic bond in chemical[4,5] or biochemical reactions.[6] Fundamental biological processes like the duplication of DNA, the transformation from DNA-A to DNA-B are controlled by the conformational change of carbohydrate rings.[7] The pyranose ring conformations are a major factor in the biological functions and the binding specificity of glycosaminoglycans.[8–13] In addition, recent atomic force microscopy experiments have shown that single amylose, dextran, pullulan and pectin chains owe their elasticity to the conformational change between chair and boat conformations.[14] Six-membered ring conformations contribute to the reactivity and physical properties of transition metal containing ring systems.[15,16] Our ongoing studies show that the potential energy surface of conformational change is a fundamental factor that controls the stereochemistry and the side reactions of glycosylation reactions.[17]

The description of these processes requires quantitative characterization of the ring conformation and the conformational change. Qualitative descriptions of ring shape always follow from some ideal reference conformations, such as the boat, chair or twistboat and use the IUPAC conformational nomenclature.[18] The IUPAC nomenclature uses superscripts and subscripts to describe the atoms above and below the reference plane, respectively, and thus provides an instant visual image of the conformations. By contrast, the standard quantitative descriptions of six-membered ring conformation, such as the Cremer–Pople (CP) parameters, describe the conformation in terms of spherical polar coordinates derived from the Fourier transform of the puckering coordinates.[19] The interpretation of the spherical parameters requires the knowledge of the location of all 38 basic conformations on the sphere. Thus, even when the quantitative conformational parameters are given, it is necessary to specify the closest basic conformation given by its IUPAC name. For example, the θ=90°, ϕ=205° angular

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Keywords: carbohydrates; conformation; ring transformations.

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Table 1. The endocyclic torsion angles of the 38 ideal basic conformations of pyranoses

	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6
${}^{1}\mathrm{C}_{4}$	60.0	−60.0	60.0	−60.0	60.0	−60.0
${}^{4}\mathrm{C}_{1}$	−60.0	60.0	−60.0	60.0	−60.0	60.0
${}^{1,4}\mathrm{B}$	0.0	60.0	−60.0	0.0	60.0	−60.0
$\mathrm{B}_{2,5}$	60.0	0.0	−60.0	60.0	0.0	−60.0
${}^{\mathrm{O},3}\mathrm{B}$	60.0	−60.0	0.0	60.0	−60.0	0.0
$\mathrm{B}_{1,4}$	0.0	−60.0	60.0	0.0	−60.0	60.0
${}^{2,5}\mathrm{B}$	−60.0	0.0	60.0	−60.0	0.0	60.0
$\mathrm{B}_{\mathrm{O},3}$	−60.0	60.0	0.0	−60.0	60.0	0.0
${}^{1}\mathrm{S}_{5}$	30.0	30.0	−60.0	30.0	30.0	−60.0
${}^{\mathrm{O}}\mathrm{S}_{2}$	60.0	−30.0	−30.0	60.0	−30.0	−30.0
${}^{3}\mathrm{S}_{1}$	30.0	−60.0	30.0	30.0	−60.0	30.0
${}^{5}\mathrm{S}_{1}$	−30.0	−30.0	60.0	−30.0	−30.0	60.0
${}^{2}\mathrm{S}_{\mathrm{O}}$	−60.0	30.0	30.0	−60.0	30.0	30.0
${}^{1}\mathrm{S}_{3}$	−30.0	60.0	−30.0	−30.0	60.0	−30.0
${}^{1}\mathrm{H}_{2}$	45.0	−15.0	0.0	−15.0	45.0	−60.2
${}^{3}\mathrm{H}_{2}$	60.0	−45.0	15.0	0.0	15.0	−45.0
${}^{3}\mathrm{H}_{4}$	45.0	−60.0	45.0	−15.0	0.0	−15.0
${}^{5}\mathrm{H}_{4}$	15.0	−45.0	60.0	−45.0	15.0	0.0
${}^{5}\mathrm{H}_{\mathrm{O}}$	0.0	−15.0	45.0	−60.0	45.0	−15.0
${}^{1}\mathrm{H}_{\mathrm{O}}$	15.0	0.0	15.0	−45.0	60.0	−45.0
${}^{4}\mathrm{H}_{5}$	−15.0	45.0	−60.0	45.0	−15.0	0.0
${}^{\mathrm{O}}\mathrm{H}_{5}$	0.0	15.0	−45.0	60.0	−45.0	15.0
${}^{\mathrm{O}}\mathrm{H}_{1}$	−15.0	0.0	−15.0	45.0	−60.0	45.0
${}^{2}\mathrm{H}_{1}$	−45.0	15.0	0.0	15.0	−45.0	60.0
${}^{2}\mathrm{H}_{3}$	−60.0	45.0	−15.0	0.0	−15.0	45.0
${}^{4}\mathrm{H}_{3}$	−45.0	60.0	−45.0	15.0	0.0	15.0
${}^{1}\mathrm{E}$	30.0	0.0	0.0	−30.0	60.0	−60.0
E_{2}	60.0	−30.0	0.0	0.0	30.0	−60.0
${}^{3}\mathrm{E}$	60.0	−60.0	30.0	0.0	0.0	−30.0
E_{4}	30.0	−60.0	60.0	−30.0	0.0	0.0
${}^{5}\mathrm{E}$	0.0	−30.0	60.0	−60.0	30.0	0.0
E_{O}	0.0	0.0	30.0	−60.0	60.0	−30.0
${}^{4}\mathrm{E}$	−30.0	60.0	−60.0	30.0	0.0	0.0
E_{5}	0.0	30.0	−60.0	60.0	−30.0	0.0
${}^{\mathrm{O}}\mathrm{E}$	0.0	0.0	−30.0	60.0	−60.0	30.0
E_{1}	−30.0	0.0	0.0	30.0	−60.0	60.0
${}^{2}\mathrm{E}$	−60.0	30.0	0.0	0.0	−30.0	60.0
E_{3}	−60.0	60.0	−30.0	0.0	0.0	30.0

coordinates most closely match the ${}^{5}\mathrm{S}_{1}$ conformation and it is slightly distorted towards the $\mathrm{B}_{1,4}$ conformation. Such qualitative descriptions are often expressed as linear combinations,[26] but we are not aware of any quantitative definitions using such a representation. Comparison between shapes can be quantified mathematically by a projection operation. In the case of ring puckering, the puckering coordinates of the ring under study need to be projected onto those of ideal reference conformations such as the ideal boat, chair and twistboat conformations.

In this paper, we use these concepts to quantitatively describe six-membered ring conformations in terms of linear combinations of the ideal basic reference conformations and take advantage of the visual image created by the IUPAC names. In addition to introducing new concepts we would like to eliminate some of the major obstacles to the widespread use of quantitative conformational descriptions. All previous conformation definitions require the installation of FORTRAN computer programs to calculate the conformational parameters. For the occasional user with no experience in program installations and lack of facilities with a FORTRAN compiler, this is a major obstacle. To overcome this barrier we introduced an internet site (http://www.nrc.ca/ibs/6ring.html) where all calculations described in this paper can be carried out through a simple and easy-to-use interface. On this site the conformation is visualized and the viewer can rotate the structures. Another obstacle of previous methods is the requirement for a complete set of either Cartesian coordinates or torsion angles. In contrast, for rigid conformations experiment typically provides an incomplete set of endocyclic ring torsion angles from NMR coupling constants applying the Karplus equations and their refinements.[20,21] For this reason, we use torsion angles to describe ring puckering and we take advantage of ring closure and redundancy conditions to reduce the required input data to the minimum three torsion angles. We provide a table of equations for the calculation of the missing torsion angles and these equations can be used through our web interface. We found in our study of conformations that visualization programs that allow the rotation of the structure is essential for the understanding of the molecular structure. Since these programs normally require Cartesian coordinates it is not possible to use them when only torsion angles are available. To bridge this gap we also provide calculations on the internet site to determine a set of Cartesian coordinates of a six-membered ring with standard bond length and angles of a given conformation and use a simple plugin to enable the visualization, rotation and manipulation of the ring conformation. Through the simplification of the concepts and making the method generally available we wish to enable a wide range of chemists to benefit from the quantitative characterization of pyranose and other six-membered ring shapes at a time when the significance of ring conformation in chemical reactivity, biological function and physical properties is becoming increasingly recognized.

1.1. Conformational descriptions

Pyranose rings have 38 basic conformations[22] (Table 1) but it takes only three independent parameters to describe these conformations uniquely. Hendrickson described the conformational space of the pyranose ring as a sphere of which the radius is the puckering amplitude and the position on the sphere determines the type of conformation.[23] The spherical conformational map can be considered as a polar coordinate representation of the three puckering eigenvectors of an ideal hexagon (Fig. 1). The polar coordinates can be equivalently derived by Fourier transform of a redundant set of puckering parameters, such as six puckering displacement coordinates relative to a mean plane or six endocyclic torsion angles. The most popular definition was introduced by Cremer and Pople (CP) who defined a suitable mean reference plane on the basis of Cartesian coordinates of the ring atoms.[19]

The three orthogonal reference axis (x, y, z) (Fig. 1) represent displacements into ideal chair (z), twistboat (x) and boat (y) conformations. Moving from the origin towards the north and south pole of the sphere (i.e. along the z axis) represents displacement into the ${}^{1}\mathrm{C}_{4}$ and ${}^{4}\mathrm{C}_{1}$ chair forms, respectively. The azimuthal angle (θ) measures the deviation from the pole and as such indicates the deviation from an ideal chair conformation. Movement on the surface of the sphere along the θ angle represents the chair inversion coordinate. Distortion from the midpoint to the equator (i.e. in the x, y plane) in the conformational space signifies

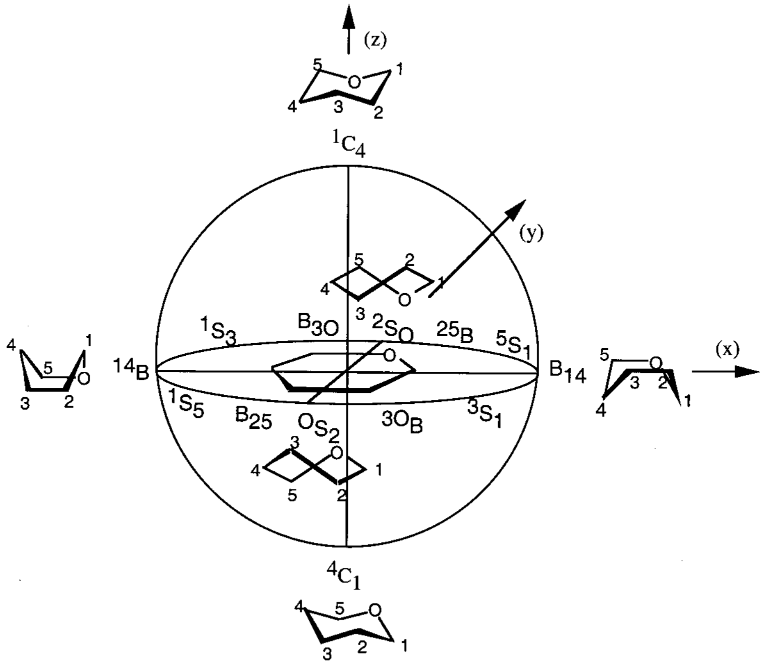


Figure 1. Spherical mapping of pyranose conformations.

displacement from planar ring into boat or twistboat conformations or any combination of these. The equator is also called the pseudorotational itinerary which describes a low energy pathway of interconverting boat and twistboat conformations which are related by the permutation of atom numbering. The meridian angle (ϕ), also called pseudorotational phase angle determines which of the six boat or six twistboat conformations contribute to the conformation. All quantitative ring characterization of pyranose ring shapes are variants of how to determine the spherical polar coordinates.

