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Note Added in Proof. During the referring process, the very recent and important paper by Bryce et al. (*J. Org. Chem.* **1992**, *57*, 1690) was brought to our attention. In it, novel monocyclic mixed acceptors are reported and show good reduction potentials and a basically planar structure which becomes more distorted with bulky substituents.

Registry No. **2a**, 98507-05-2; **2b**, 98507-16-5; **3**, 143104-94-3; **4**, 143104-95-4; **5**, 143104-96-5; **6**, 143104-97-6; **7**, 143104-98-7; **8**, 143104-99-8; **9**, 143105-00-4; **10**, 143105-01-5; **11**, 2498-66-0; **12**, 120086-28-4; **13**, 143105-02-6; BTC, 1000-70-0; 6,13-pentacenedione, 3029-32-1; 5,12-naphthacenedione, 1090-13-7.

Supplementary Material Available: X-ray data for **13** as well as ^{1}H NMR spectra for compounds **3–6** and microanalytical data for compounds **7–10** and **13** (12 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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Gas-Phase Basicity of N^1,N^1-Dimethylformamidines: Substituent Polarizability and Field Effects and Comparison with Brønsted Basicity in Solution

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Gas-phase basicities (GBs) for a series of 11 N^1,N^1-dimethylformamidines (**15–25**) bearing substituents with heteroatoms and/or π-bonds linked directly to the N^2 atom or separated by a $(CH_2)_n$ group are obtained from proton transfer equilibria measurements using FT-ICR mass spectrometry. Comparison of the GBs obtained here with those reported previously for formamidines with alkyl groups (**1–14**) (*J. Org. Chem.* **1991**, *56*, 3669–3673) confirms the earlier conclusion that for all derivatives, even for compounds with a second potentially basic site in the substituent, the N^2 atom is the favored site of protonation in the gas phase. Relative GBs of formamidines **1–25** are linearly correlated to the substituent polarizability and field effects. Deviations are observed for bifunctional compounds containing the OMe and NMe_2 groups, for which the additional lone pair enhances the basicity. The sensitivity of the amidine group to the global substituent effect (polarizability, field and "two electron pairs") as compared to the amino group in amines appears to be reduced by a factor of about 1.6 because of charge delocalization. A comparison of the gas-phase substituent effects with the substituent effects in a hydroxylic solvent (95.6% ethanol–water mixture) shows that the field effect in the gas phase is twice as large as that in solution. An electron-withdrawing field effect of the cyclopropyl group is confirmed.

Introduction

Although compounds containing the amidine group are known as very strong bases,[1,2] investigations on the gas-phase basicities and substituent effects have been reported only for imidazole and its derivatives,[3-5] 1,1,3,3-tetramethylguanidine (TMG),[6] which is the strongest monofunctional organic base in the current basicity scale,[4] and a series of N^1,N^1-dimethyl-N^2-phenylformamidines ($Me_2NCH{=}N\text{-}4\text{-}C_6H_4X$, X = NO_2, CN, COMe, Br, H, Me).[7] In a previous paper[8] we have studied the gas-phase basicity of N^1,N^1-dimethyl-N^2-substituted-formamidines [FDM*R, substituent R at N^2 restricted to alkyls; Me (**1**), Et (**2**), *n*-Pr (**3**), *i*-Pr (**4**), c-C_3H_5 (**5**), *n*-Bu (**6**), *i*-Bu (**7**), *s*-Bu (**8**), *t*-Bu (**9**), *n*-C_5H_{11} (**10**), *t*-C_5H_{11} (**11**), *n*-C_6H_{13} (**12**), c-C_6H_{11} (**13**), and 1-Adam (**14**)].

In this paper we extend our study to formamidines **15–25** with R = $(CH_2)_nX$ (n = 0, 1, 2, 3; X = heteroatomic and/or unsaturated group) at the N^2 atom. We report also the revised GB value for the 1-adamantyl derivative

$Me_2NCH{=}NR$ (FDM*R)

15: R = OMe
16: R = NMe_2
17: R = CH_2CN
18: R = CH_2CF_3
19: R = $CH_2C{\equiv}CH$
20: R = $CH_2CH{=}CH_2$
21: R = CH_2Ph
22: R = $(CH_2)_2CN$
23: R = $(CH_2)_2OMe$
24: R = $(CH_2)_2NMe_2$
25: R = $(CH_2)_3NMe_2$

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Table I. Experimental GB Values Obtained for Proton-Transfer Equilibria between FDM*R (B) and Reference Bases (ref) in kcal mol^{-1}

