Hammett–Taft and Drago models in the prediction of acidity constant values of neutral and cationic acids in methanol†

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The Hammett and Taft one-parameter model and Drago dual-parameter model have been applied to a very wide series of dissociation constants in methanol of carboxylic aliphatic acids, benzoic acid derivatives, phenols, protonated amines, anilinium and pyridinium derivatives. Both models can be successfully used to predict pK values in methanol of any member of the neutral and cationic acid families studied. Similarities and differences in the solvation behavior between the studied series of compounds have been pointed out.

The relationship between the solvent dependent parameters in both models has been established and it shows that the Hammett–Taft ρ value can be explained by means of the electrostatic and covalent components without any other contribution.

The Hammett–Taft model has been widely used to predict the acidity constant values of organic compounds in aqueous solution. The expression of the model is given in eqn. (1), where pK

$$\mathrm{p}K = \mathrm{p}K^0 - \rho\Sigma\sigma \qquad (1)$$

refers to the dissociation constant of an organic compound, pK^0 is the pK of the unsubstituted parent compound, ρ is the reaction constant for a particular equilibrium and σ is a constant assigned to a specific substituent. Eqn. (1) was derived by Hammett for aromatic compounds, but, according to Taft, the same expression is valid for aliphatic compounds. In this case the parameters should be denoted by the symbols ρ^* and σ^*.[1–3] σ and σ^* show different values for the same substituent and, in addition, some substituents show different σ values in phenols, anilines or pyridines.[2] In this paper we will refer to eqn. (1) for either aliphatic or aromatic compounds, using the appropriate constants in each case. Eqn. (1) and tabulated σ values have also been successfully applied to benzoic acid derivatives in different pure solvents[4] and water–organic solvent mixtures.[5] However, the reaction constant, ρ, is solvent dependent and it is clearly influenced by both non-specific and specific solute–solvent interactions.[3] Therefore, the parameters of the Hammett–Taft equation should be derived for each chemical family of compounds in the solvent of interest.

In the electrostatic–covalent (ECW) model proposed by Drago[6] a two-term four-parameter approach is used to accommodate covalent and electrostatic contributions. Each acid and each base are proposed to have a tendency to undergo electrostatic, E_A and E_B, and covalent, C_A and C_B, bonding. When applied to properties other than enthalpies (*e.g.*, IR, NMR, EPR, UV–vis, spectral shifts), the equation takes the form of eqn. (2), where $\Delta\chi$ is a general symbol for the physicochemical measurement. The electrostatic or charge-controlled component of the donor–acceptor interactions is given by E_AE_B, and the covalent or frontier-controlled component of the interaction by C_AC_B. The constant term W is a non-zero intercept, which incorporates any constant contribution to the reaction of a particular acid (or base) that is independent of the base (or acid) it reacts with.

$$\Delta\chi = E_AE_B + C_AC_B + W \qquad (2)$$

In many studies concerned with the influence of the structural changes on reactivity, the interest is in determining the influence of a substituent change on the chemistry of a family of compounds. When E and C values of each member of the family are not known, a dual substituent constant approach is proposed.[7,8] This substituent constant analysis is carried out with eqn. (3) where $\Delta\chi^X$ is the measured property of the

$$\Delta\chi^X = d^E\Delta E^X + d^C\Delta C^X + \Delta\chi^H \qquad (3)$$

X-substituted compound and $\Delta\chi^H$ is the measured property of the parent hydrogen compound.

Eqn. (3) is a two-parameter equation analogue to the Hammett equation. The dual-parameter analogues to σ are ΔE and ΔC, while the dual-parameter analogues to ρ are d^E and d^C. Interpretations of the parameters follow those of the Hammett equation, except information is now available on the covalent and electrostatic components of σ and ρ. The d parameters, like ρ, depend on the demand made by the constant reactant (its E and C) on the family of reactants and on the sensitivity of the family to the substituent change (s^E and s^C), $d^E = s^EE$ and $d^C = s^CC$. The components of d, like those of ρ, often have not been determined. When these quantities are not known, it becomes difficult even to interpret the signs of d. The combination of signs of E and s^E determines the sign of d^E, while the combination of C and s^C determines the sign of d^C. Besides the initial studies on pK_a and infra-red frequencies of several organic compounds and on the logarithm of rate constants of some reactions,[7,8] this dual-parameter substituent approach has been used recently in the analysis of ^{19}F NMR chemical shifts,[9] bond dissociation energies,[10] and kinetic parameters[11] of different types of compounds.

