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Maria Di Vincenzo, Sophie Cerneaux, Istvan Kocsis, Mihail Barboiu. Artificial Water Channels - Toward Next-Generation Reverse Osmosis Membranes. Andreas Sapalidis. Membrane Desalination. From Nanoscale to Real World Applications, Routledge, 2020, 9780367030797. hal-03031112

**HAL Id: hal-03031112**

**<https://hal.science/hal-03031112v1>**

Submitted on 7 Dec 2020

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# Artificial Water Channels - toward next-generation Reverse Osmosis Membranes

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## Abstract

Natural systems have evolved for millions of years to transport metabolites across the cell membranes. Among them, Aquaporins (AQPs) are biological channels known for fast water transport with ion exclusion. AQPs can be mimicked using simpler artificial water channels-AWCs to explore the naturally evolved water transport in artificial systems and to assess the basis for biomimetic desalination processes. Selective water translocation has been shown to depend on water-wires spanning the pore that induce dipolar orientation. Toward this objective, AWCs combining a particularly broad range of self-assembling features: H-bonding, water recognition, hydrophobic effects, etc. This might play an important role in the ability to finely control the hydrophilic or hydrophobic the constitutional domains of the channel responsible, for selective recognition and high-water translocation, respectively. Then, densely packed AWCs incorporated within TFC polyamide membranes will lead to a greater fundamental understanding on how selective pores can be optimized at the nanoscale to facilitate ultrafast and highly selective transport of water for the treatment of saline feed streams. Future routes to robust desalination membranes including AWCs will solve pressing challenges, such as the stability, scalability and fabrication of membrane for water desalination, ultrapure water production and the storage of clean energy applications

## 1. Introduction

Universal access to safe drinking water is a fundamental need and human right. [1] Competition over increasingly contaminated freshwater during the last decades has made the availability of this resource a serious global challenge for the 21st century. Water scarcity and the problems associated with the lack of the clean water are well known. Because oceans hold 97.5% of the total water in our planet, [2] desalination is considered as one of important solutions to problem of freshwater scarcity, along with environmental remediation technologies and conservation policies. Currently, about 100 million m<sup>3</sup>/day of desalinated water is being produced, with an annual increase of more than 10% [3].

Treated as a lack of essential resource; it is becoming increasingly urgent in the context of simultaneous growth of population and economic activities. To address the increasing demand for water supply, several cutting-edge technologies have been explored during the last decades.[4] Current technologies are based on thermal processes (Multi Effect Desalination – MED or Multi Stage Flash- MSF) and membrane processes (pressure driven Reverse Osmosis-RO, voltage driven Electrodialysis-ED, Membrane Distillation-MD and Forward Osmosis-FO), with RO being the dominant process used for seawater or brackish water desalination. [5] Most of the reverse osmosis membranes relies on an anisotropic polymerized thin-film composite (TFC) polyamide-PA layer produced by interfacial polymerization on an underlying porous support layer, commercially available polysulfone, all integrated into spiral wound modules for fitting in pressure vessels [6]. Current Reverse Osmosis-RO desalination can produce water at < \$ 1/m<sup>3</sup>, which is about 5 times the cost of treated surface water. Energy use has dropped but is still about twice the thermodynamic minimum required when operating at 60% recovery, is around 1.2 kWh/m<sup>3</sup> and this value increase above 1.5 kWh/m<sup>3</sup> at 80% recovery. [6] Closed-circuit RO will soon allow operating at these high recovery regimes but with higher minimum energy requirements.

There is need for membrane innovation. The target of the future membrane is to increase both the water permeability while achieving high salt rejection. As pointed out recently, in many cases selectivity matters as much if not more than permeability. Efficiency may increase in the coming years by changing the process conditions, or by changing the membranes. [7]

The RO desalination, using thin-film composite-TFC membranes, has evolved over the years bringing down the costs significantly. [8] But, the desalination is still relatively expensive. More than half of a century has passed since the first functional RO membrane was designed. [9] Despite the fundamental knowledge, the material structure understanding is highly important for the up-scale from the laboratory films toward membranes, modules and further process designs. New materials bearing promise for higher productivity in desalination have been developed in recent years, consequentially leading to the emerging research fields of thin-film nanocomposites-TFN [10] and biomimetic membranes [11]. The prime objective nowadays is to explore the naturally evolved desalination pathways and assess the possibilities of using them as the basis for 'engineered' desalination processes of enhanced performance. Recent research projects propose to find an easily scalable Artificial Water Channels AWC approach that could be immediately applied to desalination systems to increase their energy efficiency. This chapter will describe the incipient context and evolution of Artificial Water channels field.

