Journal of Chromatography, 118 (1976) 345–356

CHROM. 8908

GAS–LIQUID CHROMATOGRAPHY OF SEVERAL FAMILIES OF ISOMERIC 1,2,3-TRISUBSTITUTED CYCLOHEXANOLS AND CYCLOPENTANOLS AND THEIR ACETATES*

J. W. BOVENKAMP** and R. Y. MOIR
Department of Chemistry, Queen's University, Kingston, Ontario (Canada)
and
A. A. CASSELMAN and R. A. B. BANNARD
Defence Research Establishment Ottawa, Ottawa (Canada)
(Received October 6th, 1975)

SUMMARY

The gas chromatographic retention times for several families of isomeric 1,2,3-trisubstituted cyclohexanols and cyclopentanols and their acetates have been determined on two columns (DEGS and QF-1) which differ in polarity and hydrogen bonding characteristics. The effects of acetylation, configuration, ring size, and column properties on the retention times of the 1,2,3-trisubstituted alcohols are examined.

INTRODUCTION

The relationship between chromatographic retention behaviour and molecular structure has been a widely discussed topic. The retention index system of Kováts[1] has been accepted as a general method of compound identification and has been recently investigated by Schomburg and Dielmann[2]. Ashton *et al.*[3] have found for extensive sets of isomeric dihalocycloalkanes that the order of elution of the isomers is the same (except for the fluoro compounds) and that individual isomers can be quickly identified from their retention times. Intramolecular hydrogen bonding has been shown to have a marked effect on the retention times of aminocyclohexanols[4] and nitrophenols[5].

In our studies on the formation and scission of 3-substituted cyclohexene and cyclopentene oxides[6–14], gas–liquid chromatography was used extensively and effectively both for preparative separations of stereoisomers and for the analysis of product mixtures. However, no systematic comparative examination was made of the gas chromatographic behaviour of the wide variety of stereochemically closely related 1,2,3-trisubstituted cyclopentanols and cyclohexanols resulting from the oxide scission

* Issued as DREO Report No. 735.
** Present address: National Research Council of Canada, Ottawa, Canada.

reactions and the ensuing structural elucidation studies. In the work now to be described, the gas chromatographic retention times of these compounds were measured under identical conditions on two columns of widely differing polarities (DEGS and QF-1). The resultant data are discussed from the standpoint of the effect of functionality, location, and steric orientation of substituents on retention times and the possible utility of the latter for tentative structural assignments.

EXPERIMENTAL

An F & M Scientific Research Chromatograph, Model 5750 (Hewlett-Packard), equipped with a thermal conductivity detector (bridge current 150 mA) and a Model 3370 B electronic integrator (Hewlett-Packard), which provided a readout of retention times, were used. Two columns (10 ft. × 1/8 in. O.D. stainless steel, DMCS treated) were employed. The solid support in both cases was Chromosorb G AW DMCS, 80–100 mesh, and the stationary phase was 4% DEGS in one column and 4% QF-1 in the other. Instrumental conditions were standardized as follows; temperatures: column 170°, injector 240°, detector 300°; carrier gas: helium, flow-rate 25 ml/min.

The compounds (10 mg) were dissolved in methanol (50 μl) and 1 μl of cyclohexanol was added as an internal chromatographic standard. Aliquots (1 μl) of the resultant solutions were injected into the chromatograph. A specific compound was selected with respect to each column (DL-1,3-di-O-methyl-(1,3/2)-1,2,3-cyclohexanetriol for the DEGS column; DL-2-O-acetyl-1,3-di-O-methyl-(1,3/2)-1,2,3-cyclohexanetriol for the QF-1 column) and repeated injections were made at random intervals to monitor the reproducibility of the method. The dead volumes for each column were determined by injecting 2-μl aliquots of air into each of the columns under the standard conditions of operation specified above.

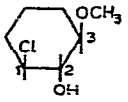
RESULTS AND DISCUSSION

The retention times reported in this paper have been adjusted for the appropriate dead volumes (*i.e.*, 0.72 min for the DEGS column and 0.74 min for the QF-1 column). Injections (15) of DL-1,3-di-O-methyl-(1,3/2)-1,2,3-cyclohexanetriol at random intervals on the DEGS column gave an average retention time of 4.92 $\pm$ 0.04 min. Similarly, twelve injections of DL-2-O-acetyl-1,3-di-O-methyl-(1,3/2)-1,2,3-cyclohexanetriol on the QF-1 column gave an average retention time of 7.51 $\pm$ 0.05 min. The retention time for cyclohexanol (internal standard) was 0.71 $\pm$ 0.02 min on DEGS and 0.49 $\pm$ 0.02 min on QF-1. Thus, retention times relative to cyclohexanol may be calculated for all the compounds by subtracting from the values shown in Tables I–IV the appropriate value for cyclohexanol.

