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From functional rescue to promising therapeutic
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Review

SI : Pharmacological chaperones

Vasopressin receptors and pharmacological chaperones: from functional rescue to promising therapeutic strategies

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ABSTRACT

Conformational diseases result from protein misfolding and/or aggregation and constitute a major public health problem. Congenital Nephrogenic Diabetes Insipidus is a typical conformational disease. In most of the cases, it is associated to inactivating mutations of the renal arginine-vasopressin V2 receptor gene leading to misfolding and intracellular retention of the receptor, causing the inability of patients to concentrate their urine in response to the antidiuretic hormone. Cell-permeable pharmacological chaperones have been successfully challenged to restore plasma membrane localization of the receptor mutants and to rescue their function. Interestingly, different classes of specific ligands such as antagonists (vaptans), agonists as well as biased agonists of the V2 receptor have proven their usefulness as efficient pharmacochaperones. These compounds represent a potential therapeutic treatment of this X-linked genetic pathology.

Keywords: antidiuretic hormone, V2 vasopressin receptor, congenital Nephrogenic Diabetes Insipidus, vaptans, biased agonists, therapeutic rescue.

Abbreviations: AVP, arginine-vasopressin; AQP2, aquaporin-2; cNDI, congenital Nephrogenic Diabetes Insipidus; GPCR, G protein-coupled receptor; PC, pharmacological chaperones; V2R, vasopressin type 2 receptor.

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1. Introduction: the X-linked genetic disease cNDI

Regulated water excretion by the kidney is crucial to preserve water homeostasis of our body. The adjustment of water renal reabsorption, to respond to increase in blood osmolality (hypernatremia) or decrease in blood volume (hypovolemia), mainly depends on the release of the antidiuretic hormone arginine-vasopressin (AVP) from the pituitary [1-3]. Binding of AVP to the vasopressin type 2 receptor (V2R), a Gs protein-coupled receptor (GPCR) localized at the basolateral membrane of the principal cells of the kidney collecting duct, results in an intracellular cAMP-dependent signaling cascade of events. Among them, phosphorylation of the water channel aquaporin-2 (AQP2) and its translocation from storage compartments to the apical surface of the cells are of primary importance. Water from pro-urine which enters the cells exits via aquaporin-3 and aquaporin-4 at the basolateral side, leading to water reabsorption and urine concentration. Upon restoration of water balance, the level of plasma AVP drops and AQP2 is internalized, leaving the apical membrane watertight again.

Disorders that interfere with proper urine concentration can be life-threatening, especially in children. One such disease is the congenital form of Nephrogenic Diabetes Insipidus (cNDI) [4]. Indeed, cNDI is a rare inherited disease, characterized by insensitivity of the kidney to AVP and absence of water reabsorption. It results in polyuria and compensatory polydipsia, and may lead to severe dehydration and electrolyte imbalance (hypernatremia) in the case of inadequate water supply.

The X-linked form of cNDI is caused by mutations in the V2R gene [5]. To date, over 200 different V2R mutations have been described. V2R mutations are divided into five different classes. Class II mutations (the most prevalent, more than 50%) are most frequently missense mutations (amino acid substitutions). These mutations result into misfolded, trafficking-deficient receptors that do not reach plasma membrane of the basolateral side of the principal cells of the kidney collecting duct. Indeed, most of the mutants are retained in the endoplasmic reticulum (ER) and in the ER-Golgi intermediate compartment. Consequently, V2R mutants are unable to interact with circulating AVP [6]. These V2R mutants, rather than resulting in nonfunctional proteins (mutants from classes III and IV) are intrinsically functional, as demonstrated by overexpression in heterologous cell expression systems [7].

cNDI-untreated adult patients may have a daily output of 15-20 L of highly dilute urine. Newborn infants often suffer from hypernatremic dehydration with symptoms of irritability, poor feeding and weight gain. In addition, repeated periods of brain dehydration may result in permanent brain damage, mental retardation and seizures can occur. The main strategy for treating cNDI patients consists of a sufficient water supply to replace the urinary water loss, but this can seriously impact on the quality of life due to excessive drinking and urine

voiding. Some diuretics, like hydrochlorothiazide, amiloride or the cyclooxygenase inhibitor indomethacin, have been proven effective to reduce urine output by up to 50% [8]. However, diuretics may affect the sodium and potassium balance in patients and therefore these treatments require tight monitoring of serum electrolytes and osmolality.

