Correlation between hardness and basicity (pK$_a$) of substituted anilines

Abhishek Das[1], Someswar Chatterjee[2]*

[1]Dept. of Chemistry, GERF (Accredited Institution of University of Mysore) Kalyani, Nadia, West Bengal, (INDIA)
[2]Dept. of Chemistry, K.N.College (Affiliated to The University of Burdwan), Murarai, Birbhum,
West Bengal, PIN-731219, (INDIA)
E-mail : someswar_76@yahoo.com
Received: 21st November, 2009 ; Accepted: 1st December, 2009

ABSTRACT

In this work the correlation between hardness and basicity (pK$_a$) of substituted anilines and N-Alkylated anilines has been studied. The hardness values of PhNH$_2$, o-, m-, and p- substituted NH$_2$-PhNH$_2$, Me-PhNH$_2$, Cl-PhNH$_2$, NO$_2$-PhNH$_2$ and N-alkylated anilines (PhNHMe, PhNHEt, PhNHPh) have been calculated using Koopmans' relation. The calculation of the energies of HOMO & LUMO of the above compounds has been done semi-empirical quantum mechanically (using AM1 & PM3 semi-empirical Hamiltonian) with the help of ArgusLab4.0 software. It is found that hardness value of aniline decreases along with substitution. The high correlation between pK$_a$ values and hardness of substituted anilines and N-Alkylated anilines indicate the hardness bears direct relationship to the basicity of substituted anilines.

© 2009 Trade Science Inc. - INDIA

KEYWORDS

INTRODUCTION

The basicity of organic compounds is an important factor to explain the rate of elimination (E) or substitution (S) reaction in organic chemistry. The influence of base on the elimination-substitution competition has also been explained in terms of basicity of the organic substrates or reagents.

It is well-known that the variation basicity or acidity of the substituted organic compounds with reference to the mother compounds are explained in terms of inductive effect *(I)*, resonance effect *(R)*, steric effect etc. of the substituent groups. For example, the basicities of o-, *m*-, *p*- substituted anilines, are explained in terms of *R*- & *I*-effect, whereas the steric effect is important factor to explain the basicities of *N*-alkylated anilines derivatives. As aniline is a weak base due to its strong resonance effect, the basicity of its is indicated by the pK$_a$ value of its conjugate acid ($C_6H_5N^+H_3$) as follows-
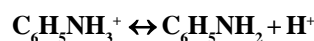
$$C_6H_5NH_3^+ \leftrightarrow C_6H_5NH_2 + H^+$$

$$K_a = \frac{[C_6H_5NH_2][H^+]}{[C_6H_5NH_3^+]}$$

$$pK_a = -\log \frac{[C_6H_5NH_2][H^+]}{[C_6H_5NH_3^+]} \qquad (1)$$

Unlike aniline the pK$_a$ values of aniline derivatives are measured using equation (1). The pK$_a$ values[1] of aniline derivatives (TABLE 1) show that all the nitroanilines are weaker bases than aniline. The decreased basicities of *o-* & *p*-nitroanilines are explained in terms of strong *-R* effect, whereas the basicity of *m*-nitroaniline is explained in terms of strong *-I* effect of the electron-attracting *–NO$_2$* group. In the same way the decreased basicity due to halogen atoms in the ring are explained in terms of *-I* effect of halogen atom.

The electron-releasing methyl group in the ring increases the basicity of aniline derivatives, more so from the *o-* & *p*-position than from the *m*-position (TABLE 1), due to the higher electron densities at the carbon atoms, *o-* & *p-* to the *–Me* group and consequent decrease in the resonance effect, but comparatively lower electron density at the *C*-atom, m- to the -Me group and subsequent increase in the *R*-effect.

Again, the phenomenon of steric inhibition of resonance are used to explain the fact that *N*-Alkylated anilines are stronger bases than aniline (TABLE-1). It may be expected that the opposite to be true, since alkyl groups have a +I effect and consequently increased resonance effect. Also, since an >N-Et substituent increases the basic strength more than an >N-Me, the observed results cannot be explained on the basis of polar effects. The explanation offered is that a steric effect operates due to the ortho effect. Since the ethyl group is larger than the methyl, the steric effect is greater for the former, and hence there is greater steric inhibition of resonance in the former. Thus, in the former, the lone pair on the *N*-atom is more available for protonation, and consequently the basicity of *N*-ethylaniline is greater than that of *N*-methylaniline.

