MOLECULAR ROTATIONS OF FULLY ACETYLATED ALDOPYRANOSYL HALIDES IN RELATION TO THEIR STRUCTURES

THE RELATION AMONG THE SLOPES OF SOME $[M]_D^{20}-R_D$ (FOR HALOGEN) PLOTS

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Abstract—In order to explain the relation between the slopes of some $[M]_D^{20}-R_D$ (for halogen) plots of fully acetylated aldopyranosyl halides, three methods (i.e. Hudson's, Whiffen's (or Brewster's), and PM-methods) have been tested. The most available method is the PM-method which is based on the conception of the dynamic coupling effect between a pair of unit groups in a molecule.

RECENTLY, it was reported that straight lines can be obtained for fully acetylated aldopyranosyl halides, R–X where X is F, Cl, Br or I by plotting molecular rotation, $[M]_D^{20}$ against atomic refraction, R_D (or polarizability, α) of X.[1,2] Concerning the relation among the slopes of these $[M]_D^{20}-R_D$ (for halogen) plots, an empirical rule was found (expressed by using only the symbol, $<$).[1] No one, however, tried to use any calculation method of optical rotation, in order to explain this relation. In this article, three methods of estimating the molecular rotation, $[M]_D$ in terms of the molecular structure are examined to see whether they are useful in interpreting the relation among the slopes of some $[M]_D^{20}-R_D$ (for halogen) plots, and if possible, to express this relation by using the symbol ($=$).

The slopes shown in Fig. 1 of the previous paper (except for those drawn in dashed lines*) are applied here as Fig. 1 which shows the following two clear characters. (1) $[M]_D^{20}-R_D$ (for halogen) plots of the α-D (or β-L) series are only approximately parallel to each other. (2) $[M]_D^{20}-R_D$ (for halogen) plots of the β-D series are apparently not parallel to each other. These two characters cannot be explained either by Hudson's isorotation rule[3,4]† or by Whiffen's[6] (or Brewster's[7]) conformational dissymmetry rule, as shown below.

According to Hudson's rule,[3] which is based on van't Hoff's principle of optical superposition,[4,8] the molecular rotation, $[M]_D^{20}$ of the fully acetylated aldopyranosyl halide should be divided into two parts, A_X (the partial molecular rotation of X-1—C-1—H-1 moiety) which is indifferent to the remainder of the molecule and B

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* As is apparent in Fig. 1 of the previous paper,[1] a dashed line is made by using only one halide point (and a hydride point), and therefore, strictly speaking, it cannot be named as $[M]_D^{20}-R_D$ (for halogen) plot and is not treated in this article.

† Symbols are as follows: Ar, arabinose derivative; Ga, galactose derivative; G, glucose derivative; M, mannose derivative; Rh, rhamnose derivative; Ri, ribose derivative; Xy, xylose derivative.

‡ Concerning the physical meaning of Hudson's isorotation rule for the case of non-substituted aldopyranose has already been explained.[5]
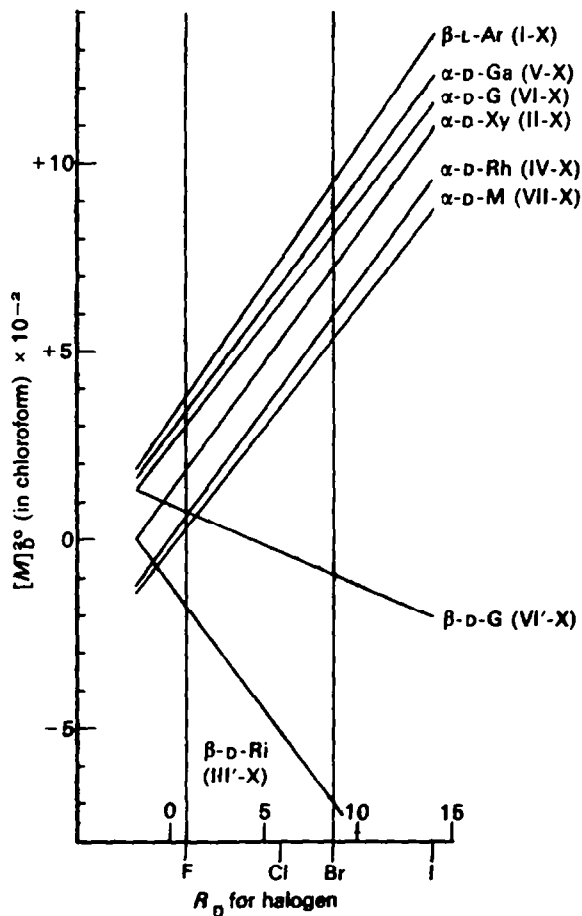
Fio. 1. Molecular rotation, $[M]_D^{20}$ of fully acetylated aldopyranosyl halide as a function of the atomic refraction (R_D) of its halogen atom.[*][†]

