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STRUCTURAL INVESTIGATION OF PHENOLS AND ALCOHOLS USING SILYLATION AND GAS CHROMATOGRAPHY

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SUMMARY

It is shown that, if a phenol or alcohol is partly transformed into its trimethylsilyl (TMS) ether, and the mixture is then separated by gas chromatography using a polar stationary phase, valuable structural information can be obtained on the basis of the retention times of the hydroxy compound and its ether. For phenols, it is possible to determine the substitution pattern and the type of substituents at the *ortho*-positions; for alcohols a distinction can, among other things, be made between primary, secondary and tertiary alcohols. Conversion into TMS ethers is also of value for the resolution of mixtures of hydroxy compounds that are difficult to separate as such by gas chromatography.

INTRODUCTION

It has been shown that, for alkylphenols with similar molecular weights, the retention time in gas chromatography on a polar stationary phase decreases with increasing number of *ortho*-situated alkyl groups. The reason for this is the shielding effect of these groups, which reduces the interaction between the phenolic hydroxyl group and the polar molecules in the stationary phase. On a non-polar phase, however, the same shielding causes phenols to be separated in the reverse order, *i.e.*, among alkylphenols with similar molecular weights, non-*ortho*-substituted compounds will have the shortest retention times and di-*ortho*-substituted compounds the longest.

These relationships have been utilized for the separation of mixtures of phenolic compounds[1] and have also been used for the type determination of phenols. Thus, Fitzgerald[2] has shown that, when plotting the logarithms of the retention times of alkylphenols on a non-polar phase (Apiezon L) against those on a polar phase (dodecyl benzenesulphonate), the phenols fall into three groups comprising non-*ortho*-, mono-*ortho*- and di-*ortho*-substituted compounds. Accordingly, by chromatographing an alkylphenol on the two stationary phases, it is possible to decide the alkyl-substitution pattern around the phenolic hydroxyl group.

In the present investigation, it is shown that the same information can be obtained by using only one polar stationary phase, provided that the alkylphenol and its trimethylsilyl (TMS) ether are chromatographed simultaneously and that the

ratio between their adjusted retention times is used. The basis of this method is that the retention times of the TMS ethers of alkylphenols with similar molecular weights, in contrast to those of the free phenols, are relatively independent of *ortho*-substitution.

The silylation method is valuable not only for the investigation of *ortho*-substitution of alkylphenols, but also for structural elucidation of phenols containing other functional groups. As will be shown later, particularly large effects are obtained for phenols with groups capable of forming internal hydrogen bonds with the phenolic hydroxyl group.

As an extension of the work on phenols, the silylation method was applied to some alcohols in order to ascertain its value for the structural investigation of these hydroxy compounds; the compounds studied were primary, secondary and tertiary aliphatic alcohols and some types of aromatic alcohols.

Advantages of the present method are the facts that only one stationary phase is needed and that the ratio between the retention times of the hydroxy compound and its TMS ether is taken. This ratio is independent of change in the carrier-gas flow-rate, and also of small changes in column temperature, as the two compounds are co-chromatographed.

EXPERIMENTAL

Apparatus and columns

The gas chromatographic investigation was carried out with a Perkin-Elmer gas chromatograph (model 900) with a flame ionization detector. Steel columns (0.125 in. O.D.) 1.8 m long for phenols and 3.6 m long for alcohols were packed with 5% (w/w) of cyanosilicone GE XE-60 (Applied Science Labs., State College, Pa., U.S.A.) on acid-washed and DMCS-treated Chromosorb G (80–100 mesh). The carrier-gas (nitrogen) flow-rate was about 30 ml/min, and the operating temperature was 75, 150 or 200° (see Tables I–V). The gas hold-up time was evaluated by injecting methane.

Procedure

The silylation was carried out by adding a few drops of hexamethyldisilazane to one drop or a small crystal of a phenol or alcohol in a test-tube. The reaction between hexamethyldisilazane and a hydroxy compound can take place rapidly, but it may be sluggish, depending on the structure. With certain compounds, no heating is necessary; with others, heating the test-tube over a small flame for a short period is recommended.

