Characterization of an Aquaporin-2 Water Channel Gene Mutation Causing Partial Nephrogenic Diabetes Insipidus in a Mexican Family: Evidence of Increased Frequency of the Mutation in the Town of Origin

CRISTINA BOCCALANDRO,* FABRIZIO DE MATTIA,† DONG-CHUAN GUO,† LI XUE,† PHILIP ORLANDER,* TERRI M. KING,† PRATEEK GUPTA,† PETER M.T. DEEN,‡ VICTOR R LAVIS,* and DIANNA M. MILEWICZ†
*Division of Endocrinology and †Division of Medical Genetics, University of Texas Houston Medical School, Houston; and ‡Department of Cell Physiology, University of Nijmegen, Nijmegen, The Netherlands.

Abstract. A Mexican family with partial congenital nephrogenic diabetes insipidus (NDI) that resulted from a mutation in the aquaporin-2 water channel (AQP2) was characterized, and the source of this rare mutation was traced to the family’s town of origin in Mexico. Affected individuals with profound polyuria and polydipsia were homozygous for an autosomal recessive missense V168M mutation in the AQP2 gene. Expression in oocytes revealed that, although retained in the endoplasmic reticulum (ER) to a great extent, a considerable amount of the partially functional AQP2-V168M was expressed at the plasma membrane, and that its ER retention was less than AQP2-T126M, a functional mutant in severe recessive NDI. None of the affected AQP2-V168M individuals had neurologic deficits, which also suggested a milder form of the disease. The homozygous individuals reported subjective improvement in polyuria and polydipsia with the use of dDAVP (1-desamino-8-D-arginine-vasopressin). When clinically tested, infusion of dDAVP at variable doses produced a partial increase in the urinary osmolality in homozygous individuals and decreased their water intake. Heterozygotes were unaffected when compared with controls. Samples were obtained from the population of the Mexican town of origin of the family; 30% of the population was heterozygous for the V168M AQP2 mutation and 1% was homozygous for the mutation. The high frequency of this rare mutation in the town provides evidence for an important health care problem in the village with consequences for future generations.

Diabetes insipidus is defined by a 24-h urine volume greater than 3 L and urinary osmolality less than 300 mOsm/kg (1). Diabetes insipidus can be of central or nephrogenic origin, and it can be acquired or hereditary. Individuals affected with nephrogenic diabetes insipidus (NDI) are prone to severe dehydration if unable to access liquids and can experience failure to thrive, mental retardation, and death early in life (2–5). Adequate intake of water allows a normal lifespan and good physical and mental development (6).

Inherited NDI results from mutations in two different genes; 90% occur in the gene that codes for the vasopressin 2 receptor (AVPR2) found on the X chromosome (7) and 10% in the gene for aquaporin-2 (AQP2) (8). The aquaporin membrane pore is located in the collecting duct cells and is the primary target by which vasopressin regulates permeability of water. AQP2 (xM_006751) is located on chromosome 12q13, consists of four exons and encodes a 271–amino acid protein with six transmembrane domains. Thirty mutations in AQP2 have been reported, most commonly recessive missense mutations that cause misfolding of the protein and retention in the endoplasmic reticulum (ER) (3,4,9–16). Dominant mutations are less common and are characterized by retention of AQP2 in the Golgi complex region, late endosomes/lysosomes, or basolateral membrane due to the formation of heterotetramers of normal and abnormal AQP2 (17–21).

We have identified a family from Mexico with familial NDI caused by a recessive mutation in the AQP2 gene. The mutant aquaporin-2 is partially functional in Xenopus oocytes. Affected family members reported improvement in thirst and urination with the use of nasal and oral dDAVP (1-desamino-8-D-arginine-vasopressin), prompting the study of the clinical differences between homozygous, heterozygous and controls. Finally, a genetic epidemiologic study was performed in the town of origin of the family in Mexico.
Materials and Methods

Water Deprivation Tests

The study was approved by the Institutional Review Board of the University of Texas Health Science Center at Houston. Written informed consent was obtained from the family members that participated in the genetic and clinical studies, and verbal informed consent was obtained from the townspeople in the genetic epidemiologic study done in Mexico. Clinical studies were done at the Clinical Research Center of The University of Texas Health Science Center at Houston.