Among the organic solvents, methanol is the closest to water in structure and properties, and acidic dissociation in it takes place in a way analogous to that in aqueous solution. So, the

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† pK_{MeOH} values and Hammett–Taft and Drago substituent constants for carboxylic acids, phenol derivatives, protonated amines and anilinium derivatives, and pyridinium derivatives are available as supplementary data. For direct electronic access see http://www.rsc.org/suppdata/p2/1999/1953, otherwise available from BLDSC (SUPPL. NO. 57591, pp. 8) or the RSC Library. See Instructions for Authors *via* the RSC web page (http://www.rsc.org/authors).

substituent constants derived and widely validated for aqueous solution could be also suitable to predict pK values of acids in methanol, pK_{MeOH}, if the solvent dependent parameters, ρ and pK^0 in the Hammett–Taft equation and d^{E}, d^{C} and $\Delta\chi^{\mathrm{H}}$ in the Drago equation, involved in the models are known. In a very recent paper[12] a comprehensive and critical compendium of the pK_{MeOH} values of acids, is given. pK_{MeOH} values and pK in water, pK_{w}, for each studied chemical family were fitted to the well known equation derived from the theory established by Izmailov,[13] eqn. (4), where the slope value, a, is the acid strength

$$\mathrm{p}K_{\mathrm{MeOH}} = a\,\mathrm{p}K_{\mathrm{w}} + b \qquad (4)$$

resolution and it accounts for the methanol effect on the dissociation process with respect to that of water, and the intercept, b, is related to the solute solvation. The pK_{MeOH} values and the σ and σ^* values for the substituents[2,14] have been the basis for deriving the parameters of the Hammett–Taft equations in methanol, and, in the same way, pK_{MeOH} values and Drago's ΔE and ΔC values for substituents[8] allow the computation of d^{E} and d^{C}, and allow the establishment of suitable equations for the chemical families studied here.

The purposes of this paper are to apply both models to establish robust equations to be used to predict pK values in methanol, to verify their reliability in this solvent, and to prove the consistency of the results achieved by means of both approaches.

Results and discussion

The values of the primary constants of the studied compounds, both pK_{MeOH} values and Hammett–Taft[2,14] and Drago's[8] substituent constants, used in this work are given as electronic supplementary material.† Carboxylic acids are those given in ref. 12 for which Drago and/or Hammett–Taft substituent constants are available and some others not included in that reference because of the lack of pK_{w} values or other reasons given there. However, pK_2 of succinic and malonic acids, which were included in ref. 12, have been excluded here since they are outliers, probably because they are the only anionic acids.

Phenol derivatives included are also those given in ref. 12 with the same conditions pointed out for carboxylic acids. In this instance 2,6-di-*tert*-butyl-4-nitrophenol included in ref. 12 has been excluded here because it is a clear outlier. However, four new 2,6-di-*tert*-butylphenol derivatives[15,16] have been added.

N-Protonated amines are also those given in ref. 12 for which Drago and/or Hammett–Taft substituent constants are known, but 22 new members,[17,18] not included in the previous series because their pK_{w} were not published, have been added here. However, 20 pK_{MeOH} values of new protonated amines given in reference 17K of reference 17 have been excluded because all the points given there lie about two pK units below those predicted by eqn. (4) (see below) despite fitting a straight line well with a slope very similar to that of eqn. (4). So, this apparently systematic deviation could be originated in the calibration of the potentiometric system used in pK_{MeOH} determination. However, no mention of the calibration procedure appears in the original work and, in addition, a solution of hydrochloric acid in a methanol–dioxane mixture had been used as the titrant solution which may have caused variation of the solvent medium, and therefore of pK values, during the titration. *N*-Protonated pyridine derivatives used are from ref. 12 too.

Hammett–Taft model

The σ substituent parameter values used are from refs. 2 and 14 and they are also given as supplementary material.† There is another slightly different set of values derived by factor analysis from the pK values of benzoic acid derivatives in seven solvents including protic and dipolar aprotic ones.[19,20] Probably these 50 new parameters, corresponding to 25 substituents both *meta* and *para*, have a more general value since they were derived from a set of 35 monosubstituted benzoic acids[21] in the mentioned solvents. However, not all the σ values for the substituents of the compounds studied here were revised in ref. 19. So, the availability of the given values derived from data in aqueous solution and the similarity between methanol and water make them appropriate to use in everyday practice, at least for pK_{MeOH} predictions.

