

## From Natural to Bioassisted and Biomimetic Artificial Water Channel Systems

MIHAIL BARBOIU\* AND ARNAUD GILLES

*Adaptive Supramolecular Nanosystems Group, Institut Europeen des Membranes, ENSCM-UMII-UMR CNRS 5635, Place Eugene Bataillon CC047, 34095 Montpellier, France*

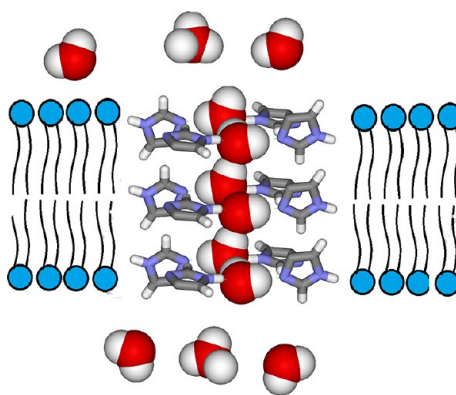
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### CONSPECTUS

**W**ithin biological systems, natural channels and pores transport metabolites across the cell membranes. Researchers have explored artificial ion-channel architectures as potential mimics of natural ionic conduction. All these synthetic systems have produced an impressive collection of alternative artificial ion-channels.

Amazingly, researchers have made far less progress in the area of synthetic water channels. The development of synthetic biomimetic water channels and pores could contribute to a better understanding of the natural function of protein channels and could offer new strategies to generate highly selective, advanced water purification systems. Despite the imaginative work by synthetic chemists to produce sophisticated architectures that confine water clusters, most synthetic water channels have used natural proteins channels as the selectivity components, embedded in the diverse arrays of *bioassisted artificial systems*. These systems combine natural proteins that present high water conductance states under natural conditions with artificial lipidic or polymeric matrixes. Experimental results have demonstrated that natural biomolecules can be used as bioassisted building blocks for the construction of highly selective water transport through artificial membranes. A next step to further the potential of these systems was the design and construction of simpler compounds that maintain the high conduction activity obtained with natural compounds leading to fully synthetic *artificial biomimetic systems*. Such studies aim to use constitutional selective artificial superstructures for water/proton transport to select functions similar to the natural structures. Moving to simpler water channel systems offers a chance to better understand mechanistic and structural behaviors and to uncover novel interactive water-channels that might parallel those in biomolecular systems.

This Account discusses the incipient development of the first artificial water channels systems. We include only systems that integrate synthetic elements in their water selective translocation unit. Therefore, we exclude peptide channels because their sequences derive from the proteins in natural channels. We review many of the natural systems involved in water and related proton transport processes. We describe how these systems can fit within our primary goal of maintaining natural function within *bioassisted artificial systems*. In the last part of the Account, we present several inspiring breakthroughs from the last decade in the field of *biomimetic artificial water channels*. Researchers have synthesized and tested hydrophobic, hydrophilic and hybrid nanotubular systems. All these examples demonstrate how the novel interactive water-channels can parallel biomolecular systems. At the same time these simpler artificial water channels offer a means of understanding the molecular-scale hydrodynamics of water for many biological scenarios.

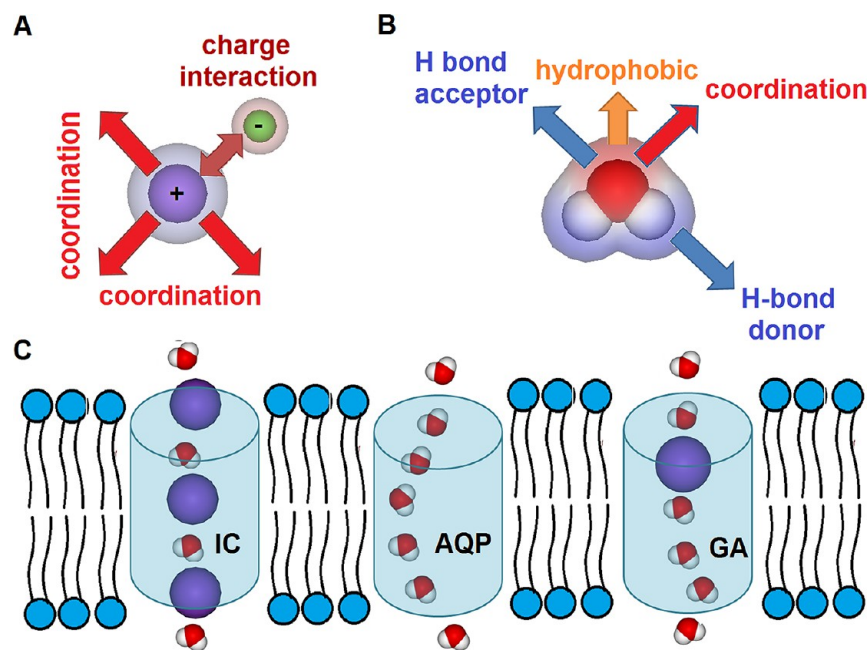


### Introduction

Most of the physiological processes depend on selective exchanges of metabolites between the cell and its exterior. Water plays the crucial roles in such translocation events, related to its complex, not yet fully understood behaviors at the molecular level.<sup>1–3</sup> Artificial ion-channels have been

extensively studied with the hope to mimic the natural ionic conduction via protein channels.<sup>4,5</sup>