Although understanding of cNDI from molecular and cell biological point of view has largely increased since the cloning of the V2R gene in 1992 [9-11], developing alternative strategies to manage water homeostasis and induce antidiuresis in cNDI patients is still obvious. The V2R is a "natural" target for establishing new forms of therapies, and rescue of its function is a very elegant and specific approach. Here starts the story of pharmacological chaperones (PC).

2. Antagonists to the rescue: known compounds with novel pharmacological chaperone activity

Chemical chaperones, like glycerol and DMSO, were shown for instance to correct mutants of the AQP2 water channel, as assessed by protein maturation, cellular targeting and water permeability [12]. Taking the concept of chemical chaperones further, artificial mutants of the multidrug resistance P-glycoprotein-1, a cell surface transporter which interacts with a panel of cytotoxic agents, were functionally rescued. Indeed, ER-retained mutants were targeted to the plasma membrane and their functional rescue was demonstrated using specific substrates or inhibitors like vinblastin, cyclosporin or verapamil [13]. These compounds were proposed to stabilize a specific native-like conformation of the transporter, allowing its release from the ER quality control cell system.

The concept was applied to the mutants of V2R responsible for cNDI, based on the idea that pharmacological ligands act by binding to and stabilizing specific conformations of their receptors. Selective cell-permeant nonpeptidic V2R antagonists (which block the V2R in an inactive conformation) were assessed to check whether they could facilitate the folding of mutant receptors that are retained in ER and unable to interact with AVP [14]. The experiments were successful. Given that these antagonists are specific to the V2R and that they perform chaperone-like activity, Drs. Bichet and Bouvier termed these compounds pharmacological chaperones (PC) [15]. Other names like pharmacochaperones or pharmacoperones have then been proposed.

The first antagonist (or inverse agonist) to be used was SR121463, a selective high-affinity V2R ligand [14]. An overnight treatment of the cells retaining different V2R mutants into an intracellular compartment converted precursor forms into fully glycosylated mature receptors that were targeted to the cell surface. Once correctly localized at the plasma membrane, these mutants were able to differentially bind AVP and produce a correlated cAMP intracellular signal. Interestingly, V2R membrane-impermeable peptidic antagonists were unable to mimic the SR121463 effect, indicating a PC intracellular effect. The PC-driven V2R mutant rescue was not limited to SR121463, because another nonpeptidic antagonist, VPA985, reproduced equivalent results. Since the publication of this outstanding study, SR121463 was used to rescue a larger panel of V2R mutants [16-19] and different other antagonists (or inverse agonists) were tested for their PC properties, such as the V1AR-selective SR49059 [17, 20], the mixed V1A/V2R YM087 [21] and the V2R-selective OPC31260 and OPC41061 [22]. A list of the different PC used to rescue cNDI V2R mutants is presented in **Table 1**, as well as the different receptor mutants for which the PC beneficial effect was proven. Very importantly, the PC effect was also reproducible in polarized renal cells where V2R mutants were appropriately targeted to the basolateral membrane, the natural localization of the wild-type V2R [23]. In addition, because of their target specificity, the PC compounds are active at nanomolar concentrations on cultured cells [22]. This is a tremendous advantage, compared to chemical chaperones which are active at micromolar concentrations or even more.

Interestingly, the concept of PC developed for V2R mutants responsible for cNDI was applied to other GPCR families [24] but also to the V1A and V1B subtypes of the vasopressin receptor family, strengthening the idea that PC action can be generalized to many intracellular-retained misfolded mutant receptors. Regarding vasopressin receptor family, SSR149415, which is a specific nonpeptidic antagonist for V1B was demonstrated to rescue plasma membrane localization and function of the V1B mutant 341FN(X)₂LL(X)₃L350 [25]. Then, the selective nonpeptidic antagonist SR49059 was shown to rescue the functional properties of surface-impaired D148A/N/E mutants of the V1A receptor subtype [26]. To date, no more study has been investigated using PC to rescue other artificial mutants of V1AR, V1BR or the vasopressin-related oxytocin receptor.