Some compounds, *e.g.*, 4-formylphenol and certain halophenols, react so rapidly that silylation must be carried out in diethyl ether medium in order to achieve only partial reaction; with such compounds, it is best to dissolve the sample in diethyl ether and then to add an ether solution of hexamethyldisilazane. For sluggishly reacting compounds, *e.g.*, those in which the hydroxyl group is protected from attack by the presence of large *ortho*-situated groups, trimethylchlorosilane should be added as catalyst. In this instance, ammonium chloride is formed; a precipitate can also appear in the absence of trimethylchlorosilane, *e.g.*, with certain halophenols and salicylic acid, but it disappears on heating.

It should be noted that only partial silylation is required, as the hydroxy compound and its TMS ether should be co-chromatographed. It is not possible to give a general procedure for performing the silylation reaction, but satisfactory results can be obtained empirically.

RESULTS AND DISCUSSION

Phenols

Alkylphenols. The results obtained for alkylphenols are collected in Table I; the following discussion refers to a temperature of 150° for phenols unless otherwise stated. It can be seen that, for the compounds investigated, the ratio (R) between the retention time of the phenol and its TMS ether is 4.2 or higher for alkylphenols without *ortho*-substituents, 3.5–4.3 for phenols with one *ortho*-situated alkyl group and 1.5–2.6 for phenols with two such alkyl groups. There is a slight overlap between the first two groups, as 2-isopropyl-5-methylphenol has an R value corresponding to a non-*ortho*-substituted phenol. In fact, phenols with *ortho*-situated isopropyl groups tend to give high R values (see, *e.g.*, 2-isopropylphenol and 2,6-di-isopropylphenol). 2-Benzylphenol behaves like an alkylphenol, its R value being 4.1, whereas 2-phenylphenol (with an R value of 2.5) falls among the di-*ortho*-substituted alkylphenols.

A comparison between 3-substituted and the corresponding 4-substituted compounds shows that the R values for the former are consistently greater than those for the latter. Thus, on the basis of the R values for alkylphenols, one can determine the substitution pattern *ortho* to the phenolic hydroxyl group and also (to some extent) at the *meta*- and *para*-positions.

Halophenols. Non-*ortho*-substituted halophenols have R values higher than 5.4, whereas the values for the mono- and di-*ortho*-substituted halophenols studied are below 2.3 (see Table II); thus, it would seem to be possible to distinguish the former group from the other two. These last two groups, however, unlike the corresponding alkylphenols, cannot be distinguished on the basis of their R values. It can be seen that methyl groups elsewhere than in the *ortho*-position have only a slight effect on the R values for chlorophenols, while additional chlorine atoms in the *meta*- and *para*-positions increase the R values (see, *e.g.*, 3-chloro-, 4-chloro-, 3,4-dichloro- and 4-chloro-3-methylphenol).

A methyl group in the free *ortho*-position of a mono-*ortho*-chlorophenol decreases the R value (as expected), but, surprisingly, a chlorine atom in the same position increases the R value (see, *e.g.*, 2-chloro-, 2-chloro-6-methyl- and 2,6-dichloro-phenol). It should be noted that we did not study certain types of halophenols, for example, those non-*ortho*-chloro-substituted but having alkyl groups at one or both of the *ortho*-positions; it may well be that these types can interfere with mono- and di-*ortho*-substituted halophenols.

A comparison between the R values in Tables I and II shows that, for the compounds studied, only mono- and non-*ortho*-substituted alkylphenols can be distinguished from halophenols.

Phenols with various functional groups. The functional groups dealt with in this section all contain an oxygen atom capable of forming a bond to the hydrogen atom of the phenolic hydroxy-group when located *ortho* to this group. This fact decreases the retention time for certain *ortho*-substituted phenols to an extent such

