JOURNAL OF PHYSICAL ORGANIC CHEMISTRY, VOL. 9, 255–261 (1996)

PARTITION COEFFICIENTS AND INTRAMOLECULAR HYDROGEN BONDING. 1. THE HYDROGEN-BOND BASICITY OF INTRAMOLECULAR HYDROGEN-BONDED HETEROATOMS

MICHEL BERTHELOT*, CHRISTIAN LAURENCE AND DENIS FOUCHER

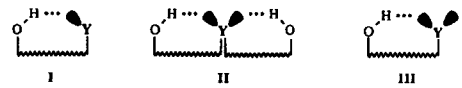
Laboratoire de Spectrochimie, Faculté des Sciences et des Techniques, Université de Nantes, 44072 Nantes, Cedex 03, France

AND

ROBERT W. TAFT

Department of Chemistry, University of California, Irvine, California 92717, USA

Measurements were made in CCl_4 of the formation constant K_{HB} of the 1:1 hydrogen-bonded complexes between the reference donor 4-fluorophenol and the intramolecular hydrogen-bonded systems I (one lone pair on heteroatom Y, one intramolecular hydrogen bond: 8-hydroxyquinaldine and 2-(2-hydroxyphenyl) benzoxazole); II: (two lone pairs, two intramolecular hydrogen bonds: 2,2'-dihydroxybenzophenone and 1,8-dihydroxyanthrone) and III (two lone pairs, one intramolecular hydrogen bond: tropolone, salicylic acid derivatives and guaiacol). The pK_{HB} values and the structural vibrational studies show that system I has a non-zero hydrogen-bond basicity which is due to the oxygen atom. In system II the non-zero basicity is explained by the two oxygens and the breaking of one intramolecular hydrogen bond. In the push-pull system III (e.g. tropolone), in spite of the great decrease of the basicity of the free lone pair by the intramolecular hydrogen bond (e.g. compared with tropone), Y remains the major site for intermolecular association. However in guaiacol, a non push-pull system III, the cooperativity effect makes the phenolic oxygen the major site.



I II III

INTRODUCTION

The partitioning equilibrium of solute molecules between water and immiscible organic solvent is of particular importance in drug design, not only because it correlates with biological activity[1,2] but also because it encodes a wealth of structural information.

Partition coefficients first provide information on the solute–solvent and solute–water intermolecular forces.[3] Their quantitative unravelling is important for understanding and predicting not only drug delivery, drug transport and drug distribution, but also drug recognition by and binding to the receptor, since solute–solvent and solute–receptor interactions are of the same basic nature. As repeatedly shown, hydrogen bonding (hereafter referred to as HB) is among the most important of these interactions[4] and the need for quantitative comparison of HB donors or acceptors explains the recent development of solute HB donor ability (HB acidity) and HB acceptor ability (HB basicity) scales for use in drug design.[5,6]

Partition coefficients also provide information on the effective solute structure in the solvent considered, in terms of those structural features – conformation, ionization, self-association, tautomerism and intramolecular HB[7] – which are very solvent dependent. From this point of view, structural information deduced from partition coefficients is better approached with spectroscopic solution studies than with *in vacuo* structures calculated by quantum mechanics or with solid-state structures determined by x-ray techniques.

* Author for correspondence.