After comparison with values recently recommended by IUPAC,[22] most σ values were taken from ref. 14. In fact, data of ref. 14 agree very well with the "more reliable values" given in ref. 22 for CH_3, NO_2, OCH_3, F, Cl, and Br both *meta* and *para* substituents, since all of them are in the uncertainty range of those of ref. 22. The same happened with other σ values used if they were compared with the "less reliable data" of ref. 22 with four exceptions: σ_m for CN, $NHCOCH_3$ and SO_2CH_3 and σ_p for I. Since the values from ref. 22 are always included in the set of values from various sources given in ref. 14 for each substituent, we have chosen the recommended ones in ref. 14. Anyway, the largest difference between the values from both sources is 0.08. Moreover, σ values given in ref. 23 and computed from apparent pK values in ethanol–water mixtures also agree very well with those used in this work.

It is well known that the ρ parameter is solvent dependent and that it accounts for the solvent attenuation of the substituent effect.[1] Both methanol and water are solvents with amphiprotic and neutral character but they show significant differences in polarity and hydrogen bond abilities. So, the Kamlet–Taft parameters (π^*, α and β) are 1.09, 1.17 and 0.47 for water and 0.60, 0.93 and 0.62 for methanol.[24] Then, they show different solvation capabilities for both the neutral and ionic species, and this should be reflected in ρ_{MeOH} and ρ_{W} values, ρ values in methanol and water respectively, for the different chemical families analyzed here. Therefore, the a and b parameters of eqn. (4) should be related to the Hammett–Taft solvent dependent parameters for each family of compounds since they account for the same solvation interactions. So, combining eqn. (1) derived for aqueous solution and eqn. (4), the parameters of eqn. (1) for methanol can be calculated according to the relationships (5) and (6).

$$\rho_{\mathrm{MeOH}} = \rho_{\mathrm{W}}\, a \qquad (5)$$

$$\mathrm{p}K^0{}_{\mathrm{MeOH}} = a\,\mathrm{p}K^0{}_{\mathrm{W}} + b \qquad (6)$$

Drago model

Two types of substituents were reported: one involves transmission of the substituent properties through space and through the σ-bonding system of the molecule (non-conjugative or localized interaction). The other involves transmission through the π systems as well as through space and σ bonds (conjugative interaction). The non-conjugative interaction is operative for substituents on alkyl chains and on the 3-position of a phenyl ring; the conjugative interaction is the operative mechanism for transmission by 4-substituents. The substituents will be labeled 3-X for non-conjugative and 4-X for conjugative and, in spite of these labels, their use is not restricted to phenyl rings. Nearly 1000 experimental data, $\Delta\chi$, including different kinds of physicochemical measurements were fitted to eqn. (3) and the corresponding 3- and 4-ΔE^{X} and ΔC^{X} were calculated.[8] By convention, the typical electron-releasing substituents, *e.g.*, 3-CH_3, have positive ΔE^{X} and ΔC^{X} values while the typical electron-withdrawing substituents, *e.g.*, 3-Cl, have negative ΔE^{X} and ΔC^{X} values. There are systems in which the substituent change makes significant contributions to the reactive centre *via* both localised and delocalised mechanisms. When both effects contribute, the 3- and 4-substituents are inappropriate. A set of 2-X substituents have been reported for substituents on carbon two or three bonds removed from

Table 1 pK^0 and ρ parameters in water and in methanol from eqn. (1): $pK = pK^0 - \rho\Sigma\sigma$