The advancement of NMR structure determination prompted the development of torsion angle based definitions of puckering.[24] Zefirov, Palyulin and Dashevskaya (ZPD) showed that torsion angle based definitions eliminate some of the deficiencies of the CP definitions, i.e. the CP conformational descriptions are sometimes contrary to stereochemical intuition.[25] Haasnoot has introduced a set of definitions similar to ZPD but he used simpler equations which he refers to as truncated Fourier (TF) transform.[26] The approximate nature of these equations introduce some error which is comparable to the uncertainty in the experimentally determined geometrical parameters.

There exist an unfortunate inconsistency between the spherical coordinate based definitions and the intuitive stereochemical definitions. Intuitively one would describe an envelope conformation as an equal mixture of an equally distorted chair and boat conformations. Similarly, the halfchair conformations are expected to be equal mixtures of ideal twistboat and chair conformations. For this reason, one would expect these conformations to be halfway between the pole (chair) and the equator (boat or twistboat) of the sphere at 45° meridian angle on the northern hemisphere. The alternative spherical descriptions are not only inconsistent with the intuitive stereochemistry, but also inconsistent with each other in the description of halfchair and envelope conformations. The halfchair conformations appear at 51, 55 and 35° azimuthal angles (on the northern hemisphere) in the CP, ZPD or TF definitions, respectively. The envelope conformations appear at 55, 51 and 35° azimuthal angles in the same three definitions. An additional goal of this paper is to show the relationship between the linear combination type description proposed here and the spherical description. This connection leads us to a new proposal for spherical coordinates which eliminate the aforementioned inconsistency and places the halfchair and sofa conformations exactly at 45° azimuthal angle.

2. Definitions and methods

2.1. Basic definitions

We consider the internal coordinate space of the six-membered ring that consists of six bond lengths (R), six bending angles (α) and six torsion angles (τ). Any conformation can be expressed in terms of distortions from the planar regular hexagon, which has nine planar and three out-of-plane vibrational degrees of freedom. Therefore, the 12 planar internal coordinates (R, and α) and six torsion angles (τ) contain a total of six redundancies. Following the recommendations of Pulay and coworkers,[27] one may eliminate the redundancies by constructing symmetrized linear combinations of the individual bending and torsion angles that correspond to the irreducible representation of the D_{6h} point group. For both the bending angles and the torsion angles, three deformational and three redundancy coordinates arise. The three torsional deformations correspond to the three *canonical displacements* that bring the regular hexagon into chair ($^1C_4$), boat ($^{1,4}B$), and twistboat ($^OS_2$) conformations. In this paper, we represent these canonical distortions by the vectors of the six torsion angles of the ideal $^1C_4$, $^{1,4}B$, and $^OS_2$ conformation as defined by Prelog[28] and Cano:[29]

Table 2. Formulas for calculating redundant torsion angles

	6 Missing	5,6 Missing	5,6 Missing	4,6 Missing
$\tau_1=$				
$\tau_2=$				
$\tau_3=$				
$\tau_4=$				$\frac{1}{3}\tau_1 - \frac{2}{3}\tau_3 - \frac{2}{3}\tau_5$
$\tau_5=$		$\frac{1}{2}\tau_1 - \tau_3 - \frac{3}{2}\tau_4$	$\tau_1 + \tau_2 - \tau_3$	
$\tau_6=$	$-\sum_{i=1}^{5} \tau_i$	$-\frac{3}{2}\tau_1 - \tau_2 + \frac{1}{2}\tau_4$	$-\tau_1 + \tau_3 + \tau_4$	$-\frac{4}{3}\tau_1 - \tau_2 - \frac{1}{3}\tau_3 - \frac{1}{3}\tau_5$

	4,6 Missing	4,6 Missing	3,6 Missing	3,6 Missing
$\tau_1=$				
$\tau_2=$				
$\tau_3=$			$\frac{1}{2}\tau_1 - \frac{3}{2}\tau_4 - \tau_5$	$-\frac{1}{2}\tau_1 - \tau_2 - \frac{1}{2}\tau_4$
$\tau_4=$	$-\tau_1 - 2\tau_2 - 2\tau_3$	$\tau_1 + \tau_2 - \tau_5$		
$\tau_5=$				
$\tau_6=$	$\tau_2 + \tau_3 - \tau_5$	$\tau_2 + \tau_3 - \tau_5$	$-\frac{3}{2}\tau_1 - \tau_2 + \frac{1}{2}\tau_4$	$-\frac{1}{2}\tau_1 - \frac{1}{2}\tau_4 - \tau_5$

	4,5,6 Missing	3,5,6 Missing	2,4,6 Missing
$\tau_1=$			
$\tau_2=$			$\frac{1}{3}(-2\tau_1 - 2\tau_3 + \tau_5)$
$\tau_3=$		$-\frac{1}{2}\tau_1 - \tau_2 - \frac{1}{2}\tau_4$	
$\tau_4=$	$-\tau_1 - 2\tau_2 - 2\tau_3$		$\frac{1}{3}(\tau_1 - 2\tau_3 - 2\tau_5)$
$\tau_5=$	$2\tau_1 + 3\tau_2 + 2\tau_3$	$\tau_1 + \tau_2 - \tau_4$	
$\tau_6=$	$-2\tau_1 - 2\tau_2 - \tau_3$	$-\frac{3}{2}\tau_1 - \tau_2 + \frac{1}{2}\tau_4$	$\frac{1}{3}(-2\tau_1 + \tau_3 - 2\tau_5)$

$$F_1 = \{60, -60, 60, -60, 60, -60\} \tag{1a}$$

$$F_2 = \{0, 60, -60, 0, 60, -60\} \tag{1b}$$

$$F_3 = \{60, -30, -30, 60, -30, -30\} \tag{1c}$$

To make these definitions precise, a general $T = \{\tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_6\}$ is defined as a vector of six endocyclic torsion angles $\tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_6$ defined by the $C_1C_2C_3C_4$, $C_2C_3C_4C_5$, $C_3C_4C_5O$, $C_4C_5OC_1$, $C_5OC_1C_2$ and $OC_1C_2C_3$ atom sets, respectively. Using the same notation, the torsional redundancy contributions can be written as:

$$R_4 = \{60, 30, -30, -60, -30, 30\} \tag{2a}$$

$$R_5 = \{0, 60, 60, 0, -60, -60\} \tag{2b}$$

$$R_6 = \{60, 60, 60, 60, 60, 60\} \tag{2c}$$

Any torsion vector can be expressed exactly as a linear combination of three canonical torsion vectors F_i and three redundancy torsion vectors R_i:

$$T = \sum_{i=1}^{3} \lambda_i F_i + \sum_{i=4}^{6} \lambda_i R_i \tag{3}$$

Since all six canonical and redundancy vectors are orthogonal to each other, the λ_i coefficients of Eq. (3) can be determined by a simple projection of T on vectors $\{F_i, R_i\}$:

$$\lambda_i = \langle T|F_i \rangle / n_i^2 \tag{4}$$

where we use the $\langle P|S \rangle$ notation for the scalar product between torsion vectors P and S with components p_j, s_j:

$$\langle P|S \rangle = \sum_{i=1}^{6} p_i s_i \tag{5}$$

and n_i is the norm of F_i:

$$n_i = \sqrt{\langle F_i|F_i \rangle} \tag{6}$$

Let us call λ_i, i=1,2,3 of Eq. (3) the *canonical projection coefficients* and λ_i, $i = 4, 5, 6$ of (3) the *redundancy projection coefficients*. The redundancy contributions arise from the interdependence of the bending angles and torsion angles. Therefore, as long as no ring bending displacement is made, the torsional redundancy coefficients are zero. Similarly, as long as no torsional (out-of-plane) deformation is made, the analogous bending redundancy contributions are zero. For this reason, it is logical to *define* that puckering distortions can be expressed as a linear combination of F_1, F_2 and F_3 while any additional (i.e. redundancy) component of the torsion vector is considered as a ring bending distortion. These definitions follow the spirit of the natural internal coordinates introduced by Pulay and coworkers[27] with small differences in the notation and scaling that is specific to the problem of pyranose conformations.

From NMR coupling constants the full set of six torsion angles cannot be determined. By setting the redundancy contribution to zero, the missing torsion angles can be determined from the redundancy equations. We have to emphasize that this is only an approximation since this condition is exact only for infinitesimally small displacements from the regular hexagon. However Haasnoot studied the analogous Fourier transformation terms for a large database of organic ring structures and found this assumption to be valid.[26] Table 2 summarizes a useful set of expressions to determine

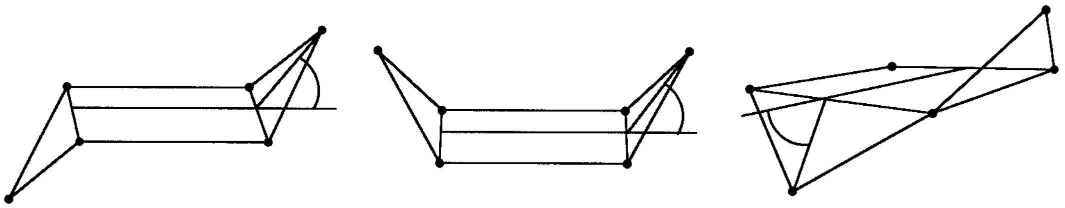


Figure 2. Interplanar angle as a measure of out-of-plane displacement in three canonical conformations.

the missing torsion angles for six-membered rings from a minimum set of three torsion angles. The derivation of these formulas is given in Appendix A.

The projection coefficients, λ, are dimensionless quantities whose unit value represents the displacement of a six-membered ring from planarity to an ideal conformation. Alternatively, the projection coefficients can be expressed in angular units (i.e. in degrees, or radian) by multiplying the projection coefficients by the value of the amplitude of torsion angle in the definition of the ideal conformations, which is 60°. The expression in angular units makes this definition independent of what degree of deformation is called ideal. For example, the chair conformation of cyclohexane, which is probably the closest to ideal conformation is characterized by torsion angles whose absolute value is less than the 60° considered ideal by Prelog[28] and Cano.[29]

2.2. Projective conformer identification

In analogy to the canonical projection coefficients, Eq. (4) can be used with all 38 basic conformations to determine the *basic projection coefficients* λ_i, $i = 1, \ldots, 38$. In practice, we only need to consider the chair, boat and twistboat projections coefficients since those of the intermediate envelope and halfchair conformations can be calculated from these.

