

Electrolytic Transport in Modified Carbon Nanotubes

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ABSTRACT

Molecular dynamics simulations were used to study ionic flow in carbon nanotubes with the goal of using carbon nanotubes as artificial protein channels found in cell membranes. Previous simulations show that water and molten ions enter carbon nanotubes spontaneously. Our simulations show that ion occupancy in a carbon nanotube solvated in an electrolyte is very low for a (16,16) uncapped tube. When partial charges were placed on the rim atoms of the tube and an external electric field was applied, it was found that the ion occupancy increased significantly. To mimic an ion channel in a membrane, functional groups were attached at the ends and the tube was placed in a slab. The functionalized tube was found to conduct ions in the presence of an electric field. It is also shown that cationic or anionic selectivity could be obtained by symmetrical placement of the functional groups.

Introduction. Transport of molecules through macromolecular pores is of considerable importance in many biological and nanoelectromechanical systems. Ion channels in cell membranes are crucial for shaping electrical signals and controlling flow of ions and fluids across cells. Channels have interesting properties such as gating and selective permeability that are still topics of active research. In recent years, engineered ion channels have been developed to function as a single-molecule detection system.^{1,2} In an applied potential, an ionic current is carried by the ions that bathe both the sides of the lipid bilayer. When the target molecule binds to the binding site in the pore, the current is modulated. The frequency of binding reveals the concentration of the analyte, and the duration and amplitude of the events reveal its identity. Though engineered channels have significant advantages including high sensitivity, wide dynamic range, and biocompatibility, their lack of durability makes them reliable only in a lab setting. In this paper, we investigate the possibility of a nanoscale device that is far less complex than a biological system and which incorporates the functionality of ion channels into artificial nanotubes. A review of recent literature shows that promising options for such a device that can be practically realized would be gold nanotubule membranes,^{3,4} ion beam etched silicon nitride membranes,⁵ or single carbon nanotubes. Carbon nanotubes being rigid and having exciting electrical and mechanical

properties seem ideal for an integrated circuit chip design, but fundamental questions have to be addressed regarding transport of water and ions through it. Quantitative information on fundamental modes of water transport and transport rates have been obtained through carbon nanotubes of diameters of about 150 nm.⁶ Hummer et al.⁷ showed by molecular dynamics simulations that water molecules enter nanotubes of as small as 8.1 Å diameter even though carbon is hydrophobic. In their experiments, Miller and Martin⁸ show that it is possible to control the rate and direction of electrosmotic flow through nanotube membranes of large diameters (120 nm). The behavior of water molecules and ions through hydrophobic carbon nanotubes is of critical importance because ion channels such as K⁺-channels have their selectivity filter lined with hydrophobic residues that facilitate transmembrane movement of ions and water without sticking to the side wall. But transport of ions in these channels is stabilized by polar interactions with surrounding proteins, which is a feature that the nanotube lacks. Therefore, fundamental questions have to be answered regarding transport of ions in an electrolytic solution through nanotubes.

The modeling of nanotubes by molecular dynamics simulations has shown that water and pure molten salt may enter the nanotube cavity. Hummer et al.⁷ showed that for a (6,6) tube at a pressure of 1 bar and 300 K, even though the average binding energy of water inside the tube is higher than in the bulk, the higher energy states are less occupied inside the tube than in the bulk. Therefore, excess chemical potential of the water inside the tube is lower than in the bulk and water enters to wet the tube. Mashl et al.⁹ report,

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in their simulations of water at room temperature, of ice-like hexagonal structures at a critical nanotube diameter and that in its ordered state water forms a distinctive hydrogen bonding network with a mobility that is a small fraction of that of bulk water. Noon et al.¹⁰ also show helical ice sheets in physiological conditions in carbon nanotubes. Molten potassium iodide too spontaneously enters the tube because inside the nanotube potassium iodide forms a stable crystal-like structure, thus lowering the energy.¹¹

