Investigation of Solvent Effects on Interaction of Single-Strand DNA with Open-End of Single Walled Carbon Nanotubes Using QM and MM methods

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ABSTRACT

The interaction of biomolecules with carbon nanotubes (CNTs) has generated a great deal of interest in the past few years. The interaction between B-form single-strand DNA (ssDNA) and single-walled carbon nanotubes (SWCNTs) is a subject of intense current interest; however there are a relatively small number of papers in the literature dealing with interaction of DNA and SWCNTs. In this work we investigate interaction of ssDNA with open-end of SWCNT; using AMBER, MM+ and OPLS force fields in molecular mechanic (MM) method. We study effects of increase the molecular number of solvent on interaction of ssDNA with SWCNTs, using these force fields too. The interaction of ssDNA with open-end of SWCNT in water and ethanol have been calculated using density functional theory (DFT) at the theoretical level of B3LYP/6-31G (d, p) and have been made a comparison between dipole moment; energy and atomic charges in vacuum; water and ethanol. Our results show that interaction of ssDNA with open-end of SWCNT could be optimum in polar solvent.

Keywords: DNA; SWCNTs; interaction; solvent effect

INTRODUCTION

Nanoscience is one of the most important researches in modern science [1]; therefore the quest for nanoscale structures with practical applications is rapidly passing from the realm of dreams to reality [2]. The discovery of carbon nanotubes (CNTs) that are nano-sized materials with excellent mechanical and electrical properties and have been proposed to be used in a variety of application fields [3-4]. CNTs are a new allotrope of carbon originated from fullerene family, which will revolutionize the future nanotecnological devices [5]. There are two types of CNTs: single-walled nanotubes (SWCNTs) and multi - walled nanotubes (MWCNTs) [6]; that they have three conformation: armchair (n, n), zigzag (n, 0) and chiral (n, m) [6-16]; these conformations have individual properties [17]. SWCNTs have been considered as the leading candidate for nanodevice applications because of their one-dimensional electronic bond structure, molecular size, and biocompatibility, controllable property of conducting electrical current and reversible response to biological reagents [7]; hence SWCNTs make possible bonding to polymers and biological systems such as DNA and carbohydrates [8]. Many unique properties of DNA have inspired researches to combine this

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biological material with SWCNTs to explore its nanobiological applications [18]. SWCNTs and ssDNA have complementary structural features which make it possible to assemble them into a single [9]; stable structure: segments of ssDNA are extremely flexible, strongly hydrophilic biopolymers, while SWCNTs are extremely stiff, strongly hydrophobic nanorods [10]. Recent work has shown that ssDNA interacts very strongly with SWCNTs [11]; and ssDNA has been recently demonstrated to interact covalently and noncovalently with SWCNTs too [15-18-19-20-21-22]; but the interaction details of the ssDNA with SWCNTs have not yet been fully understood [10-13]. Molecular modeling by Zheng et al suggested that DNA hybridize with SWCNTs by wrapping around them, with the interaction strength being provided by π-stacking (noncovalently binding), with the plane of the aromatic nucleotide bases to the surface of the SWCNTs [12]. Hu et al mentions that DNA can be interact covalently to oxidizing open-ends of SWCNTs [18]; therefore the interaction of ssDNA with SWCNTs is not limited to the outer surface of the SWCNTs; it can be inserted into a SWCNT [13] and it can be interaction with open-ends of SWCNTs too, To date, the focus in this interaction has been on placing ssDNA at the open-ends of SWCNTs [14]. Therefore in present study the interaction of ssDNA with open-end of SWCNTs was investigated using molecular mechanic (MM) method in different force fields and solvent effects on this interaction by quantum mechanics (QM) method have been investigated too. For the simulation of the solvent effects by QM method, the self consistent reaction field method (SCRF) is most commonly use [23]. We report here solvent effects on the optimum level of this interaction with employ QM/MM methods.

