Int. J. Electrochem. Sci., 6 **(2011)** 5031 - 5037

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

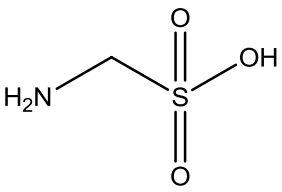
Predictions of Solvent Effects on Ionization Constants of Two Sulfonic Acids

S. Jameh-Bozorghi[1,], M. Darvishpour[2], S. Mohhammadi[2] and Z. Javanshir[3]*

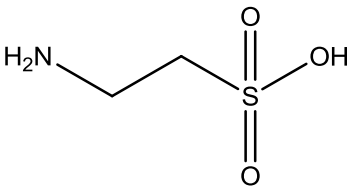
[1] Department of Chemistry, Toyserkan Branch, Islamic Azad University, Toyserkan, Iran.
[2] Department of Chemistry, Arak Branch, Islamic Azad University, Arak, Iran
[3] Department of chemistry, faculty of science, young researchers club, Ardabil branch, Islamic Azad University, Ardabil, Iran
[*]E-mail: sjamebozorgi@gmail.com

Received: 4 July 2011 / *Accepted:* 16 September 2011 / *Published:* 1 October 2011

In this article, we couple hartree fock theory (HF) with three Polarisable Continuom Models (PCM) to calculate the aqueous and nonaqueos pK_a of two sulfonicacids, aminomethanesulfonic (**1**) and Taurine or 2-aminoethanesulfonic acid (**2**). No empirical correction terms were employed in the calculations except for the free energy of solvation of the acids (H^+) adjusted to give the best match with experimental data. The calculated studies show, for aminomethansulfonic acid the use of solution-phase optimized geometries gives pK_a values in excellent agreement with experimental measurements. Conversely, calculations for this acid which have been based on gas-phase geometries lead to a mean absolute error <0.01 pK_a in water solvent and <0.55 pK_a in DMSO solvent compared to experimental measurements. We found that the computational methods for some acids such as Taurine, did not comply with experimental values.



(1)
aminomethanesulfonic acid



(2)
Taurine or
2-aminoethanesulfonic acid

Keywords: Aminosulfonic acids, PCM, Solvent effect, HF, pK_a

1. INTRODUCTION

For approaches in which the solvent is modeled, the solvent acidity and basicity have a significant influence on the reactions and equilibria in solutions. In particular, differences in reactions or equilibria among the solvents of higher permittivity are often caused by differences in solvent acidity and/or basicity.

Because of the importance of solvent acidity and basicity and in order to express them quantitatively, various empirical parameters have been proposed [1]. In order to make reliable predictions of the acid-base properties of macroligands with large number of ionizable sites such as dendrimers, one needs to develop and validate computational methods that accurately estimate the acidity constants (pK_a) of their chemical building blocks [2]

As a continuum polarizable medium, biomolecules modeled in explicit molecular detail have become widely used in recent years [3,4]. However, no current method combines broad conformational sampling with a rigorous solvation model that can predict the energetical and conformational effects of solvent on macromolecules or any other compounds quantitatively and efficiently.

In principle, molecular dynamics and free-energy simulations that monitor protonation events can model accurately the energetic effects of solvation and conformational relaxation of biomolecules. However, despite recent progress, these techniques may fail to converge in a reasonable amount of computing time and therefore do not provide reliable predictions of thermodynamic properties [5,6].

There are quite extensive theoretical studies of pK_a calculation for many chemical reactions and it is known that proton plays a significant role in solution environment [7-10]. The pK_a obtained from experimental studies are not actually the absolute value and lots of uncertainties are expected in the experimentally calculated pK_a values[7-10].

The deprotonation energies of organic acids and the proton affinities of the corresponding conjugate bases are widely used for the prediction of gas-phase and aqueousphase Brönsted acidities [11-14].

Several works on the prediction of the acidity of organic and inorganic acids can be found in the literature. For instance; Catalan and Palomar [15] have investigated gas phase acidities of a number of species and have shown that calculations correlate well with the experimental data.

The ability to predict acidity using a coherent, well-defined theoretical approach, without external approximation or fitting to experimental data would be very useful to chemists [16].

Different groups have adopted various methods to incorporate the effect of solvation in the calculation of pK_a[17]. Jorgensen et al pioneered the use of ab initio methods coupled with free-energy perturbation to incorporate the effect of the solvent[18].

Aminosulfonic acids are bifunctional compounds of general interest because of their structural relation to amino acids.