## **2. Natural water channels -the Aquaporins**

Natural systems have evolved for millions of years to accept functional biostructures to transport metabolites across the cell membranes. [12,13] Most of natural physiological processes depend on selective exchanges between a cell and its environment and water is playing an important role. [14] The natural water channels, the Aquaporins (AQP) are known for their fast transport rates ( $\sim 10^8$ - $10^9$  water molecules/s/channel) and the perfect rejection of

ions. [15-18] There are several features which are important for the AQPs efficient transport:

A) *Selectivity filter-SF*: AQPs present an hourglass SF structure offering size restriction of  $\sim 3$  Å and selectivity against cations, reinforced through electrostatic repulsion in the region known as the aromatic arginine (ar/R) constriction. Water in the SF is H-bonded to the protein and to other adjacent waters, allowing the passage of only a single file of molecules. The narrowest diameter of the pore itself is large enough for the water molecules to pass having themselves, but restrictive enough to block the passage of hydrated  $\text{Na}^+$  or  $\text{Mg}^{2+}$  cations, with hydration shells  $> 3$  Å.

B) *Dipolar orientation of water wires*: An interesting collective structuration of water is taking place in the SF, the interconnected water molecules adopting a dipolar orientation outward from the center of the pore. Although protons can pass from one water molecule to another through a Grotthuss mechanism, the inversion center breaks the water wire dipole and prohibits the proton translocation. More recent studies confirm the precise dynamic clustering of water molecules in SF is strongly favored *via* donor-acceptor H-bonding, excluding other small molecules, including the hydroxide anions, as they are not able to form a stable H-bonding within the SF. [18]

### **3. Bio-assisted AQP-embedded membranes**

Their high permeability/selectivity inspired the incorporation of AQPs into membranes for desalination. [19] To tackle this problem an innovative approach was developed by using an amphiphilic artificial matrix hosting the AQPs. In terms of flexibility and stability the block copolymers offered a good solution. The first work to successfully incorporate AQPs into polymer-based vesicles, called *polymersomes* and prove the functionality of the protein. [20] The vesicles were made of a block copolymer with poly-(2-methyloxazoline)-poly-dimethylsiloxane)-poly-(2-methyloxazoline) (PMOXA-PDMS-PMOXA) units and were used to host

AQPZ, a bacterial type protein from the Aquaporin family. Using the stopped flow setup, it has been shown that the otherwise impermeable polymersomes undergo an increase of up to 800 times in water permeability when the AQPs are incorporated. (Figure 1)

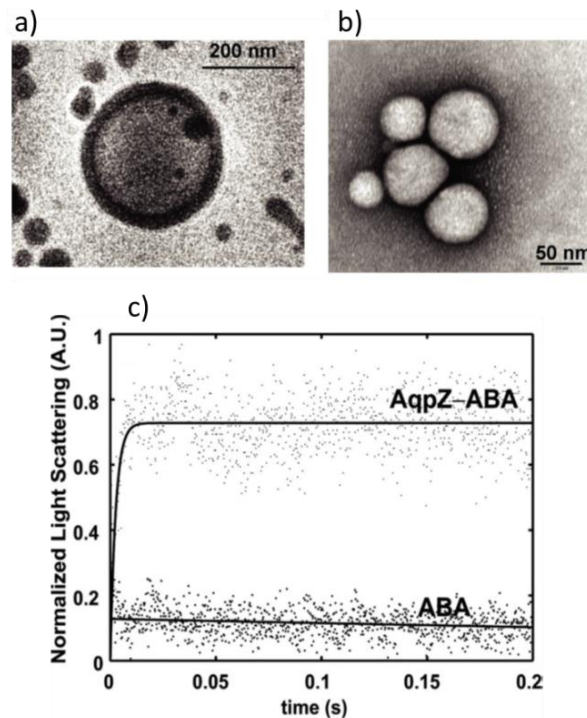


Figure 1. Cryogenic transmission electron micrograph of a polymer vesicle b) electron micrograph of a cluster of vesicles c) Stopped-flow light-scattering experiments; increase in relative light scattering with and without reconstituted AQPZ into the polymer at 5.5°C (image adapted with permission from reference [20]).

The activation energy for water to pass through the polymersomes was comparable for that obtained in the case of native protein. The typical RO membrane shows a productivity of 1  $\mu\text{m/s/bar}$ , while the modified AQPZ-ABA polymer not as a membrane is estimated for a productivity of 167  $\mu\text{m/s/bar}$ . Indeed an improvement in permeability of  $\sim 2$  orders of magnitude will not yield to a decrease in energy consumption by the same factor.

