Mechanism of How Salt-Gradient-Induced Charges Affect the Translocation of DNA Molecules through a Nanopore

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Submitted February 18, 2013, and Accepted for publication is May 20, 2013.

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Supporting Material

DNA Translocation without Pore Wall Surface Charges

Previous studies showed that the negative nanopore wall surface charges were able to decrease the DNA translocation speed significantly through the induced cationic EOF within the pore [1,2,3]. That is, contribution to the tuning of DNA velocity by item (2) shown in Fig.1 is prominent. Nonetheless, in this work the regulation of DNA translocation by salt-gradient-induced EOF is the central topic as depicted by item (3) of Fig.1. Therefore, first we neglect the influence of nanopore wall surface charges so that the variation of polymer motion by salt-gradient effect can be singled out. Mathematically, this is done by manually setting $\sigma_w = 0$ in Eq.10 and then solving those coupled equations.

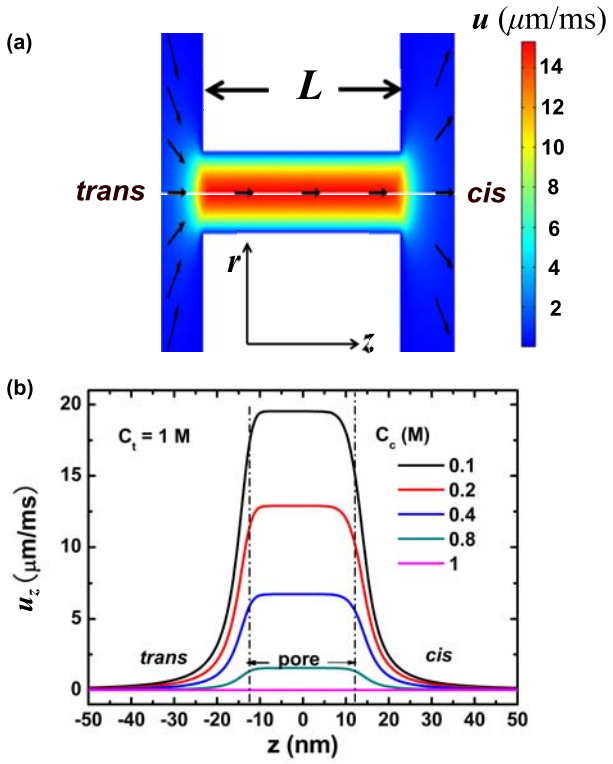

Fig.S1 (a) The 2-dimensional fluid velocity field $\boldsymbol{u}$ in the open-pore system under C_c/C_t = 0.2 M / 1 M. Here D = 8 nm while other parameters remain the same as in Fig.2, and the influence of nanopore wall surface charges has been neglected. (b) z-component fluid velocity u_z along nanopore axial direction in the open-pore under various salt gradients: C_t is fixed at 1 M, while C_c is tuned from 1 M (magenta line) to 0.8 M (olive line) to 0.4 M (blue line) to 0.2 M (red line) and to 0.1 M (black line).

The calculated velocity field $\boldsymbol{u}(r,z)$ of EOF across the open pore under salt gradient C_c/C_t = 0.2 M/1.0 M is plotted in Fig.S1a. The variation of fluid velocity field with the imposed salt gradient is further demonstrated in Fig.S1b, where z-component fluid velocity along nanopore axial direction $u_z(z)$ is plotted as a function of the salt gradient C_c/C_t. It reveals that the average speed of EOF is about several tens of μm/ms within the nanopore. On the other hand, Fig.S2 shows the DNA translocation velocity $\boldsymbol{u}_{\mathrm{DNA}}$ under *homogeneous* salt concentration where the contribution

by wall surface charges is also neglected. The molecule velocity is about hundreds of μm/ms. Thus we conclude that velocity of EOF in the open nanopore generated by the imposed salt gradient can reach 10% of that of DNA in the nanopore in the absence of salt gradient. The fact indicates that EOF caused by item (3) will retard the DNA penetrating motion obviously.