dDAVP was stopped 24 h before any testing. Baseline 24-h urine collections were performed to measure volume and urine osmolality. The technique used for the water deprivation test has been previously described (22, 23). Baseline samples for urine osmolality (Uosm), serum osmolality (Sosm), serum electrolytes, and plasma arginine vasopressin (AVP) were taken. AVP samples were collected in heparinized plasma and immediately frozen for future processing. Hyperosmolality was initiated with a continuous 3% saline infusion at a rate of 0.06 ml/kg/min. Sosm was checked hourly until a level of 300 mosm/kg was reached. Then, a second plasma sample for AVP was obtained before 1 μg of dDAVP was provided intravenously to each subject. Urine volume, Uosm, and Sosm were monitored hourly for the next 2 h.

dDAVP Challenge Test

Controls and homozygous and heterozygous family members underwent a dDAVP challenge test with water restriction as a surrogate for a full water deprivation test (24–27). Fluid intake was limited to 250 ml/h. Baseline samples for Uosm, Sosm, serum electrolytes, blood urea nitrogen, glucose, creatinine, and calcium were obtained. Urinary volume and fluid intake were monitored hourly. Uosm was checked 3 h after each dose of dDAVP to ascertain maximal effect of the drug (24–28). No further doses of dDAVP were provided when Uosm was above 800 mosm/kg (22, 24, 29). All of the dDAVP doses were provided intravenously. The first dose of dDAVP consisted in 1 μg for controls and heterozygotes and 5 μg for homozygotes. Three hours later, those with Uosm below 800 mosm/kg received a second dose of dDAVP, 4 μg for the heterozygotes and controls and 0.4 μg/kg for the homozygotes. Uosm was checked 3 h later.

Mutational Analysis

Genomic DNA from the family members was isolated from peripheral blood samples in adults and from Buccal samples in children. The DNA was extracted with the Pure Gene genomic DNA isolation kit (Gentra Systems). Intron-based primers were used to PCR-amplify the four exons of AQP2 (10). PCR amplifications were carried out with HotStarTaq DNA polymerase (Qiagen, Valencia, CA) in a twocycle amplification program to amplify the genomic DNA. The DNA fragments were sequenced with ABI Big Dye terminator kit on an ABI Prism 310 DNA Analyzer (Applied Biosystems, Foster City, CA).

Generation of the Mutant AQP2 cDNA Construct

PCR techniques were used to introduce a G502A transversion in human AQP2 cDNA, which was cloned into the plasmid pT7Ts-AQP2. The forward primer, TGCCATGGCCTTGGCTTGGG, has a NcoI restriction site at the 5′ end. The reverse primer, 5′-ATGGATCCTAAAGGAGGTGGGCCAGGGCATAGAGAACCC-3′ has a BamHI site at the 5′ end. A G502A transition was introduced into the middle of the reverse primer. PCR was performed by using the plasmid pT7Ts-AQP2 as the template. The PCR product was digested by NcoI and BamHI and inserted into the corresponding sites of pT7Ts-AQP2. The G502A mutation of AQP2 was confirmed by sequencing.

Oocyte Experiments

Linearization of the pT7Ts-AQP2 and pT7Ts-AQP2-V168M constructs, cRNA synthesis, preparation and injection of oocytes, cell swelling assays, immunoblotting, and immunocytochemistry were performed as described (30). The obtained water permeabilities were expressed as means ± SEM. Differences between groups were tested by t-test corrected by the Bonferroni multiple-comparisons procedure. Differences were considered statistically significant for P < 0.05. To determine the functionality of AQP2 mutants in relation to wt-AQP2, all immunoblot signals of AQP2 proteins in the plasma membrane of oocytes were semiquantified by densitometric scanning and compared with the signals of a twofold dilution series of wt-AQP2, which was blotted in parallel.

Because the quality of cRNA preparations and injected amounts show variation for different cRNAs, the expressed amounts of the AQP2 proteins from determined cRNA amounts is not reliable. Therefore, our analyses with AQP2-V168M focused on whether AQP2-V168M is a functional water channel and if so, to what extent compared with wt-AQP2. Also, we wanted to determine whether it is retained the ER, and if so, whether its retention is different from wt-AQP2 and from AQP2-T126M, another AQP2 mutant that confers severe instead of partial NDI in patients. For these analyses, similar protein expression levels are needed, which is much better controlled in oocytes than in mammalian cells. For determination whether a mutant is retained in the cell, the plasma membrane expression levels have to be compared for those oocytes that show similar total membrane expression levels because the level of plasma membrane expression goes up with increased expression levels.