no.	R	ref	GB(ref)^a	$\Delta G^{\circ\,b}$	GB(B)^c
14	1-Adam	FDM*-t-C_5H_{11}	233.2^d	+2.3^d	
		FDM*$(CH_2)_2NMe_2$	234.8	+1.9	
		$(Me_2N)_2C{=}NH$	234.8	+0.6^d	
		$Me_2NC(Me){=}NEt$	235.1^e	+1.1	
		$Me_2NC(Me){=}NCHMe_2$	235.8^e	+0.4	
		$Me_2NC(Me){=}NCMe_3$	237.4^e	−1.2	236.0^f
15	OMe	pyrrolidine	216.9	0.0	
		Et_2NH	217.8	−0.7	217.0
16	NMe_2	Et_3N	224.4	+3.0	
		n-Pr_3N	226.9	+0.6	
		n-Bu_3N	228.3	−1.0	227.4
17	CH_2CN	pyrrolidine	216.9	0.0	
		FDM*OMe	217.0	0.0	217.0
18	CH_2CF_3	FDM*OMe	217.0	>+3.5	
		n-Pr_2NH	219.7	+0.9	
		N-Me-pyrrolidine	221.1	−0.1	220.8
19	$CH_2C{\equiv}CH$	FDM*NMe_2	227.4	−0.8	
		n-Bu_3N	228.3	−1.8	
		FDM*Me	228.7^e	−1.9	226.6
20	$CH_2CH{=}CH_2$	FDM*NMe_2	227.4	+1.9	
		FDM*Et	229.9^d	−0.7	229.3
21	CH_2Ph	FDM*Et	229.9^d	+1.1	
		FDM*-i-Pr	231.2^d	+0.1	
		FDM*$(CH_2)_2OMe$	232.4	−0.9	231.3
22	$(CH_2)_2CN$	FDM*CH_2CF_3	220.8	+2.9	
		Et_3N	224.4	−0.6	
		c-$C_6H_{11}NMe_2$	224.9	−0.6	223.9
23	$(CH_2)_2OMe$	FDM*-i-Pr	231.2^d	+1.1	
		FDM*-t-Bu	233.0^d	−0.1	
		$Me_2N(CH_2)_4NMe_2$	233.0	−1.2	
		$(Me_2N)_2C{=}NH$	234.8	−2.4	232.4
24	$(CH_2)_2NMe_2$	FDM*-t-C_5H_{11}	233.2^d	+1.5	
		$(Me_2N)_2C{=}NH$	234.8	+0.1	234.8
25	$(CH_2)_3NMe_2$	FDM*$(CH_2)_2NMe_2$	234.8	≥+2.6	
		FDM*-1-Adam	236.0	+1.9	
		$Me_2NC(Me){=}NCHMe_2$	235.8^e	+2.3	
		$Me_2NC(Me){=}NCMe_3$	237.4^e	+0.5	238.0

[a] Values of Taft et al. cited in refs 3 and 4. [b] $\Delta G^\circ = -RT \ln K$ obtained from the equilibrium constant K for proton transfer between FDM*R and the reference base. [c] ±0.3 kcal mol^{-1}. [d] As in ref 8. [e] As in ref 9. [f] Revised value.

obtained in our current work on the extension of the gas-phase basicity scale.[9] All compounds have been synthesized and their GB values obtained from proton-transfer equilibrium constant measurements using FT-ICR mass spectrometry. The measured GB values are compared with those found previously for derivatives containing alkyl groups. The influence of alkyl and $(CH_2)_nX$ substituents at the N^2 atom on the gas-phase basicities of FDM*R is studied and compared with that found for the corresponding primary amines (RNH_2) and N,N-dimethylamines ($RNMe_2$). Comparison of GB with the Gibbs free energy of proton transfer in hydroxylic solution is also carried out.

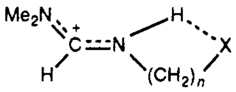
Experimental Section

The procedures of synthesis, purification, confirmation of structure, and GB measurements of FDM*R were the same as previously described.[8,10] The experimental GB values of FDM*R are given in Table I.

Results and Discussion

Site of Protonation. N^1,N^1-Dimethylformamidines **15–25** contain two nitrogen atoms, the amino (N^1) and the imino (N^2) atoms in the amidine group, and heteroatoms and/or π-bonds in substituent R, each electron-rich center being a potential protonation site in the gas phase. All the compounds can be considered as polyfunctional bases, either as derivatives of dimethylamines with the imino $CH{=}NR$ group as substituent, as derivatives of imines with the NMe_2 and R groups as substituent, or as derivatives of ethers (compounds **15** and **23**), amines (compounds **16**, **24**, and **25**), nitriles (compounds **17** and **22**), and π-bases (compounds **19–21**) bearing a $Me_2NCH{=}N$-$(CH_2)_n$ group (n = 0, 1, 2, or 3) as substituent.

Scheme I^a



^{a}X = OMe, n = 2; X = NMe_2; n = 2, 3.

In the previous paper,[8] concerning the protonation in the gas phase of FDM*Rs with alkyl groups, we have shown that all derivatives can be treated as monofunctional compounds, in which the N^2 atom in the amidino group is the preferred site of protonation.

Comparison of the GB values of FDM*R studied here (Table I) and previously[8] with those of the corresponding amines (RNH_2 and $RNMe_2$)[3,4,14–16] shows that the $Me_2NCH{=}N$ group is more basic by about 20–30 kcal mol^{-1} than the NH_2 group and by about 10–15 kcal mol^{-1} than the NMe_2 group.

Further comparison of the GB values reported previously for the parent compound FDM*Me[8] and the GBs for Me_2O, MeCN, $MeC{\equiv}CH$, $MeCH{=}CH_2$, and MePh[3,4] show that the former compound is more basic by at least 40 kcal mol^{-1}. In the case of Me_3N the difference amounts to 10 kcal mol^{-1}. Therefore, we expect a preferred protonation at the N^2 nitrogen. In compounds **17–25** the two basic groups are separated by at least one CH_2 group, thus preventing any conjugation. In compounds **15** and **16** the $Me_2NCH{=}N$ group is directly linked to the MeO and Me_2N groups, respectively. Since the $Me_2NCH{=}N$, MeO, and Me_2N groups are considered as electron-donating substituents, the conjugation effect can be neglected. The basicity of the MeO and Me_2N groups in **15** and **16** is not expected to be increased markedly as compared to an ether or an amine, respectively. For amidines **15–25** the amidine group is more basic than the other basic group in the substituent R.