Although one could use all projection coefficients to characterize a conformation, only three independent parameters are necessary for a complete characterization. To find the most suitable set of three parameters we first determine the most appropriate boat–twistboat pair of orthogonal conformations. Conformations i and j are considered orthogonal when the inner product of the corresponding torsion vectors, $\langle F_i | F_j \rangle = 0$. For example the $B_{1,4}$ and the $^{1,4}B$ boat conformations are orthogonal to the $^{O}S_2$ and the $^{2}S_O$ twistboat conformations. The closest matching conformation has the highest normalized projection coefficient relative to that of the orthogonal complementary conformations. This criteria can be quantified for any conformation j:

$$R_j = \lambda_j n_j / \lambda_k n_k \tag{7}$$

where conformation k represents the complementary orthogonal conformation to conformation j. While the values of canonical projection coefficients can be positive, negative or zero, one needs to consider only conformations with positive coefficients when searching for the most representative conformation. Projection coefficient corresponding to the $^{m}C_n$, $^{m,n}B$, or $^{m}S_n$ conformations are equal with the opposite sign to the coefficients corresponding to $^{n}C_m$, $B_{m,n}$, or $^{n}S_m$ conformations. In the following, conformation j and k will signify the basic boat and twistboat conformation pair with the maximum value of R_j. Let c stand for the chair conformation with the positive projection coefficient. Thus T can be expressed as a linear combination of the three most important orthogonal basic conformations c, j and k:

$$T = \lambda_c F_c + \lambda_j F_j + \lambda_k F_k \tag{8}$$

If the chair and boat or twistboat coefficients are comparable then T corresponds to an intermediate conformation of either envelope or halfchair type, respectively. In that case, T is best expressed as a linear combination of an intermediate type conformation plus a residual term which determine the direction of distortion from the intermediate conformation. Let us assume that the chair coefficient λ_c is larger than the boat or twistboat coefficient λ_j. In this case the conformation can be expressed as:

$$T = 2\lambda_c F_{j+c} + (\lambda_c - \lambda_j) F_j + \lambda_k F_k \tag{9}$$

where $j+c$ stands for the intermediate conformations between j and c conformations. In the derivation of Eq. (9) we use the fact that the intermediate conformations as defined by Prelog and Cano are equal, half and half mixtures of the two orthogonal components:

$$F_{j+c} = \tfrac{1}{2}(F_j + F_c) \tag{10}$$

Our criteria for a conformation to be considered of an intermediate type is:

$$1/2 < \lambda_c / \lambda_j < 2 \tag{11}$$

2.3. Length scaling

The intuitive stereochemical definition of puckering measures the displacement of an atom relative to the reference plane of four reference atoms which can be quantified by interplanar angles defined as shown in Fig. 2. Such interplanar angles conform to all expectations of intuitive stereochemistry but they cannot be defined for general conformations.[18] However, the projection coefficients defined here fulfill the same stereochemical criteria. Most importantly equal projection coefficients of chair, boat and twistboat type correspond to equally displaced conformations as it would be measured by the interplanar angle shown in Fig. 2. Consequently, the intermediate envelope and halfchair conformations have equal projection coefficients on the chair and on the boat or twistboat conformations. The consideration that the *Prelog and Cano type ideal conformations represent equal displacements from planarity* is dictated by intuitive stereochemistry and for this reason we call this choice of length scaling the *stereochemical length scaling*. Another practical choice is *normalized length scaling* by introducing normalization

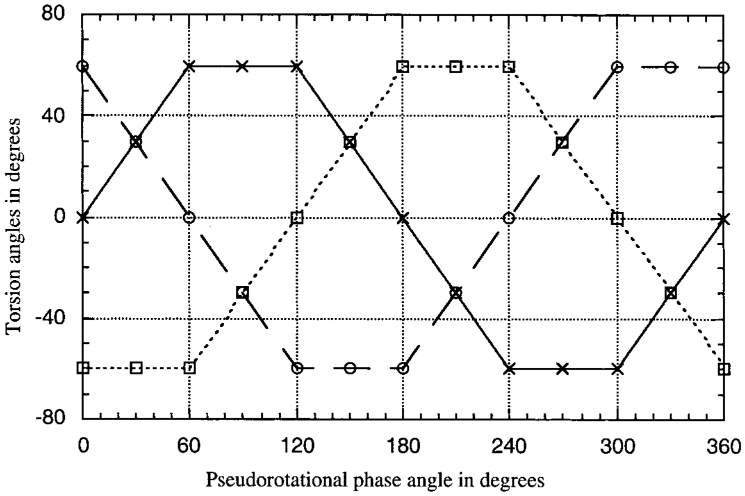


Figure 3. Endocyclic torsion angles of boat and twistboat conformations as a function of pseudorotational angle.

factors (*n* of Eq. (6)) which are unequal $\sqrt{6}\times 60$, 2×60, $\sqrt{3}\times 60$, $\sqrt{5}/2\times 60$ and $3/2\times 60$ degrees, for the ideal chair, boat, twistboat, envelope and halfchair type torsion vectors, respectively. The choice of length scaling is the source of inconsistency between the previous spherical polar coordinate representation and intuitive stereochemistry. Additional differences arise from the fact that the same Fourier transform term represents different distortions with torsion angles compared to Cartesian coordinates since they transform differently under the symmetry operations. For this reason, the CP and TF definitions of ring puckering are inconsistent not only with intuitive stereochemistry but also with one another. The CP definition puts the envelope and halfchair conformations at 54.7° ($\tan(\theta)=2^{1/2}$) and at 50.8° ($\tan(\theta)=(3/2)^{1/2}$), respectively, while their positions are interchanged in the TF definitions, the envelope being at 50.8° and the halfchair at 54.7° of azimuthal angles. On the basis of intuitive stereochemistry one would expect both the halfchair and envelope conformations to be equal mixtures of their respective basic conformations and thus appear at 45° of azimuthal angle in spherical representation.

We introduce a length scaling here that conforms to requirement that the boat and twistboat conformations are equally spaced on the equator of the conformational sphere and the intermediate envelope and halfchair conformations are halfway between the pole and the equator. Since the

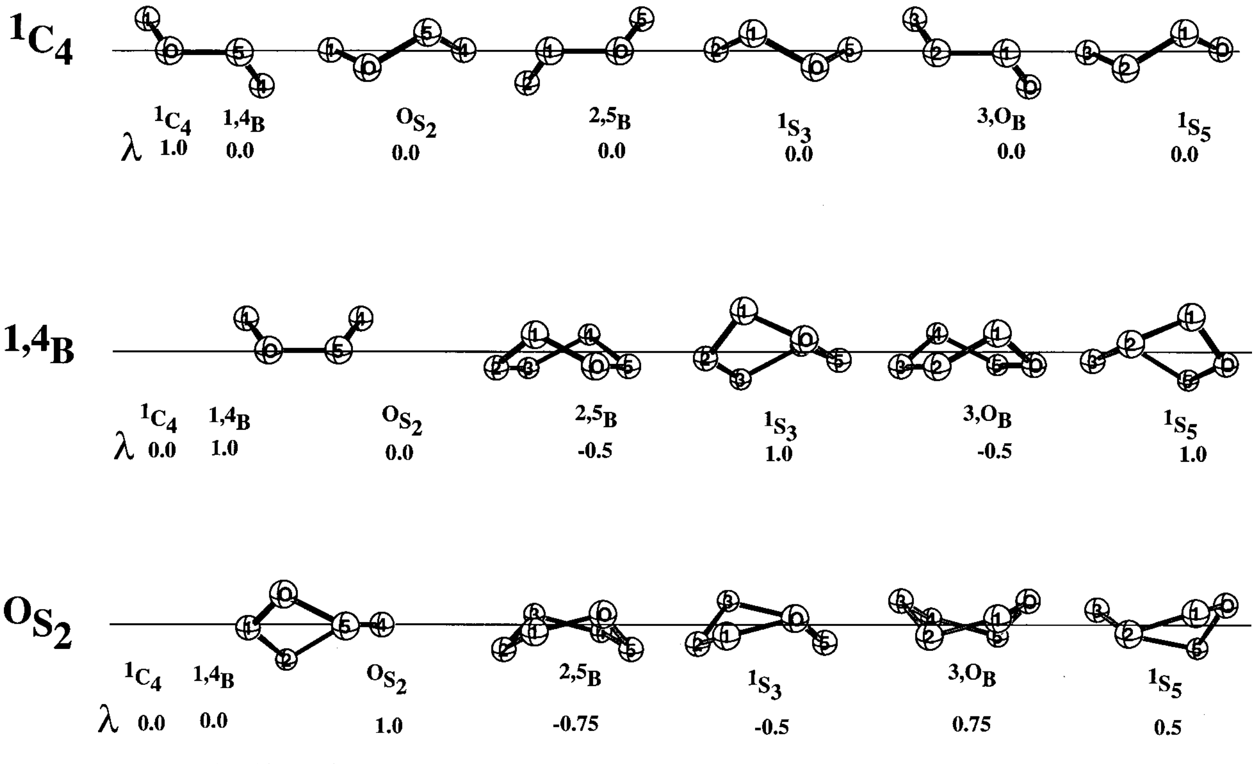


Figure 4. The projections of $^1C_4$, $^{1,4}B$ and $^OS_2$ conformations on the basic chair, boat and twistboat conformations.

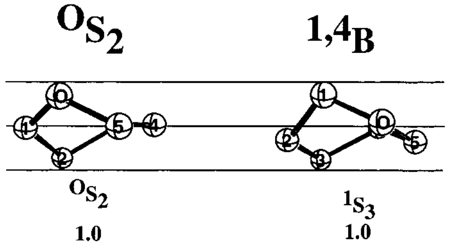


Figure 5. Comparison of the $^{O}S_2$ projection of $^{O}S_2$ ideal conformation and the $^{1}S_3$ projection of the ideal $^{1,4}B$ conformation.

pseudorotational phenomena is related to the mixing of two degenerate normal modes of the regular hexagon, the length scaling must include normalization factors to calculate the tangent of the pseudorotational phase angle:

$$\tan(\phi) = \lambda_{\text{boat}} n_{\text{boat}} / \lambda_{\text{twistboat}} n_{\text{twistboat}} \tag{12}$$

Eq. (12) is consistent with the CP definition that the zero value of the phase angle is at the $^{1,4}B$ conformation. The corresponding boat–twistboat amplitude can be calculated as:

$$q_{b+t} = (\lambda_b^2 n_b^2 + \lambda_t^2 n_t^2)^{1/2} \tag{13}$$

For the calculation of the azimuthal angle, however, we use a stereochemical length scaling to ensure that the envelope and halfchair conformations are equidistant from the pole and the equator. Thus we need to divide the normalized amplitude of Eq. (13) by the norm of the Prelog–Cano type torsion vectors. The norm, however, is different for boat and twistboat conformations and is a function of the pseudorotational phase angle. Fig. 3 shows the plot of three independent endocyclic torsion angles as a function of the phase angle of ideal conformations on the pseudorotational itinerary. Upon examination of the dependence of individual torsion angles on the phase angle, two important observations can be made: (i) there are always two torsion angles whose absolute value is 60°; (ii) two pairs of torsion angles whose sum of absolute values add up to 60°. Consequently, the norm can be expressed as

$$n(\phi) = [2 \times 60^2 + 2x^2 + 2(60 - x)^2]^{1/2} \tag{14}$$

where x is a number between 0.0 and 60.0 and is the remaining part of the phase angle after subtracting the largest integer multiple of 60.0. With the help of the normalization coefficient defined in Eq. (14), the tangent of the azimuthal angle can be calculated consistently with intuitive stereochemical definitions as:

$$\tan(\theta) = \frac{\lambda_c n(\phi)}{(\lambda_b^2 n_b^2 + \lambda_t^2 n_t^2)^{1/2}} \tag{15}$$

The overall spherical amplitude coordinate which measures the combined chair, boat and twistboat components can be expressed in a form that conforms to stereochemical length scaling using the normalization factor:

$$d = \{\lambda_c^2 + (\lambda_b^2 n_b^2 + \lambda_t^2 n_t^2)/n(\phi)^2\}^{1/2} \tag{16}$$

Although the above formalism could be simplified by adopting q_{b+t}, ϕ, and λ_c as the three representative parameters for the conformation, the full spherical representation was necessary to be compatible with the usual way CP parameters are reported.