Although very promising, using antagonists for rescuing function of the V2R and more generally GPCRs responsible for inherited conformational diseases is somehow paradoxical. First of all, because these antagonists specifically block (inhibit) their receptors, they can not directly stimulate receptor-associated signaling pathways. Regarding patients who suffer from cNDI, the therapeutic beneficial effect would be antidiuresis, through activation of a cAMP-dependent signaling cascade and particularly membrane translocation of AQP2. Indeed, using the PC antagonist strategy, functional rescue of mutants of the V2R is a subtle balance between the ability of the ligand to target cell-surface expression of the mutants and its possibility to be displaced by AVP for receptor activation [27]. In this regard, considering the antagonist affinity is an important feature for this challenge, and therefore low-affinity antagonists (those which are easily displaced by AVP) may possess a highest clinical value [28]. However, the efficiency of such low-affinity antagonist ligands in rescuing receptor function is lower than that of high-affinity ligands (the higher the affinity, the better rescue will be obvious). Moreover, high concentrations of low-affinity antagonists to be administered for clinical efficiency might lead to unwanted side effects in patients (see below section 4). In addition, compound-intrinsic factors other than affinity may influence their capacity to confer functional rescue and their extent to be displaced by AVP, like their localization in the binding pocket of the V2R, their intrinsic activity or their lipophilic value. Overall, it seems that concerning cNDI patients, the high-affinity OPC31260 (mozavaptan) and OPC41061 (tolvaptan) nonpeptidic antagonists would combine best clinical potential, in terms of cell surface rescue, low concentration to be used, and efficient displacement by AVP [22, 29].

3. Agonists and biased agonists : better pharmacological chaperones than antagonists ?

Other pharmacological approaches to treat cNDI patients may have a higher potential than the antagonist PC strategy. Indeed, agonists and biased agonists of the V2R may prove to be of higher clinical value. Theoretically, PC agonists possess advantages over antagonists since they are able to directly stimulate the V2R and induce receptor-associated signaling pathways. In this case, V2R-selective high-affinity ligands are likely to be the most appropriate to efficiently rescue plasma membrane targeting of the mutants and their direct activation. However, agonists also promote V2R internalization, and consequently a decrease in the cAMP signal, a phenomenon that could reduce the beneficial effects of these compounds. Two agonist-based PC alternative approaches have been described, and constitute very promising therapeutic strategies.

Recent investigations by Robben *et al.* indicated that ER-retained but intrinsically functional V2R mutants can be activated intracellularly by different agonists [30]. The activation surprisingly leads to sufficient cAMP increase to induce AQP2 to be translocated to the apical membrane of renal polarized cells. The recently developed nonpeptidic agonist OPC51803 and two novel agonists VA999088 and VA999089 were used in this study to rescue function of a panel of different cNDI V2R mutants (see **Table 1**). In contrast to PC-assisted receptor

folding and rescue, the localization and maturation of the cNDI mutants did not change upon ligand binding and receptor activation. Due to their structural features (small lipophilic molecule compounds which have the ability to penetrate cell membranes and reach the ER), it is surprising that these three ligands do not behave as PC and likely induce plasma membrane targeting of the different V2R mutants. Consequently, they cannot be classified as pharmacological chaperones but still constitute promising future therapeutic candidates for cNDI clinical studies [2]. Like for PC-based approaches, V2R rescue and intracellular receptor activation by OPC51803 and both VA compounds may only work for mutations that affect folding or proper intracellular transport, but neither for highly truncated receptors, nor those that lost their Gs-dependent coupled signaling pathways. These ligands may also be tested on a larger panel of cNDI mutants, in order to check their PC potential properties.

The discovery of biased agonist PC of the V2R is a novel therapeutic opportunity for cNDI patients [31]. The V2R nonpeptidic agonists MCF14 (OPC23h), MCF18 (VNA932) and MCF57 possess only part of the AVP signaling properties. Indeed, these molecules are full agonists of the Gs-dependent cAMP signal (which is responsible for AQP2 translocation and water reabsorption) but do not induce receptor internalization and arrestin-related signaling pathways (antagonists for arrestin recruitment and associated events). On a therapeutic point of view, these particular properties may lead to additional beneficial effects for cNDI patients. The ligands MCF14, MCF18 and MCF57 are high-affinity agonists for V2R and are capable of inducing cNDI mutant receptor maturation, translocation to the plasma membrane and can directly initiate a cAMP response (they may act in synergy with circulating AVP in the case of *in vivo* clinical trials). Functional rescue was demonstrated for different mutants of the V2R (see **Table 1**). They constitute a novel class of PC. Indeed, the V2R biased agonist PC, able to generate a cAMP signal and acting as noninternalizing ligands, potentially providing a long-lasting cellular response during drug administration, may constitute ideal therapeutic compounds for treating cNDI.

