

Water effect on the bond dissociation energy of O—H and N—H bonds in phenol and aniline: The testing of simple molecular dynamics model

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Abstract: A chemical microsolvation model for solution phase bond dissociation enthalpy (BDE) evaluation by means of molecular dynamics is presented. In this simple model, the primary solvent effect on the BDE values was estimated by placing of five water molecules nearby the studied functional groups evenly. Furthermore, the secondary solvent effect was reflected using the conductor like screening model (COSMO). From the quantum-chemical point of view, the molecular dynamics simulations based on the B3LYP functional in rather small basis set were performed. Despite of the constitutional limitations of the proposed model, the obtained O—H and N—H BDE values in phenol (363 kJ mol⁻¹) and aniline (369 kJ mol⁻¹) are in good agreement with the experimental solution phase data.

Keywords: molecular dynamics, DFT, B3LYP, BDE, phenol, aniline

Introduction

One of the most important parameters characterising the antioxidant or radical scavenging activity of many natural and synthetic compounds is the bond dissociation enthalpy (Bordwell et al. 1994, Pratt et al. 2004). There are available several experimental methods in gas or solution phase for determination of BDE values (Ruscic et al. 1989, Ervin 2001, Bordwell et al. 1993, Jonsson et al. 1994, McFaul et al. 1997). Despite this fact, there are many compounds which BDE values are hardly measurable or immeasurable.

The quantum chemistry combined with the computational chemistry has become a suitable tool for research of wide range of molecular properties. It can serve for calculation of quantities, which are hardly measurable, as well as for predictions of trends between them. However, calculations of larger molecules, more than 50 non-hydrogen atoms, often call for larger computational times. Therefore, it is necessary to choose an appropriate treatment which represents a reasonable compromise between the computational costs and the accuracy of results. From the theoretical point of view, the BDE values can be obtained at different theoretical levels using various chemical models.

The simplest way is to calculate the BDEs in the gas phase which are usually close but not necessarily identical with the solution phase BDEs e.g. (Rimarčík et al. 2011). Another way is to include the effect of the corresponding solvent in the cal-

ulation of BDEs. It can be performed using the continuum models, where the solvent is described as an infinite continuum enclosing the cavity with a solute molecule, by means of microsolvation chemical model that explicitly considers the interaction of a finite number of solvent molecules with the solute, or by combination of the two methods e.g. (Rimarčík et al. 2011, Klein et al. 2009, Guerra et al. 2004). All mentioned approaches are usually connected with the density functional theory calculations (DFT) employing B3LYP functional and various basis sets e.g. (Rimarčík et al. 2011, Klein et al. 2009, Guerra et al. 2004, Vagánek et al. 2013, Fu et al. 2004, Gomes et al. 2004).

The use of continuum model, only, may provide the BDE values with various accuracy. The differences from the experimental data can depend on the chosen basis set and the structure of the solute molecule. For example, Rimarčík et al. calculated the BDEs of monosubstituted tiophenols by means of B3LYP/6-311++G** level connected with the integral equation formalism of polarizable continuum model method (IEF-PCM) and obtained the BDE values being in very good agreement with experimental results (Rimarčík et al. 2011). Klein et al. found using the same computational approach for monosubstituted phenols the BDEs evidently underestimated compared to available experimental values (Klein et al. 2009). On the other hand, Guerra et al. calculated rather overestimated BDE values of *para*-substituted phenols by B3LYP/6-31G* level connected with IEF-PCM.

Guerra et al. carried out also the calculations of BDEs by means of microsolvation model at the same level of theory. They obtained BDE values being in good agreement with available experimental values, when two water molecules were added to the solute structure. However, in the formula for BDE calculation, the experimental value of phenol O—H BDE measured in benzene has been included (Guerra et al. 2004). Furthermore, the success of the microsolvation approach strongly depends on the chosen number of solvent molecules added and their location with respect to the solute molecule at the start of the geometry optimization. Due to the mentioned shortcomings of commonly used methods for solution phase BDE calculation, we decided to test the suitability of the molecular dynamics for the description of solvent effect on the BDE. We chose the phenol and the aniline which represent the important parts of many kinds of synthetic or natural primary antioxidants. Thus, the main goal of this work is to assess the suitability of the simple molecular dynamics microsolvation model for the calculation of the solution phase O—H and N—H BDE values in phenol and aniline. In this context, we will also discuss the structure of the solvent-solute system for the energetically most probable arrangement of the molecules in the system.