	Solvent	pK^0	ρ	N[a]	S[b]	r^2[c]	Ref.
Carboxylic acids							
Aliphatics	H_2O	4.66	1.62	—	—	—	2
	MeOH	9.73	1.68	38	0.26	0.957	this work
Ortho substituted benzoic acid derivatives	H_2O	4.07	0.84	13	0.23	0.951	this work
	MeOH	9.34	0.87	13	0.28	0.932	this work
Non-*ortho* substituted benzoic acid derivatives	H_2O	4.20	1.00	—	—	—	2
	MeOH	9.36	1.37	47	0.11	0.972	this work
		9.34	1.37	11	0.08	0.953	21
		9.39	1.47	38	0.08	0.980	26
Phenols							
Phenols (global)	H_2O	9.92	2.23	—	—	—	2
	MeOH	14.40	2.60	43	0.39	0.982	this work
Ortho substituted phenol derivatives	H_2O	9.97	2.32	21	0.22	0.995	this work
	MeOH	14.58	2.64	25	0.36	0.991	this work
Non-*ortho* substituted phenol derivatives	H_2O	9.89	2.24	17	0.05	0.998	this work
	MeOH	14.13	2.44	18	0.32	0.944	this work
Protonated amines							
Primary (aliphatic)	H_2O	10.40	1.83	—	—	—	2
	MeOH	12.63	1.50	6	0.23	0.770	this work
Secondary (aliphatic)	H_2O	—	—	—	—	—	—
	MeOH	9.18	2.99	4	0.07	0.998	this work
Tertiary (aliphatic)	H_2O	9.71	3.11	9	0.10	0.992	this work
	MeOH	9.26	2.05	22	0.13	0.987	this work
Anilines	H_2O	4.58	2.88	—	—	—	2
	MeOH	5.92	3.38	28	0.30	0.975	this work
Protonated pyridines							
Pyridines	H_2O	5.39	5.70	—	—	—	2
	MeOH	5.50	4.79	12	0.18	0.921	this work

[a] N: number of points. [b] S: standard deviation. [c] r^2: square of the regression coefficient.

the reaction centre. Typical examples of such systems are *ortho* substituents on a phenyl ring. The values of 3- and 4-ΔE and ΔC parameters are those reported by Drago,[8] some of them revised recently.[25] The values of the 2-X substituent constants are more tentative than the 3- and 4-X because they were derived from a lower number of experimental data.[8] Since the ΔE^X and ΔC^X values are not all known with an equal degree of certainty, the fit of the experimental data is weighted using the reported n values (see electronic supplementary information †), which indicate the confidence to be placed in the parameters. The larger the n value, the less well known the parameter, thus, the weight given in the data fit is $w = 1/n$.

Eqn. (3) has been applied to the pK_{MeOH} values of the studied chemical families. Although Drago studied the pK_w values of several series reported here, all the involved compounds were monosubstituted derivatives and in most of these fits non-revised values of the substituent parameters were used. So, we have refitted these correlations for all families, including di- and poly-substituted compounds for which ΔE^X and ΔC^X values are available. For di- and poly-substituted compounds the substituent parameters have been computed by adding the appropriate parameters for the single substituents, for instance for 3,4-dichlorobenzoic acid, $\Delta E = 3\text{-}\Delta E^{Cl} + 4\text{-}\Delta E^{Cl}$.

Because the intercept in eqn. (3) accounts for the pK of the parent compound, $\Delta\chi^H{}_{MeOH}$, must be calculated from the intercept in water, $\Delta\chi^H{}_w$, by means of the expression (7), analogous to eqn. (6).

$$\Delta\chi^H{}_{MeOH} = a\,\Delta\chi^H{}_w + b \qquad (7)$$

Carboxylic acids. Table 1 shows the parameters of eqn. (1) computed for different series of carboxylic acids from pK_{MeOH} values as well as from the pK_w values previously published or calculated here.[2,21,26] Statistical parameters of the calculated lines show low standard deviations in all instances. The selected series of carboxylic acids are the aliphatic ones and benzoic acid derivatives both *ortho*-substituted and non-*ortho*-substituted because of the well known disturbing effect of the *ortho* substituents.