Transported through the channels, the spherical ions are mostly involved in radial coordinative and electrostatic interactions with electronegative backbones like water molecules, anions, or specific organic moieties (i.e., carbonyl,



**FIGURE 1.** Schematic representation of the main supramolecular interactions (A) of spherical cations and (B) of angular dipolar water molecules with neighboring backbones. (C) Single-file columns of ions and water within ionic channels (IC) and two possible net-dipole orientation of water wires, corresponding to the water molecule dipoles running antiparallel in Aquaporin (AQP) and Gramicidin A (GA) channels. See text for details.

hydroxyl, etc.). In the meantime, the dipolar water molecules shed light on inherent more complex interactions with biological environments based on combinations of H-bonding, salt bridges, and dipolar or coordinative interactions (Figure 1A,B). Different from single-file columns of ion-channels, the preferential alignment of dipolar water molecules can create a net dipole along the channel, which is of tremendous importance in the regulation of the electrostatic pumping of charged species across the channel (Figure 1C).

Various water clusters may be confined within artificial porous architectures. They have attracted a lot of interest in a variety of fundamental processes: the self-assembly of water clusters, specific interactions with the host porous matrix, or dynamic diffusional phenomena under confined conditions.<sup>6–10</sup> Amazingly, there has been less progress in the area of synthetic water-channels, for which the main challenge is the water-conduction function: the ability of the system to selectively mediate the translocation of water through a hydrophobic barrier membrane. Despite the tremendous imagination of synthetic chemists to produce sophisticated architectures confining water clusters, most of the selected strategies have been related to the use of natural protein channels<sup>11–14</sup> as the selectivity filters embedded in the diverse arrays of artificial host materials. As far as the

production of *ultrapure water* is concerned, the hallmark of ambitious concerned applications is mostly related to desalination.<sup>15</sup> The question of how the natural protein channels/artificial host matrix hybrid systems can be efficiently used together has been partially and very recently answered.<sup>16,17</sup> However, no clear strategies converge to the easy synthetic development of robust *bioassisted hybrid systems*. With all these in mind, an obvious question arises: would it be possible to use only synthetic elements in the construction of selective water biomimetic filter units, replacing the natural proteins used by now?

Indeed, one could say that the discovery of novel synthetic systems able to form water channels is at least most of the time empirical. However, even if the discovery is empirical, then the natural proteins may serve us to tailor the functions of the synthetic systems. Understanding the natural systems' transport mechanism is often one way to bring artificial systems close to natural functions. First of all, it might be useful to improve the performances of the artificial systems for water transport in bilayer membranes closer to the natural ones. Then the scale-up toward simple membrane systems might be reliable to consider them as highly selective skin-layers on top of the existing commercial membranes used for such purposes by now.

## Biological Water-Channels as Sources of Inspiration

Potassium channels from *Streptomyces lividans* (KcsA  $K^+$ ),<sup>11</sup> Aquaporin (AQP),<sup>12</sup> Influenza A M2 (M2IA), or Gramicidin (GA),<sup>14</sup> are well-known, nonexclusive examples of proteins in which ions, water molecules, and protons are envisioned to diffuse along the water filled pores. It is worth noting that most of the protein channels share some structural aspects, such as their self-assembled multiple subunits within poly-functional transmembrane domains. These subunits are packed around a water filled pore, a crucial element in the functional conformation of the proteins. The selectivity of these protein channels is usually driven by the narrowest region of the pore, showing gating behaviors generated by the structural motion of the external subunits in response to voltage, ligand, and pH external stimuli.<sup>18</sup> The interactions between the constitutive components of the pore with water (most often a one-dimensional water wire) or with ionic species will impose a specific net dipolar moment controlling the translocation within the narrow region of the pore. Despite a wealth of experimental data on structural details of proteins channels, major issues need to be resolved at the atomic level.

