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July 27, 2017

Science

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# *Improving on aquaporins*

Membranes incorporating carbon nanotubes exhibit exceptional water transport rates

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Biological nanopores (1) can selectively and rapidly transport ions and molecules through membranes. For example, many biological ion channels conduct only one type of ion across the cell membrane, and they do so in response to external stimuli. Aquaporins transport water at astonishingly high rates (2, 3) and are efficient desalination units, in that they have excellent rejection of all ions, including protons. On page 792 of this issue, Tunuguntla et al. (4) present an artificial nanopore system that sustains water fluxes exceeding those of aquaporins, exhibits ionic selectivities comparable to those of biological ion channels, and consists of carbon nanotubes (CNTs) that are 10 nm long and merely 0.8 nm in diameter embedded in a lipid bilayer (4, 5). In CNTs with such small internal diameters, water molecules must move in a single-file configuration that is reminiscent of the arrangement of water molecules in aquaporins (see the figure). The higher water transport rate in CNTs was attributed to the absence of interactions between the water molecules and the atomically smooth CNT walls. By contrast, amino acids inside the aquaporin can donate or accept hydrogen bonds to water. Slower transport was attributed to the kinetics of hydrogen-bond formation and breakage. Tunuguntla et al. measured the energetic penalty for water molecules to enter the confined volume of a CNT at pH 7.6 and 3.0. The energy barrier was lower at the acidic pH, where protonated carboxyl moieties at the nanotube rim hindered hydrogen bonding with water. Similarly, addition of species that strengthen hydrogen bonding (kosmotropes) decreased water permeability severalfold, and adding species that weaken hydrogen bonding (chaotropes) caused a severalfold increase. These 0.8-nm CNTs also displayed water fluxes that are 10 times greater than those in 1.5-nm CNTs; simulations attributed this enhancement to fewer hydrogen bonds per water molecule in the narrower pores. The ionic selectivity of CNTs with openings as large as few nanometers was tested previously in pressure-driven filtration of saline solutions. These nanometer-wide tubes showed fast water fluxes that exceeded classical theory predictions by a few orders of magnitude (6, 7) but rejected ions only from diluted salt solutions (8). In contrast to larger CNTs, the subnanometer CNTs of the Tunuguntla et al. study exhibited a nearly 200 times greater preference for transporting cations versus anions at salinity comparable to seawater and at neutral pH. Although desalination has not been demonstrated directly (4), the nearly exclusive conduction of positively charged ions at high salinity is expected to translate into a much higher desalination ability compared to previous results (8). To compete with state-of-the-art reverse osmosis membranes, CNT systems have to overcome challenges similar to those faced by aquaporin-based membranes (9).

Technological hurdles include incorporation of CNTs in robust, defect-free matrices; packing pores at sufficiently high density ( $\sim 10^{11}$  per  $\text{cm}^2$ ) (10) to enable large water fluxes; and scale-up of membrane size to  $\text{m}^2$  areas. Although the path forward is still long, we are now a step closer. CNTs have also emerged as a promising template for creating biomimetic ion channels (5, 11). Appealing CNT structural features include their tunable diameter down to angstrom scale, an atomistically known structure with readily functionalizable groups at their opening, and the presence of a slippery hydrophobic core. In analogy with voltagegated channels, subnanometer CNTs in Tunuguntla et al. were shown to open and close in response to changes of transmembrane potential and, like a diode, to transport ions only in one direction (see the figure). Soon, narrow CNTs embedded in lipid bilayer could become the basis of artificial cells or key components of advanced, lipidbilayer-mediated interfaces between living organisms and artificial devices. Now that Tunuguntla et al. have demonstrated the possibility of beating the flow rates of the biological water channel, the next challenge is matching or surpassing their selectivity. Understanding what sets the limits of ion rejection will pave the way toward boosting selectivity of reverse osmosis membranes and helping humanity quench the “thirst” for fresh water. Future experiments and modeling with artificial channels made of CNTs, atomically thin two-dimensional materials, or other biomimetic systems are bound to address this exciting question (10).

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