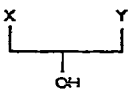
It is well known that hydroxyl groups in substituted cyclopentanols and cyclohexanols can form intramolecular hydrogen bonds with other functional groups (such as alcohols, ethers, halogens, etc.) when certain configurational conditions are met[15–20]. For example, both *cis*- and *trans*-1,2-cyclohexanediols (diequatorial *trans*-1,2) form intramolecular hydrogen bonds, and the phenomenon also occurs with *cis*- but not with *trans*-1,2-cyclopentanediols[15–17]. Also, *cis*- (diaxial *cis*-1,3 only) but not *trans*-1,3-cyclohexanediols[15] and, similarly, *cis*- but not *trans*-1,3-cyclopentane-

diols[21–23] form intramolecular hydrogen bonds. Consequently, it might be anticipated that families of compounds, which show a systematic positional and steric relationship between a hydroxyl group and another functional group capable of participating in intramolecular hydrogen bond formation, would show a corresponding systematic behaviour in chromatographic retention times. This behaviour should be especially true with polar columns which effect their separations mainly by intermolecular hydrogen bonding effects. The availability of a considerable number of 1,2,3-trisubstituted cyclohexanols and cyclopentanols of well defined geometry from our oxide ring opening studies[6–14] provided a ready means to examine the validity of this hypothesis.

The results of the investigation are given in Tables I–IV. Retention times are in minutes and are corrected for the instrument dead volume. The symbols C5 and C6 at the headings of the columns in the Tables indicate cyclopentane and cyclohexane compounds respectively. Horizontal rows (each of which represents compounds with the same configuration) have been designated by the capital letters A–E. Columns (each of which represents a family of isomers) have been designated by the small letters a–h. The numbers beneath the retention times are those assigned to individual compounds for identification purposes and increase consecutively from top to bottom of the columns. The symbols i, ii, ..., v indicate the elution order within a particular family of isomers. For example, a compound such as 9 would be listed in the Tables as having configuration A and shown in Table I, column c as C6, X = Cl, Y = OCH_3. It should also be noted in the Tables that X can be on position 1 or 2 while Y is always on position 3.



Compound 9



Configuration A

Retention times of the substituted cyclohexanols and cyclopentanols on DEGS (Table I)

Table I lists the retention times of substituted cyclohexanols and cyclopentanols on the DEGS column. The order of elution of isomers in the columns a–h is identical with one exception (in column f the order of elution of bromodiols 24 and 25 is the reverse of that found in the other columns). Therefore, the compound elution order on this polar column could be used to make tentative configurational assignments within similar types of isomeric families. As expected, the disubstituted compounds (configuration E) elute first since these have lower molecular weights and since there is one functional group less to interact with the column. The trisubstituted alcohols elute in the following configurational order, C < D < A < B.

It is well known that hydrogen bonding of alcohols to the column is a major factor in determining their retention times[4,5]. The infrared (IR) studies of Kuhn[15,16] have shown that in cyclopentane- and cyclohexane-diols hydrogen bonding strength has the following order *cis*-1,3(C6) > *cis*-1,2(C5) > *cis*-1,2(C6) > *trans*,1,2(C6). Darby *et al.*[21] have reported that a strong intramolecular hydrogen bond exists in *cis*-cyclopentane-1,3-diol. The frequency shift, and hence the strength of the hydrogen bond, for the bonded hydroxyl group (63 cm^{-1} to lower wave number compared with

TABLE I

RETENTION TIMES OF SUBSTITUTED CYCLOHEXANOLS AND CYCLOPENTANOLS ON DEGS

See text for explanation of symbols.