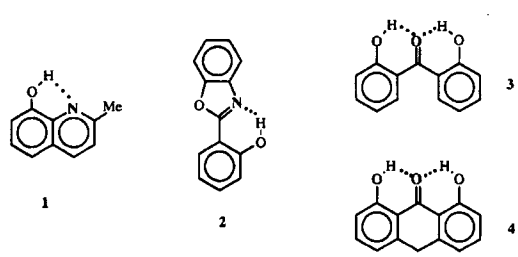
CCC 0894–3230/96/050255–07

Received 8 September 1995
Revised 8 January

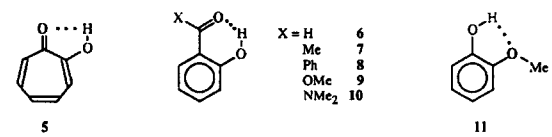
In this work, we show how partition coefficients are influenced by and can give information on intramolecular HB. Since the most important partitioning system, the octanol–water system, depends heavily on solute HB basicity,[8] this first paper deals with the measurement of the HB basicity of heteroatoms engaged in one or two intramolecular HBs. In Part 2, to follow, we will show that vibrational spectroscopic studies permit the determination of whether the intramolecular HB is retained or broken in the most common solvents used for the determination of partition coefficients, i.e. water, octanol, chloroform and alkanes. These HB basicity determinations and also IR solvation studies give a better understanding to the partition measurements that will be presented in Part 3, where we shall show the mutual enrichment of macroscopic partition results and microscopic solvation analysis for the structural knowledge of intramolecular hydrogen-bonded systems in solution.We have chosen to measure the HB basicity of the heteroatom Y in three kinds of systems, **I–III**, shown schematically.

I II III

In system **I**, the nitrogen lone pair of 8-hydroxyquinaldine (**1**) and 2-(2-hydroxyphenyl)benzoxazole (**2**) is probably no longer available for intermolecular HB and we expect a zero HB basicity at the Y atom. The same situation is anticipated for system **II**, 2,2′ dihydroxybenzophenone (**3**) and 1,8-dihydroxyanthrone (**4**) since the two lone pairs of the carbonyl group are already engaged in two intramolecular HBs. In system **III**, tropolone (**5**), salicylic acid derivatives **6–10** and guaiacol (**11**), a second lone pair is still available for intermolecular HB but charge transfer from the first lone pair is likely to reduced its charge density and, consequently, its HB basicity. To our knowledge, this lowering of HB basicity has not previously been measured. For the sake of comparison, the HB basicities of the corresponding compounds without intramolecular HB were also measured. The comparison will be made (i) by removing the OH group and/or (ii) by replacing the hydroxyl by a methoxy group. In the latter case, in order to avoid *ortho* effects of the 2-OMe substituent, the 4-OMe substituent will also be studied for compounds **6**, **7** and **9–11**.



1 2 3 4



5 11

EXPERIMENTAL

The compounds used in this study (Table 1) were commercially available, except the substituted *N*,*N*-dimethylbenzamides **28** and **29**, which were synthesized by Dr D.G. Morris at the University of Glasgow. After purification, the solids gave melting points consistent with literature data and the liquids were generally better than 99·5% pure as estimated by gas–liquid chromatography. All solutes and solvents were carefully dried by standard procedures. Fourier transform (FT) IR spectra were recorded on a Bruker IFS 48 spectrometer operating with Opus software. The cells of various path lengths (5–0·01 cm) were thermostated at 25 ± 0·2 °C. All the solutions were prepared in a dry glove-box and the measurements were carried out in tetrachloromethane. The equilibrium constant determination method has been described previously.[9] It is useful, however, to recall that the equilibrium concentrations are obtained from the absorbance of the free ν(OH) absorption of 4-fluorophenol at 3614 cm^{-1}. If the base has several sites of fixation for the phenol, the decrease in the absorbance which follows the addition of base leads to the sum of the concentrations of the different 1 : 1 HB complexes. As a consequence, the measured equilibrium constant is the sum of the HB formation constants of each site. The very dilute solutions used in this work prevent the formation of significant quantities of complexes with greater than 1 : 1 stoichiometry.