These observations suggest that in all compounds studied here and previously[8] the amidine group (the N^2 atom) is the favored site of protonation in the gas phase. However, the basicity may be increased considerably by the second basic group (X) in substituent R, particularly in the case of compounds (Scheme I) in which the intramolecular hydrogen bonding may take place in the formamidinium ions (compounds **23–25**).

Additional proof that the N^2 atom is the preferred site of protonation is given by the analysis of gas-phase substituent effects.

Substituent Polarizability and Field Effects. Correlations with σ_α and σ_F. According to the Taft and Topsom analysis,[11] the gas-phase basicities for nonconjugated alkyl derivatives depend only on the polarizability of alkyl group and should obey eq 1, where ρ_α is the reaction constant for polarizability effects and σ_α is the di-

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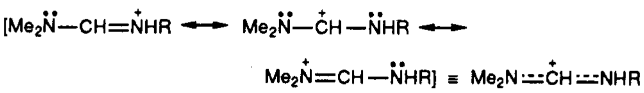
Scheme II



$$[\mathrm{Me_2\ddot{N}{-}CH{=}\overset{+}{N}HR} \longleftrightarrow \mathrm{Me_2\ddot{N}{-}\overset{+}{C}H{-}\ddot{N}HR} \longleftrightarrow \mathrm{Me_2\overset{+}{N}{=}CH{-}\ddot{N}HR}] \equiv \mathrm{Me_2N\,\underline{\cdots}\,\overset{+}{C}H\,\underline{\cdots}\,NHR}$$

Table II. Polarizability and Field Effects in Formamidines (FDM*R), Primary Amines (RNH_2), and *N*,*N*-Dimethylamines ($RNMe_2$)

				δGB,[a] kcal mol^{-1}		
compd	R	$-\sigma_\alpha$[b]	σ_F[b]	FDM*R	RNH_2[c]	$RNMe_2$[d]
14	1-Adam	0.95	0.00	7.3[e]	11.4	10.0
15	OMe	0.17	0.25	−11.7		
16	NMe_2	0.44	0.10	−1.3		0.4
17	CH_2CN	(0.54)[f]	(0.32)[f]	−11.7	−16.0	−14.3
18	CH_2CF_3	0.46	0.23	−7.9	−11.7	−10.3
19	$CH_2C{\equiv}CH$	0.61	0.12	−2.1	−2.4	−2.1
20	$CH_2CH{=}CH_2$	0.57	0.03	0.6	2.6	1.9
21	CH_2Ph	0.70	0.05	2.6	3.4	4.4
22	$(CH_2)_2CN$	(0.57)[f]	(0.17)[f]	−4.8	−7.2	
23	$(CH_2)_2OMe$	0.52	0.07	3.7	6.6[g]	
24	$(CH_2)_2NMe_2$	(0.57)[f]	(0.03)[f]	6.1		11.2
25	$(CH_2)_3NMe_2$	(0.59)[f]	(0.01)[f]	9.3		14.5

[a] Values relative to the methyl-substituted base; GB(FDM*Me) = 228.7 kcal mol^{-1}; see text. [b] Polarizability and field substituent parameters of Taft and co-workers: refs 11 and 12. [c] Values from the Taft group: ref 14 and refs cited in refs 3 and 4. [d] Values from the Taft group: ref 15. [e] Revised value. [f] Estimated values, see note 17. [g] As in ref 18.

rectional polarizability parameter of Taft and co-workers.[11-13]

$$\delta GB = \rho_\alpha \sigma_\alpha + c \tag{1}$$

The relative basicity of N^1,N^1-dimethylformamidines, δGB = GB(FDM*R) − GB(FDM*Me), represents the Gibbs free energy for reaction 2:

$$\begin{aligned} &\mathrm{Me_2N\,\underline{\cdots}\,CH\,\underline{\cdots}\,NRH^+ + Me_2N{-}CH{=}NMe} \rightleftharpoons \\ &\qquad \mathrm{Me_2N{-}CH{=}NR + Me_2N\,\underline{\cdots}\,CH\,\underline{\cdots}\,NMeH^+} \end{aligned} \tag{2}$$

In the previous paper[8] we found that the relative GBs of 11 FDM*R-containing alkyl groups (compounds **1–4**, **6–9**, **11**, **13**, and **14**) are linearly correlated to alkyl substituent polarizability. Using the revised δGB value for the 1-adamantyl derivative **14**, the following equation (in kcal mol^{-1}) is found:

$$\delta GB = -(11.5 \pm 0.7)\sigma_\alpha - 4.3 \qquad r = 0.984 \qquad s = 0.37 \tag{3}$$

Substituents containing heteroatoms and/or π-bonds can exert some influence on the reaction site not only by polarizability (P) effect but also by field (F) and resonance (R) effects. If we exclude compounds **15** and **16**, all the substituents at the N^2 atom in the FDM*R studied here are of the $(CH_2)_nX$ type ($n \geq 1$, X = heteroatomic and/or π-bonds group). As discussed above, resonance effect can be excluded, and only hyperconjugation C–H or C–C effects [almost constant for $(CH_2)_nX$ groups] may occur.