Configuration	*a; C6* $X = OCH_3$ $Y = OCH_3$	*b; C5* $X = OCH_3$ $Y = OCH_3$	*c; C6* $X = Cl$ $Y = OCH_3$	*d; C5* $X = Cl$ $Y = OCH_3$	*e; C6* $X = Br$ $Y = OCH_3$	*f; C6* $X = Br$ $Y = OH$	*g; C6* $X = OH$ $Y = OCH_3$	*h; C5* $X = OH$ $Y = OCH_3$
A) 	4.92 1,iv	5.45 5,iv	9.07 9,iv	7.77 14,iv	13.26 19,iv	33.52 24,v	13.14 28	23.69 31
(B) 	5.45 2,v	--	9.59 10,v	10.83 15,v	14.02 20,v	32.64 25,iv	—	—
(C) 	3.03 3,ii	2.15 6,ii	4.74 11,ii	2.98 16,ii	7.45 21,ii	22.82 26,ii	12.38 29	11.85 32
	—	3.85 7,iii	7.08 12,iii	5.06 17,iii	9.93 22,iii	32.60 27,iii	—	—
	1.56 4,i	1.66 8,i	2.50 13,i	2.64 18,i	3.84 23,i	3.84 23,i	8.17 30	8.96 33

the free hydroxyl) was about equal to that found by Kuhn[15,16] for *cis*-cyclopentane-1,2-diol (61 cm^{-1}). Sable *et al.*[22,23] have also reported the occurrence of intramolecular *cis*-1,3 hydrogen bonding in cyclopentane alcohols. No hydrogen bonding was detected by Kuhn[15,16] in the *trans*-1,3(C6) and the *trans*-1,2(C5) diols. In an IR study on hydrogen bonding in halohydrins, Nickon[18] found that hydrogen bonds for the *cis*-1,2 and *cis*-1,3 arrangements in the cyclohexane series are stronger than for the corresponding *trans* compounds. He also found that the bonding strengths between hydroxyl groups and halogens decrease in the order I > Br > Cl.

Although, as will be shown later, hydrogen bonding is important in explaining the retention times of the substituted cyclohexanols and cyclopentanols, other factors must be taken into account when considering absolute retention values. For example, even though the alcohols in rows C and D (which can form *cis*-1,2 and *cis*-1,3 hydrogen bonds) elute prior to the alcohols in rows A and B, where no *cis* hydrogen bonding is possible (diols in columns f, g and h excepted), on acetylation, the acetates in rows C and D generally still elute prior to those in rows A and B (Table II). Nor can the retention times be explained entirely in terms of configuration since the alcohols in row C with the functional groups arranged (3,2/1) are eluted second and the alcohols in row B which also have the groups arranged (3,2/1) are eluted last. The above situation differs from that found in the dihalocyclobutane, -cyclopentane, -cyclohexane and -cycloheptane isomers[3] where the order of elution of the isomers is the same for each set of dihalocycloalkanes (except for the fluoro compounds) (1,1- < *trans*-1,2- < *trans*-1,3- < *trans*-1,4- < *cis*-1,3- < *cis*-1,4- < *cis*-1,2-). That is, in these dihalo compounds, retention times vary regularly with configuration.

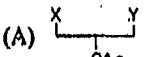
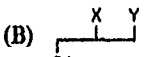
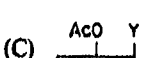
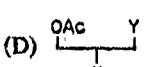
Hydrogen bonding effects become apparent when differences between retention times of alcohols of the same configurations in the C5 and C6 series are examined and during comparison of the retention times of the alcohols with those of their respective acetates. In row C (Table I), the cyclopentanols have smaller retention times than the corresponding cyclohexanols. This behaviour could be due to a lower molecular weight and to a stronger *cis*-1,2 hydrogen bond in the cyclopentane series[15,16]. Intramolecular hydrogen bonding would reduce the retention time by reducing the intermolecular hydrogen bonding to the column (DEGS forms strong intermolecular hydrogen bonds with alcohols as illustrated by the McReynolds constants[24]). In rows A, B, D, and E, except for compounds 9 and 14, 12 and 17, the cyclopentanols have longer retention times than the corresponding cyclohexanols. This behaviour is considered to be due to the fact that *trans*-1,2 intramolecular hydrogen bonding can take place in cyclohexanols but not in cyclopentanols[15,16].