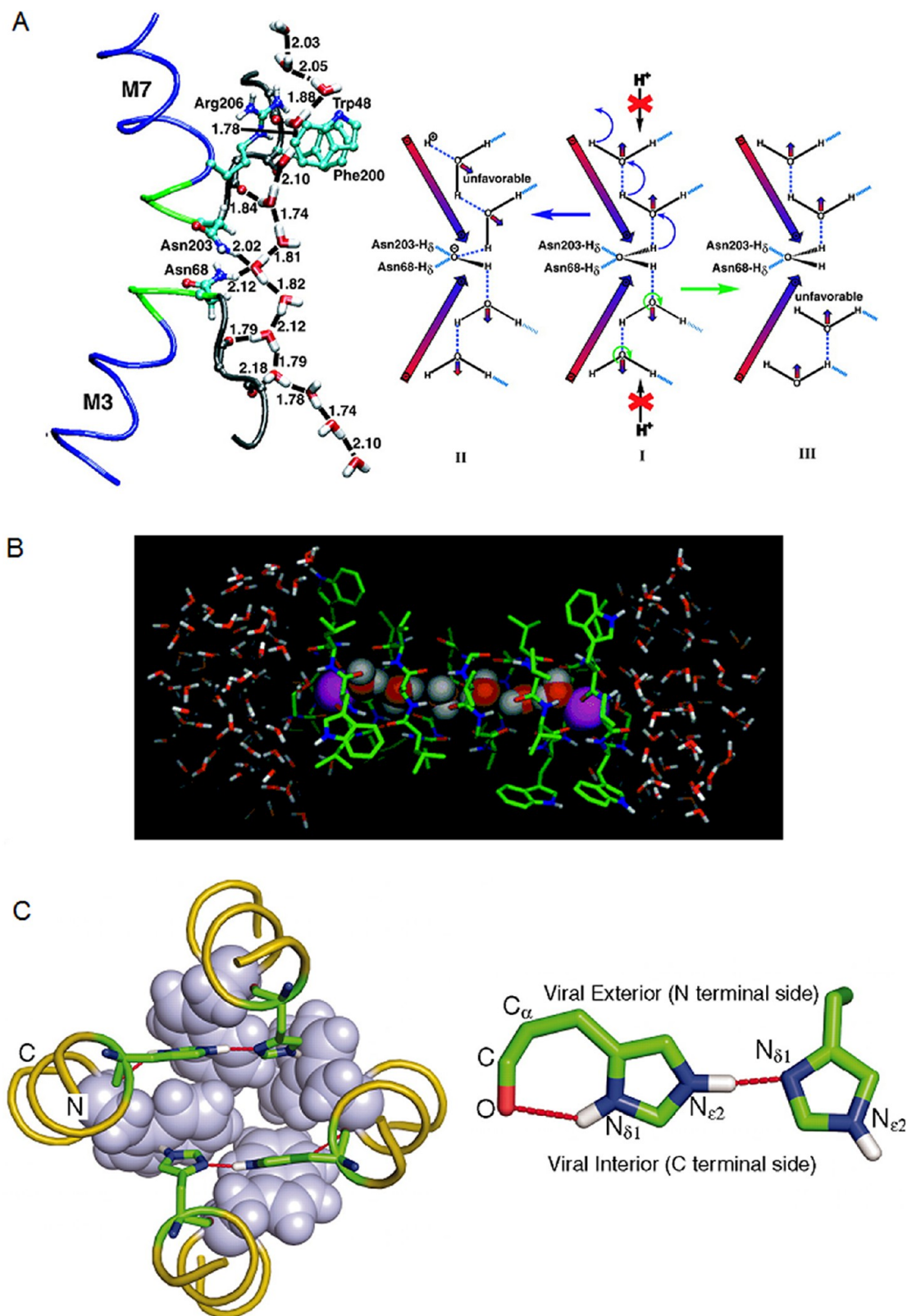
For example, Aquaporin water channels are composed of an hourglass structure with a narrowest constriction of 2.8 Å. Each water molecule in AQP water channels forms one H-bond with the wall of the protein and one with an adjacent water molecule (Figure 2A). Once they pass the center of the pore occupied by a water molecule, double H-bonded to the wall of the pore, the water molecules undergo a fliplike opposite orientation in the AQP channel.

This inversion in orientation is crucial for proton exclusion because it reverses the net dipolar moment of water wires and the electrochemical potential along the AQP pore. The AQP channel highly preventing the proton transport while permitting rapid water diffusion reflects that the structural features of oriented water wires within the synthetic pores may be important in the design of artificial pores creating (pumping) or collapsing (gating) ionic gradients throughout the membrane. Moreover, it was previously shown that the asparagine-proline-alanine sequences (NPA motifs) are highly conserved in Aquaporin water channel family. It is in the NPA area that the water dipole orientation undergoes the 180° rotation, specific water–protein interactions together with the protein electrostatic fields enforce the dipole inversion.<sup>19</sup> This orientation persists despite water translocation in single file and blocks proton transport in aquaporins basically due to the NPA motifs.<sup>20</sup>