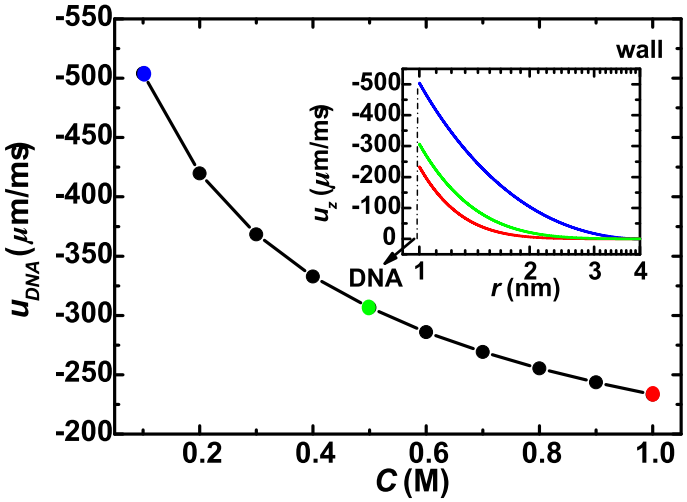

Fig.S2: DNA translocation velocity u_{DNA} as a function of *homogeneous* salt concentration $C_t = C_c = C$. Here nanopore wall surface charge density $\sigma_w = 0$. Inset plots distribution of fluid velocity $u_z(r)$ along nanopore radial direction under various salt concentration $C = 0.1$ M (blue line), 0.5 M (green line) and 1.0 M (red line).

This is quantitatively verified by Fig.S3 where the DNA translocation velocity u_z is plotted as a function of the imposed salt gradient. Comparing to DNA speed under homogenous salt concentration shown in Fig.S2, there can be up to 3% of u_{DNA} reduction (the point where $\bar{C} = 0.6$ M, $C_c = 0.2$ M and $C_t = 1$ M) when salt gradient is introduced. However, there are two obvious disagreements when compared with the experimental data [4]:

1) The calculated u_{DNA} is one order larger than that observed experimentally.

2) u_{DNA} shows increasing behavior under larger salt gradient ($C_c/C_t \rightarrow 0$), which is in contrary to the experimental trend (Fig.9, Supplementary Information of Ref.[4]).

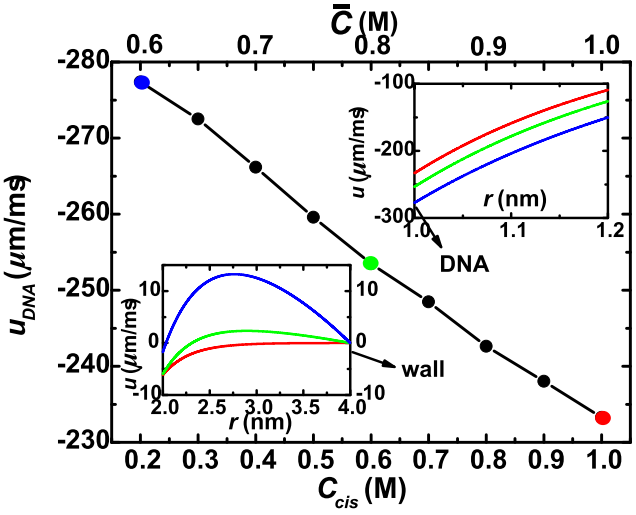

Fig.S3: DNA translocation velocity u_{DNA} as a function of salt gradient C_c /C_t. Here C_t is fixed at 1 M, while C_c varies from 1 M to 0.2 M. The influence of nanopore wall surface charges has been neglected. The upper axis plots the approximated average salt concentration $C = C_t+C_c/2$ within nanopore. Insets demonstrate distribution of fluid velocity u_z along the pore radial direction r: the lower left plots $u_z(r)$ near the surface of pore wall (D = 8 nm); the upper right plots that near the polynucleotide surface (R_{DNA} = 1 nm). Blue line stands for C_c = 0.2 M, green line for C_c = 0.6 M and red line for C_c = 1.0 M.

Both of the quantitative disagreements, the overestimated DNA translocation speed and the increasing molecule translocation speed with salt gradient, can be attributed to the negligence of SiN wall surface charges. The first: according to our previous study (Fig.3, Ref.3) without considering the retarding effect by σ_w-induced EOF, DNA speed u_{DNA} would be 1 or 2 orders of magnitude larger than the real case. The second: as shown in Fig.S1b and Fig.S2, for decreasing salt concentration C_c in the *cis* chamber while fixed C_t in the *trans* chamber, the DNA velocity keeps raising with the decreasing average salt concentration C; velocity of cationic EOF is also increasing since the salt gradient is increasing; however the increasing magnitude of the former is one order larger than that of latter; consequently, the retarding effect by the latter is overwhelmed. Here we remind that the growing of DNA velocity under smaller salt concentration is caused by the smaller net charge concentration in the nanopore and thus smaller dragging force by EOF (Fig.5, Ref.3).