Methods. Simulations were performed by GROMACS¹⁸ at a constant pressure of 1 bar and a constant temperature of 300 K. The system consisted of the carbon nanotube, water, and ions, and in some cases a slab and functional groups. The slab consisted of neutral atoms that mimic the interior of a hydrophobic phospholipid bilayer. The box size varied from 33 to 75 Å depending on the length and diameter of the tube and was at least twice as long as the tube length. The tube was fixed at the center of the box when there was no slab but had limited freedom of motion when inserted into a slab that was held stationary. A periodic boundary condition was applied in all three directions. The parameters for Lennard-Jones potentials and bonded interaction were taken from GROMOS 96 force field with a carbon-carbon bond length of 1.42 Å. Values for the Lennard-Jones interaction parameters for the nanotube (“C”), and water oxygen (“O”) were $\sigma_{CC} = 3.36$ Å, $\epsilon_{CC} = 0.0969$ kcal/mol; $\sigma_{OC} = 3.23$ Å, $\epsilon_{OC} = 0.129$ kcal/mol and were based on a cutoff of 15 Å. Bulk SPC/E water, having atomic charges of -0.8476 e and 0.4238 e on oxygen and hydrogen, respectively, was equilibrated (300 K) and used to fill the nanotube interior. Electrostatic interactions used the particle-mesh Ewald method with a 10-Å real-space cutoff, a 1.5-Å reciprocal space gridding, and splines of order 4 with a 10^{-5} tolerance. The SETTLE algorithm was used to constrain the geometry of the water molecules. Depending on the box size, 1033 to 2970 water molecules were used to have a constant density of 1 g/cm³. Concentrations of KCl varied from 1 to 1.85 M. The slab consisted of pseudo atoms with the same LJ parameters as that of a lipid bilayer. The partial charges for NH₃⁺ and COO⁻ were taken from the side groups of lysine and glutamic acid respectively in the GROMACS amino acid database. The simulation time varied between 2 and 7 ns and a time step of 2 fs was used in a leapfrog scheme.

Simulations and Results. Even though both water and molten ions seem to enter the tube spontaneously, when both ions and water molecules are involved the situation could be more complex because of the possible interplay between hydrophilic interactions involving the ions and water and the hydrophobic interactions involving the water and the carbon nanotube. We performed four sets of simulations: (i) Carbon nanotubes fixed in the center of a box in a solution of KCl, (ii) tubes fixed in water with artificial charges at the ends, (iii) asymmetrically functionalized tube in a pseudo bilayer, (iv) symmetrically functionalized tube in a pseudo bilayer.

(i) *Unmodified Tubes in KCl Solution:* We tested the ion occupancy inside uncapped carbon nanotubes of various

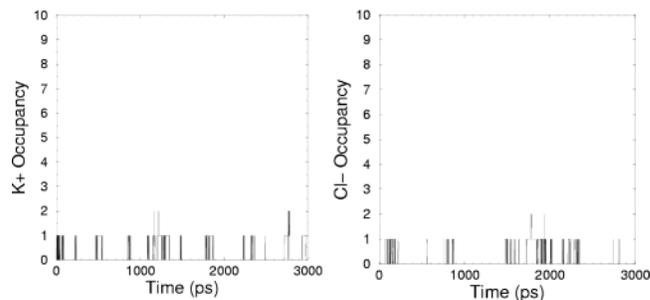


Figure 1. Very low ion occupancy in a (16,16) carbon nanotube (13.4 Å long, 21.696 Å diameter) fixed in the center of the box with a solution of 1.85 M KCl. There is neither an external electric field nor partial charges on the rim.

diameters ranging from (6,6) to (16,16) tubes in a solution of 1.85 M KCl. The tubes were fixed in the box center and were of length 13.4 Å. For a simulation with a tube of 21.7 Å diameter, the box had 925 water molecules and 40 potassium and chloride ions each. Initially the tube had 7 potassium and 6 chloride ions. Over the course of 3 ns, the ion occupancy was observed to be largely 0 or 1 as shown in Figure 1. The ions enter the tube from either ends but they do not travel across the length of the tube.

To find the energy barrier of ion permeation, we performed a molecular dynamics calculation of the free energy of solvation of an ion in the bulk and that inside a carbon nanotube by the slow growth method. The free energy of solvation is calculated by a numerical thermodynamic integration

$$\Delta G = \int_0^1 \frac{\partial H}{\partial \lambda} d\lambda$$

where H is the Hamiltonian and λ is the reaction coordinate representing the magnitude of the partial charge on the ion. As the reaction coordinate λ varied from 0 to 1 in a time of 100 ps, the force field parameters were interpolated linearly to transform the water into an ion. The ion was restrained to the center of mass of the tube by a harmonic potential of width k varying from 1000 to 5000 N/m for the solvation inside the bulk. No external electric field was applied here.

