

Substituent Effects on the Basicity of Dimethylamines

Allan D. Headley

Contribution from the Department of Chemistry, University of the West Indies, Kingston 7, Jamaica. Received May 23, 1986

Abstract: In the absence of any chelation effect the relative base strength of substituted unconjugated amines is determined by the substituents and the solvent. The relative base strength of various dimethylamines in water shows that substituent polarizability effects play a significant role. However, a comparison with gas-phase basicities shows that the relative importance of polarizability to field/inductive stabilization is greater in the gas phase than in solution.

Brauman and Blair¹ demonstrated that in the gas phase alkyl substituents increase remarkably the basicities of amines. Similar observations have been made for the relative gas-phase acidities and basicities of alkyl-substituted mercaptans,² alcohols,¹ and phenols.^{3,4} The increased basicity was interpreted as being the result of induced dipole stabilization by the alkyl substituent of the ion formed on protonation. Substituents can stabilize a charged center by resonance (R), field/inductive (F), and polarizability (P) effects. The combination of these effects on a reaction can be described by utilizing the linear structure energy relationship⁵

$$\delta\Delta G = \rho_R\sigma_R + \rho_F\sigma_F + \rho_\alpha\sigma_\alpha + c \quad (1)$$

where ρ is the reaction constant for resonance, field/inductive, or polarizability effects, respectively. In solution these substituent effects play an important role for various reactions; however, the emphasis has been for a long time on resonance and field/inductive effects. Polarizability substituent effects have often been considered to be less important or even nonexistent; for most reactions ρ_α is usually small when compared to ρ_F and ρ_R . In solution, stabilization also comes from the solvent thus making the polarizability effect an even smaller contributor to stabilization. This effect, however, is still present and can be identified in some reactions.

The solvent's ability to stabilize a charge is often characterized by (a) dipolarity/polarizability effects, (b) hydrogen bond donor ability, and (c) hydrogen bond acceptor ability.⁶ In an aqueous medium stabilization of ammonium ions can be gained mainly by solvent dipolarity/polarization and solvent hydrogen bond acceptor ability. Comparison of our recent gas-phase data for proton-transfer reactions with solution data provides an understanding of these substituent effects in solution.

Experimental Section

Gas-phase basicities in this study were determined by the pulsed ion cyclotron resonance method for determination of the equilibrium constants for proton-transfer reactions as described elsewhere.⁷⁻⁹

The solution pK_a values were determined potentiometrically by titration of the amines, limited by their solubility, with 0.1 M HCl at 298 K.¹⁰ A Graphic control GC 51174 glass-calomel combination electrode was used in conjunction with a Beckman 3500 pH meter. Stable readings

(1) Brauman, J. I.; Blair, L. K. *J. Am. Chem. Soc.* **1968**, *90*, 5636.

(2) Bartmess, J. F.; Scott, J. A.; McIver, R. T., Jr. *J. Am. Chem. Soc.* **1979**, *101*, 6046.

(3) McIver, R. T., Jr.; Silvers, J. H. *J. Am. Chem. Soc.* **1973**, *95*, 8462.

(4) Fujio, M.; McIver, R. T., Jr.; Taft, R. W. *J. Am. Chem. Soc.* **1981**, *103*, 4017.

(5) Taft, R. W. *Prog. Phys. Org. Chem.* **1983**, *14*, 247.

(6) Taft, R. W.; Abboud, M. J.; Kamlet, M. J.; Abraham, M. H. *J. Soln. Chem.* **1985**, *14*, 153.

(7) Wolf, J. F.; Staley, R. G.; Kopell, I.; Taagepera, M.; McIver, R. T., Jr.; Beauchamp, J. L.; Taft, R. W. *J. Am. Chem. Soc.* **1977**, *99*, 5417.

(8) Taft, R. W.; Wolf, J. F.; Beauchamp, J. L.; Scorrano, G.; Arnett, E. M. *J. Am. Chem. Soc.* **1978**, *100*, 240.

(9) Bromilow, J.; Abboud, J. L. M.; Lebrilla, C. B.; Taft, R. W.; Scorrano, V.; Lucchini, J. *Am. Chem. Soc.* **1981**, *103*, 5448.

