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Diffusion in Synthetic and Natural Membranes: Critical for Success

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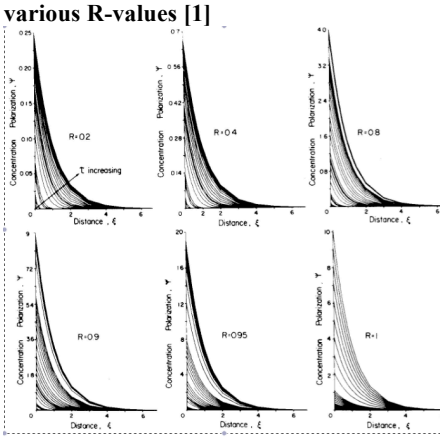
1. Introduction: Selective transport of species (solvents, ions, macromolecules such as proteins, DNA or RNA) across synthetic and natural membranes is critical for the success of pressure–driven synthetic membrane filtration processes and for the maintenance of life, respectively. We first present a brief historic view of the selective transport in these two very different systems, then, with three examples, analyze the similarities and differences of the role of diffusion.

For pressure–driven synthetic membrane filtration with processes such as reverse osmosis, ultrafiltration and microfiltration, concentration polarization (CP) and fouling can severely limit performance. Back-diffusion of solute away from the membrane plays an essential part in diminishing CP. This concentration polarization process, balancing convection to the membrane with back-diffusion, was first reported analytically in a ground breaking paper in the 1980s by Alan Michaels and his colleagues. The phenomenon was first measured by the Belfort [1] and Colton [3] groups for build-up of salt and proteins, respectively.

Fig. 1 Predictions from model of CP for various R-values [1]



Of the many transport channels that move solutes into and out of cells and the nucleus, the Nuclear Pore Complex (NPC) is the main mediator of exchange between the nucleus and the cytoplasm in all eukaryotic cells. As small molecules pass through the NPCs unchallenged, large molecules are excluded unless chaperoned across by transport factors collectively termed Karyopherins or Kaps. The translocation of the Kap/cargo protein complexes is affected by specific interactions with exposed tethered NSP1 (FG-Nups) molecules at the entrance to the nuclear pore. An exciting new result has been reported recently tracking the translocation of the Kap/cargo protein complexes using quantum dots [4]. We will also show that the classic diffusion equation describes the selective transport both in this system and in an artificial nanopore.

2. The Achilles of synthetic membrane filtration: Selective transport through a barrier, such as for a pressure-driven synthetic membrane, requires retention of retained solute on the up-stream side. The growth of concentration of the retained solute with time is termed “concentration polarization”. The transformed diffusion equation is given by:

$$\frac{\partial \psi}{\partial \tau} = \frac{\partial^2 \psi}{\partial \xi^2} + \frac{\partial \psi}{\partial \xi} \tag{1}$$

with the boundary conditions

$$\psi(\xi,0) = 0\ ,\ \psi(\infty,\tau) = 0 \ \text{ and } \ \frac{\partial \psi}{\partial \xi}_{\substack{\xi=0 \\ \tau=\tau}} + R\psi(0,\tau) = -R \tag{2a-c}$$

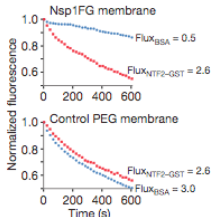
with the following transformations:

$$\tau = \frac{tV_{w0}^2}{D}\ ,\ \xi = \frac{xV_{w0}}{D},\ \psi(\xi,t) = c(x,t)/c_0 - 1 \tag{3a-c}$$

for constant suction velocity, V_{wo}. c_0 is the initial (t = 0) salt concentration, R the usual salt rejection of the membrane, and D the mutual diffusion coefficient of solute in water. This was solved using Laplace transform for three cases: when R<0.5, 0.5 ≤R<1, and R=1 (**Fig. 1**). Of special interest is the following case: R<0.5 and as $\tau \to \infty$ (get steady state solution) and is of practical import;

$$\psi_{R<1}(\xi,\infty) = \frac{R}{1-R}\exp(-\xi)$$

Fig. 2 Selective transport in AN [2]



3. Artificial nanopore (AN) of the NPC: To test whether a simple passageway and a lining of transport-factor-binding FG-Nups are sufficient for selective transport, Chait and co-workers [2] designed a functionalized membrane that incorporates these two elements. They demonstrate that this functionalized membrane behaves as a nanoselective filter, efficiently passing transport factors and transport-factor–cargo complexes that specifically bind FG-Nups, while significantly inhibiting the passage of proteins that do not. This inhibition is greatly enhanced when transport factor, Kap or NTF2, is present (**Fig. 2)**. The diffusivities are obtained from a fit of the diffusion equation.

4. Conclusions: Diffusion is an integral part of selectivity by reducing CP and plays a critical role on the artificial nanopore model of the NPC.

5. References

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