RESULTS

The HB basicity of the compounds **1–32** in Table 1 were measured on the pK_{HB} scale. This scale was introduced by Gurka and Taft[10] by choosing 4-fluorophenol as a reference donor and the standard conditions 298 K and CCl_4:

$$B + FC_6H_4OH \rightleftharpoons FC_6H_4OH \cdots B \quad (1)$$

$$K_{HB} = [\text{Complex}]/[\text{base}][FC_6H_4OH] \quad (2)$$

$$pK_{HB} = +\log K_{HB} \quad (3)$$

Later, Laurence and co-workers[9,11–15] extended this scale to a great number of functionalities and Abraham *et al.*[16] forced this scale to the sometimes more convenient 0–1 scale via the equation

$$\beta_2^H = 0{\cdot}216pK_{HB} + 0{\cdot}237 \quad (4)$$

This was done by setting $\beta_2^H = 1$ for the very strong base HMPA ($pK_{HB} = 3{\cdot}536$) and $\beta_2^H = 0$ for compounds

Table 1. pK_{HB} and β_2^H values[a] for intramolecularly hydrogen bonded molecules (**1–11**) and their non-bonded models (**12–31**)

No.	Compound	K_{HB}[b]	pK_{HB}	β_2^H	No.	Compound	K_{HB}[b]	pK_{HB}	β_2^H
1	8-Hydroxyquinaldine	3·0	0·47	0·34	**7**	2-Hydroxyacetophenone	3·6	0·56	0·36
12	Quinaldine		2·07[f]	0·68	**20**	Acetophenone	12·7	1·10	0·48
					21	2-Methoxyacetophenone	22·0	1·34	0·53
2	2-(2-Hydroxyphenyl)benzoxazole	1·8	0·26	0·29	**22**	4-Methoxyacetophenone	21·5	1·33	0·52
13	2-Phenylbenzoxazole	15·3	1·18	0·49					
					8	2-Hydroxybenzophenone	3·1	0·49	0·34
3	2,2′-Dihydroxybenzophenone	2·4	0·38	0·32	**14**	Benzophenone	11·8	1·07	0·47
14	Benzophenone	11·8	1·07	0·47	**23**	4-Methoxybenzophenone	18·8	1·27	0·51
4	1,8-Dihydroxyanthrone	2·7	0·43	0·33	**9**	Methyl salicylate	2·1	0·32	0·31
15	Anthrone		1·25[c]	0·51	**24**	Methyl benzoate	7·8	0·89	0·43
					25	Methyl 2-methoxybenzoate	30·9	1·49	0·56
5	Tropolone	20·4	1·31	0·52	**26**	Methyl 4-methoxybenzoate		1·.08[d]	0·47
16	Tropone	93·0	1·97	0·66					
					10	*N,N*-Dimethylsalicylamide	18·5	1·27	0·51
6	Salicylaldehyde	2·3	0·36	0·31	**27**	*N,N*-Dimethylbenzamide		2·23[e]	0·72
17	Benzaldehyde	6·0	0·78	0·41	**28**	*N,N*-Dimethyl-2-methoxybenzamide	301	2·48	0·77
18	2-Methoxybenzaldehyde	12·9	1·11	0·48	**29**	*N,N*-Dimethyl-4-methoxybenzamide		2·31[e]	0·74
19	4-Methoxybenzaldehyde		1·10[e]	0·47					
					11	Guaiacol	2·2	0·34	0·31
					30	Anisole	1·2	0·09	0·26
					31	1,4-Dimethoxybenzene	2·8	0·45	0·33

[a] This work, unless stated otherwise.
[b] $dm^3\ mol^{-1}$.
[c] Ref. 10.
[d] Ref. 14.
[e] Ref. 11.
[f] Calculated from Ref. 26.

without measurable HB basicity ($pK_{HB} = -1·1$). The pK_{HB} and β_2^H values are given in Table 1.

DISCUSSION

The OH group(s) of 1–11 are fully internally hydrogen bonded in carbon tetrachloride

In the IR spectra of these compounds, the absence of any band around 3600 cm^{-1} (which characterizes the stretching of a free OH group) provides evidence that these compounds are 100% internally hydrogen bonded. In the case of **3** and **4**, the carbonyl group accepts two hydrogen bonds. Also confirmed is the previous NMR finding[17] that **4** is indeed 1,8-dihydroxyanthrone and not the tautomeric isomer 1,8,9-trihydroxyanthracene.