In addition, sulfonic acid, H_2NSO_3H, and particularly some of its N-substituted derivatives (cyclamates) as well as biologically important aminoethansulfonic acid (taurine)(**2**) and aminomethen sulfonic acid(**1**) are of specific interest [19].

2. COMPUTATIONAL DETAILS

2.1. Computetional Program

Ab initio pK_a calculations are generally governed by two factors, the underlying gas-phase calculations and the solvation calculations, with the accuracy of the former tending to be more critical for the overall accuracy [20]. The methodology employed in the present study was HF/6-31+G** with polarized continuum model (PCM) solvation containing CPCM, COSMO, and IEFPCM calculations, which can be considered as adequate. Completely optimized geometries of conjugate acids were also considered to calculate the pK_a.

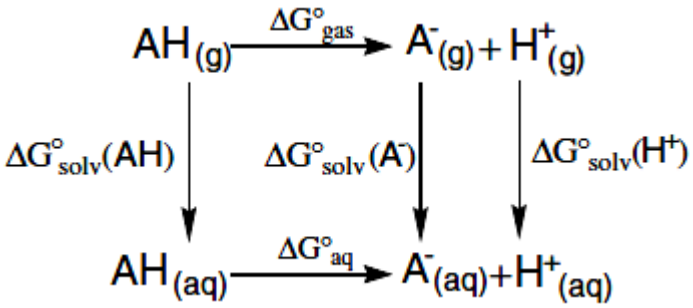
2.2. Method of calculations

In many theoretical studies pK_a of a compound is determined by the thermodynamic parameters of the local ionization of proton.

The acidity of a molecule as defined by Bronsted involves the generation of H^+ in the reaction

Eq.1 $$AH_{(gas)} \rightarrow A^-_{(gas)} + H^+_{(gas)}$$

For calculations of pKa, we used thermodynamic cycle in scheme 1.



Scheme 1. Thermodynamic cycle for calculation of pKa values of acids

Geometry optimizations for all of the compounds were performed in gas phase and solution phase on HF/ 6-31+G** level of theory. The gas-phase Gibbs free energy change ($\Delta G°_{gas}$) of Scheme 1 was calculated using Eq.2. For $G°_{gas}(H^+)$ the experimental value of -6.28 kcal/mol was used [21].

Eq.2 $$\Delta G°_{gas} = G°_{gas}(A^-) + G°_{gas}(H^+) - G°_{gas}(AH)$$

The dielectric constants used were ε= 78.39 and 46.8 to model water and DMSO solution, respectively. A common practice to calculate the aqeous Gibbs free-energy change of an acid

dissociation ($\Delta G°_{aq}$) is by summing $\Delta G°_{gas}$ and $\Delta\Delta G°_{solv}$ using the thermodynamic cycle of Scheme 1.and Eq. 3.

Eq.3 $$\Delta G°_{eq} = \Delta G°_{gas} + \Delta\Delta G°_{solv}$$

$$\Delta G°_{eq} = G°_{gas}(A^-) + G°_{gas}(H^+) - G°_{gas}(AH) + \Delta G°_{solv}(A^-) + \Delta G°_{solv}(H^+) - \Delta G°_{solv}(HA)$$

For $\Delta G°_{solv}(H^+)$ the experimental value of -264.61 kcal/mol is used[21].
Finaly, pKa is calculated according Eq. 4.

Eq. 4. $$pK_a = \frac{\Delta G°_{aq}}{RT \ln 10}$$

where R is the gas constant and T is the absolute temperature that is 298.15 k here.

3. RESULTS AND DISCUSSION

3.1. Ionization constant

The computational values of pK_a and their experimental data are listed in table 1-7. The ionization constants of the AS acids in Me_2SO were taken from the potentiometric neutralization [19].

In general, the values of dissociation energy should depend on the strength of bond between proton and active site of acid. The success in predicting pK_a for some molecules may be due to accurate estimation of dissociation energy of H^+ which is stabilized by the lone pair electrons in the p orbital.

In general, pK_a values in three methods and two solvents for aminomethansulfonic acid are larger than taurine. For this acid based on gas-phase geometries pK_a leads to a mean absolute error <0.01 in water solvent and <0.55 in DMSO unit compared to experimental measurements.