Another well-known natural molecule forming channels is the pentadecapeptide Gramicidin A (GA) which appears to be selective for the transport of the monovalent cations (Figure 2B). The GA-channel, one of the best characterized biological pores, is of primordial inspiration to design artificial synthetic ion channels.<sup>14</sup> Regarding the basic principles of the transport along GA, its dipolar structure helps overcome the high energy barrier of water and ions translocations which are synergistically transported sharing one pathway, across the cell membrane.<sup>21</sup> Particularly interesting, the dipolar alignment of water molecules imposed by the pore structure can control the ionic conduction,<sup>22</sup> including the translocation of protons via the inner-pore water wire.<sup>21</sup> This oriented single-file water wire as for an Aquaporin pore imposes a net dipole moment which is particularly influenced by the presence of the ions inside the channel. Depending on the position of the ion within the channel, two linear chains of water molecules of opposite orientation are determining the net dipole potential which is zero on average when the ion is in the middle of the channel.<sup>22</sup> Similarly, the water molecules permeate through KcsA  $K^+$  channel, together with the  $K^+$  ions in a concerted way.<sup>23</sup> Interestingly,  $K^+$  depleted KcsA  $K^+$  channel is changing its initial conformation to allow water transport 20 time faster than one-dimensional bulk diffusion of water.<sup>24,25</sup> These experiments are consistent with the liquid–vapor oscillations of water under confinement in the selectivity filter and are reminiscent with the behaviors of water molecules confined in hydrophobic nanopores, discovered by molecular dynamics simulations.<sup>26</sup>

On the same principle, the proton selectivity and low-pH gating are the key functions of M2 Influenza A (M2IA) proton channel.<sup>13</sup> Although there is some variability to set off the mechanisms, many structural features are relied to the (His<sup>37</sup>)<sub>4</sub> selectivity filter.<sup>13</sup> Despite a wealth of experimental data major issues need to be resolved at the atomic level for water/proton conductance mechanisms through M2IA proton channel. However, it was shown that Trp<sup>41</sup> residues in the close proximity of the His<sup>37</sup>-quartet exclude water molecules from the gating region due to the steric effects and only highly protonated His models present conductance state through the channel.

With all these in mind, we can observe that natural water channels show a variety of sizes and different single-file water net dipole orientations that are directly connected to their specific function. They are selective toward other permeants (ions, protons, molecules) depending strongly on the channel structure and dimensionality, channel-water



**FIGURE 2.** (A) Natural proteins in which ions, water molecules, and protons are envisioned to diffuse along the water filled pores. (A) Snapshot from MD simulation revealing the orientation of the H-bonded water wires that precludes proton conduction in AQP.<sup>19</sup> (B) Theoretical configuration of the GA channel occupied by two  $\text{Na}^+$ .<sup>17</sup> (C) Top view of the histidine-His quartet in the locked state and side view of one of the two imidazole-imidazolium dimers within the M2IA channel.<sup>13</sup> Reproduced with permission from refs 13, 17, and 19.

affinity, the average pore occupancy and the dynamics of the permeating water.

### Bioassisted Water Channels Hybrid Systems

The remarkable properties of natural water channel proteins in terms of permeability and high rejection of ions inspired many groups to use mainly AQP-embedded artificial membranes for desalination.<sup>27–33</sup> A very recent review on such biologically assisted artificial membranes incorporating AQPs for water filtration applications covers tutorial aspects together with the most used strategies for the preparation of a defect-free membrane platform.<sup>27</sup> The crucial steps are related to maintain the protein activity and to obtain high protein density on planar membrane morphology. The first related strategies have so far been limited to low protein densities in either vesicular or bilayer morphologies. Kumar et al. published a first paper that proposed the idea of incorporating AQPs in block-copolymer–BCP vesicles and even for low density of AQPZ-incorporated polymer the productivity of the membranes was at least an order of magnitude larger than values for existing salt-rejecting polymeric membranes.<sup>17</sup> Then another parallel inspiring method using the direct fusion of AQP-embedded bilayers on a hydrophilic membrane surfaces led to supported lipid membranes showing low reconstitution of membrane proteins.<sup>28,29</sup> The morphology of self-assembled biofilms follow similar behaviors for all these systems, showing discontinuous phases on the surfaces function on the volume fraction occupied by AQP in the bilayer. While the average stability times are qualitatively correct, it appears that such strategy limit the amount of functional protein that can be incorporated into membrane. Despite all these results, the major challenge relates on how scaled-up reconstituted high density membranes of reasonable available filtration area surface can be prepared. Following the seminal paper by Kumar et al.,<sup>17</sup> successful high density reconstitution of AQP in various BCP systems has been demonstrated by a significant number of papers in 2012. The simple BCP vesicle rupturing strategy was demonstrated successfully to prepare high density active AQP-confined polymer membranes on the surface or within porous membrane substrates (reviewed in ref 27).<sup>30–32</sup> Polymerization of protective cross-linked matrixes or controlled dialysis procedures have been used to incorporate AQP-confined vesicles into thin-film composites. The AQP-vesicle-containing films will combine the partial performances of the AQP-vesicles and of the cross-linked polyamide<sup>32</sup> or planar BCP<sup>33</sup> matrix material. Following the same idea, the

Gramicidin-A-GA embedded polymers have been casted<sup>34</sup> or confined within cylindrical nanopores<sup>35</sup> in order to prepare bioassisted nanomembranes. These studies relate more to selective ionic transport through artificial barriers.<sup>35</sup>

All these results show that the combination of natural proteins presenting high water conductance states within natural conditions, with artificial lipid or polymeric vesicles, has demonstrated that natural functional proteins can be used as bioassisting building blocks for the construction of artificial membranes working very close to natural ones. Within this context, the next step may be related to increase this enormous potential imagining that natural conduction activity obtained *with* natural compounds can be biomimicked using simpler compounds displaying constitutional functions *like* the natural ones.