It can be mentioned that to explain the basicity of the aniline derivatives in terms of *R*, *I* or the steric effect of the respective substituent groups, one should make the knowledge of each substituent groups separately. This difficulty motivates to search a single parameter of those compounds by which their basicity can be explained generally.

In the context of Hard-Soft-Acid-Base (HSAB) principle, Klopman et al.[2] suggested that basicity bears a direct relationship to the hardness of a base. Considering basicity in the Brønsted sense (proton affinity) and taking into account that the proton is hard, the base will

TABLE 1 : - pK$_a$ values of o-, m- & p-substituted aniline derivatives and N-alkylated aniline derivatives.

Subsistent in PhNH$_2$	pK$_a$		
	o-	*m-*	*p-*
-Me	4.39	4.69	5.12
-NO$_2$	-0.29	2.50	1.02
-Cl	2.64	3.34	3.98
-NH$_2$	4.47	4.88	6.08
PhNH$_2$		4.58	
PhNHMe		4.85	
PhNHEt		5.11	
PhNHPh		0.9	

show increasing proton affinity as its hardness increases. Thus it is expected from equation-(1) that there may be a correlation between the pK$_a$ values & hardness of aniline derivatives. Moreover the role of HSAB principle has not been studied in details to explain the basicity of aniline derivatives. Therefore, in this present paper an attempt has been made to calculate the hardness of the aniline derivatives and to set up the correlation between the hardness & pK$_a$ values of the aniline derivatives.

The aniline derivatives studied here are o-, m- & p-isomers of PhNH$_2$, NH$_2$-PhNH$_2$, Me-PhNH$_2$, Cl-PhNH$_2$, NO$_2$-PhNH$_2$ and N-alkylated anilines (PhNHMe, PhNHEt, PhNHPh).

It is expected that this study will help to explain the variation of basicity (pK$_a$ values) of aniline derivatives in terms of hardness as a single parameter.

Calculation

In the context of DFT the exact definition of hardness (η)[3,4] is the change of chemical potential (μ) with respect the number of electrons (N) i.e.

$$\eta = \frac{1}{2}\left(\frac{\partial \mu}{\partial N}\right)_v$$

The operational definition of hardness[4-7] *(η)* is,

$$\eta = \frac{I - A}{2} \tag{2}$$

where, 'I' & 'A' are the ionization potential & electron affinity of the molecules, respectively.

According to Koopmans' theorem[4-8], the molecular frontier orbital (HOMO and LUMO) energies are given by

$-\varepsilon_{HOMO} = I$ and $-\varepsilon_{LUMO} = A$

Thus, from equation- (2),

$$\eta = \frac{\varepsilon_{LUMO} - \varepsilon_{HOMO}}{2} \qquad (3)$$

The energies of HOMO & LUMO of the aniline derivative have been calculated semi-empirical quantum mechanically (AM1 & PM3 semi-empirical Hamiltonian) with the help of ArgusLab4.0 software[6,9,10]. The following three steps have performed -i) drawing of the

molecules using ArgusLab4.0 Molecular Builder, (ii) optimization of the geometry and (iii) calculation of the energies of molecular orbital. The calculated hardness values are shown in TABLE 2.

DISCUSSION

TABLE 2 shows that hardness values of o-substituted aniline are lower that that of aniline. The decrease of hardness value of o-substituted aniline indicates the

TABLE 2: The energies of HOMO & LUMO and the calculated hardness (η) values of the substituted anilines and N-alkylated anilines.