(10) Albert, A.; Sergent, E. D. *Ionization Constants of Acids and Bases*; Methuen: London, 1972.

Table I. Free Energies for Proton Transfer Equilibria Reaction of Substituted Dimethylamines in the Gas and Aqueous Phases (Values Are Relative to Trimethylamine)

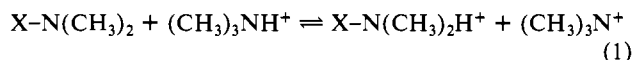
substituent, X	$\delta\Delta G$ (gas) ¹³ (kcal mol ⁻¹)	$\delta\Delta G$ (aq) ^{19,20} (kcal mol ⁻¹)
NCCH ₂	14.3	7.5
CF ₃ CH ₂	10.3	6.6
H	4.9	-1.6
CH ₃	0.0	0.0
(CH ₃) ₂ NCH ₂	-0.3	-1.2 ^a
H ₂ C=CHCH ₂	-1.9 ^a	-1.3
HC≡CCH ₂	2.1 ^a	3.4
C ₂ H ₅	-2.3	-0.6
<i>n</i> -Pr	-3.0	-0.6
C ₆ H ₅ CH ₂	-4.4	0.9
<i>i</i> -C ₄ H ₉	-4.3 ^a	0.8
<i>i</i> -C ₃ H ₇	-4.7	-1.0
<i>neo</i> -C ₅ H ₁₁	-5.0 ^a	-0.9 ^a
<i>sec</i> -C ₄ H ₉	-5.3 ^a	-1.2
<i>t</i> -C ₄ H ₉	-6.5	-1.5
<i>c</i> -C ₆ H ₁₁	-7.3	-1.6
<i>t</i> -C ₅ H ₁₁	-7.9 ^a	-1.8 ^a

^aThis study.

were obtained within 1 min. The electrode was first calibrated with a series of buffers.

Results

Table I shows the relative basicities of various substituted dimethylamines in the gas phase and aqueous medium relative to trimethylamine.



For alkyl substituents a single $\rho\sigma$ parameter correlation equation shows that in the gas phase

$$\delta\Delta G = (16.5 \pm 0.4)\sigma_\alpha + 5.8 \pm 0.3 \quad (2)$$

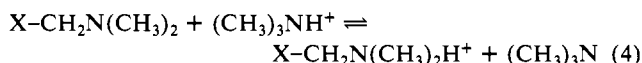
$$n = 9 \quad r = 0.998 \quad sd = 0.2$$

while in the aqueous phase

$$\delta\Delta G = (3.7 \pm 0.3)\sigma_\alpha + 0.1 \pm 0.2 \quad (3)$$

$$n = 9 \quad r = 0.975 \quad sd = 0.1$$

For heteroatom and unsaturated substituents separated by a methylene unit,



a dual parameter $\rho\sigma$ correlation equation in the gas phase is

$$\delta\Delta G = (28.7 \pm 0.4)\sigma_F + (6.7 \pm 0.3)\sigma_\alpha - 0.1 \pm 0.2 \quad (5)$$

$$n = 14 \quad r = 0.999 \quad sd = 0.3$$

while in the aqueous phase

$$\delta\Delta G = (14.4 \pm 0.6)\sigma_F + (1.0 \pm 0.6)\sigma_\alpha - 0.1 \pm 0.4 \quad (6)$$