In a second analysis, by comparing the water permeabilities conferred by similar plasma membrane expression levels of different aquaporins, one can estimate the single channel permeability. For this, the different amounts of wt-AQP2 expressed in the plasma membrane fraction of oocytes and the corresponding water permeability (Pf) values were fitted to the exponential function $y = a(1 - \exp(-bx)) + c$, where y is Pf and x is the amount of protein in arbitrary units. The amount of wt-AQP2 that would be necessary to obtain the Pf value observed for the mutants was calculated from the equation. The ratio of the amount of wt-AQP2 and mutant AQP2 for the Pf that had been obtained for the mutant indicates the single channel water permeability of the mutant in relation to wt-AQP2 in percentage.

Genetic Epidemiologic Data

Samples were collected from individuals in a town in Mexico. Subjects were asked for voluntary participation at their homes or in public areas with the aid of the local physician and nurse. Participants were over 18 yr old, born in the town, and had at least one parent native to the town. Only one sibling of each family was sampled. Buccal cell samples were collected with the Scope mouthwash technique (31, 32). The samples had no personal identifiers and were stored at 4°C until processed. DNA was extracted and AQP2 mutation in exon 2 was analyzed by direct sequencing. The genotype frequencies observed were compared with those expected under the assumption of random mating; a χ² test was used for deviation from Hardy-Weinberg equilibrium.

Statistical Analyses

Comparison between water deprivation and dDAVP tests, age groups in the population samples, and the percentage of permeability...
of the mutant relative to wt-AQP2 was determined by t test (33). Deviation from the Hardy-Weinberg equilibrium was evaluated with the bootstrapping and permutation techniques available in the genetics library as programmed in R (34).

Results

Clinical Description of the Mexican Family

The family studied was originally from a small town northeast of Monterrey, Mexico (Figure 1). Both parents were born in the same town but denied consanguinity. The town started as a ranch founded in 1600s and consists of a larger central area and six satellite communities that share the same ancestry. The total population of the town was 2078, according to the Mexican census from the year 2000 (35). Both parents of the studied family had normal thirst and urination and were healthy except for moderate hypertension in the father. The mother had experienced no miscarriages, and none of her children had died. The first four of their five children had polydipsia and polyuria soon after birth, and all had normal physical and mental development without other medical problems. At the age of 20 yr, an affected sibling (III-5) had a severe hypernatremic episode during a cesarean section. After recovering from the episode, she was treated with dDAVP and reported a 50% decrease in nocturnal thirst and urination. The index patient, the fourth child of the family, approached the endocrinology clinic at the University of Texas Houston and was the first one to be studied by our group. He worked as a construction worker in the Houston area and was able to work in hot climates without experiencing dehydration by drinking large amounts of water. He also reported a decrease in nocturnal polydipsia and polyuria by 50% when treated with dDAVP.

Mutational Analysis

DNA from the proband was used to sequence the exons and flanking intronic sequences of AQP2. A homozygous G to A nucleotide alteration was found at the position 502 in exon 2, leading to a valine to methionine alteration at amino acid 168 in the fifth transmembrane domain of the aquaporin-2 water channel. Exon 2 was sequenced using DNA from all family members. All of the affected family members were homozygous for the mutation, and all other sequenced family members were heterozygous, except the maternal grandmother who did not carry the mutation (Figure 1). Analysis of DNA from 31 white and 29 Hispanic individuals obtained from the Houston area failed to reveal the mutation. A C/T polymorphism immediately adjacent to the mutation (position 501 in exon 2) was identified in the Hispanic controls. The polymorphism did not alter an amino acid, and the frequency of the polymorphism was 14%.

Functional Analysis of AQP2-V168M

To determine the biologic basis for NDI in this family, the V168M encoding mutation was introduced in the human AQP2 cDNA contained in an oocyte expression vector, the cRNA was transcribed and then injected into oocytes. cRNA coding for AQP2-T126M, a functional mutant in recessive NDI (14), was taken along. Determination of the water permeability (Pf) of noninjected control and cRNA-injected oocytes revealed that oocytes expressing AQP2-V168M had a significantly higher Pf than control oocytes, indicating that AQP2-V168M is a functional water channel (Figure 2). At the dosages used here, AQP2-T126M did not confer any water permeability, but at high expression levels, AQP2-T126M has shown to be a functional water channel (14,36,37).