COMPUTATIONAL METHOD

A sequence of B-form ssDNA include five nucleotide (CCAAT) was linked to open-end of SWCNT with MM+, OPLS and AMBER force fields (see Fig 1). These force fields are suitable for study ssDNA interaction with SWCNTs; especially AMBER and OPLS force fields because they have been designed for biomolecules. In the first step notice to past

works; particularly study of Das and co-worker that said the best atoms of nucleotides for interaction with SWCNTs are nitrogen and oxygen atoms because they have more electron affinity [20], therefore we calculated the best interaction between nitrogen and oxygen atoms of selected nucleotides of ssDNA (see Fig 2, 3) and open-end of SWCNT in vacuum with MM+, OPLS and AMBER force fields and compared them. In many works DNA/SWCNT system have been solvated in about 4600 to 5000 water molecules [11-25] with molecular mechanic method (MM), because the optimum level of energy interaction required to many water molecules but in this work we presented the number of water molecules for solving DNA/SWCNT system in fewer than one thousand water molecules in about 215 to 735 (215 is the first number of water molecules that have been calculated base on the size of system) water molecules which in this number the energy interaction is optimum, this number of water molecules was calculated using MM+, OPLS and AMBER force fields. The quantum mechanics (QM) calculations were carry out with the GAUSSIAN 98 [28] program based on density functional theory (DFT) method, wherein the charge changes, electronic states and atomic forces have been described using this method [24] and this method could interpreted charge transfer and chemical bonds between the molecules too. We have been carried out comparison between vacuum calculation and solvents calculations, our considered solvents in this study are water and ethanol, Therefore in this study we investigated polar solvents effects on interaction ssDNA with open-end of SWCNT. The Density functional theory (DFT) method at B3LYP/6-31G (d, p) theoretical level used for vacuum and solvent effects calculations. This theoretical level corresponds to the approximation method that makes use of Beck-Style 3-parameter density functional theory (DFT) [26-27]. The Onsager model of SCRF used for investigated solvent effects, wherein recommended radii for SCRF calculation have been calculated 7.82 angstrom. This model has been selected for solvent effects study because it can be calculated the polar solvent effects very good. Visualization and analysis of the

configuration were performed with QM/MM methods.
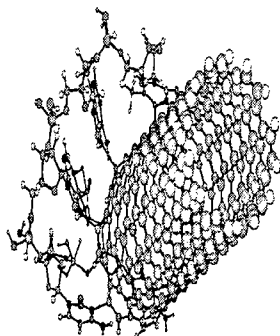
(A)
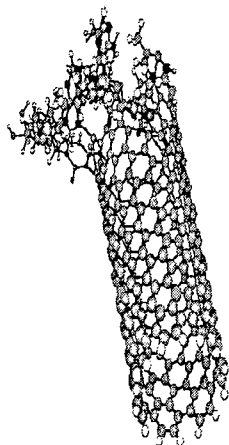
(B)

Fig.1.A and B are schematic diagrams of ssDNA interaction with open-end of SWCNT.
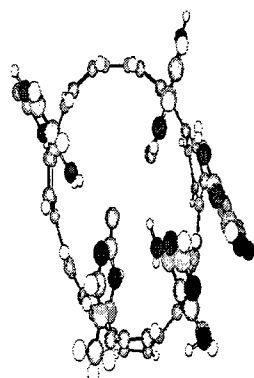

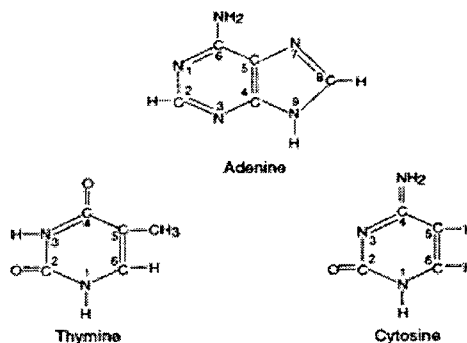**Fig.2.**This depict particularly for interactions region of ssDNA with SWCNT.