### Biomimetic Artificial Water Channels

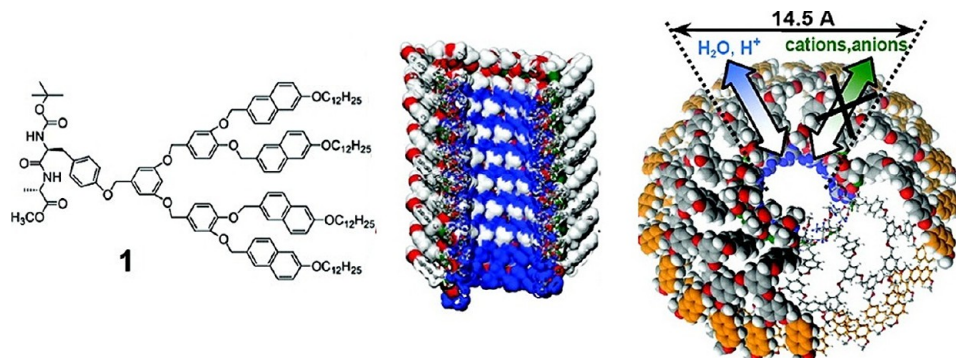
Parallel to the investigations on natural water-channels in biological or bioassisted artificial systems, are straightforward synthetic strategies to create totally *artificial biomimetic channels* using synthetic approaches. The goal of such studies is directed by natural selection of functions *with* constitutional selective artificial structures for water/proton transport *like* in the natural ones.<sup>36–52</sup> The molecular-scale hydrodynamics of water through the channel will depend on channel–water and water–water interactions and on the water in-pore electrostatic dipolar profile within the channel. Mimicking the complex superstructures of proteins is an important exploring challenge. It is more than meaningful to mimic the key parts of active filters, giving of chemical selectivity, to understand the dynamics of orientating water dipoles and their role for ion/proton pumping along the channel. Moving from complex natural to simpler water-channel systems, we would have the chance to understand better mechanistic and structural behaviors of such interactions, unlocking the door to the novel interactive water channels, paralleling that of biomolecular systems.

Different interesting synthetic building blocks have been used to generate such systems: water was shown to transport through hydrophilic, hydrophobic, or hybrid hydrophobic/hydrophilic nanotubular superstructures inserted within the bilayer membranes very efficiently (Table 1).

Water diffusion and facilitated transport of protons excluding cationic and anionic transport through bilayer membranes incorporating all-artificial water channels have been reported for the first time by Percec and co-workers.<sup>36,37</sup> The dendritic dipeptides, **1** (Figure 3), self-assemble via enhanced peripheral  $\pi$ -stacking to form stable cylindrical helical pores

**TABLE 1.** Overview of Design Principles and the Molecular Building Blocks Used to Create Artificial Water Channels and Pores

compd	nature of the channel	ref
dendritic dipeptide, (4-3,4-3,5)-	hydrophobic H-bonded central pore and stacked dendritic periphery	36, 37
alkylureidoimidazoles	hydrophilic H-bonded imidazole channel and hydrophobic peripheral chains	45
pillar[5]arenes	hybrid hydrophobic/hydrophilic cylindrical unimolecular systems.	51, 52



**FIGURE 3.** Cross section and top views of the helical pore assembled from dendritic peptide **1**. Color code:  $-\text{CH}_3$  of the protective group of Tyr, blue;  $-\text{CH}_3$  of the methyl ester of Ala, white; C, gray; O, red; N-H, green. Transport studies showed that **1** facilitated the transport of protons and water through 14.5 Å pore aperture, while excluding cationic and anionic transport. Adapted with permission from ref 37. Copyright 2007 American Chemical Society.

