A Mutation in the TRPC6 Cation Channel Causes Familial Focal Segmental Glomerulosclerosis

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Focal and segmental glomerulosclerosis (FSGS) is a kidney disorder of unknown etiology, and up to 20% of patients on dialysis have been diagnosed with it. Here we show that a large family with hereditary FSGS carries a missense mutation in the TRPC6 gene on chromosome 11q, encoding the ion-channel transient receptor potential cation channel 6 (TRPC6). The proline-to-alanine substitution at position 112, which occurs in a highly conserved region of the protein, enhances TRPC6-mediated calcium signals in response to agonists such as angiotensin II and appears to alter the intracellular distribution of TRPC6 protein. Previous work has emphasized the importance of cytoskeletal and structural proteins in proteinuric kidney diseases. Our findings suggest an alternative mechanism for the pathogenesis of glomerular disease.

Focal and segmental glomerulosclerosis (FSGS) is an important cause of end-stage renal disease worldwide, and up to one-fifth of dialysis patients have been diagnosed with it.1,2 The prevalence of FSGS is increasing yearly, and the incidence is particularly high in the black population (1,3). FSGS is a pathological entity in which the glomerulus is primarily targeted. Typical manifestations of FSGS include proteinuria, hypertension, renal insufficiency, and eventual kidney failure. Our understanding of the pathogenesis of FSGS is incomplete, and there are no consistently effective treatments.

Analysis of disease-causing mutations in hereditary FSGS and congenital nephrotic syndromes has provided new insights into the pathogenesis of nephrotic syndrome. The previous identification of at least three genes causing familial FSGS and hereditary nephrotic syndromes underscores the substantial genetic heterogeneity in this disorder (4–6). These studies have highlighted the importance of abnormalities in the podocyte and the slit

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diaphragm of the glomerulus in the development of the severe proteinuria that characterizes the nephrotic syndrome.

Previously, we identified and characterized a large New Zealand family of British origin who have autosomal dominant hereditary FSGS (fig. S1) (7). The character of the disease in this family is particularly aggressive. Affected individuals typically present with high-grade proteinuria in their third or fourth decade, and approximately 60% progress to end-stage renal disease (ESRD). The average time between initial presentation and the development of ESRD is 10 years. A genomic screen performed on this kindred localized the disease-causing mutation to chromosome 11q (8).

Haplotype analyses reduced the minimal candidate region to an approximate 2.1-centimorgan (cM) area defined by critical recombination events at D11S1390 and D11S1762 (Fig. 1A). This region contains several known genes as well as multiple novel and predicted genes, which were systematically screened for mutations by direct sequencing. After examination of 42 other candidate genes, transient receptor potential cation channel 6 (TRPC6) (GenBank accession number NP_004612) emerged as a candidate on the basis of reports of detection of TRPC6 mRNA in the kidney (9, 10). We therefore sequenced each of the 13 exons of the TRPC6 gene, along with their intron/exon boundaries. Primer sequences are provided (table S1). As shown in Fig. 1B, we discovered a missense mutation (C335A) in exon 2 from affected individuals, causing a proline-to-glutamine substitution at position 112 (P112Q) within the first ankyrin repeat of the TRPC6 protein. This variant was present in all of the affected individuals (20 affected; 1 probably affected) in our kindred, and there were no nonpenetrant carriers. The change was not found in any of the public databases of single-nucleotide polymorphisms. Furthermore, we found no evidence of the substitution in 614 chromosomes screened from a group of Caucasian controls without known renal disease, 33 of whom were from New Zealand. The allele frequencies from all markers used for linkage in this kindred and from the New Zealand controls are similar to those from the other Caucasian controls. Pro112 is highly conserved in evolution and is present in TRPC protein homologs from multiple species (fig. S2).