We calculated the free energies for an unmodified (8,8) 27 Å long carbon nanotube, with a diameter of 10.38 Å to compare our results with that of ion channels of similar diameter. The electrostatic calculations were performed by a coulombic cut off scheme. A sufficiently large cut off (20 Å) was used, and it was observed that the free energies obtained did not change much with the value of k . The relative free energy barrier of 18 kcal/mol was obtained with respect to that of an ion in the bulk restrained to the center of the box with the same harmonic potential. Calculations repeated with different force constants, and simulation times did not show any significant deviation from the result. The value of the energy barrier obtained in the simulation for an anion is of the same order as that of ion channels of similar diameter.¹² The activation energy barrier for entry of ions is caused by the fact that water molecules being immobilized inside the tube, which is in a relatively stable state with its

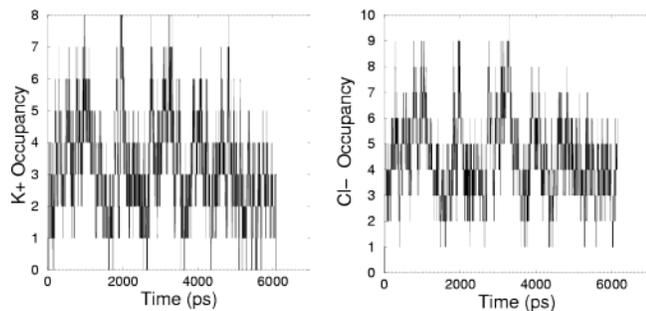


Figure 2. Ion occupancy in a (16,16) carbon nanotube (13.4 Å long, 21.696 Å diameter) fixed in a solution of 1.85 M KCl with external electric field of $E = 0.015$ V/nm and partial charges of ± 0.38 e on the rim atoms such that the dipole is oriented along the direction of the field.

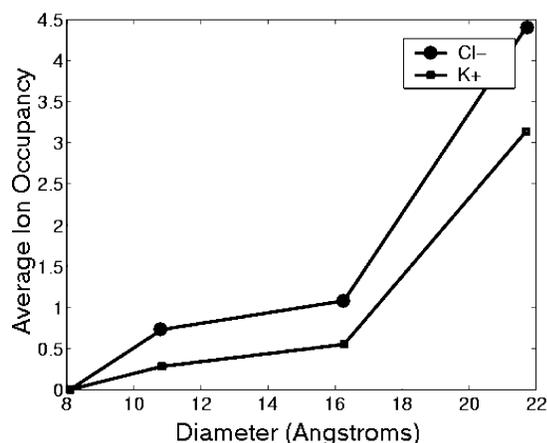


Figure 3. Variation of average ion occupancy with diameter in CNT (13.4 Å long) fixed in 1.85 M KCl with an external applied electric field of 0.015 V/nm. Partial charges of ± 0.38 e are added on the rim atoms. The chloride ion occupancy is observed to be higher than the potassium ion occupancy.

hydrogen bonded network, would require considerable energy to reorient them around the ion as they do in the bulk. This additional energy can be provided by an external field or presence of charged atoms on the nanotube.

(ii) *(16,16) Tubes Fixed in Water with Charges on the Ends.* To increase the occupancy of ions in the tube, partial charges of ± 0.38 e were placed at atoms on the rim of the tube to create a dipole—the positive charges being on the top rim and the negative charges on the bottom rim. Nonequilibrium molecular dynamics simulations were done with the tube fixed in the center of a box of length 33 Å and an applied external electric field of 0.015 V/nm, which is of comparable order to that of some ion channel membrane potentials, along the axial direction to mimic the membrane potential. It was observed that the ion occupancy is much higher (See Figure 2). Figure 3 shows how the ion occupancy varies with the diameter of the tube. An interesting observation is the fact that the average occupancy of chloride ions is higher than that of the potassium ions with a ratio of 3:2. This could be due to difference in water structure around the two ions as well as the van der Waals interaction between the ions and the nanotube. The free energy of solvation of K⁺ ions in the bulk is -84 kcal/mol and that of Cl⁻ is -71.4

