DESALINATION

A new type of artificial water channels

Desalination membranes based on the water transport through transient channels shows a new way to achieve high permeability and selectivity

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Clean water is rapidly becoming the 21st century's most precious commodity. Four billion people experience water scarcity for at least one month every year[1], and more than 350,000 children die every year from preventable waterborn diseases[2]. The socioeconomic consequences of water shortages, frequent drought events, widespread water contamination, overpopulation and overconsumption, are a common root cause of regional conflicts and global instability. Water shortages are also changing our planet: for example, the Aral Sea, a giant inland lake in Central Asia, has virtually disappeared, largely due to agricultural water overuse.

Modern water-treatment technologies, in particular reverse osmosis (RO) desalination, have been augmenting the dwindling natural freshwater resources. Seminal innovations in RO desalination, such as the invention of polyamide thin film composite (TFC) membranes and energy-recovery devices, have realized significant gains in productivity and energy efficiency[3]. Yet challenges for water treatment technologies remain. Insufficient rejection by polyamide TFC membranes of hormones, pesticides, herbicides and other micropollutants, and some ions, such as boron, force commercial water installations to use extensive and costly pre- and post-treatment stages[4]. These problems reflect inherent materials limitations: the solution-diffusion mechanism that governs transport in these membranes results in strong permeability–selectivity trade-offs for ions and poor rejection of uncharged micropollutants[5]. A different type of membrane structure is needed to avoid these problems. Biology provides some clues in the form of natural water channels, aquaporins. These protein membranes have high water permeability and near-perfect selectivity because their hydrophobic inner channels squeeze water into a single file configuration that produces a remarkably high transport rate of ~1 H_2O ns^{-1}, with nearly perfect rejection of ions and protons.

Aquaporins have been incorporated into lipid or polymer membrane matrices to create robust and scalable biomimetics membranes[6], but that strategy comes with trade-offs associated with protein cost and stability. The rapidly developing field of artificial water channels[7] has been replacing aquaporins in these membranes with their synthetic analogs (Fig. 1). Stacking of individual subunits, such as G-quadruplexes or imidazole-quartets[8], in the membrane produces defined water channels that create similar one-dimensional water wires. Sub 1 nm diameter carbon nanotube porins (Fig. 1) — short pieces of carbon nanotubes inserted into lipid or polymer membranes — also create single-file water confinement and their smooth hydrophobic walls contribute to individual channel water permeability that is even higher than that of aquaporins[9].

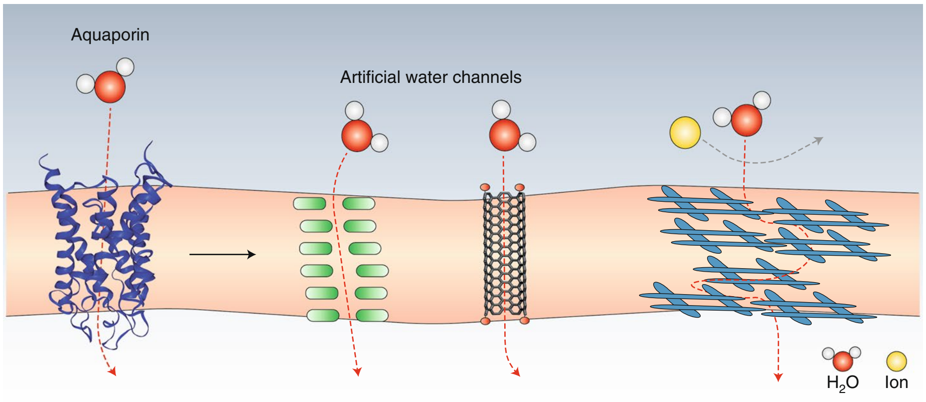

Fig. 1 | Mimicking nature's water membrane channels. Left: Aquaporin-4. Right: Imidazole quartets, represented as green stacking units; carbon nanotube porins; PAH, represented as purple cages, which cluster in the membrane to form a network of single-file water channels. Dashed red lines represent water path through each structure.

All these channels rely on permanent pores that provide the confinement required for fast transport at all times. In this issue Song et al. explore a bold new approach to engineer 'transient' confinement that creates fast water transport conditions only when several units cluster in the membrane[10]. They report a new kind of artificial water channel, peptide-appended hybrid[4]arene (PAH[4]). This molecule assembles into the lipid membrane, but, unlike other artificial water channels, it does not provide a straightforward pathway for water molecules to follow. Computer simulations revealed that the fastest way for water to cross the membrane is to follow the tortuous single-file water channels formed by contacts of the triPhe sidegroups of different PAH[4] molecules (Fig. 1). When Song et. al. introduced PAH[4] channels into the membranes of lipid vesicles, they first saw only modest unitary channel water permeability at low channel concentration. However, as they packed more PAH[4] units into the membrane, the unitary channel permeability spiked upwards, ultimately reaching values comparable to those of aquaporins. Remarkably, the PAH[4] association also produced very strong monovalent ion rejection, with the reported water/salt permselectivity of these channels reaching the value of 10^9, almost 4 orders of magnitude higher than that of modern TFC membranes.

With these performance numbers, Song et al. project that if a sufficiently high number of PAH[4] channels pack into the membrane, such an assembly will break the permeability–selectivity trade-off of the polyamide RO membranes. This possibility is exciting because, if such membranes can be manufactured at scale, they could further improve the quality of commercial desalination, and reduce overall capital and energy costs. First however, there are a number of hurdles to overcome. Very high PAH[4] loadings, which are expected to constrain the channel dynamics in the membrane, could potentially reduce the efficiency of ion blocking. In its current form, the PAH[4] membrane cannot withstand the pressures required for RO desalination; therefore, any practical applications would require putting it on a support and demonstrating that the resulting sandwich structure is robust and scalable. This support surface could potentially constrain the PAH[4] units' ability to associate and create water channels. Researchers still need to establish the efficiency of the micropollutant rejection in these channels. Nevertheless, the concept of engineering transient fast membrane water channels is exciting, as it considerably expands the range of possibilities for rational design of artificial water channels using synthetic chemistry. ❐

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