3. Discussion

First we discuss the visual significance of the projection coefficients on examples. This is followed by some examples to demonstrate how to interpret the linear combination description of conformations and the utility of this method. Further, we make a general comparison between the method introduced here and previous suggestions.

4. Examples

In this section we make extensive reference to illustrations of some conformations from different reference viewing angles without which the text could not be understood. In addition to the printed figures in this article, we provide an internet site where the discussed ring structures can be viewed and rotated (http://www.nrc.ca/ibs/pucker-suppl.html) using a free plugin called Chime from MDL International (http://www.mdli.com).

Table 3. Characterization of ring conformation as linear combination of canonical reference conformations and redundancy terms

	$^{1}C_4$	$^{1,4}B$	$^{O}S_2$	R_4	R_5	R_6	Ref.
1	0.890	0.085	−0.188	0.001	0.005	0.009	30
2	−0.060	0.084	1.079	0.005	0.010	−0.003	31
3	0.625	−0.627	−0.010	0.005	−0.008	0.021	32
4A[a]	0.813	0.048	−0.189	−0.006	0.005	0.000	33
4B[a]	0.790	0.045	−0.188	−0.006	0.007	0.001	33
5	0.008	−0.039	−1.079	−0.016	0.005	0.019	33
6	0.814	−0.097	−0.174	−0.004	0.013	0.001	33
7A[a]	0.092	0.113	−1.067	−0.017	0.013	0.019	33
7B[a]	0.079	0.110	−1.064	−0.015	0.012	0.017	33
8A[a]	0.831	0.020	−0.176	−0.003	0.005	0.003	33
8B[a]	0.828	−0.019	−0.158	−0.001	0.004	0.008	33
9	0.841	0.038	−0.152	0.006	−0.032	−0.012	33
10	−0.475	−0.229	0.469	−0.003	−0.013	−0.008	34
11	−0.452	−0.360	0.420	0.000	−0.010	−0.010	34
12A[a]	−0.417	−0.275	0.489	−0.006	−0.008	0.000	34
12B[a]	−0.403	−0.263	0.519	−0.003	−0.004	0.003	34
13A[a]	0.439	0.069	−0.491	−0.003	0.011	0.004	34
13B[a]	0.413	0.123	−0.550	−0.002	0.012	0.001	34
14	−0.431	0.008	0.406	0.003	−0.017	−0.011	34
15	−0.388	−0.169	0.492	0.002	−0.007	−0.002	34
16	0.100	−0.528	0.674	−0.005	−0.012	−0.011	32
17	−0.201	0.568	−0.346	0.002	0.011	0.003	32
18	−0.173	0.016	0.903	0.007	−0.012	−0.015	37
19	−0.267	−0.019	0.898	0.007	−0.012	−0.016	37
20	−0.504	0.056	0.558	0.004	−0.011	−0.012	38
21	−0.098	0.810	0.169	−0.008	0.012	−0.007	39
22	−0.330	0.271	0.744	0.002	−0.009	−0.013	40
23	−.017	.021	−1.125	−.019	.016	.001	42
24	.042	−.827	.046	−.005	.008	−.089	42
25	−.014	.001	−1.204	−.022	−.002	−.002	42
26	−.349	.628	.000	.000	.000	.093	43
27	−.283	.759	−.499	.022	−.014	.092	44
28	−.322	.804	.163	−.001	−.021	.092	44
29	.799	−.386	−.038	−.003	.013	.003	44
30	−1.012	−.126	−.025	−.008	−.022	−.082	45
31	.758	−.377	.021	.000	−.012	.003	45
32	.016	−.758	−.581	.026	.017	−.113	46
33	−.613	.629	.026	−.001	.002	.061	47

[a] A and B refer to two different crystal structures of the same compound.

Table 4. Characterization of ring conformation as linear combination of the most representative basic conformations

	Chair–boat–twistboat combination						Intermediate conformations where necessary					
1	0.890	${}^{1}C_{4}$	0.184	$B_{3,O}$	0.009	${}^{5}S_{1}$						
2	0.060	${}^{4}C_{1}$	0.084	${}^{1,4}B$	1.079	${}^{O}S_{2}$	1.079	${}^{O}S_{2}$	0.119	${}^{4}E$	0.013	${}^{1,4}B$
3	0.625	${}^{1}C_{4}$	0.627	$B_{1,4}$	0.010	${}^{2}S_{O}$	1.249	E_{4}	0.010	${}^{2}S_{O}$	0.002	$B_{1,4}$
4A[a]	0.813	${}^{1}C_{4}$	0.166	$B_{3,O}$	0.047	${}^{5}S_{1}$						
4B[a]	0.790	${}^{1}C_{4}$	0.164	$B_{3,O}$	0.049	${}^{5}S_{1}$						
5	0.008	${}^{1}C_{4}$	0.039	$B_{1,4}$	1.079	${}^{2}S_{O}$	1.079	${}^{2}S_{O}$	0.039	$B_{1,4}$	0.008	${}^{1}C_{4}$
6	0.814	${}^{1}C_{4}$	0.179	${}^{2,5}B$	0.011	${}^{3}S_{1}$						
7A[a]	0.092	${}^{1}C_{4}$	0.113	${}^{1,4}B$	1.067	${}^{2}S_{O}$	1.067	${}^{2}S_{O}$	0.183	${}^{1}E$	0.021	${}^{1,4}B$
7B[a]	0.079	${}^{1}C_{4}$	0.110	${}^{1,4}B$	1.064	${}^{2}S_{O}$	1.064	${}^{2}S_{O}$	0.158	${}^{1}E$	0.031	${}^{1,4}B$
8A[a]	0.831	${}^{1}C_{4}$	0.020	${}^{1,4}B$	0.176	${}^{2}S_{O}$						
8B[a]	0.828	${}^{1}C_{4}$	0.019	$B_{1,4}$	0.158	${}^{2}S_{O}$						
9	0.841	${}^{1}C_{4}$	0.133	$B_{3,O}$	0.038	${}^{5}S_{1}$						
10	0.475	${}^{4}C_{1}$	0.467	${}^{3,O}B$	0.006	${}^{1}S_{5}$	0.933	${}^{0}E$	0.011	${}^{4}H_{5}$	0.003	${}^{4}C_{1}$
11	0.452	${}^{4}C_{1}$	0.495	${}^{3,O}B$	0.150	${}^{5}S_{1}$	0.904	${}^{0}E$	0.150	${}^{5}S_{1}$	0.043	${}^{3,O}B$
12A[a]	0.417	${}^{4}C_{1}$	0.504	${}^{3,O}B$	0.031	${}^{5}S_{1}$	0.833	${}^{0}E$	0.087	${}^{3,O}B$	0.031	${}^{5}S_{1}$
12B[a]	0.403	${}^{4}C_{1}$	0.521	${}^{3,O}B$	0.003	${}^{5}S_{1}$	0.806	${}^{0}E$	0.118	${}^{3,O}B$	0.003	${}^{5}S_{1}$
13A[a]	0.439	${}^{1}C_{4}$	0.069	${}^{1,4}B$	0.491	${}^{2}S_{O}$	0.878	${}^{5}H_{0}$	0.069	${}^{1,4}B$	0.052	${}^{2}S_{O}$
13B[a]	0.413	${}^{1}C_{4}$	0.123	${}^{1,4}B$	0.550	${}^{2}S_{O}$	0.826	${}^{5}H_{0}$	0.137	${}^{2}S_{O}$	0.123	${}^{1,4}B$
14	0.431	${}^{4}C_{1}$	0.008	${}^{1,4}B$	0.406	${}^{O}S_{2}$	0.811	${}^{0}H_{5}$	0.025	${}^{4}C_{1}$	0.008	${}^{1,4}B$
15	0.388	${}^{4}C_{1}$	0.453	${}^{3,O}B$	0.077	${}^{1}S_{5}$	0.777	${}^{0}E$	0.077	${}^{1}S_{5}$	0.065	${}^{3,O}B$
16	0.100	${}^{1}C_{4}$	0.769	${}^{3,O}B$	0.191	${}^{5}S_{1}$	0.769	${}^{3,O}B$	0.199	${}^{5}H_{4}$	0.091	${}^{5}S_{1}$
17	0.201	${}^{4}C_{1}$	0.025	$B_{2,5}$	0.741	${}^{1}S_{3}$						
18	0.173	${}^{4}C_{1}$	0.016	${}^{1,4}B$	0.903	${}^{O}S_{2}$						
19	0.267	${}^{4}C_{1}$	0.019	$B_{1,4}$	0.898	${}^{O}S_{2}$						
20	0.504	${}^{4}C_{1}$	0.056	${}^{1,4}B$	0.558	${}^{O}S_{2}$	1.008	${}^{0}H_{5}$	0.056	${}^{1,4}B$	0.054	${}^{O}S_{2}$
21	0.098	${}^{4}C_{1}$	0.810	${}^{1,4}B$	0.169	${}^{O}S_{2}$						
22	0.330	${}^{4}C_{1}$	0.694	$B_{2,5}$	0.101	${}^{3}S_{1}$						
23	0.017	${}^{4}C_{1}$	0.021	${}^{1,4}B$	1.125	${}^{2}S_{6}$						
24	0.042	${}^{1}C_{4}$	0.827	$B_{1,4}$	0.046	${}^{6}S_{2}$						
25	0.014	${}^{4}C_{1}$	0.001	${}^{1,4}B$	1.204	${}^{2}S_{6}$						
26	0.349	${}^{4}C_{1}$	0.628	${}^{1,4}B$	0.000	${}^{6}S_{2}$	0.697	${}^{4}E$	0.279	${}^{1,4}B$	0.000	${}^{6}S_{2}$
27	0.283	${}^{4}C_{1}$	0.005	$B_{2,5}$	1.009	${}^{1}S_{3}$						
28	0.322	${}^{4}C_{1}$	0.804	${}^{1,4}B$	0.163	${}^{6}S_{2}$	0.644	${}^{4}E$	0.482	${}^{1,4}B$	0.163	${}^{6}S_{2}$
29	0.799	${}^{1}C_{4}$	0.386	$B_{1,4}$	0.038	${}^{2}S_{6}$	0.772	E_{4}	0.393	${}^{1}C_{4}$	0.038	${}^{2}S_{6}$
30	1.012	${}^{4}C_{1}$	0.126	$B_{1,4}$	0.025	${}^{2}S_{6}$						
31	0.758	${}^{1}C_{4}$	0.377	$B_{1,4}$	0.021	${}^{6}S_{2}$	0.754	E_{4}	0.381	${}^{1}C_{4}$	0.021	${}^{6}S_{2}$
32	0.016	${}^{1}C_{4}$	0.057	$B_{3,6}$	1.049	${}^{5}S_{1}$						
33	0.613	${}^{4}C_{1}$	0.629	${}^{1,4}B$	0.026	${}^{6}S_{2}$	1.226	${}^{4}E$	0.016	${}^{1,4}B$	0.026	${}^{6}S_{2}$

[a] A and B refer to two different crystal structures of the same compound.