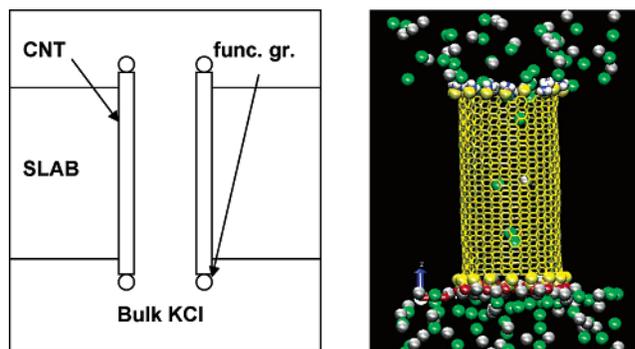


Figure 4. Schematic (left) and visualization (right) of a functionalized carbon nanotube in a bath of 1.5 M KCl. $\text{CH}_2\text{-NH}_3^+$ is attached one per carbon ring to the top and $\text{CH}_2\text{-COO}^-$ is attached at the bottom. The tube is inserted in a slab (not shown). Chloride ions are shown in darker shade. Water molecules are also not shown. Chloride occupancy is higher than potassium. A buildup of potassium ions near the COO^- is also observed.

kcal/mol.¹³ The occupancy of the Cl⁻ is higher in the tube than the K⁺ probably because the solvation of K⁺ is more favorable in the bulk.

(iii) *Asymmetrically Functionalized (16,16) Tubes in a Pseudo Bilayer.* Even though an electric field alone would drive ions into the tube, the partial charge on the rim increases the sensitivity and could be used to control the type and rate of ionic flow into the tube. This principle is the basis of tube end functionalization. Once partial charges were shown to increase occupancy, the next step was to replace them with functional groups. Both outer wall and end wall chemical functionalization attachments of nanotubes have been successfully realized in recent experiments.^{14–16} Functional group attachment can increase solubility and alter nanotube properties among other things.¹⁷ In our simulations, an asymmetric functionalization of carboxylate and amino residues was used in place of the partial charges to mimic a real ion channel at either end, respectively. Even though functionalizing the inner wall would mimic some ion channels more closely, end wall functionalization is more feasible than inner wall functionalization for tubes of small diameter.¹⁵ The functionalized carbon nanotube was then placed in a membrane-mimic with properties similar to those of a lipid bilayer with a surrounding bath of 1.5 M KCl solution (See Figure 4). An electric field of 0.15 V/nm was used to drive the ions through the tubes, and the trajectories of K⁺ and Cl⁻ ions are shown in Figure 5. Over the course of 2 ns of simulation time, the chloride current was found to be much higher than potassium ion current because K⁺ ions are “bound” electrostatically to the COO^- groups at the mouth causing an energy barrier thereby reducing the K⁺ occupancy in the tube. Thus this decorated nanotube is an example of one possible nanotube functionalization that can lead to a modulation of the ionic current via ion selectivity.

Free energy calculations were also performed for a (16,16) tube fixed in a slab for the entry of chloride ions to investigate the effect of chemical functionalization. An unmodified tube has a free energy of solvation of +3 kJ/mol, compared with that of the bulk, and is unfavorable. In the presence of polar functional groups, the free energy of