Our previous finding that familial FSGS does not recur in affected patients after renal transplantation indicates a critical role for the kidney in disease pathogenesis (11). Although expression of TRPC6 mRNA has been reported in multiple tissues, including the kidney, its distribution in the kidney is not clear (9, 10). Therefore, to define the spatial distribution of TRPC6 protein expression in the human kidney, we performed immunohistochemistry of normal human renal cortex tissue with a rabbit antibody raised against a specific human TRPC6 peptide (Fig. 2, A and B). Immunofluorescence staining revealed TRPC6 expression throughout the kidney in glomeruli and tubules. This is consistent with a recent study detecting TRPC6 mRNA in isolated glomeruli (12). The expression of TRPC6 in glomeruli is particularly noteworthy because abnormal podocyte function appears to be a final common pathway in a variety of proteinuric kidney diseases (13). To verify these immunofluorescence findings, we carried out fluorescence in situ hybridization (FISH) in human kidney sections (Fig. 2, C to F). These studies confirmed diffuse expression of TRPC6 mRNA in glomeruli and tubules in a pattern that is virtually identical to that seen with staining for antibody to TRPC6.

To determine the effect of the P112Q mutation on TRPC6 function, we studied human embryonic kidney (HEK) 293 cells transfected with mutant (TRPC6P112Q) or wild-type (WT) TRPC6 (14). The WT TRPC6 was cloned from a human kidney cDNA library. On Western blots, the abundance and mobility of the P112Q mutant were comparable to those of WT TRPC6 (fig. S3). Diacylglycerol (DAG) is a potent activator of TRPC6 (15). We therefore measured the intracellular calcium concentration ([Ca\(^{2+}\)]) using Fura fluorescence in HEK 293 cells expressing either the WT TRPC6 or TRPC6P112Q after exposure to the DAG analog OAG (1-oleoyl-2-acetyl-sn-glycerol). OAG perfusion increased late Ca\(^{2+}\) transients in cells transfected with WT TRPC6 as expected (Fig. 3A and fig. S4). Peak intracellular concentrations were significantly higher in cells expressing TRPC6P112Q as compared with WT controls ([Ca\(^{2+}\)], of TRPC6P112Q = 181 ± 25 nM versus [Ca\(^{2+}\)], of WT TRPC6 = 106 ± 15 nM; P < 0.05).

Angiotensin II, acting through its AT1 receptor, plays a critical role in the generation of proteinuria and in the progression of kidney injury in a number of kidney diseases, including FSGS (16). AT1 receptors, coupled to heterotrimeric guanine nucleotide-binding proteins (G proteins), activate phospholipase C-β (PLC-β) isoforms that hydrolyze phosphatidylinositol 4,5-bisphosphate (PIP\(_2\)). This triggers the production of inositol 1,4,5-
triphosphate (InsP₃), and DAG releases internal calcium stores and activates Ca²⁺ entry (17). We examined whether the P112Q mutation would affect angiotensin II–dependent (that is, receptor-operated) calcium signaling. HEK 293 cells were cotransfected with the AT1 receptor (AT1–yellow fluorescent protein) and with either WT TRPC6 or TRPC6P₁₁₂Ｑ. [Ca²⁺]ᵢ changes were measured after exposure to angiotensin II (Fig. 3B and fig. S5). As in the OAG experiments, the peak angiotensin II–stimulated [Ca²⁺]ᵢ was higher in cells expressing the mutant protein as compared with WT controls ([Ca²⁺]ᵢ, TRPC6P₁₁₂Ｑ = 640 ± 66 nM versus [Ca²⁺]ᵢ, WT TRPC6 = 357 ± 46 nM; P < 0.05).