Instead of a sharp ν(free OH) absorption, we observe in **1–11** a broader ν(bound OH) band at a lower frequency (Table 2 and Figure 1). The stability of the

Table 2. $\nu(OH\cdots)$ frequencies of the intramolecularly hydrogen-bonded molecules in CCl_4

No.	Compound	$\nu(OH\cdots)/cnm^{-1}$	$\Delta\nu(OH)$[a]
11	Guaiacol	3557 ± 1	43
1	8-Hydroxyquinaldine	3409 ± 1	191
3	2,2′-Dihydroxybenzophenone	3240 ± 30	360
9	Methyl salicylate	3210 ± 30	390
6	Salicylaldehyde	3200 ± 30	400
10	*N,N*-Dimethylsalicylamide	3140 ± 30	460
5	Tropolone	3130 ± 30	470
2	2-(2-Hydroxyphenyl)benzoxazole	3110 ± 30	490
8	2-Hydroxybenzophenone	3090 ± 30	510
4	1,8-Dihydroxyanthrone	3050 ± 30	550
7	2-Hydroxyacetophenone	3040 ± 30	560

[a] Calculated from $\nu(OH) = 3600\ cm^{-1}$ for a hypothetical non-bonded phenol.

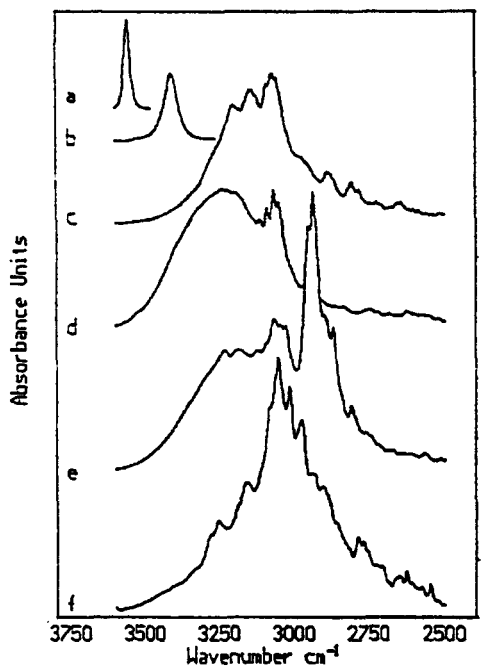


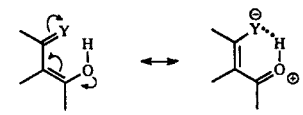
Figure 1. ν(OH···) absorptions of intramolecular hydrogen bonded molecules in CCl_4. (a) Guaiacol; (b) 8-hydroxyquinaldine; (c) 2-(2-hydroxyphenyl)benzoxazole; (d) 2,2'-dihydroxybenzophenone; (e) *N,N*-dimethylsalicylamide; (*f*) 2-hydroxyacetophenone

intramolecular HB cyclic structure depends on the acidity of the OH group, the basicity of the Y group and their spatial arrangement. It is commonly evaluated[18] by the frequency shift $\Delta\nu(OH) = \nu(\text{free OH}) - \nu(\text{bound OH})$ and by the half-bandwidth, which are not easy to evaluate since the band contour is generally complicated by the superposition of ν(CH) bands and by the presence of many sub-maxima. Nevertheless, the data presented in Table 2 allow chemically reasonable conclusions:

(a) The relatively strained five-membered rings in **11** and **1** produce the weakest HB. Structure **1** is the more stable because a pyridine nitrogen is more basic than an aromatic ether oxygen.[10]

(b) The formation of two HBs to a single carbonyl oxygen (**3**) is accompanied by a decrease in their average strength, compared with the single HB in **8**. This is confirmed in the solid state by x-ray analysis[19] and in $CDCl_3$ solution by NMR spectroscopy.[20]

(c) The push-pull mechanism in **32a** and the subsequent canonical structure **32b** increase the acidity of the OH group and the basicity of the Y atom, leading to stable HB in **2**, **5** and **6–10**.