(the partial molecular rotation of the remainder of the molecule) which is indifferent to the kind and the configuration of X at 1-position of the pyranose ring. Therefore,

$$[M]_D^{20} \text{ of a fully acetylated aldopyranosyl halide} = A_X + B \qquad (1)$$
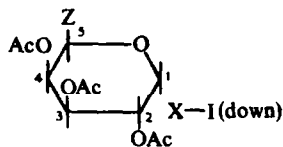
From Eq. 1, two equations are obtained, as below,

$$[M]_D^{20} \text{ of tetra-}O\text{-acetyl } \alpha\text{-}D\text{-galactopyranosyl bromide (V-Br)} = A_{Br} + B_{Ga} \qquad (2) \text{ §, ‡}$$

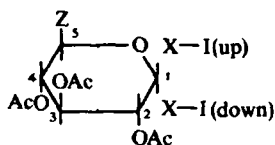[*] See footnote † on page 1559.
[†] See footnote ‡ on page 1559.
[‡] (V-) is the symbol of tetra-O-acetyl α-D-galactopyranosyl radical. V-Br means, therefore, tetra-O-acetyl α-D-galactopyranosyl bromide, and so on.
[§] Symbols of fully acetylated aldopyranosyl radicals are as follows: (I), tri-O-acetyl β-L-arabinopyranosyl radical; (II-), tri-O-acetyl α-D-xylopyranosyl radical; (III'-), tri-O-acetyl β-D-ribopyranosyl radical; (IV-), tri-O-acetyl α-D-rhamnopyranosyl radical; (V-), tetra-O-acetyl α-D-galactopyranosyl radical; (VI-), tetra-O-acetyl α-D-glucopyranosyl radical; (VI'-), tetra-O-acetyl β-D-glucopyranosyl radical; (VII-), tetra-O-acetyl α-D-mannopyranosyl radical.
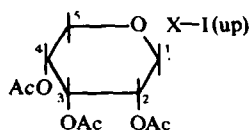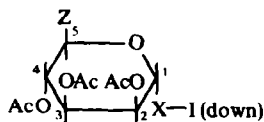
β-L-Ar, (I-X): Z = H

α-D-Ga, (V-X): Z = CH₂OAc

β-L-Ar, (I-X): Z = H

α-D-Ga, (V-X): Z = CH_2OAc

α-D-Xy, (II-X): Z = H

α-D-G, (VI-X): X-1 (up) = H: Z = CH_2OAc

β-D-G, (VI'-X): X-1 (down) = H; Z = CH_2OAc

β-D-Ri (III'-X):

α-D-Rh, (IV-X): Z = CH_3

α-D-M, (VII-X): Z = CH_2OAc

$[M]_D^{20}$ of tetra-O-acetyl α-D-galactopyranosyl fluoride (V-F) $= A_F + B_{Ga}$ \qquad (3)

From Eq. 2 minus 3,

$$[M]_D^{20} \text{ of (V-Br)} - [M]_D^{20} \text{ of (V-F)} = A_{Br} - A_F \qquad (4)^*$$

Similarly, the following two equations can be obtained.

From tetra-O-acetyl α-D-glucopyranosyl halide (VI-X),

$$[M]_D^{20} \text{ of (VI-Br)} - [M]_D^{20} \text{ of (VI-F)} = A_{Br} - A_F \qquad (5)$$

From tetra-O-acetyl α-D-mannopyranosyl halide (VII-X),

$$[M]_D^{20} \text{ of (VII-Br)} - [M]_D^{20} \text{ of (VII} - \text{F)} = A_{Br} - A_F \qquad (6)$$

The right hand sides of Eqs 4, 5 and 6 are all equal and this can be seen in all the compounds of the α-D (or β-L) series. This demands that their $[M]_D^{20}-R_D$ (for halogen) plots (not only of α-D-Ga, α-D-G and α-D-M, but also of all the α-D (or β-L) series)† should be parallel to each other. Similarly, Hudson's isorotation rule demands, at the same time, that all of $[M]_D^{20}-R_D$ (for halogen) plots of β-D series are also parallel to each other. These requirements are, however, not satisfied in Fig. 1, and Hudson's rule is apparently mistaken.