As reported in Table 1, ρ_{MeOH} and ρ_w show the same value for aliphatic saturated carboxylic acids (R-COOH) and for *ortho*-substituted benzoic acid derivatives showing that the differences in the stabilizing effect of water and methanol are irrelevant for these kind of acids. However, the ρ_{MeOH} value increases significantly for non-*ortho*-substituted benzoic acid derivatives similarly to ρ_w, showing that methanol is less efficient in the solvation of these acids than water. This is in very good agreement with the results reported previously[12] by means of eqn. (4) and given in Table 2. So, the effect of methanol on the acid strength resolution, a, is very pronounced in non-*ortho*-substituted benzoic acid derivatives whereas it is not pronounced in the *ortho*-substituted ones and in aliphatic carboxylic acids. In addition, the specific solvation effects, other than electrostatic, give a different value of the intercept, b, of eqn. (4) for each series. Then, non-*ortho*-substituted benzoic acid derivatives are less effectively solvated by methanol than the *ortho*-substituted ones. This point has been widely discussed before[12,27] on the basis of the twisting of the carboxylic group in *ortho*-substituted benzoic acids. The conformational differences very recently reported by Fiedler and Exner[28] between mono- and di-*ortho*-methyl substituted benzoic acids have not been seen here since in the 13 members of the *ortho* substituted compounds analyzed here, only 3 are methyl substituted. Moreover, these differences are very pronounced in the gas phase and in dimethyl sulfoxide solution, but are less noticeable in methanol.[29]

It should be pointed out here that the Hammett equation for *ortho*-substituted benzoic acids in aqueous solution has been calculated in this work from the pK_w of the acids studied in this work because in the literature different equations appear according to the nature of the *ortho* substituent,[2] for instance

Table 2 *a* and *b* parameters of eqn. (4) and calculated ρ_{MeOH} (eqn. (5)), pK^0_{MeOH} (eqn. (6)) and $\Delta\chi^H_{MeOH}$ (eqn. (7))

	a	*b*	N^a	ρ_{MeOH} (calc)	pK^0_{MeOH} (calc)	$\Delta\chi^H_{MeOH}$(calc)
Carboxylic acids						
Aliphatics	1.02	4.98	59	1.65	9.69	9.46
Ortho substituted benzoic acid derivatives	1.01	5.19	15	0.85	9.30	9.26
Non-*ortho* substituted benzoic acid derivatives	1.41	3.43	43	1.41	9.35	9.37
Phenols						
Phenols (global)	1.08	3.66	86	2.41	14.37	14.41
Ortho substituted phenol derivatives	1.12	3.56	29	2.60	14.73	15.10
Non-*ortho* substituted phenol derivatives	1.07	3.66	57	2.40	14.24	14.15
Protonated amines						
Primary (aliphatic)	1.03	0.69	11	1.88	11.40	—
Secondary (aliphatic)	—	—	—	—	—	—
Tertiary (aliphatic)	0.94	0.68	19	2.92	9.81	—
Anilines	1.21	0.48	25	3.48	6.02	6.17
Protonated pyridines						
Pyridines	0.94	0.67	40	5.36	5.74	5.58

[a] *N*: number of points.

Table 3 d^E, d^C and $\Delta\chi^H$ calculated from eqn. (3) for carboxylic acids, phenols and cationic acids

	Solvent	d^E	d^C	$\Delta\chi^H$	d^C/d^E	N^a	S^b	$r^{2\,c}$	Ref.
Carboxylic acids									
Aliphatics	H_2O	26.8	−3.60	4.40	−0.13	20	0.46	0.945	this work
	MeOH	21.8	−2.50	9.36	−0.11	20	0.51	0.967	this work
Ortho substituted benzoic acid derivatives	H_2O	8.05	−0.84	4.03	−0.10	10	0.39	0.865	this work
	MeOH	8.25	−0.81	9.30	−0.10	10	0.48	0.834	this work
Non-*ortho* substituted benzoic acid derivatives	H_2O	2.55	0.16	4.21	0.06	35	0.08	0.966	8
	MeOH	3.10	0.39	9.40	0.13	35	0.22	0.972	this work
Phenols									
Phenols (global)	H_2O	7.10	0.20	9.95	0.03	28	0.61	0.946	this work
	MeOH	6.70	0.55	14.28	0.08	28	0.74	0.938	this work
Ortho substituted phenol derivatives	H_2O	8.80	—	10.30	—	13	0.38	0.978	this work
	MeOH	9.50	—	14.80	—	13	0.45	0.973	this work
Non-*ortho* substituted phenol derivatives	H_2O	12.90	−1.35	9.80	−0.10	15	0.40	0.980	this work
	MeOH	11.70	−0.75	14.10	−0.06	15	0.40	0.978	this work
Protonated amines									
Anilines	H_2O	17.10	−1.60	4.70	−0.09	19	0.47	0.956	this work
	MeOH	18.00	−0.94	6.10	−0.05	19	0.69	0.941	this work
Protonated pyridines									
Pyridines	H_2O	8.10	1.90	5.22	0.23	11	0.04	0.987	this work
	MeOH	5.40	2.00	5.42	0.37	11	0.02	0.987	this work

[a] *N*: number of points. [b] *S*: standard deviation. [c] r^2: square of the regression coefficient.