32 a 32 b

(d) In **10**, the steric interaction between NMe_2 and the *ortho*-hydrogen atom of the phenyl ring prevents coplanarity of the phenyl and the amide group and lowers the stability of *N,N*-dimethylsalicylamide in comparison with other salicylic derivatives such as **7** and **8**.[18]

(e) Tropolone (**5**) is the least stable of the three push-pull ketones **5**, **7** and **8** because of the smaller ring size of the internal hydrogen bond.

The oxygen atom of 8-hydroxyquinaldine (1) is the main site for intermolecular HB

The pK_{HB} found for **1** shows that 4-fluorophenol and 8-hydroxyquinaldine form an intermolecular HB complex. The major site* of association of the phenol is probably the oxygen atom of **1**, since (a) the nitrogen lone pair is already occupied by an intramolecular HB (see above); we do not know any example where a nitrogen lone pair accepts two HBs in solution; (b) the ν(OH) band of 8-hydroxyquinaldine is shifted from 3409 to 3375 cm^{-1} when 4-fluorophenol is added; (c) the OH absorption of 4-fluorophenol in the complex has a shape and a position characteristic of an OH···O rather than an OH···N complexation; and (d) the basicity of a bound OH··· group ($pK_{HB} = 0{\cdot}47$) is higher than that of a free OH group ($pK_{HB} = -0{\cdot}12$),[9] which agrees well with the internal HB cooperativity effect.[21,22]

The weak basicity of 2-(2-hydroxyphenyl)-benzoxazole (2) results from several weakly basic sites

In **2**, the assumption that the nitrogen lone pair is no longer available for intermolecular hydrogen bonding is the more justified since the OH···N intramolecular HB is stronger in **2** than in **1**. However, at variance with **1**, compound **2** is a push-pull molecule and the basicity of the phenolic and the oxazolic oxygen might be greatly reduced by the contribution of structure **32b**. When 4-fluorophenol is added to **2**, the HB formation constant is 1·8 $dm^3 mol^{-1}$ ($pK_{HB} = 0{\cdot}26$) and two new bands appear in the spectrum: a band at 3569 cm^{-1} attributed to an

*The phenolic aromatic ring contribution is estimated, from an unpublished correlation between the pK_{HB} of π aromatic rings and substituent constants, to be approxirnately 5% of the total K_{HB}.

OH $\cdots$ π complex and a band at 3460 cm^{-1} which can result from the associations of 4-fluorophenol on both the oxazolic and the phenolic oxygen atoms. Assuming similar basicity of these two sites, the partition of the apparent equilibrium constant leads to

$$K_{HB}(\text{total}) = K_{HB}(\pi) + 2\,K_{HB}(O) \qquad (5)$$

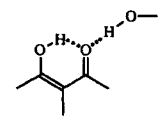
A value of $K_{HB}(\pi) \approx 0{\cdot}3$ $dm^3\,mol^{-1}$ may be estimated from the pK_{HB} vs ν(OH $\cdots$ π) correlation found for the family of π bases[23] so that $K_{HB}(O) \approx 0{\cdot}75$ $dm^3\,mol^{-1}$ and $pK_{HB}(O) \approx -0{\cdot}12$, a chemically reasonable value since the HB cooperativity effect is compensated by the push-pull mechanism.

The basicity of 2,2'-dihydroxybenzophenone and 1,8-dihydroxyanthrone might partly result from an artifact

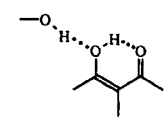
Addition of 4-fluorophenol to **3** and **4** induces no significant change in the carbonyl stretching vibration, indicating that the carbonyl group cannot accept the fixation of a third OH group. The equilibrium constants, 2·4 and 2·7 $dm^3\,mol^{-1}$ for **3** and **4**, respectively, seem too high to be explained only by the basicities of the two hydroxylic oxygens (*ca* 1·5 $dm^3\,mol^{-1}$). Since the two intermolecular hydrogen bonds are relatively weak[19,20] (see above), it cannot be excluded that a partial opening of one of these bonds occurs, leaving some room for an intermolecular association on the carbonyl.