Due to its energy efficiency, membrane technologies start to adapt the AQP water purification technologies. [21,22] The high permeability / selectivity of AQPs inspired their incorporation into membranes for water-purification applications. This way, a new branch of membrane technologies for water purification called AQP bioassisted membranes was developed. As so it was an attractive option to combine the potential of the AQPs with the current existing

technology in membrane-based water filtration. As soon as the functions of the AQPs became known, it seems logical that in order to make use of its high selectivity and water transport, the protein need to be used in conjunction with a membrane barrier. Their large-scale applications it is of interest, owing to the high costs of the AQPs production, low stability and practical synthetic constraints of membrane fabrication processes. [21-23]

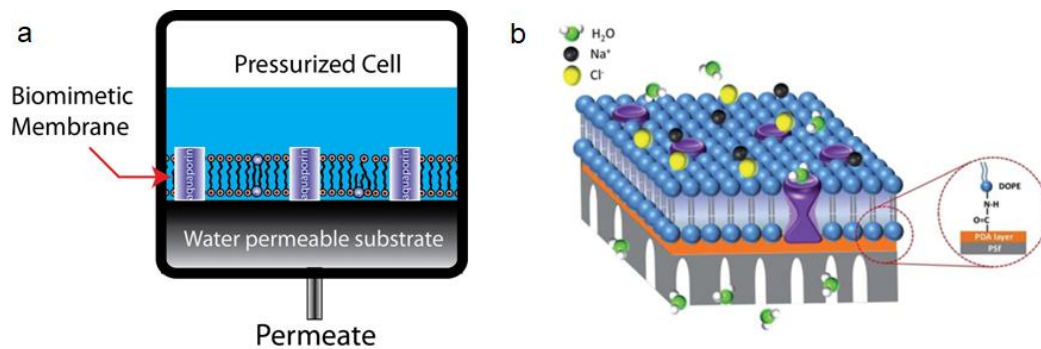


Figure 2. Schematic presentation of the structure of the AQPZ-incorporated SLB a) on charged NF membrane supports [24] and b) of a covalent amide bond 1,2-Dioleoyl-sn-glycero-3-phosphoethanolamine (DOPE) on top of a polydopamine (PDA) layer (orange), coated on a polyethersulfone (PSf) (gray) porous support. [25] (image adapted with permissions from references [24,25]).

In the simplest fashion these membranes consisted of three main components: i) AQP proteins ii) amphiphilic molecules as building blocks for the construction of protecting liposomes in which the AQPs are embedded and iii) a polymeric support for mechanical resistance. The choice for the amphiphilic molecules is argued for by the fact that the AQPs are transmembrane proteins and their native environment is partly the hydrophobic region of the lipids found in cellular membranes, meanwhile keeping the “mouths” of the protein exposed to the water from the cytosol. As such, a first reasonable strategy was to fabricate membranes having an active barrier a lipid bilayer containing AQP for the enhanced water permeation. It was shown showed that the supported lipid bilayer (SLBs) membranes are suitable impermeable platforms for incorporation of AQPs for water filtration. However, no reliable results have been obtained with such AQPs/ bilayers (Figure 2a). [24]

It was also demonstrated that the use of covalently fixed Supported Lipid Bilayers on a Psf support can yield functional membranes with higher stability. [25] This was achieved through the covalent attachment of SLBs to a polydopamine coated polyethersulfone. Using an amine functionalized lipid, the bottom half of the lipid bilayer is attached to the free carboxylic groups that can be found on the polydopamine. The covalent bonding between the bilayer and the support prevents the easy desorption of the lipid matrix, offering stability to the active layer of the membrane (Figure 2b). Nevertheless, the SLB is still prone to degradation when in contact with solutions containing detergents or high salinity, which can readily disrupt the lipid bilayer. The performances of these SLB membranes are remarkable in water filtration, although the reliability of these remains an issue for long term applications and upscaling.

In a compromise to obtain high stability and relatively good performance bio-assisted membranes a different synthetic strategy was applied by using a mix-matrix approach, when bilayer vesicles incorporating AQPs has been incorporated into traditional polyamide thin films [26]. This way the AQPs can maintain their efficiency having a basically native lipid membrane environment and at the same time, having minimal defect influences on the composite membrane in interaction with the polyamide matrix (Figure 3). The hybrid AQP-PA based membranes proved to be 40% permeable than their simple thin film composites (TFC) counterparts, meanwhile being stable for periods relevant for industrial applications at a lower energy consumption and operating cost. [27]

Most of the current designs for AQP membranes involve polymeric host materials, which can make it viable for upscaling and use in industry. [28] Active high flux AQP membranes, became the commercially available products. Production of AQP proteins is a feasible task since biological protocols and reagents are used, but the purification setup still represents an expensive and time-consuming obstacle. The question ‘how the natural proteins /artificial host matrix systems can be efficiently used together’ has been thus partially answered. [26-28]