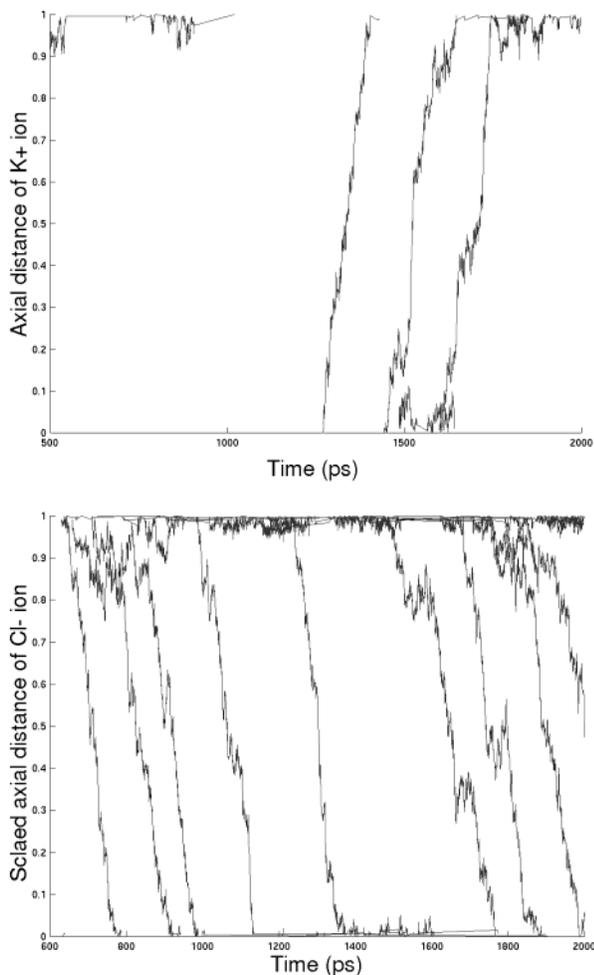


Figure 5. Positions of individual ions (K^+ on the top and Cl^- on the bottom) inside a end wall functionalized nanotube along the nanotube axis in a (16,16) tube fixed in a slab in a solution of 1.5 M KCl. The axial distance is scaled with a unit of 1 being the length of the tube. K^+ enters from the bottom and Cl^- enters from the top. There is an external electric field of 0.15 V/nm. The rate of chloride ion passage is higher than the K^+ ion passage, indicating a selectivity of anions over cations.

solvation of a Cl^- ion inside the tube is -9 kJ/mol with respect to the bulk. In the mouth region, because of the presence of an NH_3^+ group, the free energy of solvation is highly favorable compared to the bulk (-1209 kJ/mol), which can act as a barrier for selectivity of oppositely charged ions in the presence of an electric field.

(iv) *Symmetrically Functionalized (16,16) Tube in a Pseudobilayer.* Symmetric functionalization can be used to selectively transport one species. Figure 6 shows the trajectories of ions in a symmetrically functionalized (16,16) tube with COO^- on both ends and in the middle with protonated carbon atoms. The chloride occupancy is much larger compared to that of potassium.

Conclusions. The possibility of incorporating the functionality of ion channels into carbon nanotubes has been demonstrated even though naturally occurring carbon nanotubes have low ion occupancy, which is a proof of concept for modeling carbon nanotubes as “ion channels”. Single walled CNTs have delocalized π -electrons that exhibit