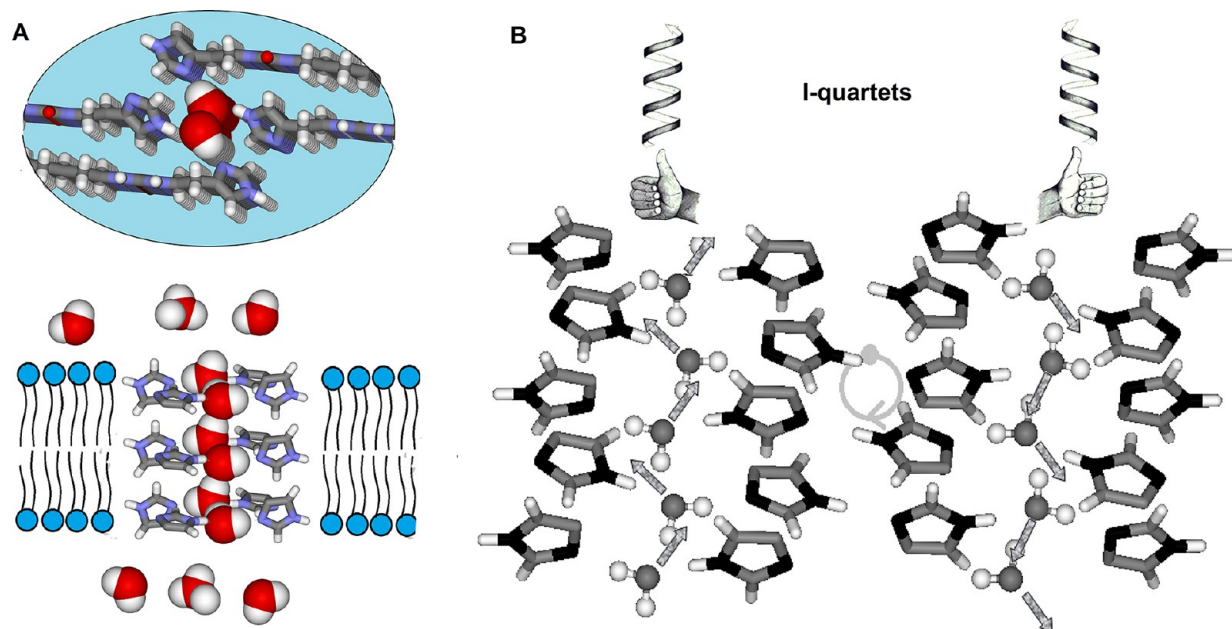
(14.5 Å in diameter) of reasonable thermal stability. Moreover, they selectively transport water molecules against ions through self-assembled hydrophobic nanotubes stable in phospholipid membranes. The ion-exclusion phenomena are based on hydrophobic effects which appear to be very important. They also fit very efficiently the theory diffusion models that the water is transported faster than in bulk water through hydrophobic pore sizes of 13–20 Å,<sup>26</sup> together with the protons translocating the pores via a Grotthuss-type<sup>38</sup> mechanism. These pores were envisioned to be the first artificial “primitive aquaporins” which transport transport water but do not reject protons.<sup>37</sup> Oppositely, supramolecular columnar ion-channel architectures recently described by our group, have been confined within scaffolding hydrophobic silica mesopores for selectively transporting ions against water.<sup>43</sup> They express a synergistic adaptive behavior: the addition of a cations drives a constitutional evolution of the channels within the pores toward the selection and amplification of the fittest-ion transporting superstructures. This is a nice example of dynamic self-instructed (“trained”) membranes where a solute prepares its own selective membrane.<sup>44</sup>

In a parallel approach, Hinds et al. showed that the carbon nanotubes-CNTs membranes offer an exciting source of inspiration to mimic natural channels.<sup>39</sup> They use the conductive CNT pores orthogonally oriented to the surface of the membrane and functionalized at the entrance with various selective “gatekeepers”. The CNTs can be considered

as artificial systems where the selectivity can be modulated at the entrance, and 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.<sup>40</sup> The frictionless water flow is a 4–5 orders of magnitude increase over what would be seen in other conventional nanoporous or AQP structures.<sup>39–42</sup> Important studies show ion-rejection at low salt concentrations which is promising for applications.<sup>41,42</sup>

Later, in another pivotal study, Barboiu et al.<sup>45,46</sup> reported that imidazole I-quartets can be mutually stabilized by inner water-wires, reminiscent with the oriented water single-file columns observed for AQP<sup>19</sup> and ion-charged GA<sup>23</sup> natural pores. In addition, the I-quartet may be considered as the representative water-quartet superstructure, reminiscent of that the most known Guanosine-G-quartet<sup>47,48</sup> is the representative for cations. The I-quartet superstructures are stable in solid state and within bilayers leading to the functional water channels (Figure 4). These systems show total ion rejection, and the ion-exclusion phenomena is based on dimensional steric effects whereas hydrophobic and hydrodynamic effects appear to be less important.<sup>47</sup>

The confined water wires, like in aquaporin channels, form one H-bond with the inner wall of the I-quartet and one H-bond with an adjacent water molecule. Moreover, the water molecules adopt a unique dipolar orientation and preserve the overall electrochemical dipolar potential along the channel. These results strongly indicated that water