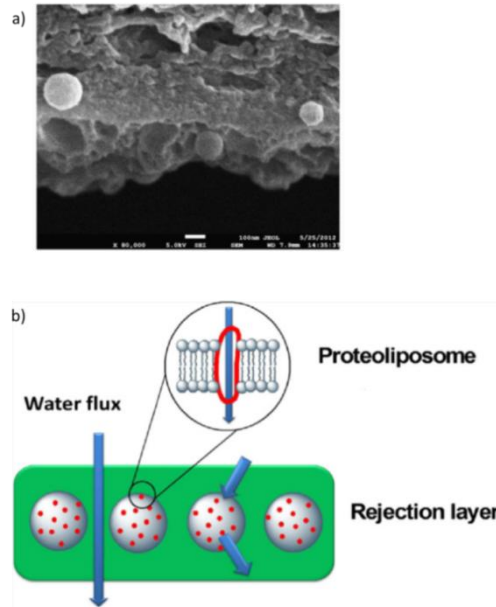


Figure 3. a) Scanning electron microscopy (SEM) image of the cross section of an AQPZ-thin film composite membrane b) Conceptual model of AQP proteoliposomes integrated into a polyamide matrix (image adapted with permissions from reference [26])

However, no clear strategies converge to the easy synthetic development of robust AQP *bio-assisted reverse osmosis (RO) or Forward osmosis (FO) membranes*, working at high pressure and high salt concentrations, incompatibles with biological AQPs. Most importantly, today not readily usable AQP-based membrane exists for desalination.

They are many challenges to use the AQP as selective transporters related to their:

- a) Long term stability when embedded in artificial membranes;
- b) Bio-stability and unconventional processing requirements: high pressure and salinity;
- c) Production - membrane proteins are challenging to mass produce;
- d) AQPs present an important flux, but not an acceptable permeability per active area, the selectivity is not reaching more than 97%, a critical problem for desalination.

A possible way forward is to replace AQPs with synthetic channels. Recent advancements have made it possible to synthesize artificial water channels-AWCs that feature efficient, yet selective transport of water based on size exclusion and H-bond clustering at the molecular level. [29] Another of the current disadvantages of biomimetic AQPs membranes is the low density of water channels per unit area of roughly 40 channels/ $\mu\text{m}^2$  [23].

#### **4. Why are Artificial Water Channels important?**

Biomimetics or biomimicry is the science behind mimicking the well-tuned natural processes. Looking to nature as a model system paves the way for new ideas in exploring sustainable water solutions. Nature should provide answers for efficient desalination. Despite the tremendous imagination of synthetic chemists to produce sophisticated architectures confining water clusters, most strategies to selectively transport water have been related to the use of natural Aquaporin as the selectivity components. A possible way forward is to replace AQPs with synthetic AWCs. Ion-rejecting, highly permeable artificial *biomimetic* channels may provide a route to producing highly efficient membranes for separations, particularly desalination. Solute-rejecting thin film composite reverse osmosis is currently the best available technology for desalination, but it suffers from high energy consumption. In practice, there is currently no economically viable RO membrane on the market! Therefore, there are incentives to further reduce cost and energy use for desalination as it becomes more widespread. Recent advancements have made it possible to synthesize AWCs that feature efficient transport of water. AWCs exhibit the following potential advantages:

- a) they are easily tunable and may be chemically optimized for desirable properties;
- b) they can be prepared on a large scale at low cost;
- c) Engineering processing without bio-related steps becomes simpler and more reproducible, they should be easily immobilized in membrane in a scalable manner;
- d) they should also be robust with a longer lifetime after incorporation into membranes.

Within this context, the next impact may be related to increase the incipient potential, imagining that high water conduction activity obtained *with* natural AQPs can be bio-mimicked using simpler compounds that can display functions *like* the natural ones, the *Artificial water channels-AWCs*, using synthetic biomimetic approaches. AWCs have been recently proposed as a biomimetic AQPs. [30,31] They are constructed from artificial

molecules defining a water-pore superstructure, surrounded by a hydrophobic exterior accommodating the membrane environment. [32-36] Despite the incipient efforts, only a few AWCs have been produced in attempts to attain the high-water permeability and significant ion rejection of AQPs. [34] Within this context, mimicking AQPs by using simple AWCs is an important endeavor from both a) the fundamental science perspective related to the deeper understanding of water structure and its transport function and applied science perspective as AWCs might have timely impact on increasing water filtration efficiency by using natural principles to change the desalination paradigms.

*Artificial ion-channels* [37-40] have been extensively developed for decades (thousands of papers in literature) with the hope to mimic the ionic conduction of natural proteins. [41,42] Amazingly, there was no systematic and little progress in the area of *Artificial water channels* before 2011. [29] It was shown that structuration of water clusters within the pores, effects on their stability, dynamic behaviors or selective translocation, once inserted in the bilayer membranes. These studies provide detailed experimental data correlated with extensive theoretical simulations on water transport with efficiency similar to that of natural channels.