3.2. Solvent effect on pK_a values

Solvents of high permittivities (ε_r >15 or 20) are called polar solvents, while those of low permittivities are called apolar or nonpolar solvents. Acceptor and donor number often plays a more important role in solvent- solved interactions. Inclusion of electron-accepting and donating abilities in acidity and basicity is also justified by the fact that the energies of the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) for molecules of various solvents are linearly correlated with the donor and acceptor numbers respectively [1].

The values of AN and DN are also included in Table 1. The solvent acidity increases with the increase in the AN value. According to table 1, acceptor number DMSO is lower than water. Therefore, production of H^+ in water solvent is more and acid-base equilibrium Eq.1 is reversed.

Observantly, pK_a value decreases in water solvent rather than DMSO. Also, the calculation results (table 1-7) show that pK_a values in water solvent are lower than DMSO.

Table 1. Dielectric constant **(** ε), AN and DN for two solvents

solvent	AN	DN	ε
water	54.8	18	78.36
DMSO	19.3	29.8	46.7

3.3. The effect of used methods on pK_a values

The calculated values of pK_a for the three methods are given in tables 1-7. The results obtained by the PCM models showed that in comparison to continuum methods COSMO and IEFPCM the CPCM model yields quite a much better agreement between the calculated and experimental values.

Table 2. Gibbs free energy and pK_a of studied aminomethansufonic acid using 6-31+g** basis set at HF level of theory with CPCM model.

solvent	HA(gas)	A^- (gas)	HA(sol)	A^- (sol)	ΔG	PK_a cal	PK_a exp
water	−18806	-18792	-18808	-18795	2579.3972	5.7611	5.75
DMSO	-18806	-18792	-18809	-18796	2580.9620	9.6556	9.12

The energies are in kj/mol

Table 3. Gibbs free energy and pK_a of studied aminomethansufonic acid using 6-31+g** basis set at HF level of theory with COSMO model

solvent	HA(gas)	A^- (gas)	HA(sol)	A^- (sol)	ΔG	PK_a cal	PK_a exp
water	-18806	-18792	-18808	-18796	2560.6590	5.7192	5.75
DMSO	-18806	-18792	-18808	-17965	2560.6091	9.5795	9.12

The energies are in kj/mol

Table 4. Gibss free energy and pK_a of studied aminomethansufonic acid using 6-31+g** basis set at HF level of theory with IEFPCM model

solvent	HA(gas)	A^- (gas)	HA(sol)	A^- (sol)	ΔG	PK_a cal	PK_a exp
water	-18806	-18792	-18808	-18796	2579.1478	5.7605	5.75
DMSO	-18806	-18792	-18808	-18706	2580.5367	9.6540	9.12

The energies are in kj/mol

Table 5. Gibss free energy and pK_a of studied taurine using 6-31+g** basis set at HF level of theory with CPCM model

solvent	HA(gas)	A^- (gas)	HA(sol)	A^- (sol)	ΔG	PK_a cal	PK_a exp
water	-1.9829	-1.9815	-1.9832	-1.9820	2484.8042	5.5498	9.06
DMSO	-1.9829	-1.9815	-1.9832	-1.9820	2487.1329	9.3043	11.18

Table 6. Gibss free energy and pK_a of studied taurine using 6-31+g** basis set at HF level of theory with COSMO model

solvent	HA(gas)	A^- (gas)	HA(sol)	A^- (sol)	ΔG	PK_a cal	PK_a exp
water	-19829	-19815	-19820	-19831	2462.1277	5.4991	**9.06**
DMSO	-19829	-19815	-19831	-19832	2462.0358	9.2107	**11.18**

Table 7. Gibss free energy and pK_a of studied taurine using 6-31+g** basis set at HF level of theory with IEFPCM model

solvent	*HA(gas)*	*A^- (gas)*	*HA(sol)*	*A^- (sol)*	ΔG	*PK_a cal*	PK_a exp
water	-19829	-19815	-19831	-19820	2487.8891	5.5567	9.06
DMSO	-19829	-19815	-19831	-19831	2483.7565	9.2919	11.18

However, comparing with CPCM, the COSMO-HF and IEFPCM-HF methods did not prove to be sufficiently accurate to predict absolute pK_a values. The reason is believed to be the atomic radii used in the solvation calculations, as well as uncertainties in the underlying gas-phase calculations [22].