To examine the effects of the P112Q mutation on ion flux, we measured current using the whole-cell patch-clamp technique (Fig. 3C). After patch break, HEK 293 cells expressing WT TRPC6 or TRPC6P₁₁₂Ｑ channels were held at –60 mV for the duration of the experiment. In normal Na⁺ extracellular solution, we detected large inward currents in cells transfected with WT TRPC6. These currents were significantly increased in cells transfected with the mutant TRPC6P₁₁₂Ｑ protein (WT TRPC6 = 1.03 ± 0.23 nA versus TRPC6P₁₁₂Ｑ = 4.21 ± 0.10 nA; P = 0.02). The addition of uridine triphosphate (UTP), carbachol, or angiotensin II augmented the inward currents in cells expressing WT TRPC6 or TRPC6P₁₁₂Ｑ. However, the magnitude of the agonist-stimulated current was two to three times greater in cells transfected with mutant than with WT TRPC6 protein. Control green fluorescent protein–transfected cells showed no appreciable UTP current in comparison to the TRPC6 transfected cells. The enhanced UTP currents established at baseline and after stimulation with Gₛ₁₁ agonist support the Ca²⁺ entry is enhanced and is particularly exaggerated in response to G-protein agonists such as angiotensin II.

We also evaluated the subcellular localization of the mutant TRPC6 protein by surface biotinylation experiments (Fig. 3D). A greater fraction of the mutant protein was associated with the plasma membrane as compared with the WT protein (densitometry measurements were as follows: WT TRPC6 = 1210.33 versus TRPC6P₁₁₂Ｑ = 23126.67 units; P = 0.05). In control experiments, no difference was found in the surface expression of the transferrin receptor (TfR) in cells transfected with either WT TRPC6 or TRPC6P₁₁₂Ｑ. Our findings are in accordance with reports by others (18, 19). This enhanced cell surface expression of TRPC6P₁₁₂Ｑ protein suggests a mechanism of exaggerated calcium signaling and flux.

Mutations in several other proteins have been identified in familial nephrotic syndrome and hereditary FSGS. Nephrin (NPHS1), the...
cause of Finnish nephropathy, is a protein of unknown function that localizes to the glomerular slit diaphragm and appears to form a zipperlike structure (20). Podocin (NPHS2) appears to anchor elements of the slit diaphragm to the cytoskeleton (21). Mutations in alpha-actinin 4 (ACTN4) may alter functions of the actin cytoskeleton in the podocyte (6, 22). CD2-associated protein (CD2AP) has been implicated in glomerular function on the basis of mouse studies (23). CD2AP also appears to have important interactions with nephrin and podocin at the slit diaphragm.

TRPC channels have been implicated in diverse biological functions such as cell growth, ion homeostasis, mechanosensation, and PLC-dependent calcium entry into cells. Calcium as a second messenger affects many of these same cellular functions. We speculate that the mutant protein may amplify injurious signals triggered by ligands bearing on whether the protein is actually expressed (24). We further speculate that the mutant protein may amplify calcium signaling conferred by the TRPC6P112Q mutation disrupts glomerular cell function or causes apoptosis (24). We further speculate that the mutant protein may amplify injurious signals triggered by ligands such as angiotensin II that promote kidney injury and proteinuria. Clinical manifestations of renal disease do not appear until the third decade in individuals with the TRPC6P112Q mutation. This is in contrast to individuals with Finnish nephropathy and steroid-resistant nephrotic syndrome, who typically develop proteinuria in utero or at birth (5). This delay may reflect the difference between these recessive disorders and the autosomal-dominant mechanism of inheritance in the family described here; in that family, the presence of one normal TRPC6 allele may postpone the onset of kidney injury. Patients with autosomal-dominant FSGS due to mutations in the ACTN4 gene also have a delayed onset of kidney disease.

Our studies identify TRPC6 as a disease gene causing hereditary FSGS. Because ion channels tend to be amenable to pharmacological manipulation, our study raises the possibility that TRPC6 may be a useful therapeutic target in treating chronic kidney disease.

References and Notes
14. The HEK 293 cell line was originally derived from human embryonic kidney tissue, and its morphological features bear little or no resemblance to those of mature renal cell lineages. Thus, the absence of TRPC6 expression in HEK cells probably has little bearing on whether the protein is actually expressed in mature kidney tissue. Examples of this phenomenon are the angiotensin receptors, which are not expressed in HEK cells but are expressed throughout the kidney.
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References and Notes
Fig S1 to S5
Table S1
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