Fig.3. The schematic diagram of nucleotides structure that interacted to SWCNT

RESULTS AND DISCUSSION

In calculation of interacted atoms of ssDNA nucleotides with open-end of SWCNT atoms in vacuum, we have been chosen seventh atom of Adenine which is nitrogen, third atom of Cytosine which is nitrogen too and oxygen of Thymine, this oxygen bind to forth atom of thymine which is carbon. These atoms have been chosen based on average of the their energy in comparison to other atoms selected from Adenine, Cytosine and Thymine, on the other hand according to our calculations in the MM+, OPLS and AMBER force fields, they have the most optimum level of interaction energy in ssDNA/open-end of SWCNT system. Energy interaction of these atoms is shown in Table 1.

Table1. Comparison Calculations of the best interaction between atoms of Adenine, Cytosine and Thymine with SWCNT in vacuum

Nucleotide		Energy (kcal/mol)		
		MM+	OPLS	AMBER
Adenine	N-1	1350.1648	411.816406	1266.72223
	N-3	1342.117	425.972595	1287.94299
	N-7	1307.51709	377.275055	1265.12464
Cytosine	O	1214.6073	452.552673	1210.34937
	N-3	1217.30981	395.803558	1206.81531
Thymine	C(4)-O	1223.65869	450.818237	1218.43359
	C(2)-O	1225.55237	451.678375	1221.11023

In Table 2 and Fig.4 have been shown that with increasing the water molecules number the optimum level of energy interaction decreased,

stability of structure has been increased. In this study we have been shown that with suitable interaction between ssDNA and SWCNT we could earn optimum level of energy interaction in the lowest water molecules number, therefore if ssDNA interacted to open-end of SWCNT this interaction could optimum even in fewer than one thousand water molecules, then the quality of ssDNA interaction with SWCNT is important, because it is effective on the number of water molecules for system solution and achieved to the optimum level of energy interaction in the lowest water molecules number. Pay attention to Table 2 again, we see which OPLS and AMBER force fields could show this subject better than MM+ force field because they could descript solvent simulations and non-binding interactions in system and also OPLS force field is better than AMBER force field. Therefore calculated effects of water molecules number on system solving and achieved to optimum level using molecular mechanic (MM) method required to creating the best interaction in system and selected the best force field for calculation.

Table2. Optimum energy with increasing of water molecules number

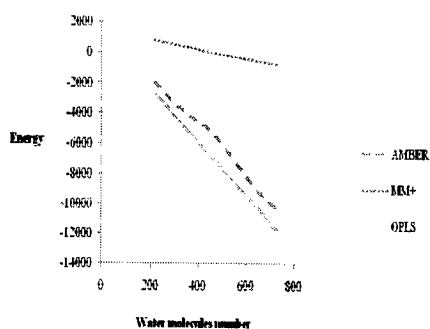| Solvent molecules number	Energy (kcal/mol)		
	MM+	AMBER	OPLS
215	782.4465	-2001.7	-2655.39
342	386.6173	-3959.26	-4987.34
465	-34.0549	-5408.12	-7078.27
638	-508.448	-8919.12	-10108.2
735	-794.541	-10430.7	-11781.1

Fig.4. The optimum level of energy interaction decreased with increasing the water molecules number.