TABLE I

ADJUSTED RETENTION TIMES AND RETENTION-TIME RATIOS (*R*) FOR ALKYLPHENOLS

Substituent or compound	*Temperature (°C)*	*Retention time (min)*		*R*
		Phenol	*TMS ether*	
Non-ortho-substituted				
Phenol	150	2.46	0.57	4.3
3-Methyl	150	3.54	0.81	4.4
3-Ethyl	150	5.02	1.04	4.8
4-Methyl	150	3.39	0.81	4.2
4-Ethyl	150	4.93	1.12	4.4
4-*sec.*-Butyl	150	8.75	1.87	4.7
4-*tert.*-Butyl	150	8.51	1.75	4.9
4-*tert.*-Pentyl	150	12.6	2.62	4.8
3,4-Dimethyl	150	5.80	1.30	4.5
3,5-Dimethyl	150	4.98	1.04	4.8
5-Ethyl-3-methyl	150	7.06	1.42	5.0
3,4,5-Trimethyl	150	10.0	2.20	4.5
2-Naphthol	200	6.05	1.44	4.2
4-*tert.*-Octyl	200	3.41	0.94	3.6
4-*n*-Nonyl	200	4.51	1.22	3.7
4-Cyclohexyl	200	5.00	1.46	3.4
4-Benzyl	200	10.3	2.72	3.8
4-Phenyl	200	10.8	2.76	3.9
Mono-ortho-substituted				
2-Methyl	150	2.62	0.75	3.5
2-Ethyl	150	3.45	0.92	3.7
2-Isopropyl	150	4.06	1.01	4.0
2-*tert.*-Butyl	150	5.48	1.57	3.5
2-Benzyl	150	59.3	14.4	4.1
2-Phenyl	150	18.8	7.56	2.5
2,3-Dimethyl	150	4.59	1.30	3.5
2,4-Dimethyl	150	3.68	1.08	3.4
2,5-Dimethyl	150	3.74	1.05	3.6
5-Isopropyl-2-methyl	150	6.38	1.55	4.1
2-Isopropyl-5-methyl	150	5.52	1.28	4.3
2-*tert.*-Butyl-4-methyl	150	6.71	2.01	3.3
2,4-Di-*tert.*-butyl	150	11.1	2.98	3.7
2-*tert.*-Butyl-5-methyl	150	7.12	1.95	3.7
2,3,5-Trimethyl	150	6.32	1.67	3.8
2,4,5-Trimethyl	150	5.92	1.63	3.6
1-Naphthol	200	5.20	1.32	3.9
2-Benzyl	200	6.26	2.03	3.1
2-Phenyl	200	2.68	1.25	2.1
Di-ortho-substituted				
2,6-Dimethyl	150	2.42	1.24	2.0
2-Methyl-6-*n*-propyl	150	4.13	2.03	2.0
2-Methyl-6-*tert.*-butyl	150	3.98	2.01	2.0
6-Allyl-2-methyl	150	3.71	2.24	1.7
2,6-Di-isopropyl	150	4.63	1.81	2.6
2,6-Diallyl	150	5.95	3.90	1.5
2,4,6-Trimethyl	150	3.35	1.71	2.0
2,3,5,6-Tetramethyl	150	6.68	3.27	2.0

TABLE II

ADJUSTED RETENTION TIMES AND RETENTION-TIME RATIOS (R) FOR HALOPHENOLS

Substituent	*Temperature (°C)*	*Retention time (min)*		*R*
		Phenol	*TMS ether*	
Non-ortho-substituted				
3-Fluoro	150	3.66	0.58	6.3
4-Fluoro	150	3.38	0.63	5.4
3-Chloro	150	10.0	1.38	7.2
4-Chloro	150	10.3	1.65	6.2
4-Chloro-3-methyl	150	13.4	2.20	6.1
3,4-Dichloro	150	38.2	3.70	10.3
4-Bromo	150	16.8	2.60	6.5
Mono-ortho-substituted				
2-Fluoro	150	0.90	0.51	1.8
2-Chloro	150	~1.4	~1.4	~1
2-Chloro-5-methyl	150	2.1	~2	~1.1
2,4-Dichloro	150	4.14	2.97	1.4
2,4-Dichloro-3,5-dimethyl	150	7.55	5.90	1.3
2,5-Dichloro	150	4.21	2.57	1.6
2,4,5-Trichloro	150	12.4	5.44	2.3
2-Bromo	150	~2.1	~2.1	~1
2-Iodo	150	4.55	3.66	1.2
Di-ortho-substituted				
2-Chloro-6-methyl	150	1.42	1.89	0.75
2,4-Dichloro-6-methyl	150	~3.9	~3.9	~1
2,6-Dichloro	150	3.98	2.46	1.6
2,3,4,5,6-Pentachloro	200	7.05	2.01	3.5

that R values below 1 are obtained, *i.e.*, the free phenol has a shorter retention time than the corresponding TMS ether (see Table III). R values below 1 are unusual outside this group of phenols, the only other compound found in this investigation with such an R value is 2-chloro-6-methylphenol.