When comparing the retention times of alcohols with the same configuration, the dimethoxy alcohols (columns a and b) have the shortest retention times, followed by the 3-methoxychlorohydrins (columns c and d; the retention times of compounds 16 and 3 are identical within experimental error), the 3-methoxybromohydrins (column e; the retention times of compounds 28 and 19 are identical within experimental error), the 3-methoxydiols (columns g and h), and then the bromodiols (column f). In agreement with the McReynolds constants[24], the importance of intermolecular hydrogen bonding on this column is shown here by the long retention times of the diols when compared with those of the other compounds of similar molecular weight. Thus, the retention times of the diols in columns g and h are much greater than those of the corresponding dimethoxy alcohols in columns a and b. Similarly,

TABLE II

RETENTION TIMES OF SUBSTITUTED CYCLOHEXANOL AND CYCLOPENTANOL ACETATES ON DEGS

See text for explanation of symbols. The values in parentheses indicate percentage change in retention time of the acetates relative to the corresponding alcohols (Table I).

Configuration	*a; C6* $X = OCH_3$ $Y = OCH_3$	*b; C5* $X = OCH_3$ $Y = OCH_3$	*c; C6* $X = Cl$ $Y = OCH_3$	*d; C5* $X = Cl$ $Y = OCH_3$	*e; C6* $X = Br$ $Y = OCH_3$	*f; C6* $X = Br$ $Y = OAc$	*g; C6* $X = OAc$ $Y = OCH_3$	*h; C5* $X = OAc$ $Y = OCH_3$
(A) 	9.16 (+86) 34,v	3.43 (−37) 38,iv	12.58 (+39) 42,v	4.58 (−41) 47,iv	17.76 (+34) 52,v	38.08 (+14) 57,v	19.27 (+47) 61	9.90 (−58) 64
(B) 	4.90 (−10) 35,iv	—	9.56 (0) 43,iv	6.66 (−39) 48,v	13.34 (−5) 53,iii,iv	25.95 (−20) 58,iii	—	—
(C) 	3.86 (+27) 36,ii	2.84 (+32) 39,ii	5.58 (+18) 44,ii	3.48 (+16) 49,ii	8.13 (+9) 54,ii	25.48 (+12) 59,ii	13.36 (+8) 62	10.14 (−14) 65
(D) 	—	2.90 (−25) 40,iii	9.33 (+32) 45,iii	3.90 (−23) 50,iii	13.35 (+34) 55,iii,iv	36.25 (+11) 60,iv	—	—
(E) 	1.91 (+22) 37,i	1.06 (−36) 41,i	2.99 (+20) 46,i	1.62 (−39) 51,i	4.62 (+20) 56,i	4.62 (+20) 56,i	5.95 (−27) 63	4.10 (−54) 66

the retention times of the bromodiols in column f are much longer than those of the corresponding methoxybromohydrins in column e. The above arguments become even more convincing when the retention times of the acetates are compared with those of the alcohols.

Retention times of the substituted cyclohexanol and cyclopentanol acetates on DEGS (Table II)

In contrast to the situation found in Table I, the retention times of the cyclopentane acetates on DEGS (Table II) are substantially shorter in every instance than those of the corresponding cyclohexane acetates (compare columns a and b, c and d, g and h). The values in parentheses beneath the retention times in Table II indicate the percentage change in retention time of the acetate relative to that of the corresponding alcohol on the same column. For the most part, the change in retention time on acetylation can be explained in terms of hydrogen bonding. In *trans*-1,2-disubstituted cyclohexanols (row E) intramolecular hydrogen bonding is possible[15,16]. On acetylation, the opportunity for hydrogen bonding no longer exists and one would expect an increase in retention time (also a small increase in retention time would probably be expected because of the increase in molecular weight). Thus, the disubstituted cyclohexane acetates 37, 46, and 56 exhibit increases in retention times of 20 to 22%. The negative change in retention time (—27%) for the cyclohexane diacetate 63 can be explained by the fact that in the diol one hydroxyl can bond intramolecularly while the other cannot.

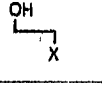
In *trans*-1,2-disubstituted cyclopentanols intramolecular hydrogen bonds do not form and hence these alcohols form strong intermolecular bonds with the column. On acetylation, the formation of intermolecular hydrogen bonds with the column is no longer possible and thus the percentage change in retention times for the acetates 41, 51, and 66 relative to their alcohols are —36, —39, and —54%, respectively. The same reasoning explains the percentage changes in retention times found for the trisubstituted acetates in row A. That is, the presence of *trans*-1,2 intramolecular hydrogen bonds leads to positive changes in retention times for the trisubstituted cyclohexanols on acetylation (compounds 34, 42, 52, 57, and 61) while the absence of *trans*-1,2 intramolecular hydrogen bonds in the cyclopentanols leads to negative changes in retention times on acetylation (compounds 38, 47, and 64). These interpretations are substantiated by the negative change (—26%) in retention time exhibited on this column by *trans*-3-methoxycyclohexanol on acetylation (retention times of alcohol and acetate 3.04 and 2.25 min, respectively). Since no internal hydrogen bonding can take place in this alcohol, the change in retention time is negative.

