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CHROMATOGRAPHIC ADSORPTION CONSTANTS AND π ELECTRON DELOCALIZATION ENERGIES

CORRELATION OF VALUES

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SUMMARY

Adsorption values on Sephadex LH-20 Dextran for a large number of aromatic organic molecules have been correlated with the delocalization energies of these compounds. The delocalization energies may be calculated from molecular orbital theory. Since delocalization energies are more readily obtained than experimental resonance energies, *K* values for this system may be predicted in many cases from theoretical considerations.

INTRODUCTION

A previous publication[1] has demonstrated that the adsorption (*K*) value for planar aromatic hydrocarbons on Sephadex LH-20 Dextran can be linearly correlated with the resonance energies of these compounds if methanol or isopropanol is the eluting solvent. The relation is maintained when acetonitrile is substituted for the alcohols but fails if either DMF or THF is the eluant[2].

Since resonance energies are not easily found in the literature we have continued our effort to correlate *K* values with another energy parameter. Delocalization energies (*DE*) of electrons are readily calculable using the molecular orbital (MO) theory. For this reason it was decided to compare *K* values with the calculated *DE* values. Using *DE* values a host of compounds, for which resonance energies have not been determined, could be studied and hopefully the correlation extended.

MATERIALS AND METHOD

K values for all compounds were determined using the columns, gel, and detectors previously described[1]. V_0 was determined from the elution value of Blue Dextran and $(V_0 + V_i)$ from the elution values of acetone and hexane, which were identical. Both V_0 and $(V_0 + V_i)$ showed little day-to-day variation. *K* values were computed in the standard way. The standard deviation was ± 0.07.

DE values were calculated from Huckel MO theory[3,4] as the difference between the total energy of the π electron system and the energy that the system would have if all its double bonds were localized. The calculations were performed with the MO parameterization recommended by STREITWIESER[3] and the *DE* values are reported in units of the so-called resonance integral. Although it is generally conceded that calculated *DE* values are not as accurate a measure of the resonance energy for hetero-molecules as for hydrocarbons, their usefulness for molecules containing heteroatoms has been demonstrated previously[4].

RESULTS

A least squares solution for *K vs. DE* for five planar, unsubstituted hydrocarbons and hexane yields the equation

$$K = 0.233\,(DE) + 0.924 \tag{1}$$

K values, both experimental and calculated, and *DE* values are listed in the first part of Table I. The pooled standard deviation for these six compounds is $\pm$ 0.09. The pooled standard deviation for the correlation of *K* with resonance energies for ten aromatic hydrocarbons was $\pm$ 0.08 (ref. 1). The correlation of *K* with *DE* is then essentially as reliable as the correlation with resonance energy.

Eqn. 1 was used to calculate *K* values for the rest of the compounds listed in Table I. Agreement between computed and experimental values is very good except

TABLE I

PREDICTABILITY OF *K* VALUES FROM *DE* VALUES

Compound	*DE*	$K_{\mathrm{Exptl.}}$	$K_{\mathrm{calc.}}$	Δ
Hexane	0.00	1.00	0.92	0.08
Benzene	2.00	1.33	1.39	0.06
Naphthalene	3.68	1.71	1.78	0.07
Anthracene	5.31	2.15	2.16	0.01
Phenanthrene	5.45	2.36	2.19	0.17
Fluorene	4.75	1.93	2.03	0.10
Toluene	2.15	1.33	1.42	0.09
Chlorobenzene	2.05	1.40	1.40	0.00
Nitrobenzene	2.50	1.50	1.51	0.01
Benzonitrile	2.40	1.40	1.48	0.08
Benzyl alcohol	2.00	1.39	1.39	0.00
Anisole	2.21	1.46	1.44	0.02
Xylene	2.30	1.28	1.46	0.18
1-Chloro-4-nitrobenzene	2.55	1.56	1.52	0.04
2-Methylnaphthalene	3.83	1.66	1.82	0.16
1-Chloronaphthalene	3.73	1.73	1.79	0.06
2-Chloronaphthalene	3.73	1.80	1.79	0.01
1-Nitronaphthalene	4.11	1.78	1.88	0.10
1-Cyanonaphthalene	4.10	1.74	1.88	0.14
2,6-Dimethylnaphthalene	3.98	1.62	1.85	0.23
1,2,3,4-Tetrahydronaphthalene	2.00	1.44	1.39	0.05
Biphenyl	4.38	1.62	1.94	0.32
trans-Stilbene	4.88	1.84	2.06	0.22
Diphenylamine	4.47	1.85	1.96	0.11

for the alkyl hydrocarbons and the non-planar compounds. DE values for the alkyl hydrocarbons are unreliable since they run counter to the resonance energy trend; the equation will give rise to calculated K values which are too high in the case of non-planar structures for the reasons previously outlined[1].