## **5. Where are we now? Where are we going in this newborn field?**

The target of the future membrane is to increase both the water permeability by 3 to 5 folds of the currently best TFC membranes while achieving/maintaining 99,9% salt rejection. As pointed out recently in many cases selectivity matters as much if not more than permeability.

Next research might provide answers to essential question related to:

a) complicated interactional scenarios related to water transport through biomimetic pores

b) bio-inspired desalination with membranes that mimic mechanisms of natural desalinators.

We know that the AQPs are the representative proteins for the water transport across cell membrane, but their structures are tremendously complicated. Simpler architectures encapsulating water may provide excellent and valuable models for understanding/designing

novel biomimetic water channel systems. Although there is a rich inventory when it comes to molecular encapsulation of water, in most cases the host systems are highly polar which prohibits them to be used in conditions similar to the one offered by the membrane to AQPs. As so, the development of the AWCs is highly important. The first synthetic water transporting systems have been reported in 2011 [30] and the term of *Artificial water channels* has been coined practically one year later [31]. The common features of the AWCs are the presence of a central pore, which is a confining hydrophilic or hydrophobic region that allows the passage of water, and a hydrophobic shell that permits the insertion into the lipid membranes and subsequent analysis for water transport. There are main approaches towards designing these systems, when considering the structure of channels:

- *Single molecular channels*, as one molecular entity that can span the length of the bilayer;
- *Self-assembled supramolecular channels* that can self-assemble from multiple molecular components into architectures spanning the bilayer.
- *Nanochannels* related to Carbon Nanotubes and GO materials and membranes

**5.1. Single Molecular Channels.** The pillar[5]arenes, PAP1 are the first reported single molecular channels (Figure 4a) [43]. Intramolecular H-bonds between lateral hydrazide arms confer robustness, keeping the membrane spanning channels intact, when inserted into a lipid bilayer. PAP1 have a relatively low water transport rate: up to 40 molecules of water/s/channel. Like in AQPs, PAP1 display water selectivity against  $H^+$  and  $OH^-$  ions. The explanation for this is the impeded proton hopping through a broken, discontinuous water wire, while the cation transport can be attributed to carrier transport mechanism. Following up on these results a second generation of more hydrophobic pillar[5]arenes, PAP2 containing poly-Phe arms showed a osmotic water permeability of  $3.5 \cdot 10^8$  water/s/channel [44], being in the range of AQPs and CTNs. Nevertheless, PAP2 channels present a drawback when it comes to ionic selectivity.