Acetylation of the trisubstituted alcohols in row C (*cis*-1,2 hydrogen bonding can occur in both cyclohexanols and cyclopentanols), as expected, produces a positive percentage change in every case except for the diol 32, in which one hydroxyl can bond internally while the other cannot. In row D, the percentage change for the cyclohexanols is positive, as would be predicted, since both *trans*-1,2 and *cis*-1,3 hydrogen bonding are possible in the corresponding alcohols (the retention time data does not distinguish between the two). The negative percentage change for the cyclopentane acetates 40 and 50 is unexpected since a *cis*-1,3 hydrogen bond should be possible in the corresponding alcohols 7 and 17. Thus, it appears that a *cis*-1,3 intramolecular bond is not formed in the alcohols 7 and 17 (or at best a weak bond is

TABLE III

RETENTION TIMES OF SUBSTITUTED CYCLOHEXANOLS AND CYCLOPENTANOLS ON QF-1

See text for explanation of symbols.

Configuration	*a; C6* $X = OCH_3$ $Y = OCH_3$	*b; C5* $X = OCH_3$ $Y = OCH_3$	*c; C6* $X = Cl$ $Y = OCH_3$	*d; C5* $X = Cl$ $Y = OCH_3$	*e; C6* $X = Br$ $Y = OCH_3$	*f; C6* $X = Br$ $Y = OH$	*g; C6* $X = OH$ $Y = OCH_3$	*h; C5* $X = OH$ $Y = OCH_3$
(A) 	2.34 1,v	1.46 5,iv	3.43 9,v	1.76 14,iv	4.53 19,v	4.04 24,v	3.05 28	2.49 31
(B) 	2.27 2,iv	—	2.79 10,iv	2.14 15,v	3.55 20,iii,iv	3.89 25,iv	—	—
(C) 	1.66 3,ii	1.21 6,ii	2.19 11,ii	1.61 16,iii	3.17 21,ii	1.65 26,ii	3.01 29	2.15 32
(D) 	—	1.31 7,iii	2.75 12,iii	1.56 17,ii	3.55 22,iii,iv	3.80 27,iii	—	—
(E) 	1.04 4,i	0.64 8,i	1.23 13,i	0.78 18,i	1.59 23,i	1.59 23,i	1.66 30	1.16 33

formed). This conclusion is reinforced by the highly negative percentage change in retention time observed in proceeding from the diol 31 (in which *cis*-1,3 hydrogen bonding is a possibility) to the diacetate 64.

In row B, the negative value for the percentage change in retention time for compound 48 is as expected since no internal hydrogen bonds can form in the corresponding alcohol 15. In the bromodiol 25, which corresponds to the diacetate 58, one hydroxyl can bond internally while one cannot, leading to a negative value. For the cyclohexane series, the slightly negative or unchanged retention times for the acetates 35, 43, and 53 corresponding to the alcohols 2, 10, and 20 are the only examples, except for the diol cases discussed above, in which the values for the percentage changes in retention times are not positive. This behaviour is probably due to the fact that a sizeable proportion of the alcohols 2, 10, and 20 can exist in the conformation in which the hydroxyl group occupies the axial position. In this conformation, no intramolecular hydrogen bond can form.

When families of isomeric acetates are compared in the cyclohexane series, those with the same orientation elute in an order which approximates the increase in molecular weight. For example, in row A (Table II), the molecular weights of the cyclohexane acetates increase in the order $34 < 42 < 61 < 52 < 57$ whereas the retention times increase in the order $34 < 42 < 52 < 61 < 57$. For any row in Table II, the retention times of the cyclopentane acetates increase as the molecular weight increases. In contrast to the excellent separations of the alcohols (Table I), the retention times of acetates in isomeric families are often almost identical (*e.g.*, compounds 39 and 40, 43 and 45, 53 and 55, 58 and 59). Therefore, the elution order on DEGS in families of isomeric acetates of this type would be unsuitable for tentative structural assignments.