If a K value for a phenol is computed using eqn. 1, the value obtained is too low in nearly every case. This discrepancy can be assigned to increased adsorption of the molecule to gel through hydrogen bonding through the phenolic hydroxyl. A corrected form of the equation can be written as:

$$K = 0.233\,(DE) + 0.924 + n(0.23) \qquad (2)$$

The last term corrects for the number (n) of hydroxyls on the molecule. DE, experimental and computed K values (using eqn. 2), and differences for phenolic compounds are listed in Table II.

The agreement between theoretical and calculated values is fair with a few notable failures. Both 2-hydroxy- and 2-nitrophenol are known to have H-bond inter-

TABLE II

CORRELATION OF K VALUES WITH DE VALUES AND H-BOND FUNCTIONS FOR PHENOLS

Compound	DE	$K_{\text{Exptl.}}$	$K_{\text{calc.}}$	Δ
Phenol	2.20	1.05	1.06	0.01
2-Hydroxyphenol	2.30	1.64	1.94	0.30
3-Hydroxyphenol	2.30	1.87	1.94	0.07
4-Hydroxyphenol	2.30	1.65	1.94	0.20
2,3-Dihydroxyphenol	2.50	2.14	2.22	0.08
2-Chlorophenol	2.24	1.71	1.67	0.04
3-Chlorophenol	2.24	1.64	1.67	0.03
4-Chlorophenol	2.24	1.73	1.67	0.06
2-Nitrophenol	2.50	1.48	1.75	0.27
3-Nitrophenol	2.50	1.70	1.75	0.05
4-Nitrophenol	2.50	1.67	1.75	0.08
1-Naphthol	3.80	2.23	2.06	0.17
2-Naphthol	3.80	2.08	2.06	0.02
1,3-Dihydroxynaphthalene	4.00	2.69	2.34	0.35

TABLE III

CORRELATION OF K VALUES AND DE VALUES FOR ANILINE DERIVATIVES

Compound	DE	$K_{\text{Exptl.}}$	$K_{\text{calc.}}$	Δ
Aniline	2.23	1.03	1.07[a]	0.04
N-Methylaniline	2.25	1.03	1.08[a]	0.05
N,N-Dimethylaniline	2.27	1.50	1.45	0.05
2-Chloroaniline	2.28	1.33	1.45	0.12
3-Chloroaniline	2.28	1.41	1.45	0.04
4-Chloroaniline	2.28	1.34	1.45	0.11
2-Nitroaniline	2.03	1.50	1.54	0.04
3-Nitroaniline	2.03	1.54	1.54	0.00
1-Naphthylamine	3.03	2.18	2.07[a]	0.11
2-Naphthylamine	3.02	2.14	2.07[a]	0.07

[a] Computed using eqn. (2)

actions between the *ortho* groups[5] and therefore do not hydrogen bond to the gel. K values for these two compounds, computed by eqn. (1), are 1.48 and 1.52, respectively. These values agree more closely with the experimental values. The "too high" value for hydroquinone and "too low" value for 1,3-dihydroxynaphthalene cannot be rationalized on this basis.

Ring-substituted anilines give values predictable by eqn. 1 but aniline, N-methylaniline and the two isomeric naphthylamines have experimental values which are higher by 0.29 units than computed values. These compounds give a better correlation using eqn. 2. The differences noted in behavior may arise from steric considerations. Data and calculated values are given in Table III.