Computational Details

All molecular dynamics (MD) simulation and DFT calculations were performed by means of the ORCA 3.0.2 program package (Neese F 2012) using B3LYP (keyword B3LYP) (Becke-3-parameter-Lee-Yang-Parr) hybrid functional (Becke AD 1988, Lee et al. 1988). In MD simulations, the 6-31G* (Rassolov et al. 2001) basis set for all atoms except the carbon atoms was used. For the carbon atoms the 3-21G (Binkley et al. 1980) basis set was employed. This basis set combination was selected due to the good computational time and accuracy ratio. The trajectories were propagated with a time step of 60 a.u. The Velocity-Verlet scheme was used to integrate the classical Newton equations of motion. The duration of the MD simulations was at most 1.45 ps (1000 steps). The all other calculation settings were default. To estimate the solvent effect on the BDE values, we placed five water molecules nearby the studied functional groups evenly. Furthermore, the implicit solvation method COSMO (Klamt et al. 1993) (Conductor like Screening Model) was also included in MD simulations.

Results and Discussion

As mentioned above, the continuum models can estimate bulk solvent effects well but the descrip-

tion of short interactions such as hydrogen bonding can fail. Therefore, we decided in this work to test the simple microsolvation model using MD calculations where five water molecules are evenly distributed close by the studied functional groups. The chosen number of the water molecules ensures the uniform covering of the studied functional groups by the solvent molecules. The distance between the oxygen atom of every water molecule and the heteroatom of the studied functional group is within 3–4 angstroms.

In order to verify the reliability of the relatively small basis sets employed in the proposed model, we carried out testing calculations of molecular geometries. The geometry optimizations of phenol, aniline and their radicals in gas phase were performed using B3LYP functional connected with the mentioned basis sets (6-31G* for N, O and H atoms and 3-21G for C atoms) and at the B3LYP/6-311++G** level of theory (reference calculations). The B3LYP/6-311++G** approach is widely applied for the theoretical study of reaction enthalpies, giving reliable optimal geometries and BDE values in good agreement with experimental results (Klein et al. 2006, Klein and Lukeš 2006a, Rimarčík et al. 2011). The comparison of obtained bond lengths is shown in the Fig. 1. The B3LYP/6-311++G** values are given in the parenthesis. For aniline and phenol, the experimental values for the bonds which do not contain a hydrogen atom are also shown (given in italic) (Fukuyo et al. 1982, Zavodnik et al. 1988). The experimental values are obtained from the X-ray diffraction analysis where the position of H atoms cannot be determined directly. Thus, we do not show experimental data for the H atom containing bonds. Fukuyo et al. presented the bond lengths for two independent aniline molecules, therefore, the intervals of bond lengths are shown in the Fig. 1. From the Fig. 1, it can be seen that the bond lengths obtained using the combination of 6-31G* and 3-21G basis sets differ from the 6-311++G** ones only at the third decimal place. Moreover, the calculated values are in good agreement also with the found experimental results. Therefore, the chosen basis sets combination gives sufficient geometries for the assessment of reaction enthalpies of simple molecules.

After MD run, we obtained a set of geometries for the solvated aniline, phenol, the corresponding radicals and the hydrogen atom. Then, the geometries with the lowest energy were selected. The main limitation of the suggested microsolvation model is the fact that the solvent molecules can depart from the studied functional group. Therefore, we consider only lowest energy configurations with the water molecules being still nearby OH or NH₂ group.