As we stated above, each coefficient represents a quantitative description of displacements of an atom pair in either in the same (boat) or in opposite (chair, twistboat) directions with respect to a reference plane. First, we demonstrate the visual significance of the basic projection coefficients on the example of the ideal ${}^{1}C_{4}$ chair, ${}^{1,4}B$ boat, and ${}^{O}S_{2}$ twistboat conformations. Fig. 4 shows these three conformations from six different viewing angles corresponding to the ${}^{1}C_{4}$, ${}^{1,4}B$, ${}^{O}S_{2}$, ${}^{2,5}B$, ${}^{1}S_{3}$, ${}^{3,O}B$, and ${}^{5}S_{1}$ basic projections. The ${}^{1}C_{4}$, ${}^{1,4}B$ and ${}^{O}S_{2}$ projections of the conformations are best viewed by looking at the molecule either through the projection of the C_1–C_4 axis on the reference plane or perpendicular to this direction in the reference plane. To keep the illustration simple and easy to follow we show only the viewing angles perpendicular to the C_1–C_4 axis in Fig. 4. For the interpretation of the ${}^{1}C_{4}$, and ${}^{1,4}B$ projections, the molecule is best viewed at from a direction such that atoms C_2, C_3, C_5 and O are rotated into one plane as much as possible around the C_1–C_4 axis and viewed perpendicular to the C_1–C_4 axis. The parallel displacement of the atom pair up or down with respect to the atoms C_2, C_3, C_5 and O plane represents the boat type distortion while the antiparallel displacement of the same two atoms corresponds to the chair type distortions. The ${}^{O}S_{2}$ conformation can also be best viewed at perpendicular to the C_1–C_4 axis, but rotated in such a way that the C_1, C_3, C_4 and C_5 atoms are in one plane as much as possible. Similarly, the ${}^{2,5}B$ and ${}^{3}S_{1}$ projections correspond to the C_2–C_5 viewing axis while the ${}^{3,O}B$ and ${}^{1}S_{5}$ projection coefficients are best interpreted viewing perpendicular to the C_3–O axis. To be consistent with the IUPAC nomenclature, the atoms are numbered clockwise looking from the top of the molecule and the lower numbered atoms are always on the left side of the picture.

We take the ideal ${}^{1,4}B$ conformation as an example which has nonzero projection on all other boat and twistboat conformations. Viewing the ${}^{1,4}B$ conformation perpendicular to the C_2–C_5 axis, atoms C_2 and C_5 are below the average plane defined by the rest of the atoms which is expressed in the -0.5 value of the ${}^{2,5}B$ projection coefficient. (See Fig. 4). In this case, the reference plane should be considered as an average plane of C_1, C_3, C_4 and O, since the reference atoms do not lie in the same plane. Looking perpendicular to the C_2–C_5 axis but regarding the opposite displacements of atoms C_1 and C_3 with respect to the C_2, C_4, C_5 and O average plane, we see that these two atoms are very much displaced from the reference plane and the magnitude of displacement is similar as the displacement of atoms C_1 and C_4 from the C_2, C_3, C_5, and O reference plane. Accordingly, the ${}^{1}S_{3}$ projection coefficient of the ${}^{1,4}B$ conformation is unity. This is an interesting finding, since it means that the largest projection coefficient does not necessarily correspond to the

Table 5. Characterization of ring conformation in terms of spherical polar parameters

	Amplitude		Phi		Theta	
	Eq. (16)	CP	Eq. (12)	CP	Eq. (15)	CP
1	0.91	0.54	298	296	12	12
2	1.08	0.79	85	88	93	92
3	0.89	0.68	181	180	45	56
4A[a]	0.83		286		13	
4B[a]	0.81		285		13	
5	1.08		268		90	
6	0.83		237		13	
7A[a]	1.07		277		85	
7B[a]	1.07		277		86	
8A[a]	0.85		277		12	
8B[a]	0.84		262		11	
9	0.85		286		10	
10[b]	0.67	0.44	119	119	135	128
11[b]	0.73	0.47	135	137	129	124
12A[ab]	0.66	0.45	123	122	129	128
12B[ab]	0.66	0.47	120	118	128	120
13A[ab]	0.66	0.42	279	276	48	53
13B[ab]	0.69	0.44	284	282	53	58
14[b]	0.59	0.37	89	85	137	132
15[b]	0.62	0.41	112	111	128	123
16	0.87	0.63	132	131	83	82
17	0.77	0.53	332	332	105	105
18	0.92	0.63	89	87	101	97
19	0.94	0.64	91	89	107	102
20	0.75	0.49	83	80	132	128
21	0.89	0.69	10	11	96	96
22	0.79	0.59	67	65	115	108
23	1.12	0.74	271	271	91	91
24	0.83	0.83	177	178	87	96
25	1.20	0.81	270	270	91	90
26	0.72	0.60	0	0	119	107
27	1.05	0.79	330	333	106	94
28	0.90	0.78	10	10	111	95
29	0.89	0.52	185	186	26	26
30	1.02	0.71	190	191	173	158
31	0.85	0.53	177	175	27	33
32	1.05	0.82	214	210	89	95
33	0.88	0.60	2	2	134	119

[a] A and B refer to two different crystal structures of the same compound.

[b] The CP parameters calculated by Lichtenthaler et al. have been converted to conform with the carbohydrate atom numbering starting with C_1 and consequently, the $^{1,4}B$ conformer being at 0° angle and the $^{1}C_4$ conformation on the top hemisphere.

closest basic conformation. As we have mentioned above, the most suitable basic conformation is the conformation which has the highest normalized projection coefficient relative to the orthogonal projections (Eq. (7)).

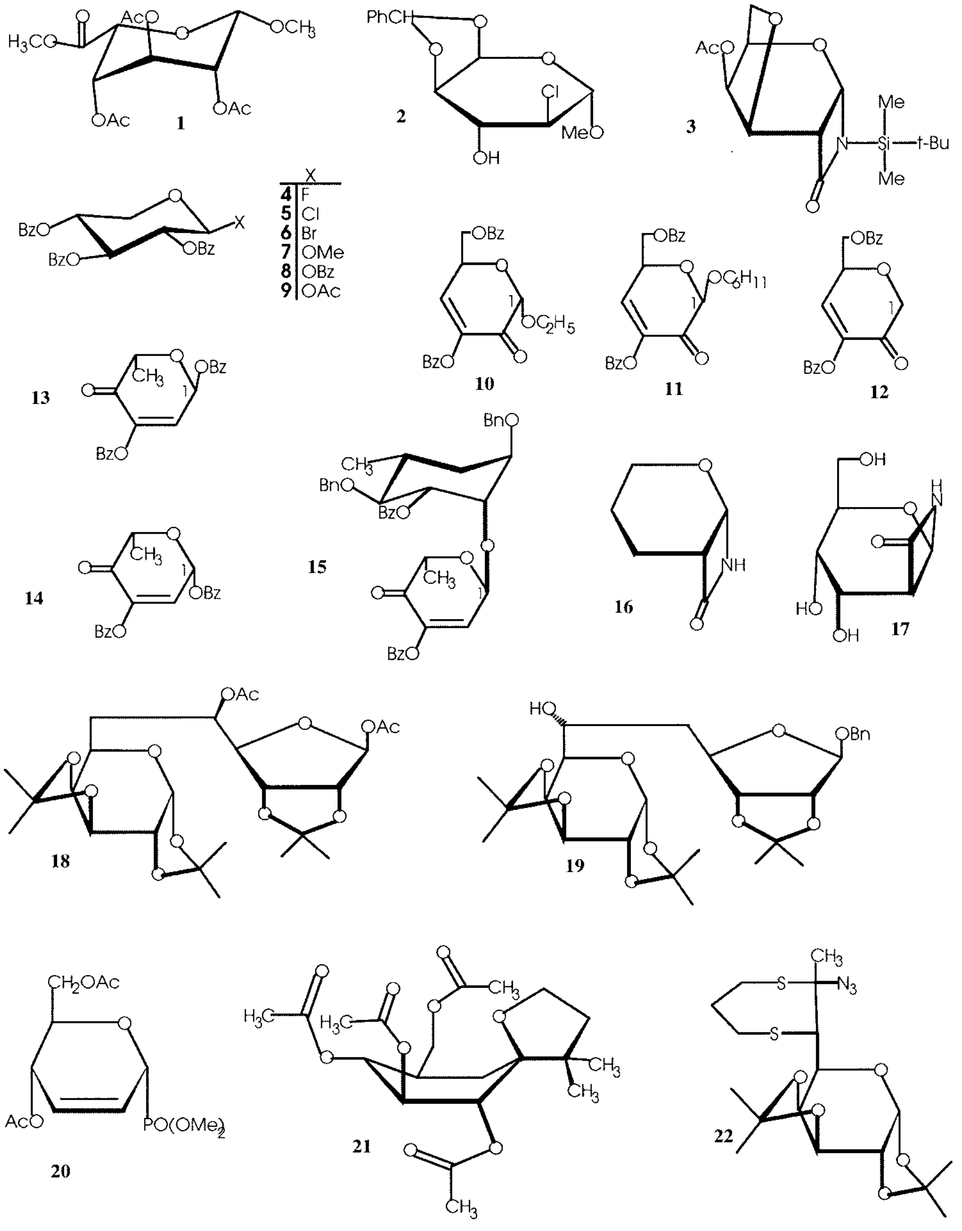
The $^{O}S_2$ conformation is shown on the third panel of Fig. 4 and similarly to the $^{1,4}B$ conformation this conformation also has nonzero projections on other boat and twistboat conformations. The -0.75 value of the $^{2,5}B$ projection coefficient signifies that atoms C_2 and C_5 are displaced parallel and below the average plane of atoms C_1, C_3, C_4 and O. Looking at the values of the coefficients and the relative displacements of the atoms, we see that the larger coefficients indeed represent larger displacements with respect to the reference plane. For example, the $^{1}S_3$ coefficient of the $^{1,4}B$ conformation is equal to the $^{O}S_2$ projection onto itself. By looking at these two conformations from the corresponding viewing angles the displacements are indeed equal which is illustrated in Fig. 5.