The functional groups which cause an R value below 1 when located at the *ortho*-position are formyl, acetyl, ester and nitro groups. Judging from the R values, formyl and nitro groups form stronger hydrogen bonds than the other groups mentioned. A methoxy group in the *ortho*-position gives a remarkably constant R value of about 1.5, which is affected by neither the type of group present in the *para*-position nor the temperature. However, a hydrogen-bond-forming group at the other *ortho*-position can change the R value, as with 6-formyl-2-methoxyphenol. As the R value for this compound is below 1, it shows the expected hydrogen-bond-forming predominance of the formyl group over the methoxy group. Surprisingly, 2,6-dimethoxyphenol has an R value of 2.3.

For phenols containing formyl, acetyl or nitro groups at the *meta*- or *para*-positions, the R values are considerably greater than when the same functional groups are in the *ortho*-position. Thus, the two kinds of phenols can be readily distinguished. In Fig. 1, the ranges of R values for different types of phenols are shown; these ranges are based on the compounds investigated in this work and may be changed when more compounds are included.

TABLE III

ADJUSTED RETENTION TIMES AND RETENTION-TIME RATIOS (*R*) FOR PHENOLS WITH VARIOUS OXYGEN-CONTAINING SUBSTITUENTS

Substituent	*Temperature (°C)*	*Retention time (min)*		*R*
		Phenol	*TMS ether*	
Non-ortho-substituted				
4-Methoxy	150	9.4	2.2	4.3
4-Formyl	150	55.3	6.0	9.2
4-Acetyl	150	72.6	9.3	7.8
3-Formyl	200	4.15	0.83	5.0
4-Formyl	200	6.40	1.10	5.8
4-Acetyl	200	7.77	1.52	5.1
4-Propionyl	200	9.45	1.85	5.1
3-Nitro	200	11.2	1.46	7.7
4-Nitro	200	18.0	2.24	8.0
Mono-ortho-substituted				
2-Methoxy	150	2.05	1.47	1.4
2-Methoxy-4-methyl	150	3.13	2.11	1.5
4-Allyl-2-methoxy	150	6.40	4.15	1.5
4-Ethoxymethyl-2-methoxy	150	11.9	7.95	1.5
4-Formyl-2-methoxy	150	20.5	13.6	1.5
4-Acetyl-2-methoxy	150	28.2	19.4	1.5
2-Formyl	150	1.48	4.63	0.32
2-Acetyl	150	2.74	5.20	0.53
2-Isobutoxycarbonyl	150	5.32	8.80	0.60
2-Phenoxycarbonyl	150	33.2	61.8	0.54
2-Nitro	150	2.42	7.33	0.33
4-Formyl-2-methoxy	200	3.11	2.05	1.5
4-Acetyl-2-methoxy	200	3.98	2.64	1.5
2-Methoxy-5-nitro	200	10.8	4.70	2.3
2-Phenoxycarbonyl	200	4.41	6.38	0.69
Di-ortho-substituted				
2,6-Dimethoxy	150	9.31	3.96	2.4
6-Formyl-2-methoxy	150	7.65	13.6	0.56
6-Formyl-2-methoxy	200	1.44	2.04	0.71

R values measured at 200°. Some of the phenols investigated had inconveniently long retention times at 150°; these were chromatographed at 200°, and a few were chromatographed at both temperatures. The compounds studied at 200° were limited, and no general conclusions can be drawn from the results. For non-*ortho*- and mono-*ortho*-substituted alkylphenols, the *R* values are lower at 200° than at 150° (see Table I). An exception to this is constituted by 1- and 2-naphthols, undoubtedly because the substituent in this instance is fused to the parent phenol. No measurements were made at 200° for di-*ortho*-substituted alkylphenols; however, it is reasonable to assume that the *R* values for this group are also lower at 200° than at 150°. It is concluded that the *R* value limits previously mentioned for the three types of alkylphenols and based on measurements at 150° are not applicable to values obtained at 200°. The *R* values at 200° given in Table I should, however, afford some guidance for the structural assignment of alkylphenols at this temperature.