Intramolecular HB greatly reduces the basicity of the free carbonyl lone pair of tropolone and salicylic derivatives

Infrared spectroscopy shows that the major site for HB in **5–10** is the free carbonyl lone pair (structure **33**) since (i) the asymmetric shape of the ν(OH) band of 4-fluorophenol resembles those generally found[24] for 4-fluorophenol–carbonyl complexes (Figure 2) and (ii) the carbonyl stretching vibration undergoes a shift to lower wave numbers similar to, but less than, those observed in 4-fluorophenol–carbonyl complexes. Figure 3 illustrates those shifts for 2-methoxyacetophenone ($\Delta\nu = 18$ cm^{-1}) and 2-hydroxyacetophenone ($\Delta\nu = 13$ cm^{-1}). We did not find evidence for any association on the hydroxylic oxygen atom (structure **34**). The low formation constant of this potential complex (*ca* 0·75 $dm^3\,mol^{-1}$) is negligible for tropolone (**5**) ($K_{HB} = 20{\cdot}4$) and *N*,*N*-dimethylsalicylamide (**10**) ($K_{HB} = 18{\cdot}5$), but might contribute slightly to the equilibrium constant of the other salicylic derivatives **6–9** ($K_{HB} = 2{\cdot}1$–$3{\cdot}6$).



33



34

The pK_{HB} values in Table 1 show the strong decrease in the intramolecularly bonded carbonyl basicity in comparison with the H, 2-OMe and 4-OMe derivatives. Comparison with the unsubstituted derivative reveals that a smaller relative attenuation, i.e. $[pK_{HB}(2\text{-OH}) - pK_{HB}(H)]/pK_{HB}(H)$, is found for the five-membered internal hydrogen bonding (tropolone: 34%) than for the six-membered type (compounds **6–10**: 43–64%). However, this difference does not stem only from the intramolecular HB effect but also from the opposing electron-donating effect of the

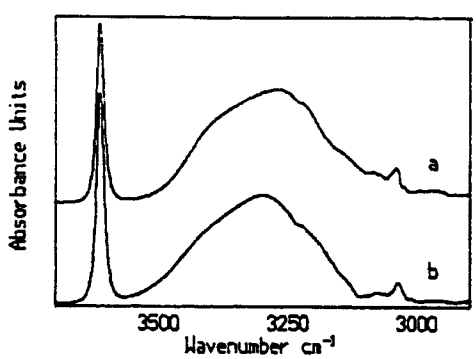


Figure 2. Association of 4-fluorophenol with tropone and tropolone. (a) Tropone (6×10^{-3} M); 4-fluorophenol (4×10^{-3} M) (b) Tropolone (7×10^{-2} M); 4-fluorophenol (4×10^{-3} M)

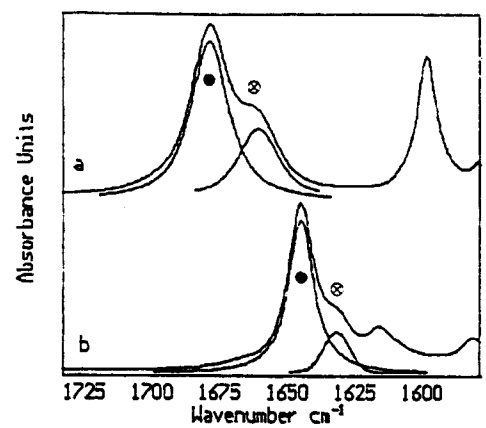
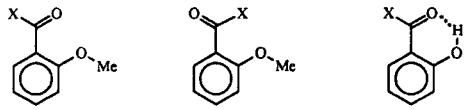