4. Clinical trials

A small-scale short-term clinical trial has been set up using SR49059, a low-affinity antagonist for V2R (it is specific for the V1A receptor subtype) [21]. Different patients with R137H, W164S and Δ 62-64 mutations were treated with the nonpeptidic antagonist. Interestingly, SR49059 significantly decreased the 24-h urine volume and water intake, demonstrating a successful PC behavior *in vivo*. However, because of potential interference with the cytochrome P450 metabolic pathway (hepatic toxicity), the development of this molecule was discontinued during clinical phase II. To date, no other clinical trial has been developed for cNDI patients. Recently, the cell-permeable nonpeptidic antagonist OPC41061 (tolvaptan, Samsca) has been approved in USA and Europe for the treatment of hyponatremia in the syndrome of inappropriate antidiuretic hormone secretion and congestive heart failure. This ligand may be of high therapeutic value for novel clinical trials for treating cNDI in the future, provided that it can be displaced by AVP *in vivo*.

5. Conclusions and Perspectives

There have been many advances in the identification of PC compounds for potentially treating cNDI. In principle, V2R-specific PC have more desirable properties as V2R mutant therapeutics than current nonspecific treatments like thiazides with indomethacine. The use of biased agonist PC is of particular clinical interest. Because the rescuing properties of these ligands have been analyzed to only a few misfolded receptors, it would be important to investigate their PC properties on a larger panel of V2R mutants (most of the mutants from class II are potential candidates to be treated). Like in the case of cystic fibrosis, a combination of selective PC with proteostasis regulators may constitute an ideal drug therapy

[32]. Indeed, since most of the V2R mutants are ER-retained, rejected by the ER quality control system, and consequently targeted to the ubiquitin-proteasome degradation pathway, proteostasis regulators which modify the cellular pathways responsible for protein quality control and trafficking may improve/complement the activity of PC. The X-linked genetic disease cNDI provides an excellent example of how the study of a rare pathology can provide new insights into the knowledge and treatment of conformational diseases.

Conflict of interest

The authors declare that there are no conflicts of interest.

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Table 1. Overview of pharmacochaperones with potential for treatment of cNDI and of V2R mutants that are rescued.

Compound	Intrinsic activity	Specificity	Plasma membrane rescue	Functional rescue	Reference
SR121463 (satavaptan, Aquila®)	Inverse agonist	V2R	L59P, Δ 62-64, L83Q, Y128S, S167L, A294P, P322H, R337X	all	[14]
			Δ V278, L292P, R337X	L292P, R337X	[16]
			S167T, V206D	both	[23]
			L44P, Δ 62-64, R113W, I130F, S167T, G201D, T204N, V206D	none*	[22]
			Δ 62-64, S167T, C319Y, P322S, W323H	not tested	[17]
			L44P, L59P, Y128S, A294P, R337X	L44P, A294P, R337X	[31]
			V88M	no affinity for AVP	[18]
			L83Q	L83Q	[19]
VPA985 (lixivaptan)	Inverse agonist	V2R	L59P, Δ 62-64, L83Q, Y128S, S167L, A294P, P322H, R337X	all	[14]
SR49059 (relcovaptan)	Antagonist	V1AR	R137H	R137H	[20]
			C319Y	C319Y	[17]

			L44P, I130F, S167T	L44P, I130F, S167T	[22]
			Δ 62-64, R137H, W164S	all	[21]
YM087 (conivaptan, Vaprisol [®])	Antagonist	V1AR/V2R	L59P, Δ 62-64, L83Q, Y128S, R137H, W164S, A165D, S167L, A294P, P322H	all	[21]
OPC31260 (mozavaptan)	Inverse agonist	V2R	L44P, Δ 62-64, R113W, I130F, S167T, G201D, T204N, V206D	L44P, I130F, S167T	[22]
OPC41061 (tolvaptan, Samsca [®])	Antagonist	V2R	L44P, Δ 62-64, R113W, I130F, S167T, G201D, T204N, V206D	L44P, I130F, S167T	[22]
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OPC51803	Agonist	V2R	none	L44P, Y128S, I130F, S167T, Y280C, R337X	[30]
VA999088 (VA88)	Agonist	V2R	none	L44P, Y128S, I130F, S167T, Y280C, R337X	[30]
VA999089 (VA89)	Agonist	V2R	none	L44P, Y128S, I130F, S167T, Y280C, R337X	[30]

MCF14 (OPC23h)	Biased Agonist	V2R	L44P, Y128S, A294P, R337X	L44P, A294P, R337X	[31]
MCF18 (VNA932)	Biased Agonist	V2R	L44P, Y128S, A294P, R337X	L44P, A294P, R337X	[31]
MCF57	Biased Agonist	V2R	L44P, Y128S, A294P, R337X	L44P, A294P, R337X	[31]

*In this study, SR121463 was used at 1 μ M, a high concentration enabling plasma membrane rescue, but rendering very difficult displacement of this PC with AVP.