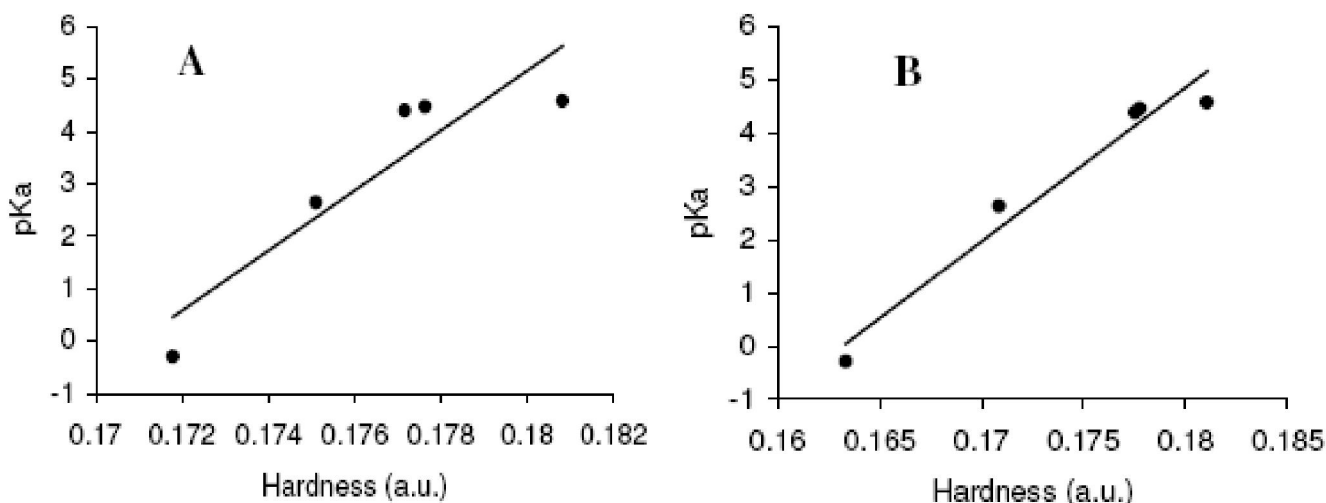| Molecules	AM1 Semi-empirical hamiltonian			PM3 Semi-empirical hamiltonian		
	ε_{HOMO} (a.u.)	ε_{LUMO} (a.u.)	η(a.u.)	ε_{HOMO} (a.u.)	ε_{LUMO} (a.u.)	η(a.u.)
$PhNH_2$	-0.34809	0.013549	0.180819	-0.353885	0.008207	0.181046
o-NH_2-$PhNH_2$	-0.345164	0.010116	0.17764	-0.350753	0.004767	0.17776
o-Me-$PhNH_2$	-0.339235	0.015095	0.177165	-0.345213	0.009821	0.177517
o-Cl-$PhNH_2$	-0.346564	0.003652	0.175108	-0.343008	-0.001253	0.170877
o-NO_2-$PhNH_2$	-0.379818	-0.036234	0.171792	-0.372874	-0.046183	0.163345
m-NH_2-$PhNH_2$	-0.346976	0.010032	0.178504	-0.353598	0.004507	0.179052
m-Me-$PhNH_2$	-0.343445	0.013845	0.178645	-0.348573	0.008658	0.178615
m-Cl-$PhNH_2$	-0.352321	0.000828	0.176574	-0.350166	-0.003392	0.173387
m-NO_2-$PhNH_2$	-0.379842	-0.040602	0.16962	-0.376919	-0.043914	0.166502
p-NH_2-$PhNH_2$	-0.342425	0.007295	0.17486	-0.350103	0.002306	0.176204
p-Me-$PhNH_2$	-0.337777	0.012679	0.175228	-0.343885	0.007849	0.175867
p-Cl-$PhNH_2$	-0.346691	-0.000239	0.173226	-0.346647	-0.003739	0.171454
p-NO_2-$PhNH_2$	-0.384149	-0.042708	0.170720	-0.380672	-0.045233	0.167719
PhNHEt	-0.309455	0.024376	0.166915	-0.315192	0.01567	0.165431
PhNHMe	-0.308874	0.024429	0.166651	-0.31364	0.015649	0.164644
PhNHPh	-0.303493	0.007402	0.155447	-0.313515	0.004512	0.159013

Figure 1 : Correlation between hardness & pK$_a$ of the o-substituted anilines in (A) Using AM1 semi-empirical hamiltonian & (B) Using PM3 semi-empirical hamiltonian.

Full Paper

TABLE 3 : Correlation equations (pK$_a$ = mη + c) for substituted and N-Alkylated anilines

Substituted anilines	AM1 Semi-empirical hamiltonian			PM3 Semi-empirical hamiltonian.		
	m	c	r	m	c	r
ortho	571.05	- 97.64	0.91	298.11	-47.18	0.98
meta	216.35	-34.26	0.90	196.14	-25.72	0.93
para	238.59	- 45.32	0.57	291.55	- 46.48	0.75
N-alkylated	360.17	- 55.09	0.99	672.89	-106.08	0.99

proton affinity of aniline is decreased along with substitution in ortho position. Like *o*-substituted anilines, *m*- and *p*- substituted anilines and N-Alkylated aniline are soft molecules compare to aniline.