Because the quality of produced cRNA and the injected amounts can vary, total membranes of these oocytes were immunoblotted for AQP2 to reveal their expression levels (Figure 3). At moderate expression levels, AQP2-V168M and

Figure 1. Pedigree of the Mexican family. Darkened symbols indicate individuals with nephrogenic diabetes insipidus (NDI) and the proband is indicated with an arrow. The amino acid alteration in the aquaporin-2 (AQP2) protein is indicated below the symbol. V, valine (wild-type sequence); M, methionine (mutant sequence). Individuals marked M/M were affected, and individuals marked V/V or V/M (heterozygotes) were unaffected.

Figure 2. Osmotic water permeability of oocytes expressing aquaporin-2 (AQP2)–V168M. Oocytes were not injected (c) or were injected with the indicated amounts (ng) of cRNAs encoding wild-type AQP2 (WT-AQP2), AQP2-V168M, or AQP2-T126M. Two days after injection, the mean water permeabilities (Pf ± SEM in µm/s; n = 12) were determined in a standard swelling assay. Significant differences between samples (P < 0.05) are indicated by asterisks.
AQP2-T126M were expressed as 29 kD nonglycosylated and 32 kD high-mannose glycosylated proteins (Figure 3, upper panel), which is characteristic for ER-retained AQP2 proteins (30), whereas wt-AQP2 was only detected as a 29-kD band. At higher expression levels (10 ng cRNA), however, complex-glycosylated (40 to 45 kD; wt-AQP2 and AQP2-V168M) and a 27-kD degradation product (AQP2-V168M, AQP2-T126M) were detected as well.

Immunoblotting of plasma membranes of these oocytes revealed a clear plasma membrane expression for wt-AQP2 and AQP2-V168M at every injected amount, whereas AQP2-T126M was not detected in the plasma membranes (Figure 3, middle panel). To relate the plasma membrane and total membrane expression levels, total membranes equivalents of 1-, 3-, and 10-ng injections were treated with endoglycosidase F, which removes all sugar moieties, and immunoblotted for AQP2 (Figure 3, lower panel). The immunoblot signals were densitometrically scanned and semiquantified by comparison with the immunoblot signals obtained from a twofold dilution series of wt-AQP2 (data not shown). As reported, a decreased ratio of plasma membrane versus total membrane expression for an AQP2 mutant compared with that of wt-AQP2 indicates that the mutant protein is retained within the cell (38).

As can be seen in Figure 3, AQP2-V168M showed a reduced plasma membrane versus total membrane ratio than wt-AQP2 (e.g., compare signals of 3 ng AQP2-V168M to 10 ng wt-AQP2). Densitometric analysis revealed a fourfold reduced plasma membrane expression of AQP2-V168M compared with wt-AQP2. Compared with AQP2-T126M, however, the trafficking of AQP2-V168M to the plasma membrane was much better because the total membrane expression level from 3 ng AQP2-T126M cRNA was in between those of 1 and 3 ng AQP2-V168M (Figure 3, bottom), whereas no plasma membrane expression was detected for AQP2-T126M, in contrast to that of oocytes injected with 1 ng AQP2-V168M cRNA. This indicated that AQP2-V168M is impaired in its transport to the membrane compared with wt-AQP2, but that its trafficking to the plasma membrane is significantly better than of AQP2-T126M. Determining the conferred water permeabilities (Figure 2) for similar plasma membrane expression levels of wt-AQP2 and AQP2-V168M revealed that the ability of AQP2-V168M to confer water permeation is about 58% of that of wt-AQP2.

Immunocytochemical analysis of these oocytes showed a dispersed intracellular expression for AQP2-V168M and AQP2-T126M, although AQP2-V168M also revealed a weak plasma membrane expression (Figure 4, A and B), which is
consistent with ER retention for both mutants and a partial plasma membrane expression of AQP2-V168M. As anticipated, wt-AQP2 was only detected in the plasma membrane (Figure 4C). Uninjected oocytes, which were taken as controls, did not show any staining (Figure 4D), confirming the specificity of the AQP2 antibodies.