Retention times of the substituted cyclohexanols and cyclopentanols on QF-1 (Table III)

As anticipated, the retention times of the alcohols on this less polar column (Table III) are substantially shorter than on DEGS (Table I). The decreasing importance of hydrogen bonding on QF-1 is also shown by the fact that without exception the retention times of the cyclopentanols in Table III are shorter than those of the cyclohexanols. In addition, the retention times of the diols are often smaller than those found for the comparable chlorohydrins or bromohydrins (*e.g.*, $28 < 9$ and 19; $29 < 21$; $24 < 19$; $26 < 21$).

The increase in molecular weight is clearly becoming more important in determining the magnitude of the retention times than are hydrogen bonding effects. The elution order within a given isomeric series of alcohols on QF-1 more closely resembles that found for the acetates on DEGS than that found for the alcohols on DEGS.

Retention times of the substituted cyclohexanol and cyclopentanol acetates on QF-1 (Table IV)

From Table IV, it is evident that some difunctional acetates on QF-1 actually have longer retention times than the trifunctional acetates in the same series (*e.g.*, $37 > 35$ and 36; $46 > 43$; $56 > 53$). It is noteworthy that this phenomenon occurs only in the cyclohexane series and involves only trifunctional acetates in rows B and C which have two of the groups in a *cis*-1,2 relationship. The acetates in rows A and D, in which the three groups have an all *trans* relationship (all the groups can

TABLE IV

RETENTION TIMES OF SUBSTITUTED CYCLOHEXANOL AND CYCLOPENTANOL ACETATES ON QF-1

See text for explanation of symbols. The values in parentheses indicate percentage change in retention time of the acetates relative to the corresponding alcohols (Table III).

Configuration	*a; C6* $X = OCH_3$ $Y = OCH_3$	*b; C5* $X = OCH_3$ $Y = OCH_3$	*c; C6* $X = Cl$ $Y = OCH_3$	*d; C5* $X = Cl$ $Y = OCH_3$	*e; C6* $X = Br$ $Y = OCH_3$	*f; C6* $X = Br$ $Y = OAc$	*g; C6* $X = OAc$ $Y = OCH_3$	*h; C5* $X = OAc$ $Y = OCH_3$
(A) 	7.51 (+220) 34,v	2.71 (+86) 38,iv	8.86 (+158) 42,v	3.75 (+113) 47,iv	12.29 (+171) 52,v	22.54 (+458) 57,iii	16.73 (+448) 61	6.62 (+166) 64
(B) 	2.12 (−7) 35,ii	—	2.54 (−9) 43,i	4.97 (+134) 48,v	3.47 (−2) 53,i	17.62 (+354) 58,ii	—	—
(C) 	1.56 (−6) 36,*i*	2.23 (+84) 39,*ii*	5.07 (+132) 44,*iii*	2.90 (+80) 49,*ii*	6.25 (+97) 54,*iii*	23.50 (+1,324) 59,iv,v	13.53 (+350) 62	7.98 (+272) 65
(D) 	—	2.40 (+83) 40,iii	7.08 (+157) 45,iv	3.17 (+103) 50,iii	9.39 (+165) 55,iv	23.47 (+518) 60,iv,v	—	—
(E) 	2.37 (+128) 37,iii	1.30 (+103) 41,i	3.35 (+172) 46,ii	1.90 (+144) 51,i	4.35 (+174) 56,ii	4.35 (+174) 56,i	7.57 (+356) 63	4.52 (+290) 66

be equatorial), have substantially longer retention times than the difunctional acetates in row E. This unusual relationship in the cyclohexane series undoubtedly owes its origin to the known enhanced accessibility of the equatorial *vs.* axial substituents[25–27]. In the difunctional compounds, the two groups can both be equatorial, whereas in rows B and C the compounds exist as a mixture of two conformations in which either one or two of the functional groups may be axial. Thus, it would appear that a large proportion of the trifunctional acetates, which have shorter retention times than their difunctional counterparts, exist as the conformer with two axial groups. This observation is supported by the 220 MHz NMR coupling constants observed for these trifunctional acetates[28].