Carboxylic acids correlate surprisingly well with eqn. 1, with a few exceptions. These are terephthalic, 3-nitrobenzoic and 3-hydroxy- and 4-hydroxybenzoic acids. The last two compounds should give low computed values because of the hydrogen bonding of the hydroxyl group. Using eqn. 2 computed values for these compounds are 1.85 and 1.86, respectively. This compares very well with the experimental value for the 3-hydroxy acid, but still leaves considerable error for 4-hydroxybenzoic acid. All values are listed in Table IV. These results imply that H-bonding between the gel and the carboxyl group is unimportant except in a few special cases. One of the principal insights gained, therefore, by the correlation of adsorption constants and DE values is not necessarily a quantitative differentiation between all various substituted hydrocarbons, but rather an understanding of the relative importance of π electron interaction, hydrogen bonding, and steric effects in these molecules.

TABLE IV

CORRELATION OF K VALUES AND DE VALUES FOR CARBOXYLIC ACIDS

Compound	DE	$K_{\text{Expt.}}$	$K_{\text{calc.}}$	Δ
Benzoic acid	2.76	1.50	1.57	0.07
Phthalic acid	3.25	1.59	1.68	0.09
Isophthalic acid	3.25	1.72	1.68	0.04
Terephthalic acid	3.25	2.19	1.68	0.51
2-Chlorobenzoic acid	2.82	1.51	1.58	0.07
3-Chlorobenzoic acid	2.82	1.67	1.58	0.09
4-Chlorobenzoic acid	2.82	1.65	1.58	0.07
2-Nitrobenzoic acid	3.16	1.79	1.66	0.13
3-Nitrobenzoic acid	3.16	2.02	1.66	0.36
2-Hydroxybenzoic acid	2.07	1.67	1.62	0.05
3-Hydroxybenzoic acid	2.07	1.86	1.85[a]	0.01
4-Hydroxybenzoic acid	2.08	2.19	1.86[a]	0.33
1-Carboxynaphthalene	4.47	1.95	1.96	0.01
2-Carboxynaphthalene	4.45	1.96	1.96	0.00

[a] Calculated using eqn. 2

The last group of compounds to be considered, the heterocycles, are a very mixed bag. If eqn. 1 is used, some compounds have "too high" computed values, some "too low", and some within possible errors. This last group includes pyrazole, 1,2,4-triazole, benzotriazole, 2-methylfuran and coumarone. Those in the "too low" computed group all contain an imidic hydrogen as in pyrrole, indole, carbazole and imidazole. The average difference between experimental and calculated values is 0.39

units. This probably represents the hydrogen bond between the imide hydrogen and the gel.

It is interesting to note that of the seven "imidic" heterocycles, the four without an N atom adjacent to the N–H bond show H-bonding whereas the three with a –NH–N structure do not, *i.e.* they fit eqn. 1. Thus pyrazole and imidazole give identical calculated *DE* values but very different *K* values.

Compounds of the type pyridine, quinoline, pyrimidine, and phenazine all have experimental *K* values less than the calculated values. This may present difficulties in calculating *DE* values in heterocyclic systems containing only pyridine type N. Data and computed values using eqn. 1 are listed in Table V.

TABLE V

CORRELATION OF *K* VALUES AND *DE* VALUES FOR HETEROCYCLES

Compound	*DE*	$K_{\text{Expt.}}$	$K_{\text{Calc.}}$	Δ
Pyridine	1.00	1.21	1.39	0.18
Nicotinic acid	2.75	1.34	1.56	0.22
Quinoline	3.08	1.63	1.78	0.15
Isoquinoline	3.07	1.33	1.78	0.45
Pyrrole	1.25	1.01	1.00[a]	0.01
Indole	3.08	2.08	2.03[a]	0.05
Carbazole	4.04	2.47	2.46[a]	0.01
Imidazole	1.27	1.55	1.61[a]	0.06
Pyrazole	1.27	1.28	1.22	0.06
Pyrimidine	1.08	1.26	1.38	0.12
Phenazine	6.08	1.73	2.34	0.61
1,2,4-Triazole	1.31	1.36	1.23	0.13
Benzotriazole	3.42	1.74	1.72	0.02
2-Methylfuran	1.20	1.25	1.22	0.03
Coumarone	2.07	1.54	1.62	0.08

[a] Calculated using eqn. 1 + 0.30. The latter term represents the hydrogen bond contribution of the imide group.

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