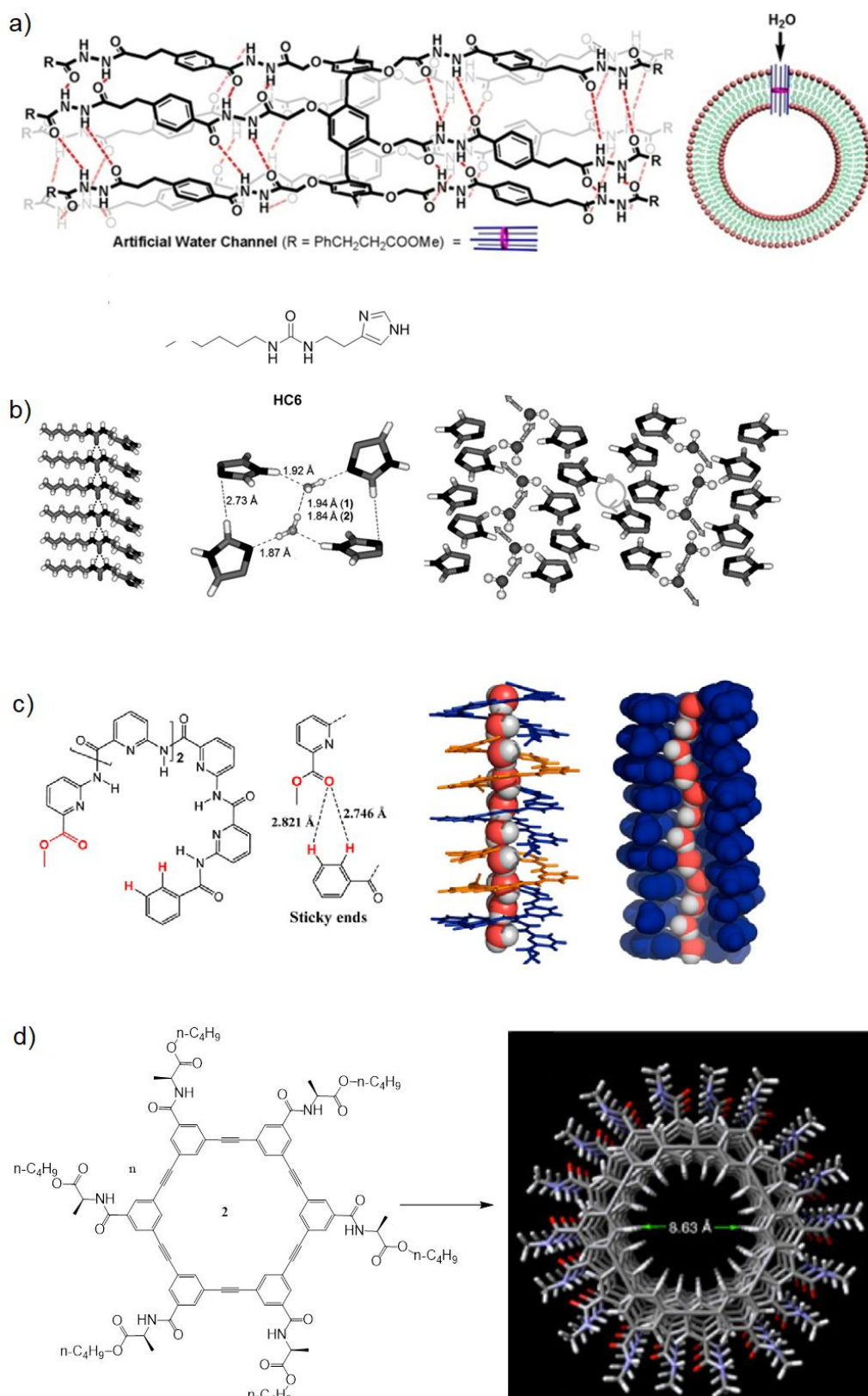


Figure 4. a) Single molecular PAP1 water channels [43]; b) Single crystal structure of hexyl-ureidoethylimidazole and its related urea H-bonding ribbons and of I-quartets that present d) dipolar orientation of water [34]; c) X-ray single crystal structure and d) representation of a single water file Aquafoldamers [48] d) Simulated structure of macrocyclic channels [49].  
(image adapted with permissions from reference [34,43,48,49])

Having an inner pore size of  $\sim 5$  Å, they allow the passage of cations according to their hydration energy. More interestingly, PAP2 channels may be packed in a hexagonal arrangement in 2D membranes, thus the fabrication of active thin layers is possible. [45-47]

**5.2. Self-assembled supramolecular channels.** The second category of AWCs use a non-covalent self-assembly strategy, that often confer the supramolecular channels properties that are not predictable and differ completely from that of their building blocks. Based on this concept it has been reported that AWCs based on alkylureido-imidazoles, can self-assembly in tubular imidazole I-quartet channels, mutually stabilized by water wires (Figure 4b) [34]. They show similar structural features as found in the AQP pores, with a central pore size of  $\sim 2.6$  Å. The water molecules form a single molecular wire adopting a unique dipolar orientation inside the chiral I-quartets. The I-quartet channels are able to transport  $\sim 1.5 \times 10^6$  water/s/channel, which is within two orders of magnitude of AQPs' rates but most important, reject all ions except protons.[34] This ion-exclusion selectivity is important and unique for the AWCs. It is based on dimensional steric reasons, whereas hydrophobic and hydrodynamic effects appear to be less important. The I-quartets have been found to efficiently transport protons when an osmotic pressure is applied, in the absence of any pH gradient. This highlights the importance of oriented dipolar water-wires inside the channels, allowing polarization and synergetic *antiport* proton translocation through the bilayer membrane.

Small oligopyridine molecules that are able to self-assemble into helical *Aquafoldamers* with a pore of  $\sim 2.8$  Å, close to the size of narrowest region in AQPs (Figure 4c). [48] The supramolecular nanopore contains a single file of water molecules. Interestingly, when water permeability tests were performed the channels showed no osmotic pressure induced water transport, but when under proton gradient was applied, they presented observable water transport. This underlines the dependence between the chain-like confinement of the water inside the pore and translocation capabilities of the channel, however a standardized value for

water channel permeability needs to be determined. The channels showed no transport of  $\text{Na}^+$  and  $\text{K}^+$  cations, making them a viable option for desalination applications.

With a similar approach, giant macrocycle able of self-assembly into tubular channels *via* stacking and H-bonding interactions have been recently synthesized (Figure 4d). [49] Although the size of the pore of 4-5 Å would normally offer little selectivity, remarkably the channels can selectively transport  $\text{K}^+$  against both  $\text{Li}^+$  and  $\text{Na}^+$  cations. The transport of water occurs in a similar fashion as the one observed in the case of CNTs, a hopping of water molecules between voids having no specific binding to the walls of the pore. The determined osmotic water permeability of these hydrophobic channels is  $\sim 4.9 \times 10^7$  water/s/channel.