According to Whiffen's (or Brewster's) rule,[6,7] the halogen atom, X at 1-position of the pyranose ring contributes only to the partial molecular rotations of three

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* In testing the applicability of three methods of estimating molecular rotation, in terms of the molecular structure, it is convenient to use two definite kinds of halogen atom, chosen arbitrarily out of F, Cl, Br, and I. In this article, F and Br are used. (Fig. 1).

† See footnote † on page 1559.

conformational units such as (X-1—C-1—C-2—H-2), (X-1—C-1—C-2—OAc-2) and (X-1—C-1—O*—C-5).*

It is clear in structural formulaes that from the standpoint of the types of these three conformational units, some aldopyranose series belong to the same class. Concretely speaking, each of β-L-Ar, α-D-Xy, α-D-Ga and α-D-G†‡ has the units {X-1 (down)—C-1—C-2—H-2 (up)}, {X-1 (down)—C-1—C-2—OAc-2 (down)} and {X-1 (down)—C-1—O*—C-5}. When their X-1 changes from F atom to Br atom, $[M]_D^{20}$ values of these four halides should, therefore, shift in the same direction by the same magnitude. In other words, $[M]_D^{20}-R_D$ (for halogen) plots of β-L-Ar, α-D-Xy, α-D-Ga and α-D-G should be parallel to each other. Similarly, Whiffen's (or Brewster's) method demands also that $[M]_D^{20}-R_D$ (for halogen) plots of α-D-Rh and α-D-M should be parallel to each other. These are, however, not satisfied in Fig. 1 and Whiffen's (or Brewster's) method is clearly imperfect.

PM-method[10]—For comparison of the slopes of $[M]_D^{20}-R_D$ (for halogen) plots, the angular coefficient (tan θ) is used as in the previous paper[1] (but here, θ is the angle between a $[M]_D^{20}-R_D$ (for halogen) plot and the axis of abscissa). The values of tan θ of the $[M]_D^{20}-R_D$ (for halogen) plots have already been given in Table 5 of the previous paper[1] and they are shown again here in Table 1.§

TABLE 1. SLOPE OF $[M]_D^{20}-R_D$ (FOR HALOGEN) PLOT OF FULLY ACETYLATED ALDOPYRANOSYL HALIDES

Derivative of	Compound	Angular coefficient (tan θ)
β-L-Arabinose	I-X	1·4500
α-D-Xylose	II-X	1·3875
α-D-Rhamnose	IV-X	1·3750
α-D-Galactose	V-X	1·3625
α-D-Glucose	VI-X	1·3000
α-D-Mannose	VII-X	1·2875
β-D-Glucose	VI'-X	−0·4250

On the other hand, it is obvious in Fig. 1 that tan θ can be defined by the next equation,

$$\tan \theta = k\{[M]_D^{20} \text{ of bromide} - [M]_D^{20} \text{ of fluoride}\} \div (R_D \text{ of Br atom} - R_D \text{ of F atom}) \tag{7}$$

but here, k is a proportionality constant which is determined by the magnitude of the unit scale on the axes (of abscissa and ordinate). As the values of R_D of Br atom and F atom are 8·741 and 0·81, respectively,[20] (R_D of Br atom − R_D of F atom) is 7·931

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* O* means the ring oxygen atom.

† According to NMR spectroscopy, bromides of β-L-Ar, α-D-Xy, α-D-G and α-D-M are all in C 1 conformation in their chloroform solutions. The same may be presumed also in the fluorides.[9]

‡ Table 1 shows only the compounds which are in C 1 conformation in their chloroform solutions. According to NMR spectroscopy, tri-O-acetyl β-D-ribopyranosyl bromide is believed to be in 1 C conformation,[9] and it is not treated here.

§ It should be noted here that the ordinate indicates one hundredth of $[M]_D^{20}$ value.

and Eq. 7 can be rewritten as below,

$$\tan \theta = K\{[M]_D^{20} \text{ of bromide} - [M]_D^{20} \text{ of fluoride}\} \qquad (8)$$

where K is another constant.

Now, we try to apply the PM-method to Eq. 8. The calculation of the partial molecular rotation here, however, is difficult.* †   In this article, therefore, the partial molecular rotation caused by the dynamic coupling effect (a kind of mutual interaction) between a pair of unit groups is shown by using some symbols.‡ Moreover, the author tries to offset as many of these terms as possible.