$$n = 10 \quad r = 0.994 \quad sd = 0.4$$

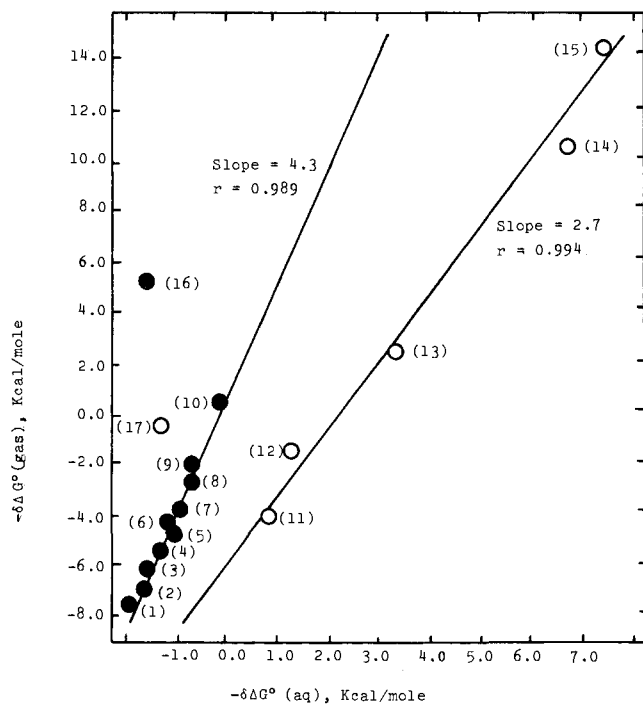


Figure 1. Gas phase vs. aqueous basicities of substituted dimethylamines: ordinate, $\delta\Delta G^\circ(\text{gas})$ (kcal mol⁻¹); abscissa, $\delta\Delta G^\circ(\text{aq})$ (kcal mol⁻¹); (1) *tert*-amyl; (2) *c*-C₆H₁₁; (3) *tert*-butyl; (4) *sec*-butyl; (5) neomyl; (6) isopropyl; (7) isobutyl; (8) *n*-propyl; (9) ethyl; (10) methyl; (11) benzyl; (12) allyl; (13) propargyl; (14) CF₃CH₂; (15) NCCH₂; (16) H; (17) (CH₃)₂NCH₂.

Discussion

Polarizability Effect. Figure 1 shows a plot of basicities in the gas phase vs. basicities in aqueous medium. An important observation arises from this plot, namely, the basicities increase linearly with the bulkiness of the alkyl substituent in both gas and aqueous phases. This observation is consistent with that of Brauman and Blair.¹ The slope indicates that stabilization in the gas phase is 4.3 times greater when compared to that in solution. Stabilization by alkyl substituents in an unconjugated position is accomplished almost entirely by polarizability.^{11,12} Polarization potentials developed recently offer a quantitative measure of a substituent's polarizability effect.¹³ Analysis of this effect in both gas and aqueous phases can be examined by a single parameter $\rho\sigma$ analysis. Equations 2 and 3 show an aqueous polarizability attenuation factor, $\rho_\alpha(\text{gas})/\rho_\alpha(\text{aq})$, of 4.5 ± 0.3 , which is consistent with the slope obtained. A value of unity would indicate that the effect being examined is the same in both phases. Values of unity have been obtained for large highly dispersed carbocations that are not specifically solvated.¹⁴ Solvation plays an important role in the magnitude of the ratio.

A close examination of reaction 1 shows substantial solvation by hydrogen bond acceptance of the solvent from the ammonium ion. This type of solvent stabilization represents a major form of stabilization. It now becomes apparent why the hydrogen substituent does not correlate with the other substituents in Figure 1. The hydrogen substituent, in addition to having different hyperconjugation forms, also offers an additional site for hydrogen bond formation. For primary amines a similar $\rho\sigma$ treatment shows that solvation is so important that substituent polarizability stabilization is essentially nonexistent.¹⁵

- (11) Stutchbury, N. C.; Cooper, D. L. *J. Chem. Phys.* **1983**, *79*, 4967.
 (12) Bordwell, F. G.; Drucker, G. E.; McCollum, G. J. *J. Org. Chem.* **1976**, *41*, 2786.
 (13) Hehre, W. J.; Pau, C.; Headley, A. D.; Taft, R. W.; Topsom, R. D. *J. Am. Chem. Soc.* **1986**, *108*, 1711.
 (14) Wolf, J. F.; Abboud, J. L. M.; Taft, R. W. *J. Org. Chem.* **1977**, *42*, 3316.