Recently, the research on water channels has been pushed a step further showing that a self-assembled "T-channel" is formed with morphological characteristics reminiscent to natural Gramicidin-A [32]. The formation of an aqua-lubricated channel is generated via H-bonding between water molecules and carbonyl groups identical to the carbonyl strings in AQPs. Vesicles incorporating "T-channels" show fifty times higher water permeability than control vesicles but this system does not show water/ion selectivity.

**5.3. Nanochannels:** At the nanolevel, carbon nanotubes-CNTs offer an exciting source of inspiration to mimic natural channels. [45-47] The CNTs can be considered as artificial systems where the selectivity can be modulated at the entrance, the net dipolar orientation of water molecules and the electroosmotic flow of actively pumped chemicals can be controlled through the inner CNT cores at important flow rates. The frictionless water flow is 4–5 orders of magnitude increasing over what would be seen in other conventional nanoporous or AQP structures. Important studies show ion-rejection at low salt concentrations which is promising for applications. In the past few years, membranes based on graphene and graphene oxide (GO) have gained considerable interest for their potential for desalination. [50] The swollen membrane allows any selectivity as water molecules are transported with ions. However, the

spacing in a GO laminar membrane can be controlled by physically restraining the membrane from swelling. When interlayer spacing is reduced to 7.0 Å, the ion permeation rate was reduced by two orders of magnitude while the water permeation rate was only halved.

**6. Outline beyond state of art:** All these examples studied must restore some balance to our understanding of the biomimicking of natural AQPs and remains an important exploring challenge. These findings show that natural channels can be bio-mimicked using simpler artificial compounds displaying constitutional functions like the natural ones (Table 1). Biomimicking the complex superstructures of proteins at molecular level is an important exploring challenge. The artificial water channels with a simplified structure, allow the dynamic structural behaviours of confined superstructures of water to be elucidated. The current research on AWCs is focused on their synthesis, molecular simulations and transport properties in lipid bilayer membranes. The osmotic water permeability of artificial systems ranges from several orders of magnitude lower than that of AQP1, with similar or even better values for Carbon Nanotubes CTNs (Table 1).

The large cross-sectional area of AQPs (9.0 nm<sup>2</sup>) is somewhat disproportionate in regards with the size of its active water pore. It is important to note that the effective cross-sectional area of the AWCs channels in 2D layers will take up significantly less space than proteins. From an engineering point of view, this could potentially increase by orders of magnitude their permeability per surface area when compared with AQPs.

The two main challenges for AWCs are i) to design tailored channels that reject salt but allow the easy passage of water molecules and ii) the transfer of the AWCs from the nanomolecular level to that of large-scale membrane materials. Although this has been partly achieved using AQPs, no studies have been reported yet on integrating the AWCs within active layers casted onto polymeric membrane supports.



Table 1. Performance overview of artificial water channels and pores (adapted with permission from reference [3]).

Water Channels	Net Permeability for water / Single channel permeability	Selectivity	Ref.
Aquaporins – AQPs.	167 $\mu\text{m/s/bar}$ $4 \times 10^9$ water molecules/s/channel	High selectivity for water, perfect rejection of ions/ $\text{H}^+$	18,20
Carbon Nanotubes- CTNs Estimated diameter = 15 $\text{\AA}$	300 $\mu\text{m/s/bar}$ , $1.9 \times 10^9$ water molecules/s/channel	-	45
Carbon Nanotubes- CTNs Estimated diameter = 8 $\text{\AA}$	520 $\mu\text{m/s/bar}$ , $2.3 \times 10^{10}$ water molecules/s/channel	ion rejection in dilute solutions	45
Hydrophilic I-quartets, channel (2.6 $\text{\AA}$ )	3-4 $\mu\text{m/s/bar}$ $1.5 \times 10^6$ water molecules/s/channel	high selectivity for water, reject all ions except protons	34
Aquafoldamers, Hydrophilic channel (2.8 $\text{\AA}$ )	No permeability reported	high selectivity for water, reject all ions except protons	48
Hydropobic peptide tubular macrocyclic pores (6.4 $\text{\AA}$ )	51 $\mu\text{m/s/bar}$ $4.9 \times 10^7$ water molecules/s/channel	no selectivity for water, high conduction for $\text{K}^+$ and $\text{H}^+$	49
Hydrazide appended Pillar[5]arene, <b>PAP1</b> unimolecular channel (6.5 $\text{\AA}$ )	$8.6 \times 10^{-6}$ $\mu\text{m/s/bar}$ 40 molecules/s/channel	no selectivity for water conduction for alkali cations no conduction for $\text{H}^+$	43
Peptide appended Pillar[5]arenes, <b>PAP2</b> unimolecular channel (5 $\text{\AA}$ )	swelling: 30 $\mu\text{m/s/bar}$ or $3.5 \times 10^8$ shrinking: 1 $\mu\text{m/s/bar}$ or $3.7 \times 10^6$ molecules/s/channel	no selectivity for water, good conduction for alkali cations	44
Double helical water T-channels (~2.5-4 $\text{\AA}$ )	No permeability reported	Enhanced conduction states for cations and for $\text{H}^+$	149
RO membrane	2 $\mu\text{m/s/bar}$	99,8% rejection of salts versus water	20
FO membrane RO membrane	2,5 $\mu\text{m/s}$ 5,3 $\mu\text{m/s}$	-	5,6