As seen in its structure, tri-O-acetyl β-L-arabinopyranosyl bromide (I-Br), has eleven unit groups, such as Br-1 (down), H-1 (up), OAc-2 (down), H-2 (up), H-3 (down), OAc-3 (up), H-4 (down), OAc-4 (up), H-5 (down), H-5 (up), and R°. § Any two members (i and k) of these unit groups can couple dynamically with each other to cause the partial molecular rotation, $[\mu]_{D(ik)}^{20}$.‡ Of course, the sum of all the partial molecular rotations, $[\mu]_{D(ik)}^{20}$'s in the molecule should be equal to the molecular rotation, $[M]_D^{20}$ of the substance.
Therefore,

$$[M]_D^{20} \text{ of I-Br} = \sum [\mu]_{D(ik)}^{20} \qquad \text{(in I-Br)} \qquad (9)$$

Now, the partial molecular rotations, $[\mu]_{D(ik)}^{20}$'s of I-Br are divided into two classes,— the one is that caused by the dynamic coupling effect of Br-1 (down) and the other is indifferent to Br-1 (down).

$$\therefore [M]_D^{20} \text{ of I-Br} = \sum_{k \neq Br-1} [\mu]_{D(Br-1, k)}^{20} \qquad \text{(in I-Br)} +$$

$$\sum_{j \neq k \neq Br-1} [\mu]_{D(jk)}^{20} \qquad \text{(in I-Br)} \qquad (10)$$

Concretely speaking, the first term of the right-hand side of Eq. 10 is as follows,

$$\sum_{k \neq Br-1} [\mu]_{D(Br-1, k)}^{20} = \text{Br-1 (down)} \wedge \{\text{H-1 (up)} + \text{OAc-2 (down)} + \text{H-2 (up)}$$

$$+ \text{H-3 (down)} + \text{OAc-3 (up)} + \text{H-4 (down)} + \text{OAc-4 (up)} + \text{H-5 (down)}$$

$$+ \text{H-5 (up)} + \text{R°}\} = \text{Br-1 (down)} \wedge (\text{tri-}O\text{-acetyl β-L-arabinopyranosyl radical})$$

$$= \text{Br-1 (down)} \wedge (\text{I-}) \qquad (11)$$

Combining Eq. 11 with Eq. 10,

$$[M]_D^{20} \text{ of I-Br} = \text{Br-1 (down)} \wedge (\text{I-}) + \sum_{j \neq k} [\mu]_{D(jk)}^{20} \qquad \text{(in I-)} \qquad (12)$$

Similarly, from tri-O-acetyl β-L-arabinopyranosyl fluoride, I-F,

$$[M]_D^{20} \text{ of I-F} = \text{F-1 down)} \wedge (\text{I-}) + \sum_{j \neq k} [\mu]_{D(jk)}^{20} \qquad \text{(in I-)} \qquad (13)$$

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* The principal reasons for it are as follows; (1) We have no accurate knowledge concerning the most stable internal conformation of O—Ac bond which has minimal potential and makes the (Ac) group rest. (2) The (OAc) radical has not an optically cylindrical symmetry axis.

† This forces us to give up the trial of investigating the slope itself of $[M]_D^{20}$–R_D (for halogen) plot.

‡ (i) $\wedge$ (k) (or $[\mu]_{D(ik)}^{20}$) means the partial molecular rotation, contributed by the dynamic coupling effect between the groups, i and k. The notation $\wedge$ can be treated in the same way as the multiplication symbol, × of the algebra.[12]

§ R° is the symbol of the pyranose ring which is composed of five carbon atoms and one oxygen atom.

From Eq. 12 minus Eq. 13,

$[M]_D^{20}$ of I-Br $-$ $[M]_D^{20}$ of I-F $=$ Br-1 (down) λ (I-) $-$ F-1 (down) λ (I-)

$$= \{Br - F\}\text{-1 (down)} \lambda \text{ (I-)} \qquad (14)$$

From Eqs 8 and 14,

$$\tan \theta \text{ of } \beta\text{-L-Ar} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (I-)} \qquad (15)$$

Similarly, six other equations can be obtained for six series (α-D-Xy, α-D-Rh, α-D-Ga, α-D-G, α-D-M, and β-D-G), as follows.

$$\tan \theta \text{ of } \alpha\text{-D-Xy} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (II-)} \qquad (16)$$

$$\tan \theta \text{ of } \alpha\text{-D-Rh} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (IV-)} \qquad (17)$$

$$\tan \theta \text{ of } \alpha\text{-D-Ga} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (V-)} \qquad (18)$$

$$\tan \theta \text{ of } \alpha\text{-D-G} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (VI-)} \qquad (19)$$

$$\tan \theta \text{ of } \alpha\text{-D-M} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (VII-)} \qquad (20)$$

$$\tan \theta \text{ of } \beta\text{-D-G} = K\{Br - F\}\text{-1 (down)} \lambda \text{ (VI'-)} \qquad (21)$$

The values of the left-hand sides of Eqs 15–21, have already been given in Table 1 and they are not equal to each other which corresponds to the fact that all the $[M]_D^{20} - R_D$ (for halogen) plots in Fig. 1 are not strictly parallel to each other. Moreover, it should be noticed again here that Eqs 15–21 are obtained separately, and the purpose in this article is to find, if possible, any relationship among them. Some new conditional equations which can be obtained as follows, may introduce a key for this.