Figure 3. Carbonyl frequency shifts on association with 4-fluorophenol. (a) 2-Methoxyacetophenone (0·32 M); 4-fluorophenol (0·03 M). (b) 2-Hydroxyacetophenone (0·20 M); 4-fluorophenol (0·15 M). The curves under both spectra correspond to the free (●) and bonded (⊗) carbonyl absorptions as obtained by a band-fitting program.

ortho-hydroxy group. A first idea is then to compare the basicities of the 2-OH and the 2-OMe derivatives, but IR carbonyl absorptions and AM1 calculations show that the 2-OMe derivatives are in conformation **35a** or **35b**, which cannot be compared with conformation **35c**.



35a **35b** **35c**

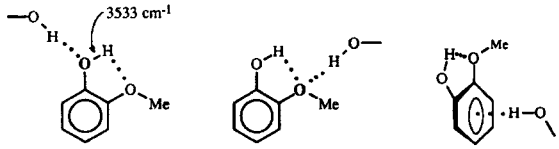
The best model for the electronic effect of the 2-OH ··· group seems to be the 4-OMe substituent and indeed we find a very satisfactory correlation [equation (6)] between the basicities of the five salicylic compounds **6–10** and their *para*-methoxy models **19**, **22**, **23**, **26** and **29**.

$$pK_{HB}(2\text{-OH}) = 0{\cdot}76\ pK_{HB}\ (4\text{-OMe}) - 0{\cdot}47$$
$$R = 0{\cdot}999,\ s = 0{\cdot}02 \quad (6)$$

In this equation, the intercept is satisfactorily greater than the statistical factor log2, which reduces the basicity of the 2-OH derivatives (one carbonyl lone pair available for the association) when compared with the 4-OMe derivatives (two lone pairs).

Guaiacol

4-Fluorophenol can give complexes **11a–c** with guaiacol. The $\nu(OH\cdots\pi)$ absorption of 4-fluorophenol in the complex **11c** is hidden under the $\nu(OH\cdots O)$ band of guaiacol at 3555 cm^{-1}.

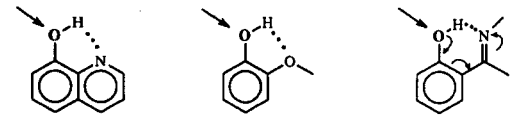


11a **11b** **11c**

It is well established that anisoles are (partly) HB π acceptors.[25] The π basicity of guaiacol can be estimated from *p*-dimethoxybenzene. The $\nu(OH\cdots\pi)$ band of the 4-fluorophenol–*p*-dimethoxybenzene complex at 3351 cm^{-1} gives $K_{HB}(\pi) = 0{\cdot}48\ dm^3\,mol^{-1}$ calculated from the relationship between pK_{HB} and $\nu(OH\cdots\pi)$ in the family of π bases.[23] The complex **11a** is the easiest to detect from the shift of the $\nu(OH\cdots O)$ band of guaiacol from 3555 cm^{-1} in free guaiacol to 3533 cm^{-1} in its complex **11a**. The complex **11b** cannot be detected since the $\nu(OH\cdots O)$ band of 4-fluorophenol which appears at 3477 cm^{-1} can originate from **11b** and/or **11a**. However, it appears that the cooperativity effect of the intramolecular HB increases the basicity of the OH oxygen atom of guaiacol while the remaining free lone pair of the OMe oxygen atom must not have a very significant basicity. In summary,

$$K_{HB}(\text{guaiacol}) = 2{\cdot}2 = K_{HB}(\mathbf{11a}) + K_{HB}(\mathbf{11b}) + K_{HB}(\mathbf{11c}) \quad (7)$$

and if $K_{HB}(\mathbf{11b})$ is neglected and $K_{HB}(\mathbf{11c})$ is subtracted, we have: $K_{HB}(\mathbf{11a}) \approx 1{\cdot}7\ dm^3\,mol^{-1}$. This value for the HB basicity of the oxygen atom in an OH ··· intramolecular HB compares well with those found previously for **1** and **2**. Molecules **1** and **11** are not push-pull systems and the cooperativity effect is greater in OH ··· N than in OH ··· O intramolecular HB, whereas in **2** the push-pull effect opposes the cooperativity effect.