Thus, in the present series, the gas-phase basicities may depend on the combination of the substituent P and F effects,[11-13] in the form of the multiple linear relation 4, where ρ_F and σ_F are the reaction constant and substituent parameter of Taft and co-workers[11,13] for field effect, respectively, and ρ_α and σ_α have the same meaning as in relation 1.

$$\delta GB = \rho_\alpha \sigma_\alpha + \rho_F \sigma_F + c \tag{4}$$

The δGB values for compounds **15–25**, together with field and polarizability parameters, are presented in Table II. For comparison purposes, δGB values for corresponding amines (RNH_2 and $RNMe_2$), except $Me_2N(CH_2)_nNH_2$ in which the Me_2N group is preferentially protonated, are also given in this table.

Table II shows that the amidine group is the least sensitive to the gas-phase $(CH_2)_nX$ substituent effects as it has been observed previously for the other FDM*Rs containing alkyl groups at the N^2 atom.

Quantitative analysis of the experimental δGB values, based on relation 4 (Table III), confirms that the global gas-phase substituent effect in FDM*R, except compounds containing the NMe_2 and OMe groups, is correctly described by P and F contributions. For calculating parameters of relation 4 for the δGB values of the FDM*R, RNH_2 and $RNMe_2$ series, a common set of 15 substituents (R = CH_2CF_3, $CH_2C{\equiv}CH$, $CH_2CH{=}CH_2$, and CH_2Ph and the 11 alkyl groups which fit eq 1) has been taken into account (for this set of substituents σ_α and σ_F are, as required, poorly correlated, $r = 0.297$). Consequently, compounds **15–17** and **22–25** cannot be included in the set because of the lack of either gas-phase data for amines or substituent constants.

The sensitivity to both P and F effects of the amidino group in the FDM*R series compared to that of the amino group in RNH_2 is significantly decreased (by a factor of about 1.6). This lowering of sensitivity has been attributed previously to the difference in localization of the positive charge on the functional group in the corresponding acids.[8] In the case of FDM*R the charge is delocalized between the N^1 and N^2 atoms (Scheme II) while in RNH_2 the charge is localized on the reaction site, i.e., the amino nitrogen.

The δGB values for FDM*OMe (**15**) fit[19] eq 4a: if the resonance effect is not operative (vide supra), we can exclude any synergy (basicity enhancement) between the lone pair of the N^2 atom in the functional group and the lone pairs of the oxygen atom for the binding of the proton.

It will be noted that the δGB values for FDM*NMe_2 (**16**) deviates[19] by +1.9 kcal mol^{-1} from eq 4a and that the δGB

Table III. Correlations between δGBs of FDM*R, RNH_2, and $RNMe_2$ with σ_α and σ_F Values[a] for the 15 Substituents[b] (eqs 4a–c), and of FDM*CH_2X, XCH_2NH_2, and XCH_2NMe_2 for the 10 Substituents,[c] Common to the Three Series (eqs 4d–f)

no.	series	ρ_α	ρ_F	*c*	correl coeff	std dev
4a	FDM*R	−11.77 ± 0.77	−38.16 ± 1.81	−4.52	0.994	0.42
4b	RNH_2	−18.63 ± 0.57	−62.49 ± 1.34	−6.09	0.999	0.31
4c	$RNMe_2$	−17.09 ± 0.77	−52.91 ± 1.80	−5.93	0.997	0.41
4d	FDM*CH_2X	−5.18 ± 0.86	−21.81 ± 0.89	−0.31	0.995	0.57
4e	XCH_2NH_2	−8.30 ± 0.45	−32.84 ± 0.47	0.20	0.999	0.30
4f	XCH_2NMe_2	−8.19 ± 0.90	−28.67 ± 0.93	−0.32	0.997	0.60

[a] δGB value relative to the GB of FDM*Me (eq 2). Data from Table II in ref 8 and Table II presented here. [b] R: Me, Et, *n*-Pr, *i*-Pr, *n*-Bu, *i*-Bu, *s*-Bu, *t*-Bu, *t*-C_5H_{11}, *c*-C_6H_{11}, 1-Adam, CH_2CF_3, $CH_2C{\equiv}CH$, $CH_2CH{=}CH_2$, CH_2Ph. [c] X: H, Me, Et, *n*-Pr, *i*-Pr, CN, CF_3, $C{\equiv}CH$, $CH{=}CH_2$, Ph; σ_α and σ_F values taken from refs 11 and 13.

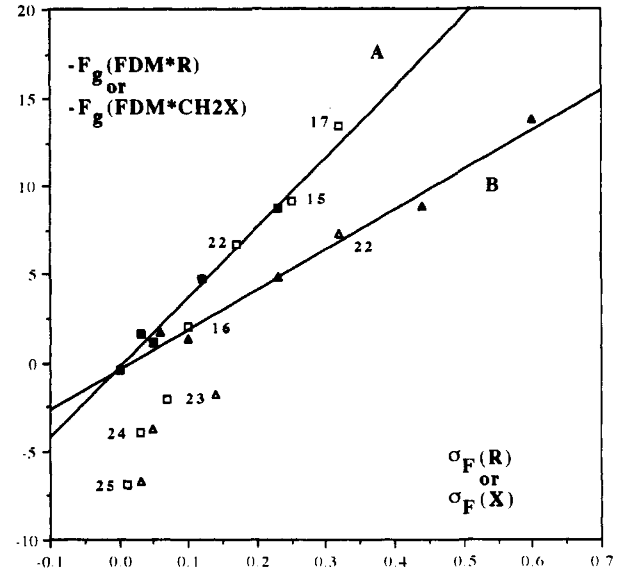


Figure 1. Field contributions (−Fg in kcal mol^{-1}) for the FDM*R (■, line A) and FDM*CH$_2$X series (▲, line B) vs field parameters σ_F(R) and σ_F(X), respectively. The open symbols correspond to data points excluded from calculations of parameters for eq 4 (Table III), see text.

for Me$_2$NNMe$_2$ deviates by +4.1 kcal mol^{-1} (3.7 kcal mol^{-1} with statistical correction) from eq 4c. Taft et al.[20] have evaluated the relief of lone pair/lone pair repulsion in the neutral base upon protonation to approximately +2.0 kcal mol^{-1} for pyridazine. Though the three systems are not strictly similar (rigid framework or not, same or different hybridization of nitrogens), we assign the two deviations to the relief of lone pairs repulsion.