2-chloro, 2-hydroxy, *etc.* Because the present series shows different kinds of *ortho* substituents, the same acids used in the methanol correlation have been selected. As expected, the results are in good agreement with the parameters given in ref. 2 for 2-chloro derivatives since the substituents in our series are halogens, CH_3, CH_3O and NO_2, and most of them show the same kind of inductive (acid strengthening) and resonance effects (acid weakening), with the exception of NO_2 which shows the opposite mesomeric effects.

The values calculated by means of eqns. (5) and (6), ρ_{MeOH}(calc) and pK^0_{MeOH}(calc) have been included in Table 2 and they show a very good agreement with values given in Table 1. This agreement proves the consistency of the pull of coefficients derived for eqns. (1) and (4) for both solvents, methanol and water.

The results for benzoic acid derivatives using Drago's model are given in Table 3 and they agree with those obtained from the Hammett equation. For the *ortho* derivatives the fits are not so good as for the non-*ortho* derivatives, probably due to the steric effects of the substituents. Although it is not possible to rule out the lower reliability of the 2-ΔE^X and 2-ΔC^X parameters, in comparison with the 3- and 4-Δ ones, this fact has a minor relevance since the fits obtained with other *ortho*-derivatives series (see below) are good. No direct comparison with aliphatic carboxylic acids can be made since they can be treated as formic or acetic acid derivatives, and 2-, 3- or 4-Δ substituent constants can be used. In this instance, different parameters can be obtained and no reasons to select one of them can be argued. The best correlations have been obtained using the acetic acid model, XCH_2COOH, and 3-ΔE and 3-ΔC parameter constant substituents. The results are in Table 3.

Values calculated by means of eqn. (7), $\Delta\chi^H_{MeOH}$(calc), are given in Table 2. The good agreement with pK^0_{MeOH} (Table 1), pK^0_{MeOH}(calc), and $\Delta\chi^H_{MeOH}$ shows the consistency of the different approaches studied.

Phenol derivatives. pK_{MeOH} values of phenol derivatives have also been fitted to eqn. (1). Although the whole set of available phenol derivatives fit eqn. (1) well, two different series were considered here, the *ortho*-substituted and non-*ortho*-substituted compounds. The obtained parameters as well as those from pK_w values are given in Table 1. The statistics of correlations are also very good here. The comparison of ρ_{MeOH} and ρ_W shows that methanol has a slightly lower ability to solvate all kinds of phenols than water. In contrast with the behaviour of benzoic acid derivatives, in this instance ρ_{MeOH} and ρ_w for *ortho* substituted phenols are slightly higher than those for non-*ortho* ones. This agrees very well with the results obtained by means of eqn. (4)[12] and it is explained by the different character of the resonance in both kinds of aromatic compounds.

Even here eqns. (5) and (6) have been used to obtain ρ_{MeOH}(calc) and pK^0_{MeOH}(calc) values (Table 2) and a very good agreement with those given in Table 1 has been achieved too.

All the phenols fit the Drago's equation well. When phenols are divided into *ortho* and non-*ortho* groups improved correlations are obtained and the d^C value becomes negligible for the *ortho* substituted series. Since no covalent contribution is noticeable for the *ortho* substituted phenol series, the ratio between d^E values in methanol and in water agrees with the *a* value (1.08 and 1.12, respectively). As expected, Table 2 shows the suitability of eqn. (7) to estimate $\Delta\chi^H_{MeOH}$(calc). These values prove again the consistency between the models studied here.

Cationic acids. All the analyzed cationic acids can be grouped into two main series, protonated amines and protonated pyridines. The first group can also be divided according to the aromatic or aliphatic character and this last one divided again into primary, secondary and tertiary amines. All of these series fit eqn. (1) well and the equation parameters, as well as those from pK_w, are given in Table 1. Statistical parameters are quite good in all instances except, perhaps, for the short primary aliphatic amine series.