Out of all the projection coefficients any three independent projections uniquely describes the conformation. Table 3 includes the characterization of selected pyranose conformations in terms of linear combinations of the three canonical reference conformations and the three redundancy terms corresponding to Eq. (4). The three most suitable projection coefficients based on Eqs. (8) and (9) are listed in Table 4. The left side of Table 4 uses only chair, boat and twistboat type conformations as the basis for description while equivalent description in terms of intermediate conformations is provided on the right side, when appropriate. The redundancy coefficients in Table 3 are generally significantly smaller than the puckering coefficients in agreement with previous findings of Haasnoot[26] and Zefirov et al.[25] Table 5 affords the characterization of the conformation in terms of spherical polar coordinate representation introduced in Eqs. (12), (15) and (16) and compares them to the Cremer–Pople parameters where these are available.

Methyl (methyl 2,3,4-tri-*O*-acetyl-β-L-idopyranoside) Uronate (**1**) (Scheme 1) crystallizes in the $^{1}C_4$ conformation contrary to most pyranoses which prefer the $^{4}C_1$ conformation.[30] In terms of canonical conformations **1** is described as 0.89 $^{1}C_4$, 0.09 $^{1,4}B$ and -0.19 $^{O}S_2$ (Table 3). The description in terms of the most suitable set of basic conformation is 0.89 $^{1}C_4$, 0.18 $B_{O,3}$ and 0.01 $^{5}S_1$ (Table 4). Essentially this is a $^{1}C_4$ chair conformation which is flattened at the C_3 end. Throughout this paper, we use the dimensionless projection coefficients which take the ideal conformation as a reference. However, we show on this example how one may interpret the same coefficients in angular units obtained simply by multiplying the dimensionless coefficients with the torsion angle amplitude of the ideal conformations, which is 60°. The conformation of **1** is described in angular units by the 53.4° $^{1}C_4$, 10.8° $B_{O,3}$ and 0.6° $^{5}S_1$ expression which signifies that the conformation can be derived from a planar conformation with the set of three displacements: (i) all torsion angles are displaced by 53.4° towards $^{1}C_4$ with alternating signs starting with negative displacements at τ_1, (ii) τ_2, τ_5 are displaced by 10.8° and τ_1, τ_4 by $-10.8°$ towards $B_{O,3}$ and, (iii) τ_3, τ_6 are displaced by 0.6° and τ_1, τ_2, τ_4, τ_5 by $-0.3°$ towards $^{5}S_1$.

4,6-*O*-(*S*)-Benzylidene-2-chloro-2-deoxy-α-D-idopyranoside (**2**) (Scheme 1) is a rare example of a pyranose which crystallizes in a twistboat conformation.[31] This conformation can be described as a linear combination of 1.08 $^{O}S_2$, 0.08 $^{1,4}B$ and 0.06 $^{4}C_1$. Fig. 6 shows this conformation from the appropriate viewing angles. As expected from the coefficients, the boat and the chair components are so insignificant that they are not noticeable.

4-*O*-Acetyl-3,6-anhydro-*N*-(tert-butyldimethylsilyl)-2-C:α-*N*-carbonyl-2-deoxy-α-D-galactopyranosylamine[32] (**3**) (Scheme 1) is an excellent example to show the significance of the length scaling adopted in our definition of the azimuthal angle and also that of the linear combinations. The conformation of **3** is close to an ideal envelope (shown in Fig. 7) which can be shown by the equal contributions from the $^{1}C_4$ (0.625) and the $B_{1,4}$ (0.627) boat conformations. In terms of spherical polar coordinates this conformation is found exactly halfway, at $\theta=45°$ based on the definition introduced in Eq. (15), but described by a

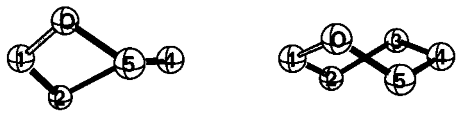


Scheme 1. The structures of **1**–**22**.

θ_{CP}=56° azimuthal angle based on Cremer–Pople parameters. The quantitative description in terms of the 1.25 E_4 conformation (Table 4) suggest a large envelope type distortion which can also be quantified by the corresponding interplanar angle of 67° (i.e. defined in Fig. 2), in comparison to the ideal value of 54.74°.

Lichtenthaler and Lindner determined the crystal structures of 2,3,4-tri-*O*-benzoyl-β-D-xylopyranosyl derivatives, namely fluoride (**4**), chloride (**5**), and bromide (**6**), methyl glycoside (**7**), 1-*O*-benzoyl (**8**) and 1,2-dichloride (**9**) (Scheme 1).[33] The conformation of these compounds is characterized as either a distorted $^1C_4$, or ^2S_O conformation. The distortion from the $^1C_4$ is mainly oriented towards the ^5H_O conformation which is the intermediate between $^1C_4$ and ^2S_O. In addition, to the distortion towards the ^5H_O half-chair conformation, these conformations are described as flattened at the C_2 or the C_3 end of the chair. Although, these qualitative conformational descriptions are correct, the linear combination description allows a more precise definition of the direction of the distortion. Table 4 reveals that **5**, has an essentially undistorted ^2S_O conformation while **7** has a ^2S_O conformation with distortion in the direction of the $^{1,4}B$ and $^1C_4$ which results in an overall displacement of C_1 towards the ^1E conformation.

While **4** and **6** are described in the original paper as $^1C_4$ distorted towards ^5H_O conformation with flattening of the chair at the C_3 and C_2 atoms, respectively. The linear combination description shows that the distortion is better characterized as toward the $B_{3,O}$ (or E_O) and $^{2,5}B$ (^5E) directions. In other words, **4** and **6** are overall flattened at atom C_3 and C_2 and the twisting distortion is only a minor contribution. In this case the linear combination description has a clear advantage of quantitatively describing the distortion. When the distortions are relatively small, it is difficult to tell



2 from different viewing angles

Figure 6. The pyranose ring atoms of **2** from different viewing angles.

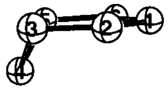


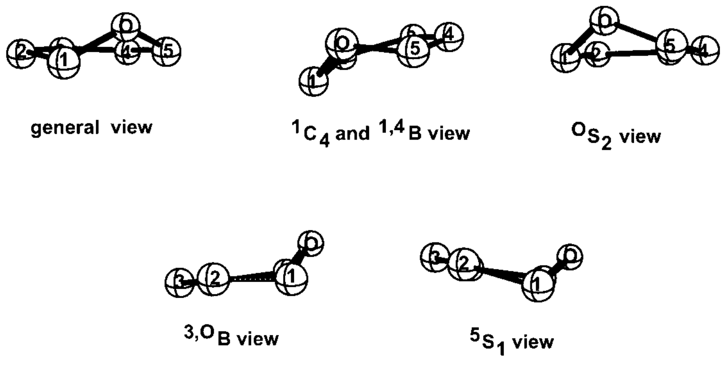
Figure 7. The conformation of **3**.

visually if they are along the $B_{3,0}$, ^2S_O or the $^{2,5}B$ directions, since these types of distortions have very high projections on each other. For example, the distortion of **4** from the chair conformation can be quantified as 0.166 $B_{O,3}$ and 0.047 $^5S_1$ ($R(B_{O,3})=4.08$) or alternatively as 0.189 ^2S_O and 0.048 $^{1,4}B$ ($R(^2S_O)=3.41$). Both descriptions are correct but the first one is the most representative according to the criteria in Eq. (7). The second alternative is useful when the conformations of **4** and **6** are compared.

Lichtenthaler et al. studied 2,6-*cis*- and 2,6-*trans*-substituted dihydropyronones (**10** through **15**, see Scheme 1). They found an unusual conformation between an envelope and a halfchair conformations which they called skewboat.[34] 2,6-*cis*-substituted dihydropyronone **11** is described by a pseudorotational phase angle of 135° which is exactly halfway between the 120° of the ^OE or 150° of the $^OH_1$ conformations.[35] The conformation of **11** is described as a combination of −0.452 $^1C_4$, −0.361 $^{1,4}B$ and 0.420 $^OS_2$ in terms of canonical conformations (Table 3). Viewing **11** from the direction perpendicular to the C_1–C_4 axis, atom C_1 is significantly displaced below the plane while atoms C_4 is only slightly above the reference plane (Fig. 8). This description is consistent with the similar magnitude negative coefficients for the $^1C_4$ and the $^{1,4}B$ projections which results from C_1 being displaced from the plane while C_4 is in the reference plane. The boat and twistboat components are better represented by the 0.496 $^{O,3}B$, and 0.151 $^5S_1$ combinations. The boat component almost exactly equals to the chair component which results in the cancellation of the displacement of C_3 but the reinforcement of the displacement of O which yields the ^OE envelope conformation with a coefficient of 0.902 (Table 4). The residual term, the 0.045 $^{O,3}B$ component represents a small displacements of both the O and C_3 atoms above the plane from the ^OE conformation which is visually not noticeable looking at the molecule perpendicular to the O–C_3 vector (Fig. 8). Note that the $^{O,3}B$ coefficients are different in the two previous descriptions since ^OE itself has 50% $^{O,3}B$ contribution. The 0.151 $^5S_1$ represents a small but significant twisting of the conformation about an axis parallel to the O–C_3 vector (shown in (Fig. 8) with corresponding displacements of C_1 below and C_5 above the reference plane.

Since the conformation of **11** is also close to the $^OH_1$ ideal conformation, it can be alternatively described by the 0.452 $^4C_1$, 0.571 $^3S_1$ and 0.135 $B_{2,5}$ linear combination which can be further converted to 0.904 $^OH_1$, 0.119 $^3S_1$ and 0.135 $B_{2,5}$ combination. In this case the envelope and the halfchair descriptions are equally suitable. This example shows the weakness of any conformational classification and characterization method, including the one proposed here, that rely on the chair, boat, twistboat, envelope and halfchair conformations. Even the most symmetrical, saturated six-membered ring compound, cyclohexane, has stationary points on the potential surface which cannot be classified as any of these five basic conformations.[36] The proposal of Lichtenthaler et al. to name a new class of conformations 'skewboat' is especially worth considering in the light of these results.[34] Further examples in Table 5 which could benefit from an intermediate description include **13B**, **16**, and **21**.

The ideal skewboat intermediate conformation between ^OE and $^OH_1$ is characterized by the torsion vector of (7.5, 0.0, −22.5, 52.5, −60.0, 37.5). Similarly we may define intermediate torsion vectors between the boat and the twistboat conformation and describe the conformations on this basis. For example, the conformation of **11** can be expressed by 0.452 $^4C_1$, 0.569 $^{O,3}B/^3S_1$ and 0.013 $^5S_1/B_{2,5}$ linear combination where the last two coefficients correspond to conformations intermediate between the boat and the twistboat. The large difference between the last two coefficients shows that this description is the most appropriate. Alternatively, this conformation can be described as 0.904 $^OE/^OH_1$, 0.117 $^{O,3}B/^3S_1$ and 0.013 $^5S_1/B_{2,5}$ linear combination. An advantage of the linear combination description is that the residual term 0.117 $^{O,3}B/^3S_1$ clearly indicates that this conformation is closer to the pseudorotational itinerary



general view

$^1C_4$ and $^{1,4}B$ view

$^OS_2$ view

$^{3,O}B$ view

$^5S_1$ view

Figure 8. The conformation of **11**.