Aue and Bowers have interpreted the basicity enhancement in compounds R$_2$N(CH$_2$)$_n$X (e.g. X = OR, NR$_2$; R = H, Me) in terms of intramolecular hydrogen bonding in the protonated forms.[18]

In the case of formamidines we observe deviations[19] for FDM*(CH$_2$)$_n$X (compounds **23**–**25**) from eq 4a by +5.4 kcal mol^{-1} (n = 2, X = OMe), +5.1 kcal mol^{-1} (n = 2, X = NMe$_2$), and +7.3 kcal mol^{-1} (n = 3, X = NMe$_2$). These deviations (basicity enhancement) are 1.4–1.8 times smaller than those calculated for amines. We explain the lower basicity enhancement by intramolecular hydrogen bonding in bifunctional formamidines by the charge delocalization in the protonated form (see Scheme I). The 1.4–1.8 attenuation factor is to be compared to the 1.4–1.6 attenuation factors of the *P* and *F* effects when going from amines to formamidines (Table III).

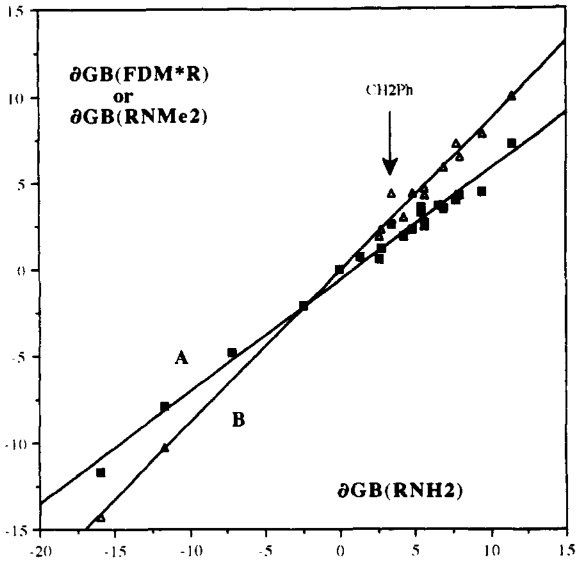


Figure 2. Relative gas-phase basicities (δGBs in kcal mol^{-1}) of FDM*R (■, line A: eq 6) and RNMe$_2$ (△, line B) vs δGBs of RNH$_2$ for all substituents studied here (Table II) and previously.[8] The only significant deviations in the same direction from lines A and B correspond to the PhCH$_2$ derivatives.

The deviations[19] observed for FDM*(CH$_2$)$_n$CN (n = 1, −1.3 kcal mol^{-1}; n = 2, −0.5 kcal mol^{-1}) from eq 4a are not significant and exclude intramolecular hydrogen bonding in these cyano derivatives.

It is interesting to include the two cyano substituents in eq 4a because of their statistical weight, particularly the CH$_2$CN group, in regard to the precision of the regression for a predictive purpose.

$$\delta\mathrm{GB} = -(11.6 \pm 0.8)\sigma_\alpha - (40.9 \pm 1.2)\sigma_F - 4.3 \qquad r = 0.996 \quad s = 0.45 \tag{5}$$

When we apply eq 4 to the subset FDM*CH$_2$X including X = alkyl, we observe very similar deviations[21] for compounds **23**–**25**. The parameters of these correlations are given in Table III (eq 4d). For comparison, eqs 4e and 4f for XCH$_2$NH$_2$ and XCH$_2$NMe$_2$, respectively, are also given using a common set of 10 substituents (footnote c to Table III).

Figure 1 illustrates the field (Fg) gas-phase substituent effect in the FDM*R (line A) and FDM*CH$_2$X (line B) series. Fg contributions (Fg = δGB − *P*) are equal to δGB + 4.52 + 11.77σ_α(R) or δGB + 0.31 + 5.18σ_α(X) for the FDM*R or FDM*CH$_2$X series, respectively. The open symbols correspond to compounds **15**–**17** and **22**–**25** containing the OMe, NMe$_2$, or CN group as substituent. Compounds **23**–**25** which can form an intramolecular hydrogen bond in the protonated forms strongly deviate from both correlation lines A and B by more than 5 kcal mol^{-1}.