The results of calculation bond length values that calculated using density functional theory (DFT) method in vacuum, water and ethanol states are same. It might be effect of interaction type ssDNA with open-end of SWCNT, on the other hand with this type of interaction the bond length values might be constant even in solvent because with this interaction product a condense region in ssDNA/open-end of SWCNT system, since water and ethanol can form hydrogen bond with ssDNA/open-end of SWCNT system, then this bond can be effective in protection of condense region. Albeit bond length values in this interaction even under the influence of solvent are fix but regarding to Tables 3, 4 and 5 that have been shown which calculated values of bond angels, atomic charges and dihedral angels in water and ethanol aren't same with calculated values in vacuum. Notice to Tables 3 and 5 in cases don't have change, solvents don't have enough interaction with interacted atoms but in other cases that changes happen, solvents have enough interaction with interacted atoms. It can be seen that ssDNA/open-end of SWCNT system distinction that protected of condense region in water and ethanol, then under the influence of these solvents bond angles and dihedral angles changed for the save system conformation. Nevertheless changes of bond angles and dihedral angles are small and these values are near to vacuum, because the level of structural optimum of ssDNA/open-end of SWCNT system in water and ethanol states is near to vacuum state, proposed energy in the Table 6 is the reason for this sentence. The data in Table 4 show that interacted atoms are under the influence of water and ethanol dielectric constant and since water and ethanol can form electrostatic bond with ssDNA/open-end of SWCNT system, it should be noted that charge distribution relation to location of interacted atoms in system. Therefore interacted atoms of Adenine, Cytosine and Thymine of ssDNA/open-end of SWCNT system have particularly charge distribution in water and ethanol, for instance nitrogen atoms by 6 and 14 numbers in this system that belong to two Cytosine have deferent charge distribution because they are under the influence of the water and ethanol dielectric constants in deferent places.

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Table3. Solvent effect on bond angels of interaction between ssDNA and open-end of SWCNT with respect to vacuum value

(A˚)Bond angles		Vacuum	Water (ε=78.39)	Ethanol (ε=24.55)
Nitrogen of Cytosine with SWCNT	N(6)-H(93)-C(54)	177.278	177.278	177.278
Nitrogen of Cytosine with SWCNT	N(14)-H(99)-C(46)	171.697	171.702	171.697
Nitrogen of Adenine with SWCNT	N(19)-H(101)-C(70)	169.411	169.401	169.401
Nitrogen of Adenine with SWCNT	N(29)-H(107)-C(66)	172.742	172.742	172.737
Oxygen of Thymine with SWCNT	O(42)-H(115)-C(62)	172.903	172.889	172.898

Table4. Calculated of total atomic charges (a. u) in vacuum and solution phases

The atom number in system ssDNA/SWCNT	Atom	Vacuum	Water (ε=78.39)	Ethanol (ε=24.55)
6	N	-0.641183	-0.641437	-0.641303
14	N	-0.627028	-0.627509	-0.627149
19	N	-0.619567	-0.62601	-0.619395
29	N	-0.502098	-0.502366	-0.501855
42	O	-0.453917	-0.452219	-0.454151
46	C	-0.134214	-0.135741	-0.134256
54	C	-0.115642	-0.116674	-0.115582
62	C	-0.242575	-0.2396	-0.242823
66	C	-0.169403	-0.169134	-0.169374
70	C	-0.047522	-0.056931	-0.047474
93	H	0.159175	0.159472	0.159252
99	H	0.116132	0.115744	0.116192
101	H	0.107863	0.107134	0.107952
107	H	0.093566	0.093548	0.093582
115	H	0.226316	0.226694	0.226286

Table5. Solvent effect on dihedral angels of interaction between ssDNA and open-end of SWCNT with respect to vacuum value

Dihedral angles (A˚)		Vacuum	Water(ε=78.39)	Ethanol(ε=24.55)
N(6) is the Number of nitrogen atom of Cytosine in system	C(4)-N(6)-H(93)-C(54)	40.116	40.052	40.272
	C(7)-N(6)-H(93)-C(54)	-141.629	-141.697	-141.624
	C(53)-C(54)-H(93)-N(6)	-167.29	-167.792	-167.313
	C(55)-C(54)-H(93)-N(6)	7.928	7.167	7.825
N(14) is the Number of nitrogen atom of Cytosine in system	C(12)-N(14)-H(99)-C(46)	-69.135	-69.135	-69.13
	C(15)-N(14)-H(99)-C(46)	94.174	94.702	94.711
	C(47)-C(46)-H(99)-N(14)	-8.928	-8.855	-8.855
	C(73)-C(46)-H(99)-N(14)	-175.694	-175.948	-175.872
N(19) is the Number of nitrogen atom of Adenine in system	C(18)-N(19)-H(101)-C(70)	0	0	0
	C(20)-N(19)-H(101)-C(70)	-164.348	-164.335	-164.32
	C(69)-C(70)-H(101)-N(19)	31.68	31.654	31.65
	C(71)-C(70)-H(101)-N(19)	-147.919	-147.941	-147.947
N(29) is the number of nitrogen atom of Adenine in system	C(28)-N(29)-H(107)-C(66)	-59.966	-60.001	-59.985
	C(30)-N(29)-H(107)-C(66)	110.983	110.96	110.969
	C(65)-C(66)-H(107)-N(29)	131.664	131.636	131.622
	C(67)-C(66)-H(107)-N(29)	-55.846	-55.86	-55.871
O(42) is the number of oxygen atom of Thymine in system	C(41)-O(42)-H(115)-C(62)	124.5	124.472	124.471
	C(61)-C(62)-H(115)-O(42)	144.65	144.628	144.659
	C(63)-C(62)-H(115)-O(42)	-48.043	-48.058	-48.016