At first, hexopyranosyl and pentopyranosyl radicals whose structures are similar to each other, are gathered in apirs.* As apparent in their structures, tetra-O-acetyl α-D-galactopyranosyl radical (V-) is obtained by replacing H-5 (up) with CH_2OAc-5 (up) in tri-O-acetyl β-L-arabinopyranosyl radical (I-).

$$\therefore \text{ (V-)} = \text{(I-)} - \text{H-5 (up)} + CH_2OAc\text{-5 (up)} \qquad (22)$$

Similarly,

$$\text{(VI-)} = \text{(II-)} - \text{H-5 (up)} + CH_2OAc\text{-5 (up)} \qquad (23)$$

Using Eq. 22 in (Eq. 18 minus Eq. 15),

$(\tan \theta$ of α-D-Ga) $-$ $(\tan \theta$ of β-L-Ar)

$$= K\{Br - F\}\text{-1 (down)} \lambda \{CH_2OAc\text{-5 (up)} - \text{H-5 (up)}\} \qquad (24)$$

Using Eq. 23 in (Eq. 19 minus Eq. 16),

$(\tan \theta$ of α-D-G) $-$ $(\tan \theta$ of α-D-Xy)

$$= K\{Br - F\}\text{-1 (down)} \lambda \{CH_2OAc\text{-5 (up)} - \text{H-5 (up)}\} \qquad (25)$$

From Eqs 24 and 25,

* Concretely speaking, {(V-) and (I-)}, and {(VI-) and II-)}.

$$(\tan \theta \text{ of } \alpha\text{-D-Ga}) - (\tan \theta \text{ of } \beta\text{-L-Ar}) = (\tan \theta \text{ of } \alpha\text{-D-G}) - (\tan \theta \text{ of } \alpha\text{-D-Xy}) \qquad (26)$$

Thus, Eq. 26 is the demand (expressed by using the symbol (=)), from the PM-method.*

By using the values of tan θ already given in Table 1, both of the left- and the right-hand sides of Eq. 26 become −0·0875.† That is to say, Eq. 26 is satisfied, quite well. This may prove that the PM-method is suitable for the purpose of explaining the relation among the slopes of $[M]_D^{20}$–R_D (for halogen) plots (as well as of interpreting the molecular rotation, $[M]_D^{20}$) of the fully acetylated aldopyranosyl halides.‡

DISCUSSION

The PM-method, like all methods based on the Kirkwood theory,[14,15] is applicable to rotatory effects related to transitions with strong electric dipole moment changes, but not to transitions with weak electric moments (as the n–π^* transition of ketones). But this does not mean that the latter compounds cannot be treated by this method; the electric dipole moment effects are often enormously stronger than the others and often dominate rotation at long enough wavelengths. The carbonyl group of acids and esters has an n–π^* transition near 220 mμ and Klyne has found Cotton effects in that region.[16] But the sodium D line may be so far away from that region that the influences of these Cotton effects will largely fade away, leaving the "background" effects dominant (as required for the use of the PM-method). Thus, the PM-method might in principle be applied to the acetylated sugars although it would be difficult in practice.§

† For lack of any suitable conditional equations, (IV-), (VII-), and (VI'-) are not treated, here.

‡ On the other hand, the value of {(tan θ of α-D-M) − (tan θ of α-D-Rh)} is −0·0875 which happens to be just equal to the value of Eq. 26 (see Table 1). For the fully benzoylated aldopyranosyl halides, however, the value of {(tan θ of α-D-M) − (tan θ of α-D-Rh)} is −0·0125 and that of {(tan θ of α-D-G) − (tan θ of α-D-Xy)} is −0·1000, and these are apparently different from each other (see Table 6 in Ref. 1). This shows that the appearance of a definite kind of substituent at 5-position (of the pyranose ring) does not always cause $[M]_D^{20}$ shift of definite magnitude.

§ The superiority of the PM-method over Whiffen's method for the non-substituted carbohydrate has already been proved as for (−)[1,2,3,4]/₄-cyclohexanepentol.[13]

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