Correlations with Amines. A good correlation is found between the δGB values of FDM*R and RNH$_2$ (eq 6, line A in Figure 2) for all substituents studied here and previously,[8] including the (CH$_2$)$_2$OMe group.

$$\delta\mathrm{GB(FDM^*R)} = (0.64 \pm 0.02)\delta\mathrm{GB(RNH_2)} - 0.60 \qquad r = 0.993 \quad s = 0.53 \quad n = 21 \tag{6}$$

For comparison, the δGB values of RNMe$_2$ have also been plotted against the δGB values of RNH$_2$ in Figure 2 [line B, δGB(RNMe$_2$) = 0.88δGB(RNH$_2$) − 0.08]. It is noteworthy that only the CH$_2$Ph derivative deviates in the

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[17] The σ_α and σ_F values for the (CH$_2$)$_n$NMe$_2$ and (CH$_2$)$_n$CN groups have been estimated by using eq i and ii. The reduction factor of $(1/2.3)^n$

$$\sigma_\alpha[(\mathrm{CH_2})_n\mathrm{X}] = -0.338 + (1/2.3)^n\sigma_\alpha[(\mathrm{CH_2})_{n-1}\mathrm{X}] \tag{i}$$

$$\sigma_F[(\mathrm{CH_2})_n\mathrm{X}] = (1/1.9)^n\sigma_F(\mathrm{X}) \tag{ii}$$

for the *P* effect has been proposed by Taft and Topsom[11] for alkyl substituents. The σ_α values for alkyl substituents being essentially additive, we have taken $\sigma_\alpha(\mathrm{C_2H_5}) - (1/2.3)\sigma_\alpha(\mathrm{CH_3}) = -0.338$ as σ_α increment for the CH$_2$ group directly linked to the reacting center. We arrived at the reduction factor of 1/1.9 for the F effect by averaging the various fall off factor for X groups other than NMe$_2$ and CN for which σ_F are known for the corresponding (CH$_2$)$_n$X moieties (X = Cl, Ph, F, OMe, CF$_3$).

[18] Aue, D. H.; Bowers, M. T. In *Gas Phase Ion Chemistry*; Bowers, M. T., Ed.; Academic Press: New York, 1979; Vol. 2; Chapter 9.

[19] Deviations (Δ, in kcal mol^{-1}) of OMe, NMe$_2$, and CN derivatives of FDM*R, RNH$_2$, and RNMe$_2$ from eqs 4a–c, respectively. R, Δ(FDM*R), Δ(RNH$_2$), Δ(RNMe$_2$): OMe, +0.4, –, –; NMe$_2$, +1.9, –, +4.1; CH$_2$CN, −1.3, 0, +0.7; (CH$_2$)$_2$CN, −0.5, −1.1, –; (CH$_2$)$_2$OMe, +5.4, +7.4, –; (CH$_2$)$_2$NMe$_2$, +5.1, –, +9.0; (CH$_2$)$_3$NMe$_2$, +7.3, –, +10.9.

[20] Taft, R. W.; Anvia, F.; Taagepera, M.; Catalán, J.; Elguero, J. *J. Am. Chem. Soc.* **1986**, *108*, 3237–3239.

[21] Deviations (Δ in kcal mol^{-1}) of OMe and NMe$_2$ derivatives of FDM*CH$_2$X from eq 4d; $-\sigma_\alpha$ and σ_F for the CH$_2$NMe$_2$ and (CH$_2$)$_2$NMe$_2$ groups were estimated.[17] X, $-\sigma_\alpha$(X), σ_F(X), Δ: CH$_2$OMe, 0.42, 0.14, 4.9; CH$_2$NMe$_2$, (0.53), (0.05), 4.8; (CH$_2$)$_2$NMe$_2$, (0.57), (0.03), 7.3.

Table IV. Correlations of the Relative Basicities of FDM*R, RNH_2, and $RNMe_2$ in the Gas Phase and in Solution (Ethanol or Water) with σ_α and σ_F Values,[a] Respectively, Using a Common Set of 13 Substituents[b]

no.	series	solvent	ρ_α	ρ_F	c	correl coeff	std dev
8a	FDM*R	(gas phase)	−10.83 ± 1.17	−41.24 ± 1.22	−3.89	0.997	0.43
8b	FDM*R	95.6% EtOH	−1.23 ± 0.85	−17.60 ± 0.89	−0.59	0.989	0.32
8c	RNH_2	(gas phase)	−18.37 ± 1.19	−63.28 ± 1.24	−5.97	0.999	0.44
8d	RNH_2	95.6% EtOH	−2.01 ± 1.14	−20.99 ± 1.19	−0.85	0.986	0.42
8e	RNH_2	H_2O	−0.59 ± 1.37	−24.18 ± 1.43	−0.43	0.984	0.51
8f	$RNMe_2$	(gas phase[c])	−17.72 ± 1.26	−54.25 ± 1.37	−6.25	0.998	0.47
8g	$RNMe_2$	H_2O	−4.53 ± 2.36	−26.69 ± 2.46	−1.90	0.967	0.87

[a] Data from Table II and refs 8, 15, 16, 22, and 23. [b] R = Me, *n*-Pr, *i*-Pr, *n*-Bu, *i*-Bu, *t*-Bu, c-C_6H_{11}, CH_2CN, CH_2CF_3, $CH_2C{\equiv}CH$, $CH_2CH{=}CH_2$, CH_2Ph, $(CH_2)_2CN$. [c] 12 points, except $(CH_2)_2CN$.