Table II. Substituent Constants for Polarizability and Inductive Effects

substituents	σ_α^{13}	$\sigma_F^{4,21}$
<i>t</i> -C ₅ H ₁₁	-0.82	0.00
C ₆ H ₅	-0.81	0.10
<i>t</i> -C ₄ H ₉	-0.75	0.00
<i>sec</i> -C ₄ H ₉	-0.68	0.00
<i>neo</i> -C ₅ H ₁₁	-0.67 ^a	0.00
<i>i</i> -C ₃ H ₇	-0.62	0.00
<i>i</i> -C ₄ H ₉	-0.61 ^a	0.00
HC≡C	-0.60	0.25
<i>n</i> -C ₄ H ₉	-0.57	0.00
<i>n</i> -C ₃ H ₇	-0.54	0.00
C ₂ H ₅	-0.49	0.00
CN	-0.46	0.60
N(CH ₃) ₂	-0.44	0.10
CH ₃	-0.35	0.00
CF ₃	-0.25	0.44
H	0.00	0.00

^a Value obtained on an additive basis with a 2.3 fall off factor.

Polarizability and Inductive/Field effects. Resonance substituent effects can be kept to a minimum by the insertion of a methylene unit between the substituent and the functional group. A three-parameter $\rho\sigma$ correlation equation, which includes resonance, field/inductive, and polarizability effects, shows no substantial resonance contribution of statistical significance. A comparison of the ρ_α values in eq 5 and 6 shows an aqueous polarizability attenuation factor of 6.7. The increase from 4.5 is not surprising since charge-induced stabilization depends on the magnitude of the charge and the distance separating it from a polarizable group.¹⁶ Here, even though the distance is the same for both phases, in solution (due to solvation) the charge on the ammonium ion is more dispersed. The aqueous field/inductive attenuation factor here is 2.0, which shows that there is a large dependence on field/inductive effect in both phases. A plot of $\delta\Delta G^\circ(\text{gas})$ vs. $\delta\Delta G^\circ(\text{aq})$ for heteroatom and unsaturated substituents shows a slope closer to unity (2.7). Thus for alkyl substituents, there is a linear relationship because these substituents are not specifically solvated.¹⁷ The dimethylamino substituent if used does not affect the correlation for the gas-phase basicities; however, in the aqueous medium the excellent correlation coefficient is totally destroyed. The dimethylamino substituent is highly solvated by water.¹⁸ Thus an enhanced value for σ_F is needed to compensate for the solvent effect.

Polarizability substituent effects play a very important role in the analysis of some proton-transfer reactions both in the gas phase and in solution. The basicity of substituted dimethylamines is influenced by polarizability substituent effects. The polarizability effect, however, does not parallel the field/inductive effect in the gas and aqueous phases since the attenuation factors for these effects are not the same. The field/inductive attenuation factor is 2.0 while the polarizability attenuation factor is 6.7 for the basicity of dimethylamines with a heteroatom or unsaturated substituent. Thus, the importance of polarizability effects relative to field/inductive effects is greater in the gas phase than in solution.

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- (15) Taft, R. W.; Topsom, R. D. *Prog. Phys. Org. Chem.*, in press.
 (16) Lawry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*; 2nd ed.; Harper and Row: New York, 1981; p 280.
 (17) Taft, R. W.; Gurka, D.; Joris, L.; Schleyer, P. v. R.; Rakshys, J. W. *J. Am. Chem. Soc.* **1969**, *91*, 4801.
 (18) Chawla, B.; Pollack, S. K.; Lebrilla, C. B.; Kamlet, M. J.; Taft, R. W. *J. Am. Chem. Soc.* **1981**, *103*, 6924.
 (19) Perrin, D. D. *Dissociation Constants of Organic Bases in Aqueous Solution*; Butterworths: London, 1972.
 (20) Spialter, L.; Pappalardo, J. A. *The Acyclic Aliphatic Tertiary Amines*; MacMillan: London, 1965.
 (21) (a) Marriott, S.; Topsom, R. D. *J. Am. Chem. Soc.* **1984**, *106*, 7. (b) Reynolds, W. F.; Gomez, A.; MacIntyre, D. W.; Tanin, A.; Hamer, G. K.; Peat, I. R. *Can. J. Chem.* **1983**, *81*, 2376.