Aliphatic protonated amines and pyridinium derivatives show ρ_{MeOH} values lower than ρ_w. This means that methanol has a higher solvation ability in comparison with water for these cationic acids and, therefore, the effect of the substituents on the dissociation is lower in methanol than in water. This can be related to the hydrogen bond basicity of methanol, which is higher than that of water, and makes easier the solvation of a cationic acid. It should be noticed that both nitrogen-protonated heterocyclic bases and secondary and tertiary amines, show the same behaviour and all fit eqn. (4) very well.[12]

On the contrary, protonated aniline derivatives show ρ_{MeOH} values higher than ρ_w as described above for phenols. This fact should be attributed to the similarity of the resonance in both series of aromatic compounds. Then, the delocalization of the lone electron pair of the basic form of aniline and the negative charge in phenolate is high and very similar. This fact can compensate for the difference in the anilinium solvation by methanol and by water and, despite the fact that the anilinium can be solvated more efficiently than the neutral phenol by both water and especially by methanol, the relative effect is the same in both cases (ρ_w/ρ_{MeOH} is 0.85). As stated before,[12] no appreciable differences have been noticed between *ortho* and non-*ortho* derivatives.

ρ_{MeOH}(calc) and pK^0_{MeOH}(calc) have been computed by means of eqns. (5) and (6) and the results are given in Table 2. As expected, results for aniline derivatives are quite good. However, the results are poorer for aliphatic amines probably because, at least in aqueous solution, each kind of primary, secondary or tertiary amine requires a different equation. Also, the literature shows significantly different parameters according to the nature of the amine (RNH_3^+ or $RCH_2NH_3^+$ for primary amines, *etc.*). Parameters given for $RCH_2NH_3^+$ have been included in Table 1 since all the pK_{MeOH} used are from compounds belonging to this family. Secondary amines in water have not been included because the very limited number of available pK_{MeOH} values makes any comparison useless. Parameter values for tertiary amines in water and in methanol have been determined here from the available values without any distinction according to the amine structure. Both series, pK_w and p$K_{MeOH,}$ fit successfully to eqn. (1) despite the fact that two different equations have been given in aqueous solution for the $RR'R''NH^+$ and $(R'CH_2)(R''CH_2)(R'''CH_2)NH^+$ series. However, parameters of pK_w have been calculated only from nine compounds which are the whole set of tertiary amines studied with known pK_w values. So, significant differences between calculated and experimental ρ_{MeOH} and pK^0_{MeOH} values should be expected. Calculated parameters for pyridines are also poor in comparison with the experimental ones. In fact, according to the presence or not of a substituent in the 2-position, different parameters for aqueous correlations are given in the literature[2] showing that their robustness is not so good as those of aliphatic carboxylic acids, benzoic acids, phenols or protonated anilines. Because of the lack of ΔE^X and ΔC^X values for most substituents of aliphatic amines, only protonated anilines and protonated pyridines have been fitted to Drago's model. Table 3 shows the parameters obtained. Even here protonated anilines show the same behaviour as non-*ortho* substituted phenols with negative d^C values and a higher contribution of the covalent term in water than in methanol. On the other hand, d^E and d^C parameters of pyridinium derivatives, as well as the ratios d^C/d^E in both solvents, differ significantly from those of protonated anilines in good agreement with the different solvation behaviour already reported.[12] Values of $\Delta\chi^H_{MeOH}$(calc) obtained by means of eqn. (7) are given in Table 2 and they show again the consistency of the models for cationic acids.

The comparison of d^C and d^E values for the studied systems shows that the electrostatic and covalent contributions act in the same direction for non-*ortho* benzoic derivatives and pyridinium compounds, and in the opposite direction in the other series. The absolute value of the ratio, d^C/d^E, is between 0.1 and 0.05 for all the systems and solvents with the exception of pyridinium derivatives for which the value is higher. This means that the electrostatic contribution prevails in all instances but this preponderance is significantly less pronounced for pyridinium derivatives as has already been noted for aqueous solution.[8]