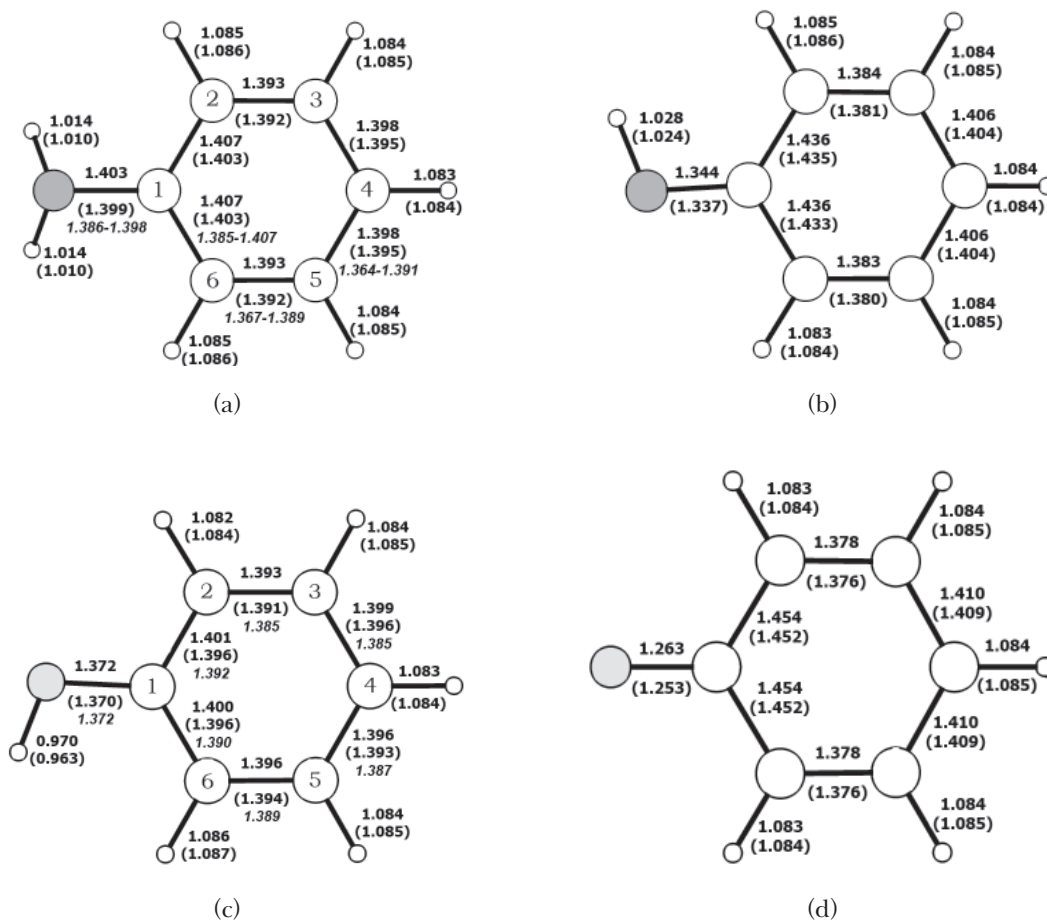


Fig. 1. The gas phase optimized bond lengths (in angstroms) of a) aniline, b) aniline radical, c) phenol and d) phenol radical obtained by B3LYP/6-311++G** (in parenthesis) and B3LYP connected with the basis sets combination (6-31G* for N, O and H atoms and 3-21G for C atoms). The chosen experimental values (in italic) (Fukuyo et al. 1982, Zavodnik et al. 1988).

The water tends to form clusters by hydrogen bonds, typically about 2 Å long. In our simulation, the water molecules without solute molecule form 4-membered ring with one molecule aside, as depicted in Fig. 2(a). This molecule is bound with another one belonging to the ring by the hydrogen bond 1.70 Å long. Very similar organization occurs for H atom Fig. 2(b). All its interactions with the present water molecules are rather weak (3–4 Å). On the other hand, aniline amino group forms three typical (1.85 Å, 2.14 Å and 2.22 Å) and one long range (3.06 Å) hydrogen bond with the solvent molecules, see Fig. 2(c). In the case of aniline radical, only one stronger hydrogen bond is formed (see Fig. 2(d)), while the phenoxyl radical interacts considerably with two water molecules, see Fig. 2(f). It is interesting that the used solvation model provides the lowest energy configuration for phenol only with the one stronger hydrogen bond between OH group and the water (1.69 Å), as shown in the Fig 1(e).

In this work, the O—H and N—H BDE values in phenol and aniline were approximated from the sums of vibrational, translational and electronic energies (further only energy) as follows

$$\text{BDE} = E(\text{ArY} \cdot \dots 5 \text{H}_2\text{O}) + E^*(\text{H} \cdot) - E(\text{ArY}-\text{H} \dots 5 \text{H}_2\text{O}), \quad (\text{Y} = \text{O}, \text{NH}) \quad (1)$$

where

$$E^*(\text{H} \cdot) = E(\text{H} \cdot \dots 5 \text{H}_2\text{O}) - E(5 \cdot \text{H}_2\text{O}) \quad (2)$$