Effect of the Mutation on Aquaporin-2 Function on Water Excretion and dDAVP Response

Family members who were homozygous for the mutation (III-3, III-5, and III-7) had a mean 24-h urinary volume of 10,542 ± 941 ml and mean Uosm of 69 ± 9 mOsm/kg (Table 1). The mean 24-h urine volume of the family members heterozygous for the mutation (II-2 and III-9) was 1500 ± 0 ml, which was similar to spousal controls (III-4 and III-6) 1275 ± 530 ml (P = 0.66). The mean Uosm in the heterozygotes was 648 ± 41 mOsm/kg, also similar to the controls (641 ± 257 mOsm/kg; P = 0.96).

Two homozygous (III-5 and III-7) and one heterozygous (II-2) family members participated in the water deprivation study (Table 2 and Figure 5). All of the baseline electrolytes, blood urea nitrogen, glucose, creatinine, and calcium levels were within normal limits. After the Sosm reached 300 mOsm/kg; the heterozygous individual had Uosm of 146 mOsm/kg and 216 mOsm/kg, respectively. The 2-h Uosm in the heterozygote subject was 521 mOsm/kg, consistent with partial NDI. Only one of the homozygous individuals (III-5) had high levels of AVP (29.6 pg/ml) at the maximum Sosm of 320 mOsm/kg.

Three homozygous (III-3, III-5, and III-7), two heterozygous (II-2 and III-9), and two control (III-4 and III-6) family members participated in the dDAVP challenge test (Table 3 and Figure 6). Baseline electrolytes, blood urea nitrogen, glucose, creatinine, and calcium levels were within normal limits. The father (II-2) had elevated systolic and diastolic BP, with means of 152 ± 12 mm Hg and 79 ± 6 mm Hg, respectively. In the homozygous individuals, the mean Uosm was 70 ± 3 mOsm/kg at baseline, 116 ± 16 mOsm/kg after the first dose, and 173 ± 15 mOsm/kg after the second dose of dDAVP. In these same individuals, the water intake had decreased, with a mean intake of 252 ± 131 ml/h between the first and second dose of dDAVP and 199 ± 143 ml/h between the second and third dose of dDAVP (P = 0.07). The mean urine volume did not decrease significantly between the first and second dose of dDAVP (P = 0.81).

The heterozygous individuals had a baseline urinary osmolality of 762 ± 274 mOsm/kg, which was not significantly different from 697 ± 34 mOsm/kg observed in controls (P = 0.76). Similarly, the results of the urinary osmolality after the first dose of dDAVP between the heterozygotes (874 ± 247 mOsm/kg) and controls (803 ± 46 mOsm/kg) were not significantly different (P = 0.78). One of the controls and one of the heterozygous required only one dose of dDAVP of 1 μg to increase urine osmolality above 800 mOsm/kg.

Genetic Studies of the Mexican Town

Buccal cell samples were collected from 222 individuals from the town of origin of the family. We evaluated DNA from 218 of the samples. We were unable to evaluate four samples (2%) because of poor DNA harvest. Fifty-nine percent of the samples were from women, and 41% were from men. The mean age of the individuals sampled was 48 ± 20 yr (women, 48 ± 19 yr; men, 49 ± 20 yr). The age distribution of the sample had a preponderance of older individuals when compared with the Mexican estate where the town is located, the Nuevo Leon estate (Figure 7). Of the total 218 samples processed, 151 samples (69%) did not have the V168M mutation in AQP2. Sixty-five samples (30%) were heterozygous for the V168M AQP2 mutation, and two samples (1%) were homozygous for the mutation. The C/T polymorphism immediately adjacent to the mutation was also observed in this population at a frequency of 8% T allele. The polymorphism did not associate with the mutation and was in Hardy-Weinberg equilibrium.

The gender distribution of the group heterozygous for the mutation was similar to the sample: 63% women and 37% men. The mean age of the individuals heterozygous for the V168M was 59 yr ± 20, 11 ± 0 yr older than the sample (P < 0.01). The two homozygous individuals were both women, 25 and 60 yr of age. Deviation from Hardy-Weinberg equilibrium for the V168M polymorphism was evaluated, and the population was found not to deviate significantly from the expectation on the basis of the marginal genotype frequencies (χ² = 3.094, P = 0.080).