Self-adapted Modulation of hydrodynamic Pressure

$\frac{\partial u_z}{\partial z} = 0$ in Eq.(6) is a requirement of liquid conservation law. It implies that the total driving force on the solvent is invariant along the nanopore axis. The derivation is as follows:

1) Since $\frac{\partial u_z}{\partial z} = 0$, the first term of Eq.(6) can be treated as: $\frac{\partial}{\partial z}\left\{\eta \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)\right\} = \frac{\partial}{\partial z}\left\{\frac{\partial P}{\partial z} - E_z\rho_e\right\} = 0$. That is, $\left(\frac{\partial P}{\partial z} - E_z\rho_e\right)$ is independent on z.
2) Then, we perform integration $\int_{-L/2}^{L/2} dz$ on $\eta \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right) = \frac{\partial P}{\partial z} - E_z\rho_e$ along the pore axis: and arrive at

$$\eta \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right) = P|_{z=-L/2}^{z=L/2} - \frac{\int_{-L/2}^{L/2} dz E_z \rho_e}{L}.$$

The physical mechanism here is the self-adapted modulation of the hydrodynamic pressure P. $\frac{\partial u_z}{\partial z} = 0$ is a requirement of the conservation law. Physically, it indicates that the z-component fluid velocity does not change along the nanopore direction. Thus, the total driving force $\left(\frac{\partial P}{\partial z} - E_z\rho_e\right)$ should be constant along the pore axis. Yet on the other hand, the ionic charge $\rho_e(z)$ induced electrical driving force $E_z\rho_e(z)$ does vary along the nanopore axis. In order to keep the total driving force invariant along the pore axis, the hydrodynamic pressure $p(z)$ performs a self-adapted change. Below we give the multiphysical calculation of hydrodynamic pressure along the nanopore axis:

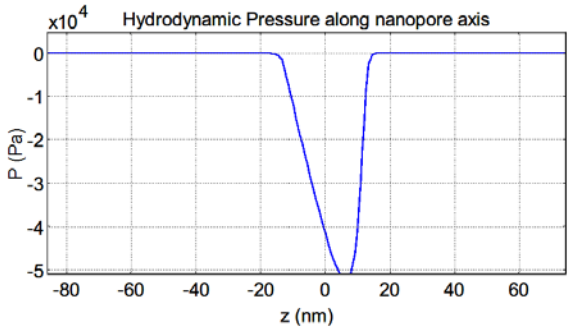

Fig.S4: the distribution of hydrodynamic pressure P along the nanopore axis. The nanopore sits from $z = -L/2 = -12.5$ nm to $z = L/2 = 12.5$ nm. The concentrations of KCl are $C_c = 100$ mM in the *cis* chamber while $C_t = 1$ M in the *trans* chamber.

The above figure indicates that the hydrodynamic pressure does perform a self-adapted change along the nanopore axis so that the total driving force on the solvent keeps invariant.

DNA Speed under Slippery Nanopore Wall

We have performed the study of DNA translocation speed under slip boundary condition. Mathematically, it is implemented by setting the second boundary condition of Eq.7 in the main context as follows:

$$u_z|_{r=R} = -b\left.\frac{\partial u_z}{\partial r}\right|_{r=R}$$

where b is slip length. $b \approx 4$ nm is suggested by Hatlo *et al*, and is used in our numerical simulation (Here we remind that there lacks a minus sign in Eq.(8) of Hatlo *et al*'s publication).

The calculated distribution of fluid velocity u_z along the nanopore radial direction r is plotted as follows:

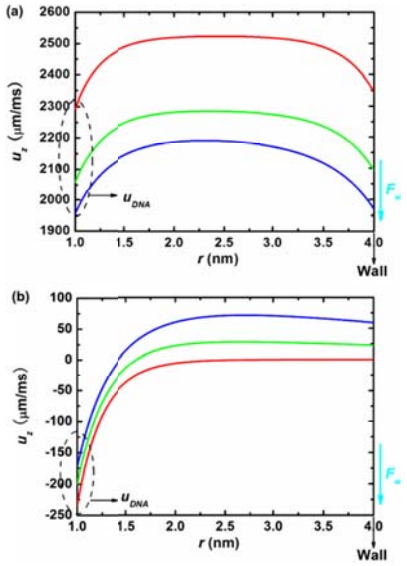

Fig.S5: Fluid velocity $u_z(r)$ along nanopore radial direction under various salt gradient $C_c/C_t = 0.2$ (blue line), 0.5 (green line) and 1.0 (red line). Here C_t is fixed at 1 M, and the pore wall surface charge density $\sigma_w = -49$ C/m^2 for (a) while $\sigma_w = 0$ for (b), and other parameters are the same as Fig.5 in the main context. The only difference between this figure and Fig.5 is that here slip boundary condition has been used for the nanopore wall where the slip length $b = 4$ nm [5]. The cyan arrow indicates the drag force $\boldsymbol{F}_w$ exerted by the pore wall on the solvent.