Table6. Theoretically calculated values of dipole moment and energy ssDNA interaction with open-end of SWCNT in vacuum and in solution phase

Phase	Total dipole moment(Debye)	Energy(hf)	Polarization energy $(\times 10^{-5})$	Total energy of solute(hf)	Total energy(Kcal/mol) (without reaction field)
Vacuum	14.3854	-3792.2241	----------------------------		
Water (ε=78.39)	14.1808	-3792.2259	-0.5003946	-3792.2259	-3792.2259
Ethanol (ε=24.55)	14.5838	-3792.2266	-0.1549142	-3792.2268	-3792.2265

Values of total dipole moment and energy of ssDNA/open-end of SWCNT system in three states have been shown in the table 6. The calculated values of total dipole moment and energy in vacuum are approximately between the calculated values of total dipole moment and energy in water and ethanol. It can be seen that values achieved for ssDNA/open-end of SWCNT system from calculation in water and ethanol are under the influence of solvents dielectric constant because in water with dielectric constant $(\varepsilon) = 78.39$, dipole moment of ssDNA/open-end of SWCNT system decreased respected to vacuum but in ethanol with dielectric constant $(\varepsilon) = 24.55$ dipole moment of ssDNA/open-end of SWCNT system increased respected to vacuum and also the optimum level of energy interaction in ethanol achieved smaller than the optimum level of energy interaction in water. It might be interaction type ssDNA with open-end of SWCNT effective on total dipole moment and energy achieved from calculations in vacuum, water and ethanol too. Nevertheless the Table 6 show interaction ssDNA with open-end of SWCNT have the optimum level of energy interaction in vacuum, and also water and ethanol are effective on decreasing the optimum level of energy interaction.

CONCLUSION

Our results from density functional theory (DFT) combined with force field calculation, indeed with these methods have been shown investigation of the ssDNA interaction with open-end of SWCNT and solvent effects on this interaction. In this work make a mention of relation between interaction quality and solvent molecules number and have been proposed if ssDNA interacted with open-end of SWCNT could optimum in fewer than one thousand water molecules. We show that the optimum level of energy interaction in considered polar solvents in this study and we have observed changes on system such as dihedral angel changes or bond angel changes in solution phase respect to vacuum. Albeit the changes obtained are very small but these phrases description that polar solvent not only don't have unsuitable effects on ssDNA interaction with open-end of SWCNT but also suitable effects on this interaction because the structural stability of this system increased under the influence of water and ethanol, however the results have been shown that the optimum level calculated this interaction in water and ethanol is near to vacuum value. These results are useful for everyone that wants work on this subject.