Only one chlorophenol, *viz.*, 2,3,4,5,6-pentachlorophenol, was examined at

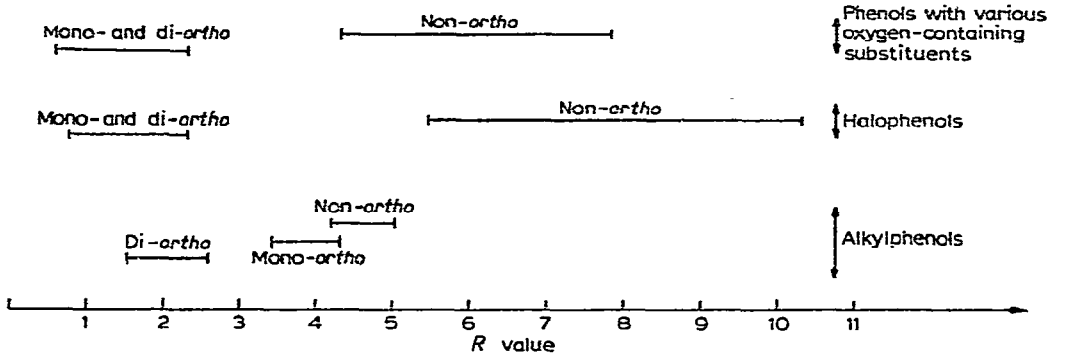

Fig. 1. Ranges of R values for phenols, valid at 150°.

200° (see Table II); the R value (3.5) was higher than for 2,6-dichloro-substituted phenols run at 150°. This is probably another example of the R value being increased by chlorine atoms in the *meta*- and *para*-positions. However, the phenol in question can still be recognized as being either mono- or di-*ortho*-substituted, as non-*ortho*-substituted halophenols have R values above 5.4 at 150°.

For phenols with oxygen-containing functional groups, the difference between R values at 200° and 150° seems to be less than for the previously discussed types of phenols (see Table III). For two 2-methoxy-substituted phenols, the R values at 200° are exactly the same (1.5) as the value found for this type of phenol at 150°. The higher value for 2-methoxy-5-nitrophenol at 200° (2.3) is most likely due to the presence of the nitro-group (*cf.* 3-nitro- and 4-nitrophenol).

Alcohols

Aliphatic alcohols. To judge from the R values in Table IV, the three main groups of alcohols (primary, secondary and tertiary) can generally be separated on the basis of these values. There is certainly an overlap between the first two groups for the three lowest-boiling primary alcohols (which, however, can be recognized from the short retention times of their TMS ethers). If these three alcohols are excluded, the R values for primary alcohols are at least 2.3, those for secondary alcohols are between 1.7 and 2.2, and those for tertiary alcohols are less than 1.7 (the values for the two tertiary alcohols investigated were 1.4). The two alicyclic alcohols tested (cyclopentanol and cyclohexanol) each have R values corresponding to primary alcohols (2.4).

Aromatic alcohols. The compounds studied in this group are divided into primary, secondary and tertiary alcohols, and the compounds within each group are arranged according to the position of the aromatic group in relation to the hydroxy-group (α, β or γ, see Table V).

As aromatic alcohols can be distinguished from aliphatic ones on the basis of their UV absorption, there is no risk of confusion between the two groups. Accordingly, a comparison of R values can be confined to the three types of aromatic alcohols and their α-, β- and γ-isomers.

The primary alcohols investigated have R values between 2.1 and 2.5 and the values show no dependence on the position of the aromatic group. α-Substituted

TABLE IV

ADJUSTED RETENTION TIMES AND RETENTION-TIME RATIOS (R) FOR ALIPHATIC AND ALICYCLIC ALCOHOLS

All experiments were made at 75°.