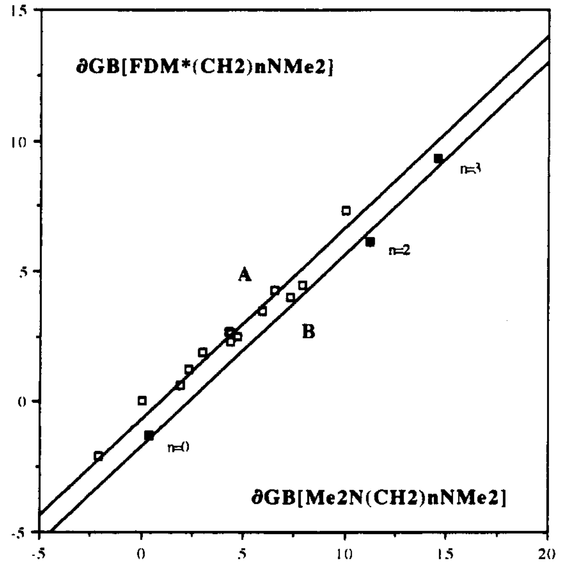

Figure 3. Relative gas-phase basicities (δGBs in kcal mol^{-1}) of FDM*$(CH_2)_nNMe_2$ (line B) and of the other FDM*R (line A: eq 7) vs δGBs of corresponding dimethylamines.

same direction from the two correlation lines, A and B, by more than 1 standard deviation. These unexpected deviations may be due to an error in the GB reported for $PhCH_2NH_2$.

Similarly, a good correlation is found between the δGB of FDM*R and $RNMe_2$ (eq 7, line A in Figure 3), except for derivatives containing the NMe_2 group in the substituent (compounds **16**, **24**, and **25**). The three compounds deviate (by about 1 kcal mol^{-1}) from eq 7 (line A) in the same direction as shown in Figure 3, in which the δGB of FDM*$(CH_2)_nNMe_2$ have been plotted against the δGB of the corresponding $Me_2N(CH_2)_nNMe_2$ (line B). A part of these systematic deviations is to be assigned to the statistical factor *RT* ln 2 in favor of the symmetrical tetramethyldiamines.

$$\delta\text{GB(FDM*R)} = (0.73 \pm 0.02)\delta\text{GB}(\text{RNMe}_2) - 0.67 \qquad r = 0.996 \quad s = 0.43 \quad n = 16 \tag{7}$$

Equations 6 and 7 are of higher predictive power than those using σ_α and σ_F, because the global gas-phase substituent basicity effect (polarizability, field, lone pairs repulsion relief upon protonation, intramolecular hydrogen bonding in the protonated forms) is similar to that observed in the corresponding amines. A wide variation of substituents R, including those bearing a basic site, may be described by eqs 6 and 7.

It will be noted that the slope (0.82) of the least squares line $\delta\Delta G_{alc}$(FDM*R) vs $\delta\Delta G_{alc}(RNH_2)$ in hydroxylic medium[22] (95.6% ethanol-water azeotropic mixture) is 1.3 times larger than the slope of the corresponding line in the gas-phase (eq 6). This observation will be discussed in the next section.

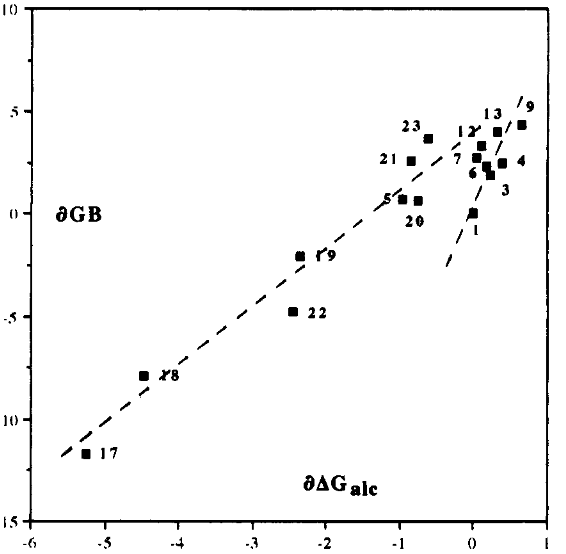

Figure 4. Relative gas-phase basicities (δGBs in kcal mol^{-1}) of FDM*R vs relative Gibbs free energies of ionization of formamidinium ions ($\delta\Delta G_{alc}$ in kcal mol^{-1}) in 95.6% ethanol–water mixture.

Comparison of the Substituent Effects in the Gas-Phase and in Solution. Investigations of substituent effects on the basicity of FDM*Rs in solution (95.6% ethanol) reported recently[22] have shown that the imino nitrogen atom is the favored site of protonation in solution, as in the gas phase. Thus, the substituent effects on the basicity of FDM*R in the gas phase (δGB) can be directly compared with those ($\delta\Delta G_{alc}$) in solution. $\delta\Delta G_{alc}$ represents the relative Gibbs free energies of ionization for formamidinium ions in 95.6% ethanol, $\delta\Delta G_{alc} = \Delta G_{alc}$(FDM*R) − ΔG_{alc}(FDM*Me) = 1.3643[pK_a(FDM*R) − pK_a(FDM*Me)].

A plot of the δGB values against the $\delta\Delta G_{alc}$ values (Figure 4) shows significant differences in the transmission of the polarizability and field effects to the N^2 atom in the gas phase and in solution. Two kinds of behavior can be distinguished, one corresponding to alkyl substituents (only *P* effect, $\sigma_F = 0$) and the other to substituents with heteroatoms and/or π bonds ($P + F +$ other effects). A similar trend has been observed by Headley[15] for dimethylamines, when the δGB values were plotted against the relative basicities in water ($\delta\Delta G_{aq}$).