Designing stable polymer matrixes capable of keeping AWCs in their active state will prove crucial for future hybrid membranes. The use of lipid bilayers or hydrophobic polymers as host matrixes, which certainly can be affected by the presence of organic solutes or surfactants in water, is not a necessary option. They have been used until now to compare the AWC with AQP One strategy to obtain active layer is to incorporate the AWC networks while forming the Polyamide PA layer of RO membrane or to imagine new cross-liked polymers in

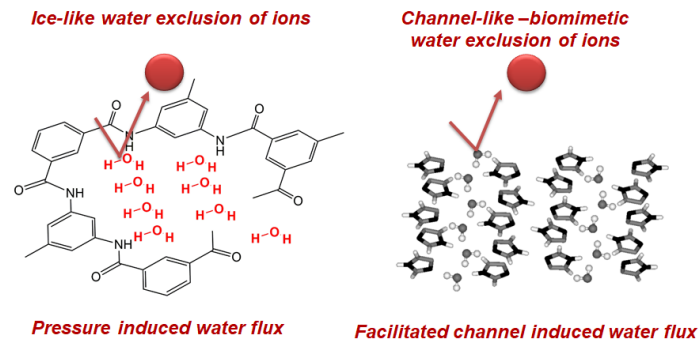
order to obtain networks of AWC within the thin layers. If AWC are covalently attached to TFC, there is no degradation of layer, only temporary channel destabilization. This way the AWCs are dense and highly robust, would be encapsulated in the dense part of the membrane while the PA matrix should be responsible for the rejections of organics.

To compete with polymeric reverse osmosis membranes, the current gold standard for desalinating seawater, water flux and rejection rates for artificial water channels need to be very close to that of AQPs. While having even higher flux values will not have a substantial impact on membrane filtration performances, highly water specific membranes will improve the quality of water produced as well as remove unnecessary pretreatment processes.

It was discovered that imidazole I-quartet i.e., stacks of four imidazoles and two water molecules, that can mutually stabilize oriented dipolar water-wires within 2.6-Å pores [34].

We know that a pore with a diameter of  $\sim 3$  Å very close to the narrowest constriction (2.8 Å) observed in AQP, is a critical prerequisite for ion-exclusion behaviours. Bigger pore diameters ( $> 3$  Å) are at long last beginning to meet encouraging signs for high water permeability ( $10^6$ - $10^8$  water molecules/second/channel), while most of these channels present ionic transport activity, thus not yet selectivity. The total ionic-exclusion by I –quartet channels suggests that they hold significant promise for the incipient development of the first effective artificial AQPs: high water permeability ( $10^6$  water molecules/s/channel) and total ionic rejection. These key features must be combined in order to exploit both the selectivity of hydrophilic H-bonding channels like I-quartets<sup>14</sup> and the high permeability of hydrophobic carbon nanotubes. Shorter channels lengths, more dense channels per unit area of surface will play an important role in developing efficient water filtration systems based on AWC technology. Given the importance of developing even more efficient membranes for desalination, this will be an exciting and challenging project, potentially redefining the paradigms of desalination (Figure 5).

## New Paradigm in Desalination Artificial Water Channels



**Figure 5.** RO versus biomimetic artificial water channels for desalination strategies (image adapted with permissions from reference [3]).

### 7. Conclusions

The *biomimetic water transport* can solve/improve the performances and life-time of the bio-assisted membrane systems in which highly selective but labile AQPs are used. In terms of **economic gain** and the **economy of matter** the artificial systems, might represent an interesting alternative. This project, scientifically **challenging and of great fundamental interest**, is leading to pioneering scientific or applicative discoveries, as literature can attest. Biomimetic water transport, fundamental in nature, should allow not only to develop new knowledge and a greater understanding on bottom-up design of multifunctional systems, but also to address different societal challenges. The thin-layer polyamide membranes, used for water desalination since 1972 has improved dramatically over the last 60 years [51], however their low-resolution structure and the transport mechanism are still poorly understood. The ultimate performance of a membrane is usually determined by an increased flux (or permeance) due to the introduction of the defects in the membrane structure lowering the selectivity which is always decreasing. The first identification of Artificial water channels-AWCs, opened the door to new applicative desalination processes close to natural ones. We speculated at this time that biomimetic Artificial Water Channels - AWCs might have timely

important influences to increase this driving force for the transport by using natural principles and to change the water desalination paradigms.

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