Discussion

We have characterized a V168M mutation in AQP2 in a family with recessive NDI from Mexico. This mutation caused a partial defect in the affected individuals. No previous AQP2

Table 1. Results of 24-h urine collection

<table>
<thead>
<tr>
<th>Individuals</th>
<th>M/M</th>
<th>V/M</th>
<th>V/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>III-7</td>
<td>11,600</td>
<td>1500</td>
<td>1650</td>
</tr>
<tr>
<td>III-5</td>
<td>9800</td>
<td>1500</td>
<td>900</td>
</tr>
<tr>
<td>III-3</td>
<td>10,225</td>
<td>1500</td>
<td>900</td>
</tr>
<tr>
<td>III-9</td>
<td>116</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>II-2</td>
<td>426</td>
<td>63</td>
<td>38</td>
</tr>
<tr>
<td>III-6</td>
<td>62</td>
<td>583</td>
<td>459</td>
</tr>
<tr>
<td>III-4</td>
<td>66</td>
<td>712</td>
<td>822</td>
</tr>
</tbody>
</table>
mutation has been described in individuals of Mexican or Latin American ethnic origin, although five Brazilian families of European ancestors were reported with AQP2 mutations (15). The V168M mutation in AQP2 has been described in a family of European descent, in which clinically affected individuals were compound heterozygotes for the V168M and a S126P mutation (16). The functional effect of the V168M mutation on AQP2 was not previously studied, as opposed to the S216P mutation (3,4). The studies in oocytes and the immunocytochemistry results revealed that AQP2-V168M was retained in the ER, a molecular defect that is common with AQP2 mutants causing recessive NDI (30). However, compared with AQP2-T126M, which is another mutant in recessive NDI, AQP2-V168M is clearly less impaired in its trafficking to the plasma membrane, because even at lower total membrane expression levels, more AQP2-V168M is detected in the plasma membrane (Figures 3 and 4). Because it is well known that an impaired exit from the ER is a consequence of misfolding and retention by molecular chaperones that exert the ER quality control, this reduced level of ER retention of AQP2-V168M compared with AQP2-T126M might indicate that AQP2-V168M is less misfolded than AQP2-T126M. This is underscored by the single channel permeability of about 58% for AQP2-V168M in relation to wt-AQP2, whereas 20% was found for AQP2-T126M (36). Our oocyte studies do not reveal whether AQP2-V168M mRNA and protein are less stable than of AQP2-T126M. However, if these stabilities are similar in vivo, the observed differences in permeability and trafficking to the plasma membrane of these AQP2 mutants would provide a cell biologic explanation for the partial improvement of the urinary concentrating capacity and thirst reduction with the use of dDAVP in the AQP2-V168M individuals and the absence of any increased urine-concentrating ability with dDAVP in the NDI patients encoding AQP2-T126M (14).

Only homozygous individuals in the family were clinically affected with partial NDI, a finding based on very high 24-h urine volumes and low urinary osmolalities in the NDI range, even after water deprivation and administration of dDAVP. The baseline AVP levels were lower than expected for patients with severe NDI. In addition, during the water deprivation and saline infusion, the AVP levels only increased outside the normal range for the Sosm in III-5, in whom the second AVP drawn was 29.6 pg/ml for a Sosm of 320 mOsm/kg, supporting the possibility of a milder type of disease.

Family members heterozygous for the AQP2 mutation (II-2 and III-9) were not clinically affected and had Uosm and urine volumes similar to those of controls. The father (II-2), 55 yr

<table>
<thead>
<tr>
<th>Table 2. Results of water deprivation testa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>III 7 (M/M)</td>
</tr>
<tr>
<td>UOsm (mOsm/kg) 65 85 98 0 130 146</td>
</tr>
<tr>
<td>Sosm (mOsm/kg) 304 304 307 0 310 317</td>
</tr>
<tr>
<td>UVol (ml/h) 410 380 460 0</td>
</tr>
<tr>
<td>AVP (pg/ml) 4.2 3.9</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>III5 (M/M)</td>
</tr>
<tr>
<td>UOsm (mOsm/kg) 76 110 142 185 224 216</td>
</tr>
<tr>
<td>Sosm (mOsm/kg) 291 294 309 321 323 316</td>
</tr>
<tr>
<td>UVol (ml/h) 400 450 750 900 900 500</td>
</tr>
<tr>
<td>AVP (pg/ml) 2.9 29.6</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>II/2 (V/M)</td>
</tr>
<tr>
<td>UOsm (mOsm/kg) 404 412 493 508 502 521</td>
</tr>
<tr>
<td>Sosm (mOsm/kg) 289 297 298 307 311 309</td>
</tr>
<tr>
<td>UVol (ml/h) 120 110 120 110 220 180</td>
</tr>
<tr>
<td>AVP (pg/ml) &lt;1.0 2.8</td>
</tr>
</tbody>
</table>