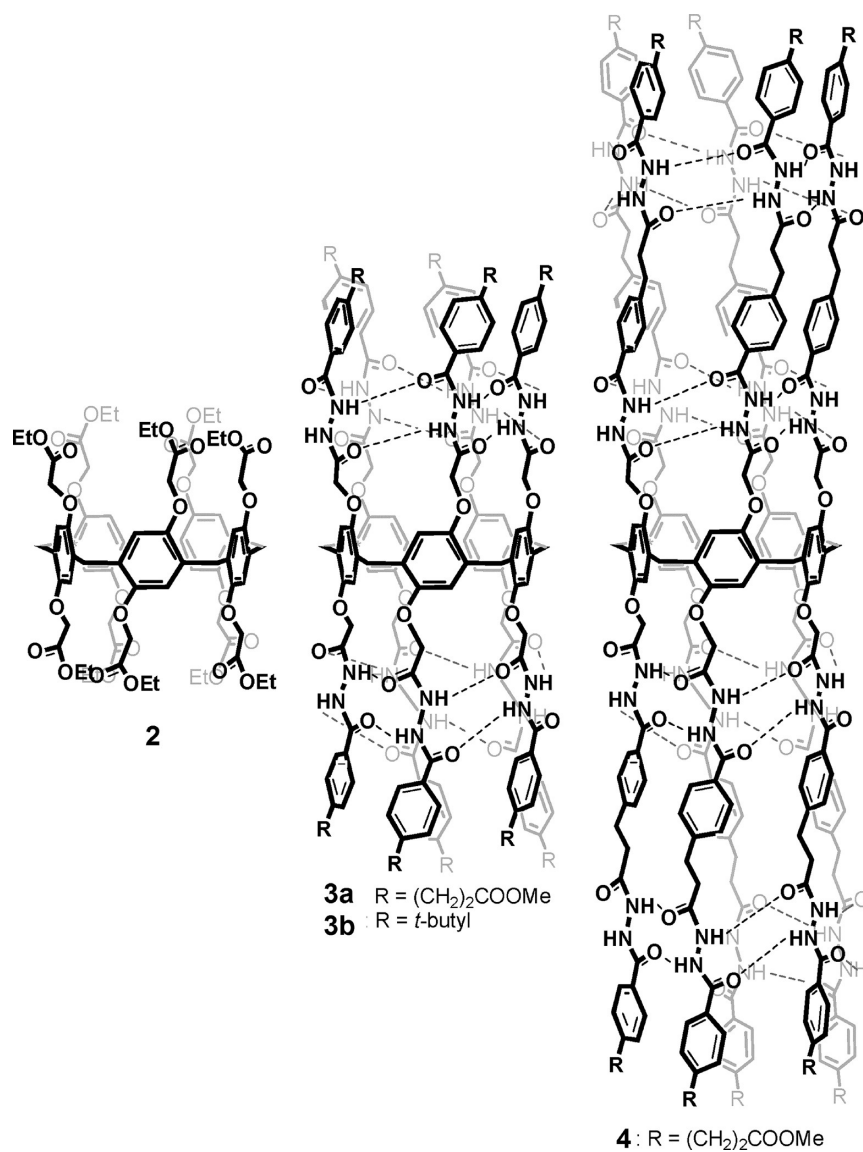
**FIGURE 4.** Cross section and top views of imidazole I-quartets generating water channels in which the water molecules present a unique dipolar orientation. Water molecules in CPK representation. The I-quartets presenting supramolecular chirality can accommodate dipolar water-wires along the length of the channel. Water molecules in ball and stick representation (see text for details).

molecules and protons can permeate the bilayer membranes through I-quartet channels. The I-quartets have provided excellent reasons to consider that *supramolecular chirality* of I-quartets and *water induced polarization (unique dipolar orientation)* within the channels may be strongly associated. Chiral surfaces are determinant to a more extended scale in asymmetric tissue morphogenesis.<sup>49</sup> Water is an electrically dipolar molecule and an exceptional (bio)lubricant and can simply read the spatial information of the asymmetric chiral superstructures to generate asymmetric dipolar-wires of dynamic behaviors. Within this context, *chiral synthetic pores orienting the dipolar water-wires within the channels* give rise to novel strategies to mimic the protein channels. I-quartet channels offer an exciting opportunity to encapsulate water-clusters in confined chiral space and might offer new possibilities to explore water behaviors very close to pore-confined biological water, exhibiting properties at the limits between solid and liquid states.<sup>24</sup> Moreover, all these unique features might confirm a number of structural descriptors explaining the structure-directed functions of natural channel proteins. The water-free I-quartet-“off form” superstructure described by Barboiu et al. is reminiscent with closed conformation of the proton gate of the M2 Influenza A M2IA protein.<sup>50</sup> The slight conformational adjustments allow the formation of water assisted I-quartet-“open form” through which protons can diffuse along dipolar oriented water-wire in the open state

pore-gate region. These artificial I-quartet superstructures obtained by using a simple chemistry are in excellent agreement with structural X-ray and NMR results as well as theoretical results and might provide accurate structural issues for understanding water/proton conductance mechanisms through the M2IA proton channel. Finally, this example represents a fundamentally important biomimetic superstructure for water/proton transport imagined using natural models and might be also related to specific evaluation of functional performances of natural channels that inspired their creation in the first time!