Relationships between parameters of Hammett–Taft and Drago models

Two sets of substituent parameters must be used according to the aromatic or aliphatic character of the analyzed compounds in the Hammett–Taft model. The relationships between these parameters and ΔE^X and ΔC^X has been proved by Drago[8] fitting the σ_I and σ values to eqn. (3). Although σ^* and σ_I do not have exactly the same meaning, both parameters account for the inductive effect of the substituent and they are proportional.[2] From wide sets of data, including acceptor and donor substituents, eqns. (8) and (9) were obtained.[8]

$$\sigma_I = -4.20\,\Delta E^X + 0.37\,\Delta C^X + 0.10 \qquad (8)$$

$$\sigma = -2.10\,\Delta E^X - 0.213\,\Delta C^X + 0.03 \qquad (9)$$

Eqns. (8) and (9) show that the electrostatic term prevails over the covalent one in both cases and covalent and electrostatic contributions act in the same direction in σ but in opposite directions in σ_I. Each of these equations shows a different d^C/d^E ratio and this may explain why different one-parameter scales are needed for aliphatic and aromatic systems. The Drago dual-substituent approach provides a unique set of substituent constants that eliminates the need for separate σ scales but it requires two different constant values for each substituent that, very often, have not yet been determined. Moreover, the non-zero intercept in eqns. (8) and (9) shows that σ_I and σ values cannot be completely explained by the electrostatic and covalent terms only.

As stated before, ρ, d^E and d^C parameters account for the studied reaction and are solvent dependent and, therefore, they must be closely related. The following relationship can be obtained from the experimental values determined here (eqn. (10)).

$$\rho = 0.28(\pm 0.02)d^E + 1.65(\pm 0.11)d^C + 0.04(\pm 0.26) \quad (10)$$
$$N = 14,\ r^2 = 0.944,\ s = 0.37,\ F = 92.9$$

This equation includes all the families studied and presented in Table 3 (two groups, *ortho* and non-*ortho*, have been considered for phenols). The zero value of the intercept in eqn. (10) shows that the ρ parameter accounts only for the electrostatic and covalent components involved in the studied process without any other contribution. Moreover, both components act in the same direction and the covalent component contributes to the ρ value about six times as much as the electrostatic one. This can be attributed to the relevance of solvation to the dissociation process, mainly related to specific solute–solvent interactions of covalent character, for instance hydrogen bonding.

It should be pointed out again that the symbol ρ embodies here both ρ and ρ^*. However, very similar coefficients have been obtained when the two series of carboxylic aliphatic acids have been omitted in the correlation. This can be due to the similarity in the physical meanings of ρ and ρ^*, but, since only two aliphatic series have been included in this study it is not possible to use eqn. (10) for general application to aliphatic and aromatic compounds.

Eqn. (10) has been obtained from 14 dissociation processes, including neutral and cationic acids, in two solvents, methanol and water, and, therefore, its value is limited to dissociation processes in these protic solvents. To test the general applicability of eqn. (10), pK values of 35 monosubstituted benzoic acid derivatives in ethanol, dimethylformamide, acetonitrile, sulfolane (thiophene 1,1-dioxide) and acetone have been fitted to eqn. (3) and five new series of d^E and d^C paired values have been obtained. ρ values for these series of acids, already published by Ludwig *et al.*,[21] as well as those obtained in this work for non-*ortho* substituted benzoic acids in water and methanol, have been correlated here with d^E and d^C values. The result shows very similar coefficients to those given in eqn. (10) with very good statistical parameters. So, values used in eqn. (10) and those derived from ref. 18 together fit eqn. (11) very well,

$$\rho = 0.29(\pm 0.02)d^E + 1.65(\pm 0.11)d^C - 0.14(\pm 0.21) \quad (11)$$
$$N = 19,\ r^2 = 0.933,\ s = 0.34,\ F = 111$$

which shows the same coefficients as eqn. (10). Also, eqn. (11) is a robust equation to relate ρ values with d^E and d^C parameters for a variety of acids in protic and dipolar aprotic solvents and it shows again the great significance of the solvent covalent contribution in acidic dissociation processes.

Conclusions

It may be concluded that the Hammett–Taft and Drago models can be successfully used to predict pK values in methanol of any member of the neutral and cationic acid families studied here. The robustness of the established equations is supported by the wide variety of the compounds used in the parameters computation, as well as the wide pK ranges covered for each chemical series.

The study shows the similarity in the solvation behaviour between *ortho* benzoic and carboxylic aliphatic acids, between phenols and protonated anilines and between protonated aliphatic amines and pyridinium derivatives.

The relationships between solvent dependent parameters of both models show the preponderance of the covalent contribution to the ρ values according to the role of the solvent in dissociation processes. In contrast, the electrostatic contribution prevails in the Hammett–Taft substituent constants.

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