a Uosm, urine osmolality; Sosm, serum osmolality; Uvol, urine volume; AVP, vasopressin.
old, showed partial NDI in two separate tests with a maximal urine osmolarity of 699 mOsm/kg, when a normal 80-yr-old individual should be able to reach at least a urinary osmolality of 823 mOsm/kg (22,24,29). It is possible that he had limited urinary concentrating capacity as a result of other causes, such as long-standing hypertension.

Usually NDI does not respond to treatment with dDAVP unless some vasopressin and AQP2 activity remains at the kidney level (39). Because of the rarity of this mutation, we had no families with other mutations available to be used as controls. The majority of the subjects with AQP2 mutations did not respond to dDAVP (3,4,11–13,15,16). Three previous studies in patients with AQP2 mutations have demonstrated partial diabetes insipidus, one individual with an autosomal recessive mutation (9) and the other two individuals with autosomal dominant mutations (17,20). AVPR2 mutations have also been reported to produce partial response to dDAVP with milder phenotypes and with mothers affected with partial NDI (15,16).

The homozygotes in our study repeatedly reported subjective improvement of thirst and urination when dDAVP was used at home, as expected if principal collecting duct cells are still responding demonstrating some AQP2 function. This was confirmed by the oocyte functional studies and the clinical studies. The Uosm increased marginally with water deprivation and dDAVP, and some functional aquaporin-2 was found in the plasma membrane of the oocytes. The urinary output in homozygotes treated with dDAVP or water deprivation was

### Table 3. dDAVP challenge test

<table>
<thead>
<tr>
<th></th>
<th>M/M</th>
<th></th>
<th></th>
<th>V/M</th>
<th></th>
<th></th>
<th>V/V</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uosm base (mOsm/kg)</td>
<td></td>
<td>69</td>
<td>73</td>
<td>67</td>
<td>956</td>
<td>568</td>
<td>721</td>
<td>673</td>
</tr>
<tr>
<td>Sosm base (mOsm/kg)</td>
<td></td>
<td>294</td>
<td>293</td>
<td>289</td>
<td>296</td>
<td>294</td>
<td>296</td>
<td>285</td>
</tr>
<tr>
<td>First dDAVP dose (mcg)</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>fluid intake (ml/h)</td>
<td></td>
<td>240</td>
<td>128</td>
<td>388</td>
<td>145</td>
<td>261</td>
<td>118</td>
<td>307</td>
</tr>
<tr>
<td>urine volume (cc)</td>
<td></td>
<td>1800</td>
<td>600</td>
<td>1552</td>
<td>125</td>
<td>516</td>
<td>200</td>
<td>452</td>
</tr>
<tr>
<td>urine output (ml/h)</td>
<td></td>
<td>450</td>
<td>150</td>
<td>388</td>
<td>31</td>
<td>129</td>
<td>50</td>
<td>113</td>
</tr>
<tr>
<td>Uosm (mOsm/kg)</td>
<td></td>
<td>109</td>
<td>135</td>
<td>105</td>
<td>1049</td>
<td>699</td>
<td>770</td>
<td>835</td>
</tr>
<tr>
<td>Second dDAVP dose (µg)</td>
<td></td>
<td>36.3</td>
<td>19.4</td>
<td>24</td>
<td>None</td>
<td>4</td>
<td>4</td>
<td>None</td>
</tr>
<tr>
<td>fluid intake (ml/h)</td>
<td></td>
<td>160</td>
<td>80</td>
<td>358</td>
<td>110</td>
<td>163</td>
<td></td>
<td></td>
</tr>
<tr>
<td>urine volume (cc)</td>
<td></td>
<td>500</td>
<td>725</td>
<td>1434</td>
<td>225</td>
<td>180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>urine output (ml/h)</td>
<td></td>
<td>167</td>
<td>242</td>
<td>478</td>
<td>75</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uosm (mOsm/kg)</td>
<td></td>
<td>179</td>
<td>183</td>
<td>156</td>
<td>692</td>
<td>956</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sosm (mOsm/kg)</td>
<td></td>
<td>301</td>
<td>303</td>
<td>297</td>
<td>291</td>
<td>296</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Uosm, urine osmolality; Sosm, serum osmolality.