In a subsequent exploration, the significant contribution by Hu et al.<sup>51</sup> shows that the polydiazide-pillar[5]arenes tubular structures can be used as single-molecular water channels in bilayer membranes (Figure 5). The transport mechanism is strongly dependent on the length of the former components: the shortest pillar[5]arenes-tetraester, **2**, induces the formation of water-wires within the stacked molecular cylinders and can successfully be used to translocate protons via bilayer membranes.<sup>51</sup> The longer polyhydrazide-pillar[5]arene compounds **3** and **4**, different from **2**, present alternating hydrophobic/hydrophilic structural domains along their cylindrical structure which disrupt the formation of water-wires within the inner channel core and thus block the proton flux along the discontinuous water phases.

In the crystal structure of **3**, the water is H-bonded and forms only water-dimers near to the hydrophilic regions of



**FIGURE 5.** Structures of pillar[5]arene derivatives used as supramolecular/unimolecular proton/water channels. Reproduced with permission from ref 51. Copyright 2012 American Chemical Society.

the channel, while other disordered water molecules can be observed in the hydrophobic region in the crystal structure, probably as disordered water molecules inside the channel.<sup>51</sup>

The medium hydrazide-pillar[5]arene **3** transport water only if two molecules of **3** are pillared in the bilayer, making its activity dependent on concentration.<sup>51</sup> The longest hydrazide-pillar[5]arene, **4**, of 3.5 nm length, perfectly fits the thickness of the bilayer and shows an excellent transport activity for water and hydroxyl anions upon a single-file molecular translocation mechanism. The unimolecular systems **3** and **4**, like the aquaporins, did not transport protons. Different from AQP, in which the control of the water/proton translocation is based on reverse-flip net-dipolar profiles

within the channel,<sup>19</sup> channels **3** and **4** are relating their selectivity to the structural disruption of water-wires along the channel.

### Concluding Remarks

The collection of recent results surveyed in this Account relates that the artificial water channels adventure is just starting. Water channel systems presented here showed that ion-exclusion behaviors are based on hydrophobic or dimensional steric effects, whereas hydrodynamic effects appear to be less important. However, the presented strategies are consistent with the reflection that it is still possible to contribute to this field by combining the *bioassistance* with the *biomimetism*. We can improve the performances by



finding the ways to work *with* biological entities as well as performing *like* protein channels accommodating both toward natural selection of functions. The result of the fast transport of water through the channels has important practical applications, since ultrapure water for biomedical or nanotechnology applications will be needed like other chemical separations using conventional membranes. What is needed is an enhanced liquid flow mechanism at the location of optimal artificial pores, and this is one critical hallmark for mimicking protein channels, or doing better. The next functional systems would require a nearly frictionless pathway, on the length scale of the diffusional pore trajectory that does not diminish the transport rate of water along the channels. The strong interactions of the water with the inner surface of the channels reduce the efficiency of water transport when compared with the natural systems. Straightforward synthetic access to superstructures disrupting the water wires formation give rise to novel strategies to constitutionally build up very selective water/proton transport devices like in aquaporins. Importantly, the single-file columns of water confined along the internal *chiral surfaces of pores* impose a net-dipole alignment of water molecules, that can influence the conduction of fluids, envisioned to simultaneously diffuse along the *dipolar hydrophilic pathways*.

All these examples unlock the door to the novel interactive water channels world, paralleling that of biomolecular systems. Conversely, the molecular-scale hydrodynamics of water within simple artificial water channels can be determined more easily than using complex biomolecules and can become of crucial relevance for many biological scenarios.

#### BIOGRAPHICAL INFORMATION

**Mihail Barboiu** received his Ph.D. in 1998 from University of Montpellier II before spending 2 years as Associate Professor at College de France, with Prof. Jean-Marie LEHN at University Louis Pasteur, Strasbourg. Since 2001, he has been CNRS Research Fellow and in 2004 Group Leader and CNRS Senior Researcher at the Institut Européen des Membranes in Montpellier, France. A major focus of his research is Dynamic Constitutional Chemistry toward Dynamic Interactive Systems: functional adaptive biomimetic membranes and biosensors, and so forth. An author of more than 160 scientific publications, Dr. Barboiu received in 2004 the EURYI Award in Chemistry.

**Arnaud Gilles** was born in Blois, France, in 1976 and received his Ph.D. degree in organic chemistry in 2007 from the University of Montpellier. After one year of postdoctoral studies in medicinal chemistry at the School of Pharmacy, Cardiff University, in 2008, he became associate Professor at the University of Montpellier in 2009. He joined the European Membrane Institute in Barboiu's

group in fall 2009 as a postdoc, to work on various projects, but mostly on functional supramolecular assemblies forming ion and water channels.

#### FOOTNOTES

\*To whom correspondence should be addressed. Phone: +33-467-149195. Fax: +33-467-149119. E-mail: mihail-dumitru.barboiu@univ-montp2.fr. The authors declare no competing financial interest. This work was conducted within the framework of DYNANO, PITN-GA-2011-289033 (www.dynano.eu), and of ANR 2010 BLAN 717 2 projects.

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