Compound	*Retention time (min)*		R
	Alcohol	*TMS ether*	
Primary alcohols			
Methanol	1.00	0.59	1.7
Ethanol	1.38	0.74	1.9
Propanol	2.23	1.06	2.1
Butanol	4.59	1.99	2.3
2-Methylpropanol	3.27	1.38	2.4
Pentanol	9.18	3.78	2.4
2-Methylbutanol	7.12	2.68	2.7
3-Methylbutanol	7.21	2.84	2.5
Hexanol	18.3	7.25	2.5
2-Methylpentanol	13.4	4.65	2.9
2-Ethylbutanol	14.3	4.73	3.0
Heptanol	35.9	13.8	2.6
Secondary alcohols			
Propanol-2	1.21	0.70	1.7
Butanol-2	2.40	1.42	1.7
Pentanol-2	4.61	2.36	2.0
Pentanol-3	4.40	2.54	1.7
3-Methylpentanol-2	8.24	3.78	2.2
4-Methylpentanol-2	6.76	3.23	2.1
3,3-Dimethylbutanol-2	5.32	2.68	2.0
Tertiary alcohols			
2-Methylpropanol-2	1.24	0.90	1.4
2-Methylbutanol-2	2.70	1.97	1.4
Alicyclic alcohols			
Cyclopentanol	11.3	4.68	2.4
Cyclohexanol	22.2	9.37	2.4

secondary aromatic alcohols have R values (2.6–2.9) higher than those for primary aromatic alcohols (2.1–2.5), and the R value for the only secondary β-isomer tested was 2.1. Of the tertiary aromatic alcohols, only one α-isomer and one β-isomer were studied; the former had an R value of 3.4 and the latter one of 1.5.

There is a distinct difference in R value between α- and β-isomers of secondary and tertiary alcohols, respectively. As seen from Table V, the difference is primarily caused by a considerable divergence in retention time between the TMS derivatives of the α- and β-forms. This somewhat unexpected result could be due to a blocking (in the α-isomer) of the aromatic ring by the TMS group, so preventing the ring from coming into contact with polar sites in the stationary phase.

It is concluded that there are certain possibilities for distinguishing between primary, secondary and tertiary aromatic alcohols on the basis of their R values (except for β-substituted secondary alcohols, which fall in the primary group). It should also be possible to decide the position of the aromatic group (α or β) for

TABLE V

ADJUSTED RETENTION TIMES AND RETENTION-TIME RATIOS (*R*) FOR AROMATIC ALCOHOLS

All experiments were made at 150°.

Compound	*Position of hydroxyl group in relation to aromatic group*	*Retention time (min)*		*R*
		Alcohol	*TMS ether*	
Primary alcohols				
Benzyl alcohol	α	2.85	1.37	2.1
o-Methoxybenzyl alcohol	α	8.48	3.76	2.3
p-Methoxybenzyl alcohol	α	11.4	4.97	2.3
2-Phenylethanol	β	3.26	1.40	2.3
3-Phenylpropanol	γ	5.39	2.18	2.5
3-Phenylprop-2-enol	γ	9.91	4.33	2.3
Secondary alcohols				
1-Phenylethanol	α	2.41	0.93	2.6
1-Phenylpropanol	α	3.40	1.18	2.9
1-*p*-Tolylethanol	α	3.47	1.27	2.7
1-Phenylpropanol-2	β	3.84	1.82	2.1
Tertiary alcohols				
2-Phenylpropanol-2	α	3.58	1.05	3.4
2-Methyl-1-phenylpropanol-2	β	4.01	2.68	1.5

secondary and tertiary alcohols. However, as β-substituted secondary alcohols mix with primary, their secondary nature must be established by some other means.

Resolution of mixtures of hydroxy compounds on XE-60 stationary phase

So far, application of silylation in the structural investigation of hydroxy compounds has been discussed. Another valuable use of silylation is for the resolution of mixtures of hydroxy compounds on XE-60 stationary phase. An inspection of the retention times in Tables I–V for phenols and alcohols reveals that many mixtures of these compounds that are not resolved when chromatographed on XE-60 can be separated on this phase after transformation into TMS ethers. This is demonstrated in Table VI for some mixtures of phenols (mostly alkylphenols) and alcohols. Common to the seven mixtures of alkylphenols is that the compounds comprising the individual mixtures belong to different *R*-value groups. For alkylphenols, the *R*-value groups are constituted by non-*ortho*-, mono-*ortho*- and di-*ortho*-substituted compounds. If the compounds in a non-resolved mixture of alkylphenols belong to the same *R*-value group, the effect of silylation on the resolution is generally slight (see, for example, the retention values of 3-ethyl-, 4-ethyl- and 3,5-dimethylphenol and, further, 2,4- and 2,5-dimethylphenol in Table I). Neither of these mixtures will be resolved after silylation. Silylation has previously been employed by Langer *et al.*[3] and Freedman and Charlier[4] to reduce tailing and improve the separation of alkylphenols in a tar-acid mixture.