REFERENCES

1. P. Kohli and C. R. Martin, Current pharmaceutical biotechnology, 2005, Vol.6, p.35.
2. G. Lu, P. Maragakis and E. Kaxiras, nano letters, 2005, Vol. 5, No. 5, p.897.
3. N. kurita, I. Komura, T. Tsukamoto and Y. Ishikawa, Helevetica Chimica Acta, 2005, Vol.88, p.751.
4. N. Siha and J. Yeow, IEEE, 2005, Vol.4, NO.2, p.180.
5. S. Daniel, T. P. Rao, K. S. Rao, S. U. Rani, G. R. H. Naidu, H. Y. Lee and T. Kawai, Sensors and Actuators B, 2007, Vol.122, p.672.
6. M. Foley, Cheap Tubes, 2005.
7. X. Li, Y. Peng and X. Qu, Nucleic acids research, 2006, Vol.34, No.13, p.3670.
8. T. Ramanathan, F. T. Fisher, R. S. Ruoff and L. C. Brinson, Chem mater, 2005, Vol.17, p.1290.
9. S. Meng, W. L. Wang, P. Maragakis and E. Kaxiras, nano letters, 2007, Vol.7, No.8, p.2312.
10. S. Meng, P. Maragakis, C. Papaloukas and E. Kaxiras, nano letters, 2007, Vol.7, No.1, p.45.
11. X. Zhao and K. Johnson, Chem. Phys. Lett, 2007.
12. M. E. Hughes, E. Brandin and J. A. Golovchenko, nano letters, 2007, Vol.7, No.5, p.1191.
13. S. Gowtham, R. H. Scheicher, R. Ahuja, R. Pandey and S. P. Karna, physical review, 2007, vol.76.
14. M. J. Moghaddam, S. Taylor, M. Gao, S. Huang, L. Dai and M. J. McCall, nano letters, 2004, Vol.4, No.1, p.89.
15. A.Star, E. Tu, J. Niemann, J. C. P Gabriel, C. S. Joiner and C. Valcke, PNAS, 2006, Vol.103, No.4, p.921.
16. G. Cuniberti, J. Yi and M. Porto, arXiv, 2002.
17. B. Gojman, H. Hsin, J. Liang, N. Nezhdanova and J. Saini, 2004.
18. C. Hu, Y. Zhang, G. Bao, Y. Zhang, M. Liu and Z. L. Wang, J.phy. Chem. B, 2005, Vol.109, p.20072.
19. C. Staii, M. Chen, A. Gelperin and A. T. Johnson, chem, 2005.
20. A.Das, A. K. Sood, P. K. Maiti, M. Das, R. Varadarajan, C. N. R. Rao, arXiv, 2007.
21. S. R. Lustig, A. Jagota, C. Khripin and M. Zheng, J. phys. Chem. B, 2005, Vol.109, p.2559.
22. S. Gowtham, R. H. Scheicher, R Ahuja and R Pandey, Computational biophysics, 2007, Vol.36, p.117.
23. A.Tsolakidis and E. Kaxiras, J. Phys. Chem A, 2005, Vol.109, p.2373.
24. D. Srivastava and S. N. Atluri, CMES, 2002, Vol.3, No.5, p.531.
25. C. Dwyer, M. Guthold, M. Falvo, S. Washburn, R. Superfine and D. Erie, nonotechnology, 2002, Vol.13, p.601.
26. Beck A.D, Chem. phys, 1993, Vol.98, p.5648.
27. Lee C. Yang W. Parr R G, phys, 1998, p.785.
28. Frisch, M.J.; Trucks, G.W.; Schlegel, H.B.; Scuseria, G.E.; Robb, M.A.; Cheeseman, J.R.; Zakrzewski, V.G.; Montgomery, J.A. Jr.; Stratmann, R.E.; Burant, J.C.; Dapprich, S.; Millam, J.M.; Daniels, A.D.; Kudin, K.N.; Strain, M.C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G.A.; Ayala, P.Y.; Cui, Q.; Morokuma, K.; Malick, D.K.; Rabuck, A.D.; Raghavachari, K.; Foresman, J.B.; Cioslowski, J.; Ortiz, J.V.; Baboul, A.G.; Stefanov, B.B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R.L.; Fox, D.J.; Keith, T.; Al-Laham, M.A.; Peng, C.Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P.M.W.; Johnson, B.; Chen, W.; Wong, M.W.; Andres, J.L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E.S.; Pople, J.A. Gaussian 98, Revision A.7, Gaussian, Inc.: Pittsburgh PA; 1998.