3.4. Discussion

The ability to predict acidity using a coherent, well-defined theoretical approach, without external approximation or fitting to experimental data, would be very useful to chemists. S K Rangarajan was a source of inspiration to all theoretical electrochemists[23]. However, the accuracy of the pK_a predictions approached the experimental error in the measured values, adding considerable utility to the pK_a predictions based on structural data[2]. The different in acidity of the compounds studied can be interpreted through inductive and resonance effects. The strong acidity of some studied compounds has been rationalized by calculating the $n \rightarrow \pi^*$ charge transfer energy between the non-bonding orbital localized on the carbon atom of the base with the negative charge and the vicinal unoccupied antibonding orbital π^* associated with the C=C, C=O, S=O or C=O groups. These stabilization interaction energies are calculated by the NBO method using the second order perturbation theory[16]. This study and previous studies show that the present methodology can predict pK_a of small molecules within the pK_a range 4-5. The theoretical pK_a values are almost equal to experimental values. However the practical applicability of this method for all types of molecules is

limited. The calculated pK_a values of very strong and weak bases are not equal to the experimentally found values, that may be due to other electrostatic interactions within acid-base equilibrium[24].

4. CONCLUSION

In the present paper we have used Hartree-Fock theory combined with continuum dielectric solvation calculations to designate acidities of two aminosulfonic acids. The values obtained from these methods could sometimes approximately match the experimental values while in some cases large deviations are found. In addition it was revealed that comparing with taurine, aminomethansulfonic yields better results of Pka prediction. Furthermre, the mean absolute error for water is much less than that of DMSO. Last, regarding to the implemented method, CPCM-HF, turned out to be a more desirable method with the highest degree of agreement with experimental values comparing to COSMO-HF and IEFPCM-HF methods.

References

1. Electrochemistry in Nonaqueos Solutions, Izutsu K., Wiley, 2002.
2. P. Barth, T. Alber, and P.B. Harbury, PNAS, 104 (2007) 4898-4903.
3. N.A. Baker, *Methods Enzymol*, 383 (2004) 94–118.
4. N.A. Baker, *Curr. Opin. Struct. Biol*., 15 (2005) 137–143.
5. J. Mongan, D.A.Case, *Curr. Opin. Struct. Biol*., 15 (2005) 157–163.
6. T. Simonson, J. Carlsson, D.A. Case, *J. Am. Chem. Soc*., 126 (2004) 4167–4180.
7. J.R. Pliego, and. J.M. Riveros, *J. Phys. Chem. A*., 105 (2001) 7241.
8. J. R. Pliego and J.M. Riveros, *Chem. Eur. J*. 8 (2002) 1945.
9. G. Schüürmann, M. Cossi, V. Barone And J. Tomasi, *J. Phys. Chem*. 102 (1998) 6706.
10. W.H. Richardson, C. Peng, D. Bashford and L. Noodleman, *Int. J. Quant. Chem*., 61 (1997) 207.
11. M.B. Smith, J. March, *March's Advanced Organic Chemistry, Sixth ed*., John Wiley, New York, pp. 359–364.
12. P. Burk, I.A. Koppel, I. Koppel, L.M. Yagupolskii, R.W. Taft, *Comp J., Chem*. 17 (1996) 30.
13. P. Burk, I.A. Koppel, *Theor. Chim. Acta*., 86 (1993) 417.
14. M.J.S. Dewar, K.M. Dieter, *J. Am. Chem. Soc*., 108 (1986) 8075.
15. J. Catalan, J. Palomar, *Chem. Phys. Lett*., 293 (1998) 511.
16. I.E. Charif et al., J. of Molecular Structure: THEOCHEM, 818 (2007) 1–6.
17. D. Gao, P. Svoronos, P.K. Wong, D. Maddalena, J. Wang and H.Walker, *J. Phys. Chem*., 109 (2005) 10776.
18. W.L. Jorgensen, J.M. Briggs and J. Gao, *J. Am. Chem. Soc*., 109 (1987) 6875.
19. R.L. Benoite , D. Beoulet and M. Frechettce, *can. J . Chem*., 66 (1988) 3038.
20. H. Huang, W.G. Han, L. Noodleman, F. Grynszpan, *Bioorg., Med. Chem*. 9 (2001) 3185.
21. M.D. Liptak, K.C. Grass, P.G. Seybold, S. Feldgus, G.C. Shields, *J. Am. Chem. Soc*., 124 (2002) 6421.
22. G. Schüürmann, *J. Chem. Phys*. 109 (1998) 9523.
23. N. Mehta and S N. Datta *J. Chem. Sci*. 121 (2009) 881-886.
24. P Hazarika, R L Sarma, M Karim, B Bezbauah, R Kalita and C Medhi *Indian Journal of Chemistry* 48A (2009) 520-525.