It may be noted that the decrease of hardness is maximum incase of NO_2-$PhNH_2$ and follows the sequence Cl-$PhNH_2$ > Me-$PhNH_2$ > NH_2-$PhNH_2$. Similarly, the relative order of hardness value of N-Alkylated anilines follows the sequence PhNHEt > PhNHMe > PhNHPh.

Figure 1 shows a good linear correlation between hardness & basicity (pK$_a$) of the *o*-substituted aniline derivatives with the corresponding correlation coefficient, r = 0.91 (using AM1 semi-empirical Hamiltonian) and with the corresponding correlation coefficient, r = 0.98 (using PM3 semi-empirical Hamiltonian).

TABLE 3 shows the results of linear correlation analysis between the pK$_a$ values and hardness of substituted anilines and N-Alkylated aniline. It is observed the pK$_a$ values and hardness of o- and m- substituted and N-alkylated aniline show good correlation coefficient while it is appreciable smaller for p-substituted aniline. The calculated pK$_a$ values (TABLE 3) of substituted and N-Alkylated aniline using the equations of TABLE 2 are in conformity with literature values.

CONCLUSION

The results of the analysis show that hardness of aniline decreases along with substitution in any position. The high correlation between pK$_a$ values and hardness of the o-substituted aniline and N-alkylated aniline supports the original idea that basicity of molecule increases with hardness. The similar studies by F. Mendez[7] shows that the high correlation between pK$_a$ values and hardness of the substituted phenol. The agreement between the present calculated results for

TABLE 4 : The pK$_a$ (Expt.) & pK$_a$ (Calc.) values of the of the substituted anilines and N-Alkylated anilines.

Molecules	pK$_a$(Expt.)	pK$_a$(Calc.) (AM1 Semi-empirical hamiltonian)	pK$_a$(Calc.) (PM3 Semi-empirical hamiltonian)
$PhNH_2$	4.58	5.61	5.16
o-NH_2-$PhNH_2$	4.47	3.80	4.21
o-Me-$PhNH_2$	4.39	3.53	4.14
o-Cl-$PhNH_2$	2.64	2.36	2.22
o-NO_2-$PhNH_2$	-0.29	0.46	0.04
m-NH_2-$PhNH_2$	4.88	4.36	4.56
m-Me-$PhNH_2$	4.69	4.38	4.49
m-Cl-$PhNH_2$	3.34	3.94	3.60
m-NO_2-$PhNH_2$	2.50	2.43	2.44
p-NH_2-$PhNH_2$	6.08	4.21	4.65
p-Me-$PhNH_2$	5.12	4.23	4.55
p-Cl-$PhNH_2$	3.98	3.64	3.30
p-NO_2-$PhNH_2$	1.02	2.91	2.24
PhNHEt	5.11	5.02	5.24
PhNHMe	4.85	4.93	4.71
PhNHPh	0.90	0.89	0.92

aniline derivatives with previously reported results[7] for other molecules additionally supports the correlation between hardness and pK$_a$ values.

Admittedly, a large number of similar substituted anilines have to examine very precisely using before arriving at a general conclusion. If these results agree with our present finding, we can conclude that variation of basicity of anilines can be explained more generally in terms of hardness parameter only and some of the correlation discussed here can be used to predict the pK$_a$ value from hardness.

REFERENCES

[1] I.L.Finar; Organic Chemistry, ELBS with Longman, 6th Edition, **1**, **(1994)**.

[2] G.Klopman; In Chemical reactivity and Reaction path, Wiley, **(1974)**.

[3] R.G.Parr, R.G.Pearson; J.Am.Chem.Soc., **105**, 1503 **(1983)**.

[4] R.G.Pearson; Inorg.Chem., **27**, 734 **(1988)**.

[5] T.K.Ghanty, S.K.Ghosh; J.Phys.Chem., **97**, 4951 **(1993)**.

[6] S.Chatterjee, I.Basumallick; Biochemistry: An Indian Journal, **1**, 83 **(2007)**.

[7] F.Mendez, M.L.Romero, F.D.Proft, P.Geerlings; J.Org.Chem., **63**, 5774 **(1998)**.

[8] T.Koopmans; Physica, **1**, 104 **(1934)**.

[9] M.A.Thompson, G.K.Schenter; J.Phys.Chem., **99**, 6374 **(1995)**.

[10] M.A.Thompson; J.Phys.Chem., **100**,14492 **(1996)**.