and the $E(\text{ArY} \cdot \dots 5 \text{H}_2\text{O})$ and $E(\text{ArY}-\text{H} \dots 5 \text{H}_2\text{O})$ are the energies of the clusters of the formed radical and the corresponding molecule with five water molecules, respectively. In the Eq. 2, the $E(\text{H} \cdot \dots 5 \text{H}_2\text{O})$ and $E(5 \cdot \text{H}_2\text{O})$ stand then for the system of the H atom with five water molecules and the system of the five water molecules only. The $E^*(\text{H} \cdot)$ represents an estimate of the hydrated H atom energy. The $E^*(\text{H} \cdot)$ value received from the Eq. 2 reached $-1303.7 \text{ kJ mol}^{-1}$. To the best of our

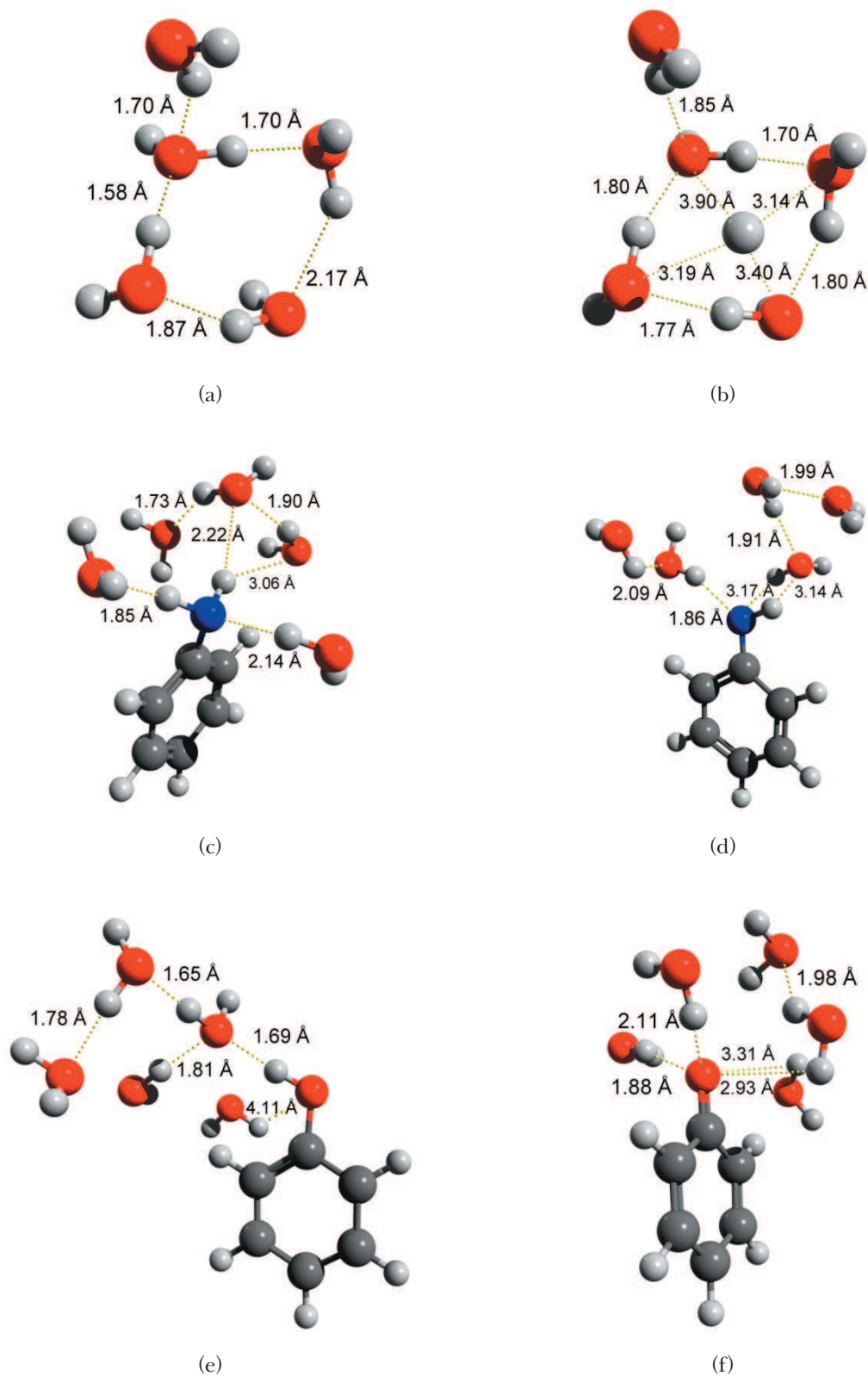


Fig. 2. The molecular dynamics geometries of studied systems corresponding to the lowest B3LYP energies, a) five water molecules; b) H atom, c) aniline, d) N-centred aniline radical, e) phenol, and f) phenoxyl radical with the five water molecules. The lengths of the selected intermolecular hydrogen bonds.