1 (3.0 $dm^3\,mol^{-1}$) **11** (1.7 $dm^3\,mol^{-1}$) **2** (0.75 $dm^3\,mol^{-1}$)

REFERENCES

1. A. Leo, C. Hansch and D. Elkins, *Chem. Rev.* **71**, 525 (1971).
2. C. Hansch, *Acc. Chem. Res.* **26**, 147 (1993).
3. N. El Tayar, B. Testa and P. A. Carrupt, *J. Phys. Chem.* **96**, 1455 (1992).
4. A. D. Hamilton, *Advances in Supramolecular Chemistry* **1**, 1 (1990).
5. M. H. Abraham, P. P. Duce, D. V. Prior, D. G. Barratt, J. J. Morris and P. J. Taylor, *J. Chem. Soc., Perkin Trans. 2* 1355 (1989).
6. M. H. Abraham, *Chem. Soc. Rev.* **22**, 73 (1993).
7. R. W. Taft and J. S. Murray, in *Quantitative Treatments of Solute–Solvent Interactions*, edited by P. Politzer and J. S. Murray, pp. 55–82. Elsevier, New York (1994).
8. M. H. Abraham, H. S. Chadha, G. S. Whiting and R. C. Mitchell, *J. Pharm. Sci.* **83**, 1085 (1994).
9. C. Laurence, M. Berthelot, M. Helbert and K. Sraïdi, *J. Phys. Chem.* **93**, 3799 (1989).
10. D. Gurka and R. W. Taft, *J. Am. Chem. Soc.* **91**, 4794 (1969).
11. J.-Y. Le Questel, C. Laurence, A. Lachkar, M. Helbert and M. Berthelot, *J. Chem. Soc., Perkin Trans. 2* 2091 (1992).
12. E. D. Raczynska, C. Laurence and M. Berthelot, *Can. J. Chem.* **70**, 2203 (1992).
13. M. Berthelot, M. Helbert, C. Laurence and J.-Y. Le Questel, *J. Phys. Org. Chem.*, **6**, 302 (1993).
14. F. Besseau, C. Laurence and M. Berthelot, *J. Chem. Soc., Perkin Trans. 2* 485 (1994).
15. C. Laurence, M. Berthelot, M. Luçon and D. G. Morris, *J. Chem. Soc., Perkin Trans. 2* 491, (1994).
16. M. H. Abraham, P. L. Grellier, D. V. Prior, J. J. Morris and P. J. Taylor, *J. Chem. Soc., Perkin Trans. 2* 521 (1990).
17. W. Geiger, *Chem. Ber.* **107**, 2976 (1974).
18. E. Steinwender and W. Mikenda, *Monatsh. Chem.* **125**, 695 (1994).

19. V. Sharma, B. Bachand, M. Simard and J. D. Wuest, *J. Org. Chem.* **59**, 7785 (1994).
20. P. E. Hansen, S. N. Ibsen, T. Kristensen and S. Bolvig, *Magn. Reson. Chem.* **32**, 399 (1994).
21. P.L. Huyskens, *J. Am. Chem. Soc.* **99**, 2578 (1977).
22. H. Kleeberg, D. Klein and W. A. P. Luck, *J. Phys. Chem.* **91**, 3200 (1987).
23. C. Laurence and M. Berthelot, unpublished results.
24. C. Laurence, M. Berthelot and M. Helbert, *Spectrochim. Acta, Part A* **41**, 883 (1985).
25. B. B. Wayland and R. S. Drago, *J. Am. Chem. Soc.* **86**, 5240 (1964).
26. T. Gramstad, *Acta Chem. Scand.* **16**, 807 (1962).