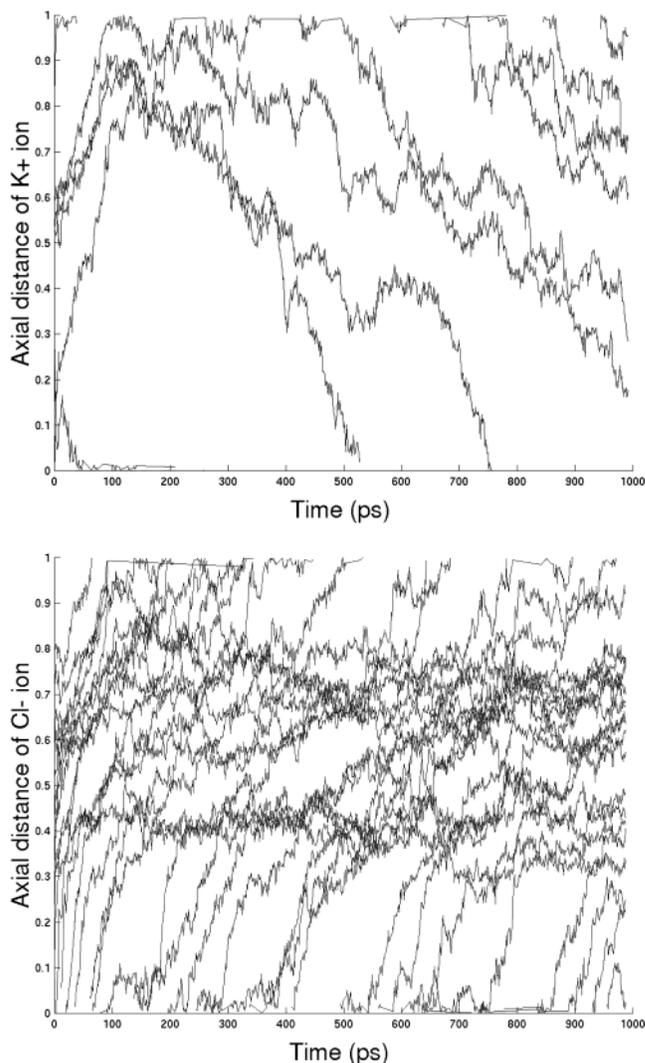


Figure 6. K^+ trajectory (top) and right Cl^- trajectory (bottom) in a symmetrically functionalized tube with COO^- groups on both ends and protonated carbon atoms in the center of the (16,16) tube. The axial distance is scaled such that the length of the tube corresponds to a unit of 1. The chloride current is much higher than that of potassium current wherein there is asymmetric functionalization because K^+ ions are electrostatically bound to the COO^- group at the mouth of the tube. The chloride ion also has to clear a barrier created by protonated carbon atoms in the center to reach the other end.

semiconducting or metallic properties. The presence of polar water molecules, cation- π effect due to the ions, or an external electric field can alter the electronic structure of CNT and hence cause field-induced polarization. Presence of functional groups also could alter the electronic structure of the carbon nanotube. A coupled density functional theory–molecular dynamics approach resulting in an improved force field could take into account such interactions in future studies.

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References

- (1) Bayley, H.; Cremer, P. S. *Nature* **2001**, *413*, 226.
- (2) Woodhouse G.; King, L.; Wieczorek, L.; Osman, P.; Cornell, B. *J. Mol. Recognit.* **1999**, *12*, 328.
- (3) Kang, Mun-Sik; Martin, C. R. *Langmuir* **2002**, *17*, 2753.
- (4) Li, J.; Stein, D.; McMullan, C.; Branton, D.; Aziz, M. J.; Golovchenko, J. A. *Nature* **2001**, *412*, 166.
- (5) Martin, C. R.; Nishizawa, M.; Jirage, K.; Kang, M. *J. Phys. Chem. B* **2001**, *105*, 1925.
- (6) Sun, L.; Crooks, R. M. *J. Am. Chem. Soc.* **2000**, *122*, 12340.
- (7) Hummer G.; Rasaiah, J. C.; Noworyta, J. P. *Nature* **2001**, *414*, 188.
- (8) Miller, S. A.; Martin, C. R. *J. Electroanal. Chem.* **2002**, *522*, 66.
- (9) Mashl, R. J.; Joseph, S.; Aluru, N. R.; Jakobsson, E. *Nano Lett.* **2003**, *3*, 589–592.
- (10) Noon, W. H.; Ausmann, K. D.; Smalley, R. E. *Chem Phys. Lett.* **2002**, *355*, 445.
- (11) Wilson, M.; Madden, P. A. *J. Am. Chem. Soc.* **2001**, *123*, 2101.
- (12) Aqvist, J.; Luzhkov, V. *Nature* **2000**, *404*, 881.
- (13) See-Wing, Chiu (private communication).
- (14) Chen, R. J.; Zhang, Y.; Wang, D.; Dai, H. *J. Am. Chem. Soc.* **2001**, *123*, 3838.
- (15) Chen, Y.; Haddon, R. C.; Fang, S.; Rao, A. M.; Eklund, P. C.; Lee, W. H.; Dickey, E. C.; Grulke, E. A.; Pendergrass, J. C.; Chavan, A.; Haley, B. E.; Smalley, R. E. *J. Mater. Res.* **1998**, *13*, 2423.
- (16) Halicoglu, T.; Jaffe, R. L. *Nano Lett.* **2002**, *2*, 573.
- (17) Sinnott, S. B. *J. Nanosci. Nanotech.* **2002**, *2*, 113.
- (18) Lindahl, E.; Hess, B.; van der Spoel, D. *J. Mol. Model.* **2001**, *7*, 306.

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