Recent conformational studies on cyclopentane compounds by Lambert *et al.*[29] (and refs. cited therein), suggest that there would be much less difference in the accessibility of cyclopentane functional groups to the column as configurations change than is the case in the cyclohexane series. This statement is supported by two observations from Table IV. First, the retention times of all trifunctional cyclopentane acetates in columns b, d, and h are substantially greater than those of the corresponding difunctional cyclopentane acetates (unlike the situation found in the cyclohexane series). Second, the differences in retention times within isomeric families of trifunctional acetates are much smaller in the cyclopentane series than in the corresponding cyclohexane series. For example, the retention times of the trifunctional cyclopentane acetates in column b, range from 2.23 to 2.71 min while for the corresponding cyclohexane acetates (column a), the retention times have a much larger range (1.56 to 7.51 min). Similarly, in column d, the range is from 2.90 to 4.97 min while in the corresponding cyclohexane acetates (column c) the range is much larger (2.54 to 8.86 min).

REFERENCES

1 E. Kováts, *Helv. Chim. Acta*, 41 (1958) 1915.
2 G. Schomburg and G. Dielmann, *J. Chromatogr. Sci.*, 11 (1973) 151.
3 D. S. Ashton, J. M. Tedder and J. C. Walton, *J. Chromatogr.*, 55 (1971) 231; 72 (1972) 269.
4 M. T. Maurette, C. Benard and A. Lattes, *J. Chromatogr.*, 63 (1971) 389.
5 P. T. Mitchell and F. Vernon, *J. Chromatogr.*, 65 (1972) 487.
6 J. A. McRae, R. Y. Moir, J. W. Haynes and L. G. Ripley, *J. Org. Chem.*, 17 (1952) 1621.
7 R. U. Lemieux, R. K. Kullnig and R. Y. Moir, *J. Amer. Chem. Soc.*, 80 (1958) 2237.
8 E. J. Langstaff, E. Hamanaka, G. A. Neville and R. Y. Moir, *Can. J. Chem.*, 45 (1967) 1907.
9 J. W. Bovenkamp, *Ph.D. Thesis*, Queen's University, Kingston, 1973.
10 R. A. B. Bannard, A. A. Casselman, E. J. Langstaff and R. Y. Moir, *Can. J. Chem.*, 45 (1967) 2605; 46 (1968) 35.
11 E. J. Langstaff, R. Y. Moir, R. A. B. Bannard and A. A. Casselman, *Can. J. Chem.*, 46 (1968) 3649.
12 R. A. B. Bannard and L. R. Hawkins, *Can. J. Chem.*, 36 (1958) 1241; 39 (1961) 1530.
13 R. A. B. Bannard, A. A. Casselman and L. R. Hawkins, *Can. J. Chem.*, 43 (1965) 2398.
14 A. A. Casselman and R. A. B. Bannard, *J. Chromatogr.*, 20 (1965) 424; 28 (1967) 462.
15 L. P. Kuhn, *J. Amer. Chem. Soc.*, 74 (1952) 2492.
16 L. P. Kuhn, *J. Amer. Chem. Soc.*, 76 (1954) 4323.
17 A. R. H. Cole and P. R. Jefferies, *J. Chem. Soc., London*, (1956) 4391.
18 A. Nickon, *J. Amer. Chem. Soc.*, 79 (1957) 243.
19 J. S. Brimacombe, A. B. Foster, M. Stacey and D. H. Whiffen, *Tetrahedron*, 4 (1958) 351.
20 R. W. Wright and R. H. Marchessault, *Can. J. Chem.*, 46 (1968) 2567.
21 A. C. Darby, H. B. Henbest and I. McClenaghan, *Chem. Ind.*, (1962) 462.
22 J. A. Franks, Jr., B. Tolbert, R. Steyn and H. Z. Sable, *J. Org. Chem.*, 30 (1965) 1440.

23 R. Steyn and H. Z. Sable, *Tetrahedron*, 25 (1969) 3579.
24 W. O. McReynolds, *J. Chromatogr. Sci.*, 8 (1970) 685.
25 E. L. Eliel, *Angew. Chem., Int. Ed. Engl.*, 4 (1965) 761.
26 N. B. Chapman, R. E. Parker and P. J. A. Smith, *J. Chem. Soc., London*, (1960) 3634.
27 B. L. Karger, R. L. Stern and J. F. Zannucci, *Anal. Chem.*, 40 (1968) 727.
28 J. W. Bovenkamp and R. Y. Moir, unpublished results.
29 J. B. Lambert, J. J. Papay, S. A. Khan, K. A. Kappauf and E. S. Magyar, *J. Amer. Chem. Soc.*, 96 (1974) 6112.