Results for three mixtures of phenols with substituents capable of forming internal hydrogen bonds when situated *ortho* to the hydroxyl group are also shown in Table VI. The retention values of the second mixture illustrate the great effect on resolution that silylation can cause for this type of phenol. Thus, while the relation-

TABLE VI

RESOLUTION OF MIXTURES OF PHENOLS AND ALCOHOLS AFTER SILYLATION

Mixture of compounds	*Retention time (min)*		*Type*
	Hydroxy compound	*TMS ether*	
Phenols (temperature 150°)			
Phenol	2.46	0.57	Non-*ortho*
2,6-Dimethyl	2.42	1 24	Di-*ortho*
4-Methyl	3.39	0.81	Non-*ortho*
2,4,6-Trimethyl	3.35	1.71	Di-*ortho*
3,4-Dimethyl	5.80	1.30	Non-*ortho*
2,4,5-Trimethyl	5.92	1.63	Mono-*ortho*
2,6-Diallyl	5.95	3.90	Di-*ortho*
2-Isopropyl	4.06	1.01	Mono-*ortho*
2-Methyl-6-propyl	4.13	2.03	Di-*ortho*
2,3-Dimethyl	4.59	1.30	Mono-*ortho*
2,6-Di-isopropyl	4.63	1.81	Di-*ortho*
2,5-Dimethyl	3.74	1.05	Mono-*ortho*
6-Allyl-2-methyl	3.71	2.24	Di-*ortho*
2-*tert.*-Butyl-4-methyl	6.71	2.01	Mono-*ortho*
2,3,5,6-Tetramethyl	6.68	3.27	Di-*ortho*
4-Methoxy	9.4	2.2	Non-*ortho*
2,6-Dimethoxy	9.31	3.96	Di-*ortho*
4-Acetyl	7.77	1.52	Non-*ortho*
6-Formyl-2-methoxy	7.65	13.6	Di-*ortho*
3-Nitro	11.2	1.46	Non-*ortho*
2-Methoxy-5-nitro	10.8	4.70	Mono-*ortho*
Alcohols (temperature 75°)			
Butanol	4.59	1.99	Primary
Pentanol-2	4.61	2.36	Secondary
Propanol-2	1.21	0.70	Secondary
2-Methylpropanol-2	1.24	0.90	Tertiary

ship between the retention times for the free phenols is 0.99, the corresponding relationship for the TMS ethers is 9.0.

Table VI also shows results for some mixtures of alcohols that are resolved on XE-60 only after silylation; like the alkylphenols, the compounds forming these mixtures belong to different *R*-value groups, *i.e.*, they are either primary, secondary or tertiary alcohols.

CONCLUSIONS

The ratio (R) between the adjusted retention times for a phenol or alcohol and its TMS ether is of value in the structural investigation of these types of hydroxy compounds. Thus, alkylphenols can be placed into one of three groups, *viz.*, non-*ortho*-, mono-*ortho*- or di-*ortho*-substituted compounds, on the basis of their R values; some information can also be obtained about alkyl groups in the *meta*- and *para*-positions.

Halophenols can be divided into two groups on the basis of their R values, *viz.*, non-*ortho*-substituted on one hand and mono- and di-*ortho*-substituted on the

other. Several phenols with oxygen-containing functional groups were also investigated; those with formyl, acetyl, ester and nitro groups in the *ortho*-position can be recognized from the fact that they have *R* values below 1. It was also found that many methoxyphenols had an *R* value near 1.5.

Aliphatic alcohols, with the exception of the three lowest-boiling primary alcohols, can be separated into primary, secondary and tertiary alcohols on the basis of their *R* values; the same appears to be possible for aromatic alcohols, with certain exceptions. Similarly, the *R* value is a useful aid to decisions about the position of the aromatic group in relation to the hydroxyl group.

In addition, silylation is of value for the resolution of certain mixtures of hydroxy compounds that are difficult to separate as such by gas chromatography. It would seem that, for successful separation after silylation, the phenols or alcohols comprising the mixture should belong to different *R*-value groups. Particularly large separation effects are obtained for phenols with substituents capable of forming internal hydrogen bonds to the hydroxyl group when situated in a position *ortho* to this group.

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