For quantitative analysis of these differences in the substituent effects on basicity of FDM*R in the gas phase and in solution (95.6% ethanol) relation 8 is applied (Table IV), where σ_α, σ_F, ρ_α, and ρ_F have the same meaning as in eq 4 and δQ represents δGB, $\delta\Delta G_{alc}$, or $\delta\Delta G_{aq}$ values. For calculation of the parameters of relation 8 applied to the δGB and $\delta\Delta G_{alc}$ values of FDM*R, the same set of 13 substituents has been used (footnote b to Table IV). These

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[22] Raczyńska, E. D. *J. Chem. Res.* **1991** (M), 763–782; (S), 90–91.

parameters are also given for the δGB, $\delta\Delta G_{alc}$, or $\delta\Delta G_{aq}$ of the corresponding amines RNH_2 and $RNMe_2$ taken from refs 3, 4, 13–16, 22, and 23.

$$\delta Q = \rho_\alpha\sigma_\alpha + \rho_F\sigma_F + c \qquad (8)$$

Correlations with σ_α and σ_F values show clearly that the polarizability effect does not parallel the field effect in the gas phase and in solution for the FDM*R, RNH_2, and $RNMe_2$ series. The significant P effect observed in the gas phase is strongly reduced by solvation. Solvent polarizability attenuation factors, $\rho_\alpha(g)/\rho_\alpha(sln)$ as proposed by Headley,[15] cannot be calculated to a useful precision due to the low statistical significance of ρ_α(sln) values. The very weak *P* effect observed for amines in water was attributed by Taft to specific solvation of the ammonium ions.[11,12] The solvation effect reduces also the F effect, but to a lesser extent.

Solvent field attenuation factors, $\rho_F(g)/\rho_F(sln)$, of 2.3 for FDM*R and 3.0 for RNH_2, on going from the gas phase to ethanol, indicate that the solvation effect of the formamidinium ions, $[Me_2N\text{---}CH\text{---}NHR]^+$, is about 1.3 times smaller than that for the ammonium ions RNH_3^+. A similar factor of 1.3 is observed when we compare the solvent field attenuation factors (gas phase vs water) of 2.0 as obtained by Headley[15] for $RNMe_2$ and 2.6 obtained for RNH_2.

The same 1.3 factor value observed in the two comparisons presented above (FDM*R vs RNH_2/ethanol and $RNMe_2$ vs RNH_2/water), though not corresponding to strictly the same solvent, indicates a similar solvation effect of protonated FDM*R and $RNMe_2$. The main factor appears to be the number of hydrogens on the protonated nitrogen.

Strikingly, a ratio of 1.3 is obtained between the slopes of direct correlations between the relative basicities (global substituent effect) of FDM*R and RNH_2 in the gas phase and in ethanol (vide supra). Similarly, a ratio of 1.3 is observed in the comparison of the relative basicities between $RNMe_2$ and RNH_2 in the gas phase and in water.[24]

It is noteworthy that the electron-withdrawing effect of the cyclopropyl group on the basicity of FDM*R observed in the gas phase[8] (deviation of the c-Pr group from the δGB vs σ_α correlation) is comparable to that in solution. We suggest that the cyclopropyl should have a positive σ_F value. The field contribution to the δGB is close to that of the allyl group, if the resonance effect ($\sigma_R^- = 0.0$) is neglected. The electron-withdrawing effect of the cyclopropyl group is also observed for the δGB of RNH_2 in the gas phase as discussed previously.[8]

Summary and Conclusion

In the gas phase, formamidines [FDM*R with R = alkyl and $(CH_2)_nX$] are more basic by about 10–15 kcal mol^{-1} than the corresponding *N,N*-dimethylamines ($RNMe_2$). The GB values for R = 1-Adam and $(CH_2)_nNMe_2$ (n = 2 and 3) are close to, or higher than, the GB value of 1,1,3,3-tetramethylguanidine. For all derivatives studied here and previously, even for those containing another basic site in the substituent R, the imino (N^2) nitrogen atom is the favored site of protonation. The gas-phase basicity of FDM*R depends linearly on the polarizability and field effects of alkyl and $(CH_2)_nX$ groups linked to the imino nitrogen atom. The resonance effect is negligible. An additional lone pair in bifunctional formamidines containing the $(CH_2)_nOMe$ and $(CH_2)_nNMe_2$ groups increases considerably their basicity. As compared to primary amines, the sensitivity of the amidine group to the global substituent effect—polarizability, field, "two electron pairs", and other possible effects of substituent R at the imino nitrogen atom—is decreased by a factor of about 1.6 because of charge delocalization in the formamidinium ions. The sensitivity of the amidine group to field effect of substituent R in the gas phase is lowered by a factor of about 2 by solvation (charge dispersion) in hydroxylic solvent (95.6% ethanol). As compared to RNH_2, the solvent field attenuation factor is reduced by about 1.3, as it is observed for the solvent attenuation of the global substituent effect. For the cyclopropyl group the field parameter (σ_F) should have a positive value, close to the σ_F of the allyl group.

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Registry No. **14**, 133835-18-4; **15**, 139033-03-7; **16**, 32150-27-9; **17**, 134166-58-8; **18**, 134166-59-9; **19**, 121508-72-3; **20**, 60598-49-4; **21**, 27159-75-7; **22**, 134166-60-2; **23**, 134166-62-4; **24**, 101398-58-7; **25**, 139033-04-8.

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[23] Perrin, D. D. *Dissociation Constants of Organic Bases in Aqueous Solution*; Butterworths: London, 1965.

[24] GB and ΔG_{aq} values of $RNMe_2$ and RNH_2 have been taken from refs 3, 4, 14–16, and 23. See also: Figure 2 in ref 22.