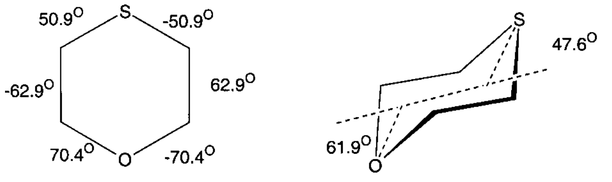


Figure 9. The conformation of the oxithiene ring.

than to the chair conformation. The CP azimuthal angle which is 124° indicates the same direction of distortion from the intermediate conformations, but its magnitude is somewhat ambiguous. In the CP definition the intermediate envelope and halfchair conformations are at 130 and 126° on the $^4C_1$ hemisphere. Based both on the linear combination description, and based on the azimuthal angles calculated from Eq. (15), which is 130° it is clear that the chair component is significantly smaller.

Further examples included in Tables 3–5 but not discussed in detail are 8-aza-2-oxabicyclo-[4.2.0]ocatan-one (**15**),[32] 2-C:1-*N*-carbonyl-2-deoxy-β-D-altropyranosylamine, (**17**),[32] 6-deoxy-6-C-(1,5-di-*O*-acetyl-2,3-*O*-isopropylidene-β-D-allo-pentofuranos-5-yl)-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose, (**18**),[37] 6-C-(benzyl 5-deoxy-2,3-*O*-isopropylidene-β-D-ribofuranosid-5-yl)-1,2:3,4-di-*O*-isopropylidene-D-*glycero*-α-D-*galacto*-hexopyranose (**19**),[37] a 2,3-unsaturated glycosyl phosphonate **20**,[38] tetra-*O*-acetyl-2,3,4,6-Desoxy-1β-D-Glucopyrannoside-1-spiro-2′-(methyl-3′tetrahydrofurannol-3′) (**21**),[39] 7-azido-8-deoxy-1,2,3,4-di-*O*-isopropyliden-6,7-*S*,*S*-trimethylene-6,7-dithio-α-*erythro*-D-*galacto*-octopyranose, (**22**) (Scheme 1).[40]

The 4-oxathiane ring has been used as an example to demonstrate the failure of the CP description of ring conformations.[25,26] The observed conformation of 4-oxathiane in 4-oxathianium bis(carbomethoxy)-methylide[41] shown in Fig. 9 indicates that the conformation is best described as a combination of a ^SC_O and $B_{S,O}$ conformations. On the other hand the CP-puckering parameters (Q_{CP}=0.648 Å, ϕ_{CP}=180°, θ_{CP}=0°) describe it as an undistorted chair. We describe this conformation as a linear combination of 1.02 ^SC_O and 0.16 $B_{S,O}$ conformations. The qualitative description is in line with the stereochemical description of this conformation by interplanar angles of 61.9 and 47.6° at the oxygen and sulfur ends, respectively. In terms of spherical polar coordinates based on the definitions introduced here, this conformation is described by d=1.04, ϕ=180°, θ=9° which indicates some distortion from the chair conformation in the direction of flattening the sulfur end of the ring. Additional examples for the failure of CP formalism can be found in Refs. 25 and 26.

DaCruze and Zimmer have surveyed the conformations of transition metal containing six-membered rings by searching the Cambridge Structural Database.[15] We selected some examples of this data set represented by structures **23** through **33** whose ring shapes and the atom numbering are shown in Fig. 10. This set of more than seven hundred cobalt(III), nickel(II) and copper(II) containing rings have shown that most inorganic rings prefer chair conformations. There are 70 boat and 41 twistboat conformations, most of which are nickel and cobalt containing rings. Metal containing ring systems provide a stringent test for any quantitative method of characterization of ring shapes. The bond length and the bond angles are different from the organic analogues and these features bring out the weaknesses of quantitative conformational descriptions. For example, Table 3 shows that the redundancy coefficients corresponding to the metal containing rings can be much more significant than those of pyranoses. Table 5 shows that the azimuthal angle in the CP definition differs from ours by more than 10° for **27**, **28**, **30**, and **33**. The CP definition can be misleading when applied to systems with largely unequal bond length.

4. Comparison with other definitions

One of the arguments against torsion angles based definition was that the expression of individual torsion angles in terms of puckering parameters is only approximate and for this reason the puckering amplitude depends on the atom numbering.[19] Since our derivation provides an exact relationship between puckering parameters and torsion angles through Eq. (3), the effect of neglecting the redundancy terms can be examined and concerns about the dependence of the puckering parameters on atom numbering can be addressed. The puckering terms are separable from the redundancy terms upon permutation of atom numbering due to their symmetry properties.

To demonstrate the effect of ring bending deformation on

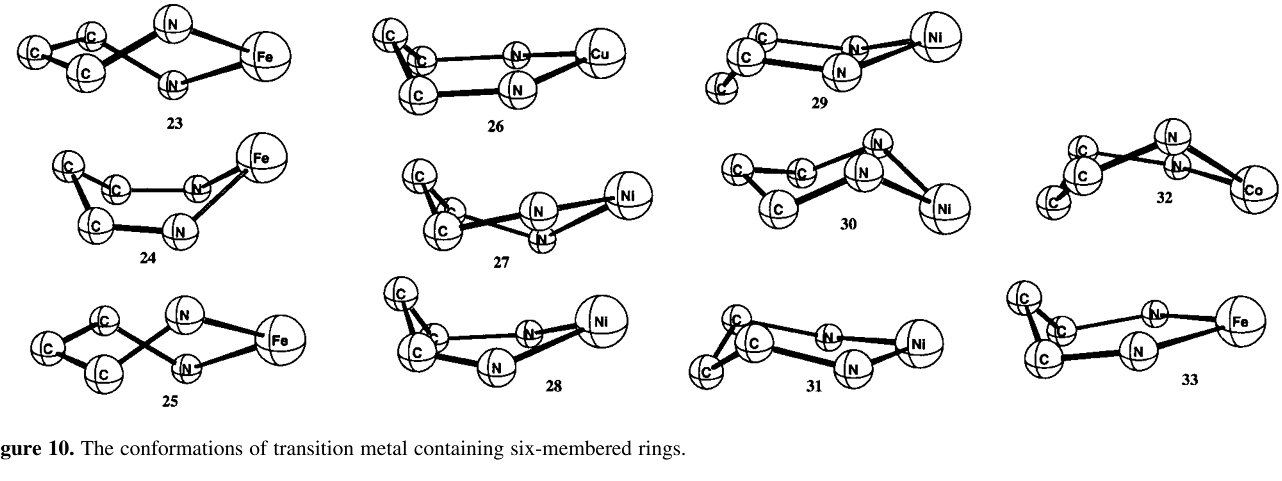


Figure 10. The conformations of transition metal containing six-membered rings.

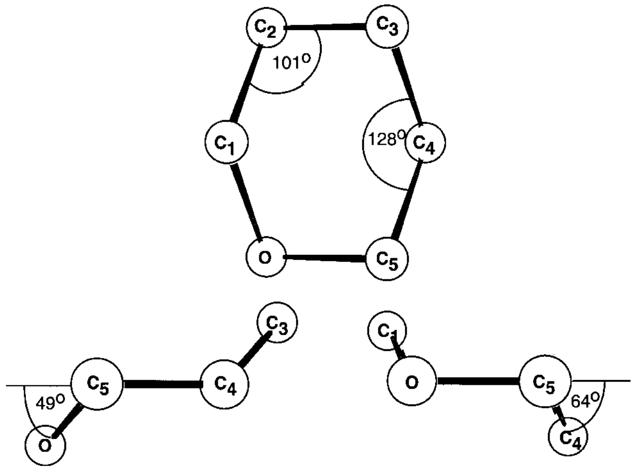


Figure 11. The effect of redundancy contribution on the chair conformation.

the puckering of the ring we choose the example of a chair conformation with severely distorted ring bending angles. The conformation shown in Fig. 11 has equal bond lengths but unequal bending angles; four of which are 101° and two are 128° as opposed to the undistorted ring with bending angles of 120°. This conformation has a unit projection coefficient on the ideal chair conformation, but due to the redundancy contribution, the torsion vector is (48, −66, 66, −48, 66, −66) as opposed to the ideal chair of (60, −60, 60, −60, 60, −60). As shown in Fig. 11, atoms C_1 and C_4 are more displaced from the reference plane than in the ideal chair without ring bending. The corresponding interplanar angle, the stereochemical measure of out-of-planarity, increases from 55 to 64° upon ring bending. However, the interplanar angle corresponding to atoms C_2, C_3, C_5 and O are all 49° which is smaller than in the undistorted ring. The average of all interplanar angles changes only insignificantly (less than 1°) upon large ring bending distortion. This example shows that our measure of puckering is consistent with the stereochemical measure of puckering even for rings with strong bending distortions or redundancy contribution. The effect of similar ring distortions on the boat conformations would be similar on the twistboat conformation.

In a Cartesian coordinate representation the redundancy which arises from the rigid movements determine the reference plane for the atomic perpendicular distortions. When puckering parameters are calculated based on Cartesian coordinates, the planar coordinates are used only to determine the reference plane. Consequently, qualitatively different structures with the same out-of-plane displacement coordinates are described by the same puckering parameters. This point is well demonstrated on chemical examples by Zefirov et al.[25] and these arguments are not repeated here.

5. Conclusions

We have introduced new definitions for the quantitative characterization of pyranose conformations which follows the spirit of the conformational nomenclature and intuitive stereochemical definition of puckering. We express a conformation in terms of linear combinations of basic ideal chair, boat, twistboat, envelope and halfchair reference conformations. The linear combination coefficients are determined by projecting the vector of torsion angles onto those of these basic conformations. The reference conformations represent equal displacement from planarity based on the stereochemical criteria of an angular displacement coordinate with respect to the reference plane of four ring atoms. Consequently, the corresponding projection coefficients conform to the stereochemical length scaling. The projection coefficient combined with the IUPAC name of the basic conformations facilitates a simple visual representation of the conformation and the results can be interpreted without making reference to the conformational map.

We have shown how one may obtain a full set of six torsion angles from three to five torsion angles using the redundancy equations. A table of expression is provided for convenience. We have represented the canonical projection coefficients in a spherical polar coordinate system which has been generally used for pyranose conformer characterization and identification. Our definitions of such parameters retain the merits of previous spherical coordinate descriptions. By introducing a mixed length scaling, which follows the logic of vector algebra for pseudorotation and is consistent with stereochemistry for chair inversion, our definitions put the intermediate envelope and halfchair conformations exactly halfway between the pole and the equator of the conformational sphere.

Acknowledgements

We have introduced an internet site (http://www.nrc.ca/ibs/6ring.html) where all parameters introduced here can be calculated from three to six torsion angles. Upon input of the incomplete set of torsion angles this site provides the values of missing torsion angles based on redundancy equations, the canonical projection coefficients, projection coefficients for the most representative set of three conformation and a visual image of the ring.