The difference between (a) and (b) is that for (a) the pore wall surface charges have been considered $\sigma_w = -49$ C/m^2, while for (b) $\sigma_w = 0$. The associated physical pictures are that for (a) the σ_w-induced cationic electroosmotic flow (EOF) has been considered while for (b) it is neglected. $\boldsymbol{F}_d$ is the hydrodynamic drag force on the translocating DNA molecule exerted by EOF, which is in the opposite direction ($+z$) to the electrical driving force $\boldsymbol{F}_e$ on anionic DNA molecule ($-z$). Thus, we expect a stronger $\boldsymbol{F}_d$ when $\sigma_w = -49$ C/m^2 in (a) than $\sigma_w = 0$ in (b). In fact, $\boldsymbol{F}_d$ is so strong that DNA velocity u_{DNA} turns positive from (b) to (a).

u_z at $r = 1$ nm is the velocity of the DNA molecule, while u_z at $r = 4$ nm is the solvent velocity near the surface of pore wall. Fig.S5a indicates that by using slippery nanopore wall boundary, there have been several profound changes compared to the situation under non-slip pore wall condition (Fig.5 in the main context): first, DNA translocation velocities u_{DNA} turn *positive* which should be interpreted as that DNA cannot get through the nanopore; second, the magnitudes of u_{DNA} are about 50 times larger than those under no-slip pore-wall boundary condition; third, the larger the salt gradient is, the smaller the DNA translocation velocity becomes (from red line to green line).

The reversed DNA translocation under slip-flow nanopore wall can be attributed to the much attenuated drag force $\boldsymbol{F}_w$ by the pore wall. Due to the excessive potassium ions in the solution, there has been an electrical driving force which points from *trans* chamber to the *cis* one exerting on the solvent. Consequently, EOF is inclined to flow from –z to +z direction as shown in the above figure and Fig.5 in the main context. The nanopore wall will put drag force $\boldsymbol{F}_w$ in the opposite direction as shown by the cyan arrow in the figure. The more slippery the nanopore wall

is, the smaller the drag force $\boldsymbol{F}_w$ becomes. As a result, the solvent moves faster towards the nanopore entrance and thus puts a stronger hydrodynamic drag force $\boldsymbol{F}_d$ on the target DNA molecule as seen in the following figure. Given sufficient slippery nanopore wall, the drag force by the nanopore wall becomes negligible, and thus the cationic EOF moves even faster from –z to +z direction, which reverses the anionic DNA translocation motion: $b\uparrow$, $\rightarrow \boldsymbol{F}_w\downarrow$, $\rightarrow u_z\uparrow$, $\rightarrow \boldsymbol{F}_d\uparrow \rightarrow$ u_{DNA} reverses.

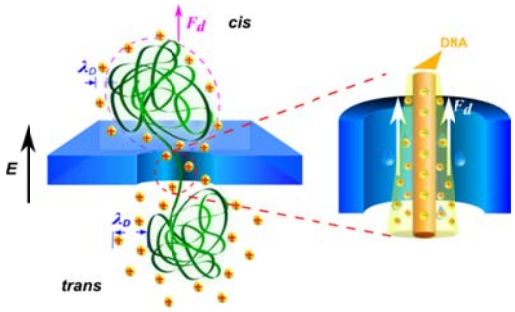

Fig.S6: Sketch for DNA translocation through the nanopore.

Fig.S5b shows that by neglecting the σ_w-induced EOF, the calculated DNA velocities under slippery boundary condition gets slowed down but not reversed compared with that shown in Fig.S3 in the **Supporting Material**. In other words, by using slippery boundary condition of nanopore wall and by assuming no pore wall surface charges σ_w=0, the calculation results also show accordance with the experiments.

Yet, based on the opposite assumptions, that one is the no-slip nanopore wall boundary condition and the other is the σ_w-induced EOF, our calculation in the main context shows better quantitative agreement with the experiments. Moreover, the two above assumptions are commonly used by the research community [2,3]. Thus we put the discussion in this supporting material to provide another potential explanation.

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