Figure 6. Results of the dDAVP (1-desamino-8-D-arginine-vasopressin) challenge test in affected and unaffected family members.

Figure 7. Age distribution of the sample collected in the Mexican town compared with the XII Censo General de Poblacion y Vivienda (Nuevo Leon) 2000 Census.
not significantly changed, but a decrease in their water intake was observed during the dDAVP challenge test.

None of the affected individuals in the Mexican family had mental or developmental abnormalities despite symptoms of polyuria and polydipsia from an early age. In addition, two undiagnosed affected individuals were identified in the Mexican town. These results indicate that some AQ2P2 mutations causing partial recessive NDI permits normal growth and mental development, even if the disease is undiagnosed. Members of other large kindreds affected with NDI have reported mental retardation or failure to thrive as a result of untreated NDI. In a family with recessive AQ2P2 mutations, 6 of 11 individuals had slow psychomotor development or mental retardation and short stature (2). Another study reported the death of three children with symptoms of diabetes insipidus in a family with recessive AQ2P2 gene mutations (4). None of the affected individuals in the Mexican family had mental or developmental abnormalities, despite symptoms of polyuria and polydipsia from an early age. In addition, two undiagnosed affected individuals were identified in the Mexican town.

The fact that each of the parents of the proband carried the same rare recessive AQ2P2 mutation led us to do a genetic epidemiologic study in the town of origin. The population sampled in the town was older when compared with the national census. In addition, more women than men were sampled. Young men in the town were often employed as seasonal migrant farm workers, and this fact may have affected the population sampled. Thirty percent of the individuals in the sample were heterozygous for the mutation, and 1% were homozygous. The frequency of individuals affected by mutations in the AQ2P2 gene in the general population of Mexico is unknown, but it is likely to be less than one in a million (8,40). The high frequency of the mutant allele in the population (15.8%) suggests a founder effect of the mutation in the population. The extraordinarily high prevalence of this recessive mutation in the town, along with the distribution of the mutation along all ages, suggests a relatively high risk of having more affected individuals born in this town. The heterozygote individuals had a similar gender distribution when compared with the entire sample, but had a mean age 11 yr older, which could be suggestive of increased admixture with other populations in the younger generations.

The polymorphism immediately adjacent to the mutation was clearly in equilibrium and was on a separate allele from the mutation. None of the individuals in the family had the polymorphism at nucleotide 501 present in their DNA. In addition, none of the individuals in the town that were homozygous for the polymorphism had the mutation. The health care workers in the town were previously unaware of the presence of NDI in the community. The life-threatening complications of NDI can be easily treated if an individual and the health care providers are aware of the condition. As an attempt to increase the alertness in the town about the disease, we have provided medical information concerning this condition to the health care workers and the population.

Conclusion
In summary, individuals affected with partial NDI in a family of Mexican origin were found to be homozygous for a V168M mutation in AQ2P2. Consistent with this phenotype, AQ2P2-V168M was retained in the ER of oocytes, but was still partially functional and less impaired in its trafficking to the cell surface than another functional AQ2P2 mutant involved in severe recessive NDI. The affected homozygous individuals reported subjective improvement of thirst and urination with the use of dDAVP. This finding was consistent with the clinical studies, which showed partial NDI. dDAVP treatment partially increased Uosm and decreased fluid intake. Heterozygotes compared with controls showed no urinary concentrating defects. In the genetic epidemiologic study of the town of origin, we found a high prevalence of the V168M mutation, suggesting a founder effect. The mutation in the population was in Hardy-Weinberg equilibrium. Affected individuals had no neurologic deficits from untreated NDI. This raises the speculation that undiagnosed cases of NDI may exist in other populations. Preventive and educational measures were implemented in the town with the cooperation of the local health authorities.

References


35. Instituto Nacional de Estadistica GeIM: Estados Unidos Mexicanos: XII censo general de poblacion y vivienda, Mexico City, Mexico, Aguascalientes, Ags., Instituto Nacional de Estadistica, Geografia e Informatica, 2000