Appendix A. Basic equations

The requirement that the redundancy coefficients λ_i, $i = 4, 5, 6$ are zero can be expressed by rearrangement of Eqs. (4) and (2a)–(2c) in matrix form:

$$\begin{pmatrix} 1 & \frac{1}{2} & -\frac{1}{2} & -1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & 1 & 1 & 0 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} \lambda_4 \\ \lambda_5 \\ \lambda_6 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{A1}$$

One torsion angle is missing

In this case we could use three equations to calculate the missing torsion angle. We choose to use the $\lambda_6=0$ condition which yields:

$$\tau_6 = -\sum_{i=1}^{5} \tau_i \tag{A2}$$

Two torsion angles are missing

If two torsion angles are missing we could use any two of the three equations to calculate the value of missing torsion angles. Here we use $\lambda_4=0$ and $\lambda_6=0$ conditions to calculate the values of missing τ_5 and τ_6. (A1) can be brought to the form:

$$\begin{pmatrix} -\frac{1}{2} & \frac{1}{2} \\ 1 & 1 \end{pmatrix} \begin{pmatrix} \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} -1 & -\frac{1}{2} & \frac{1}{2} & 1 \\ -1 & -1 & -1 & -1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{pmatrix} \tag{A3}$$

After multiplying the equation from the left by the inverse of the matrix on the left hand side:

$$\begin{pmatrix} \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} -\frac{1}{2} & \frac{1}{2} \\ 1 & 1 \end{pmatrix}^{-1} \begin{pmatrix} -1 & -\frac{1}{2} & \frac{1}{2} & 1 \\ -1 & -1 & -1 & -1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{pmatrix} \tag{A4}$$

With the explicit values of the inverse matrix Eq. (A4) reads:

$$\begin{pmatrix} \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} -1 & \frac{1}{2} \\ 1 & \frac{1}{2} \end{pmatrix}^{-1} \begin{pmatrix} -1 & -\frac{1}{2} & \frac{1}{2} & 1 \\ -1 & -1 & -1 & -1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{pmatrix} \tag{A5}$$

The matrix multiplication yields the final results:

$$\begin{pmatrix} \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} \frac{1}{2} & 0 & -1 & -\frac{3}{2} \\ -\frac{3}{2} & -1 & 0 & \frac{1}{2} \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{pmatrix} \tag{A6}$$

Using $\lambda_5=0$ and $\lambda_6=0$ conditions the set of linear equation does not have a non-trivial solution for τ_5 and τ_6 since the matrix does not have an inverse. Using $\lambda_4=0$ and $\lambda_5=0$ conditions and following the same steps as above yields an alternative expression for τ_5 and τ_6:

$$\begin{pmatrix} \tau_5 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 & -1 \\ -1 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{pmatrix} \tag{A7}$$

Three torsion angles are missing

Eq. (A1) can be rearranged τ_2, τ_4 and τ_6 are unknown as:

$$\begin{pmatrix} \frac{1}{2} & -1 & \frac{1}{2} \\ 1 & 0 & -1 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} \tau_2 \\ \tau_4 \\ \tau_6 \end{pmatrix} = \begin{pmatrix} -1 & \frac{1}{2} & \frac{1}{2} \\ 0 & -1 & 1 \\ -1 & -1 & -1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_3 \\ \tau_5 \end{pmatrix} \tag{A8}$$

References

1. Kirby, A. J. *The anomeric effect and related stereoelectronic effects at oxygen*; Springer: Heidelberg, 1983.
2. Kochetkov, N. K. *Stud. Nat. Prod. Chem.* **1994**, *14*, 201–266.
3. (a) Sinnott, M. L. *Chem. Rev.* **1990**, *90*, 1171–1202. (b) Horenstein B. A.; Bruner, M. *J. Am. Chem. Soc.* **1998**, *120*, 1357–1362. (c) Murray, B. W.; Wittmann, V.; Burkart, M. D.; Hung, S.-C.; Wong, C.-H. *Biochemistry* **1997**, *36*, 823–831.
4. (a) Deslongchamps, P.; Dory, Y. L.; Li, S. *Can. J. Chem.* **1994**, *72*, 2021–2027. (b) Zhu, J.; Bennet, A. J. *J. Am. Chem. Soc.* **1998**, *120*, 3887–3893.
5. Smith, B. J. *J. Am. Chem. Soc.* **1997**, *119*, 2699–2706.
6. (a) Liras, J. L.; Anslyn, E. V. In *Molecular Design and Bioorganic Catalysis*; Wilcox, C. S., Hamilton, A. D., Eds.; Kluwer Academic: Netherlands, 1996; pp 1–14. (b) Brameld, K. A.; Goddard III, W. A. *J. Am. Chem. Soc.* **1998**, *120*, 3571–3580.
7. Saenger, W. *The Principles of Nucleic Acid Structure*; Springer: Heidelberg, 1988 (Second Corrected Printing).
8. Klugsbrun, M.; Baird, A. *Cell* **1991**, *64*, 229–231.
9. Rouslahti, E.; Yamaguchi, Y. *Cell* **1991**, *64*, 867–869.
10. Comper, W. D. *Heparin (and Related Polysaccharides)*; Gordon and Beach: New York, 1991.
11. French, A. D.; Brady, J. W. *Computer Modeling of Carbohydrate Molecules*; French, A. D., Brady, J. W., Eds.; American Chemical Society: Washington, DC, 1990; pp 1–19.
12. Casu, B.; Choay, J.; Ferro, D. R.; Gatti, G.; Jacquinet, J. C.; Petitou, M.; Provasoli, M.; Ragazzi, M.; Sinay, P.; Torri, G. *Nature* **1986**, *322*, 215–216.
13. Rees, D. A.; Morris, E. R.; Stoddart, J. F.; Stevens, E. S. *Nature* **1985**, *317*, 480.
14. Marszalek, P. E.; Oberhauser, A. F.; Pang, Y.-P.; Fernandez, J. M. *Nature* **1998**, *396*, 661–664.
15. DaCruz, M. F.; Zimmer, M. *Inorg. Chem.* **1998**, *37*, 366–368.
16. Williams, K. M.; Cerasino, L.; Intini, F. P.; Natile, G.; Marzilli, L. G. *Inorg. Chem.* **1998**, *37*, 5260–5268.
17. (a) Nukada, T.; Bérces, A.; Zgierski, M. Z.; Whitfield, D. M. *J. Am. Chem. Soc.* **1998**, *120*, 13291–13295. (b) Nukada, T.; Bérces, A.; Whitfield, D. M. *J. Org. Chem.* **1999**, *64*, 9030–9045.
18. Schwartz, J. C. P. *J. Chem. Soc. Chem. Commun.* **1973**, 505.
19. Cremer, D.; Pople, J. *J. Am. Chem. Soc.* **1975**, *97*, 1354–1358.

20. Haasnoot, C. A. G.; De Leeuw, F. A. A. M.; Altona, C. *Tetrahedron* **1980**, *36*, 2783–2792.
21. Osawa, E.; Ouchi, T.; Saito, N.; Yamato, M.; Lee, O. S.; Seo, M.-K. *Magn. Reson. Chem.* **1992**, *30*, 1104–1110.
22. Stoddart, J. F. *Stereochemistry of Carbohydrates*; Wiley-Interscience: New York, 1971.
23. Hendrickson, J. B. *J. Am. Chem. Soc.* **1967**, *89*, 7047–7061.
24. Haasnoot, C. A. G.; De Leeuw, F. A. A. M.; Altona, C. *Tetrahedron* **1980**, *36*, 2783–2792.
25. Zefirov, N. S.; Palyulin, V. A.; Dashevskaya, E. E. *J. Phys. Org. Chem.* **1990**, *3*, 147–158.
26. Haasnoot, C. A. G. *J. Am. Chem. Soc.* **1992**, *114*, 882–887.
27. (a) Fogarasi, G.; Zhou, X.; Taylor, P. W.; Pulay, P. *J. Am. Chem. Soc.* **1992**, *114*, 8191–8201. (b) Pulay, P.; Fogarasi, G.; Pang, F.; Boggs, J. E. *J. Am. Chem. Soc.* **1979**, *101*, 2550–2560.
28. Klyne, W.; Prelog, V. *Expermentia* **1960**, *16*, 521–523.
29. Cano, F. H.; Foces-Foces, C.; Garcia-Blonco, S. *Tetrahedron* **1977**, *35*, 797–802.
30. Whitfield, D. M.; Birnbaum, G. I.; Pang, J.; Baptista, J.; Sarkar, B. *J. Carbohydr. Chem.* **1991**, *10*, 329–348.
31. Chamberlain, L. N.; Edwards, I. A. S.; Stadler, H. P.; Buchanan, J. G.; Thomas, W. A. *Carbohydr. Res.* **1981**, *90*, 131–137.
32. Urbanczyk-Lipkowska, Z.; Suwinska, K.; Luboradzki, R.; Mostowicz, D.; Kaluza, Z.; Grodner, J.; Chmielewski, M. *Carbohydr. Res.* **1994**, *256*, 1–11.
33. Lichtenthaler, F. W.; Lindner, H. J. *Carbohydr. Res.* **1990**, *200*, 90–99.
34. Lichtenthaler, F. W.; Rönninger, S.; Lindner, H. J.; Immel, S.; Cuny, E. *Carbohydr. Res.* **1993**, *249*, 305–326.
35. Note that our numbering follows the carbohydrate nomenclature to be consistent with the other examples of the text, while the original reference follows the IUPAC numbering of ring atoms.
36. Dixon, D. A.; Komornicki, A. *J. Phys. Chem.* **1990**, *94*, 5630–5636.
37. Krajewski, J. W.; Karpiesiuk, W.; Banaszek, A. *Carbohydr. Res.* **1994**, *257*, 25–33.
38. Adwidjaja, G.; Meyer, B.; Paulsen, H.; Thiem, J. *Tetrahedron* **1979**, *35*, 373–384.
39. Remy, P. G.; Cottier, L.; Descotes, G. *Acta Crystallogr.* **1980**, *B36*, 873–877.
40. Riche, C.; Pascard-Billy, C. *Acta Crystallogr.* **1975**, *B31*, 2565–2570.
41. Abbady, M. A.; Akari, S.; Morgan, M.; Ternay Junior, A. L.; Galloy, J.; Watson, W. *J. Heterocycl. Chem.* **1982**, *19*, 1473–1483.
42. Herron, N.; Grzybowski, J. J.; Matsumoto, N.; Zimmer, L. L.; Christoph, G. G.; Busch, D. H. *J. Am. Chem. Soc.* **1982**, *104*, 1999–2007.
43. Pei, Y.; Kahn, O.; Sletten, J. *J. Am. Chem. Soc.* **1986**, *108*, 3143–3145.
44. Benelli, C.; Dei, A.; Gatteschi, D.; Pardi, L. *J. Am. Chem. Soc.* **1988**, *110*, 6897–6898.
45. Dewar, R.; Fleischer, E. *Nature* **1969**, *222*, 372.
46. Collins, T. J.; Workman, J. M. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 912–914.
47. Dutta, S. K.; Ensling, J.; Werner, R.; Florke, U.; Haase, W.; Gutlich, P.; Nag, K. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 152–153.