knowledge, in the literature there is not any available theoretical or experimental value of the energy or enthalpy of the hydrated H atom. Nevertheless, the reliability of the obtained $E^*(\text{H}\cdot)$ value can be verified indirectly by means of the hydration energy of H atom. The hydration energy calculated as the difference between $E^*(\text{H}\cdot)$ and the gas phase energy of H atom ($-1304.7 \text{ kJ mol}^{-1}$) reached the value of 1 kJ mol^{-1} , while the experimental H atom hydration enthalpy was found to be -4 kJ mol^{-1} (Bizarro et al. 1999, Parker 1992).

The obtained results together with the available experimental and the chosen theoretical BDEs are listed in the Table 1. Only two works are available in the literature where the experimental O—H and N—H BDE of phenol and aniline were determined in water. Jonsson et al. found the N—H BDE of aniline of 373 kJ mol^{-1} by pulse radiolysis (Jonsson et al. 1994). Lind et al. also carried out this method obtaining the O—H BDE value of 369 kJ mol^{-1} for phenol (Lind et al. 1990). Estimated standard deviation for this method is 4 kJ mol^{-1} .

Tab. 1. The bond dissociation energies (kJ mol^{-1}) obtained using proposed microsolvation model (MD), by B3LYP with 6-31G* for N, O and H atoms and 3-21G for C atoms (DFT), and available theoretical (DFT1) and experimental values.

	MD	DFT	DFT1	exp
Aniline	369	359		373 ^b
Phenol	363	343	352 ^a	369 ^c

^a(Klein and Lukeš 2006b)

^b(Jonsson et al. 1994)

^c(Lind et al. 1990)

The works yielding the theoretical O—H BDE of phenol calculated in the water are also scarce. Guerra et al. included in their calculations the effect of the water on the O—H BDE of phenol using three different ways (Guerra et al. 2004). Using the above described microsolvation model, they obtained the value of 366 kJ mol^{-1} . When the IEF-PCM approach was used only, the found O—H BDE value reached 379 kJ mol^{-1} . Finally, the combination of the two approaches resulted in the O—H BDE value of 385 kJ mol^{-1} . Klein and Lukeš determined the value of 352 kJ mol^{-1} (see Table 1, DFT1 column) using B3LYP/6-311++G** method connected with the IEF-PCM (Klein and Lukeš 2006b). For the aniline, there was not found any theoretical value of N—H BDE calculated in the water. For the sake of the correct comparison of the

molecular dynamics results with the DFT method, we also performed the geometry optimizations of the lowest energy MD geometries using B3LYP functional connected with COSMO and the basis sets combination used in the proposed model. The found BDEs are given in the Table 1. We can see that these values are considerably underestimated compared to the presented experimental data. The values provided by the tested MD microsolvation model are 369 kJ mol^{-1} , and 363 kJ mol^{-1} for aniline and phenol, respectively. We can see that obtained BDEs are in very good agreement with available experimental data.

Conclusion

This paper has suggested an alternative approach for the theoretical calculations of the solution phase BDEs using the molecular dynamics simulations. The solvent effect is described by means of the simple microsolvation model that explicitly considers the interaction of five H_2O molecules with phenol, aniline and their radicals. Besides, the implicit solvation method COSMO was also included in the simulations. The obtained results are in good agreement with the experimental solution phase values. The 6-31G* and 3-21G basis sets connected with the B3LYP functional provide reliable results in adequate time. Thus, the molecular dynamics simulation may serve as a computationally efficient alternative to the commonly used computational approaches. Nevertheless, the main shortcoming of the presented model is the fact that the solvent molecules can depart from the studied functional group of the solute molecule. The possible solution of this problem can be the molecular dynamics calculations in the periodic box with the great number of the solvent molecules. The presented results supply some starting points for a more detailed study with additional solvents and larger basis set.

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