Long-QT syndrome (LQTS) is a rare cardiac disorder characterized by abnormal ventricular repolarization and a prolonged QT interval on the ECG. Clinically, two inherited forms of LQTS have been defined: autosomal dominant Romano-Ward syndrome and autosomal recessive Jervell and Lange-Nielsen (JLN) syndrome. Patients with both Romano-Ward and JLN syndrome are predisposed to syncope, seizures, and sudden death, typically due to polymorphic ventricular tachycardia (torsade de pointes). In addition, the JLN syndrome is associated with congenital bilateral deafness, and these patients often have a more prolonged QTc on surface ECGs. Romano-Ward syndrome is genetically heterogeneous, with at least four different known loci. Recently, homozygous mutations of one of these, KVLQT1, were reported to be responsible for JLN syndrome in three families. However, it is also clear that the disease genes in certain JLN families are not linked to the KVLQT1 locus. Thus, JLN syndrome must also be a genetically heterogeneous group of clinically related disorders.

IsK, an apparent potassium channel regulatory subunit encoded by the KCNE1 gene on chromosome 21, has recently been shown to coassemble with both K̂,LQT1, to produce the slowly activating cardiac delayed rectifier K⁺ current, Iₚ, and HERG, to regulate the rapidly activating cardiac delayed rectifier K⁺ current, Iₖ. This relationship makes KCNE1 an attractive candidate gene for LQTS, because mutations of both KVLQT1 and HERG are known to cause LQTS. Originally cloned from rat kidney, the human KCNE1 gene encodes a 129-amino-acid protein with a single putative transmembrane domain. Thus far, IsK has no sequence homology with other cloned channel subunits. Like K̂,LQT1, IsK is expressed in many tissues, including heart and inner ear. A recent study reported a knockout mouse strain with a disruption of the endogenous Knel coding sequence and absence of IsK protein. Although heterozygous mice appear normal, homozgyous null mutant mice are deaf and exhibit classic shaker/waltzer behavior. Both IsK knockout mice and
JLN patients appear to have similar developmental defects involving the strial marginal cells of the cochlea capsule, resulting in deficient endolymph production and congenital deafness. These findings support the idea that mutations in IsK may be responsible for JLN syndrome. To test this hypothesis, 84 Romano-Ward and 4 JLN patients were examined for possible mutations of KCNE1.

Methods

Clinical History of Family LQTS086

The proband (LQTS086–001) is an 8½-year-old girl who presented to the emergency room at age 3½ years after a syncopal spell while sliding into a pool. Syncope was preceded by a gasp and followed by near drowning after she lost consciousness. She had a history of recurrent syncopal events beginning at 2 years of age, including a near drowning after she lost consciousness. She had a history of syncope, palpitations, seizures, hearing loss/deficiency, and sudden cardiac death, as well as surface ECGs, exercise tests (if available), and beat-to-beat variation of T-wave morphology in leads II

DNA Collection and KCNE1 Mutation Analysis

Genomic DNA was prepared from peripheral blood lymphocytes with the Puregene DNA Isolation kit (Gentra Systems, Inc). Initial polymerase chain reaction (PCR) assays used primers 1F, 2R, 3F, and 4R of Tesson et al. To amplify additional portions of the human KCNE1 gene, primers 5F (5'-GGCCGCTGACAGCTGGAAC CTT-3') and 6R (5'-TTGATGTTGTCGTTGAGTG-3') were designed on the basis of a published full-length cDNA sequence (Genbank M26685; all base numbers in this report are based on this sequence) (Fig 2A). These primers amplify a product of 268 nucleotides containing 11 bp of 5' untranslated region and codons 1 to 72. The primer 8R (5'-TTTACAGTGTTGGGTT-3') was also designed and paired with previously published primer 3F (5'-TA CATCCGCTCAAGAG-3'). These primers amplify a product of 216 nucleotides, including the final 57 codons (eq. 71 to 129) of KCNE1. The promoter and other transcriptional control elements are not included in these assays.

Figure 1. ECG tracing from proband (LQTS086–001) at 7 years of age just before surgery, illustrating prolonged QT intervals and beat-to-beat variation of T-wave morphology in leads II (above) and V6 (below).

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Single-strand conformational polymorphism (SSCP) analysis, band elution, and DNA sequencing were performed essentially as described. Products were also analyzed on two types of 0.5X MDE gels (FMc Bioproducts), with and without 5% glycerol, run at room temperature at 8 W for 12 to 14 hours.

To confirm the presence of the D76N mutation, a restriction digest assay was designed using primers 9F (5'-CTCTAGGCTCTAGCTAGTACTG-3') and 10R (5'-CGATGATAGCTGAATGAGT-3'). These primers amplify a 115-bp product containing the mutated site. Primer 10R is mismatched at nucleotide 257, producing a T instead of a wild-type C three bases downstream from the mutation. This mismatch produces a HinfI restriction site (GACTC) in the wild-type KCNE1 gene at position 254. The D76N mutation (G254A) abolishes this restriction site. Wild-type PCR products are cleaved by HinfI at position 184 and at 254 to give a predominant product of 71 bp, whereas aberrant products containing the D76N mutation will be cleaved only at position 184, generating a 91-bp product. Genomic DNA samples were amplified with primers 9F and 10R as described at an annealing temperature of 58°C. A 3-mL volume containing 3 U HinfI, 3 X BSA, and 3 X restriction enzyme buffer II (New England Biolabs) was added to each 10-mL reaction and incubated at 37°C for 3 hours. PCR products were separated on DNA sequencing gels and visualized with autoradiography.

Direct sequencing of the KCNE1 gene was performed on PCR products of primer pairs 5F/6R and 3F/8R on an ABI 377 DNA sequencer after purification with Wizard PCR preparation kits (Promega).

Results

To test the hypothesis that IsK may be mutated in patients with LQTS, we used SSCP analyses to screen KCNE1 in a panel of affected individuals with Romano-Ward or JLN syndrome. Initial SSCP analyses using primers 1F/2R identified two affected individuals with Romano-Ward or JLN syndrome. To allow inclusion of the trans-
individuals screened, 95% were homozygous for guanine-112 and 5% were heterozygous for the change.

A novel anomalous conformer was identified in one DNA sample (LQTS086–001) from the panel of LQTS patients (Fig 2B). The patient has a diagnosis of JLN as described above. The aberrant conformer was not observed in any of the 84 patients with Romano-Ward syndrome or the 3 other JLN patients.

DNA sequence analysis of the aberrant conformer revealed a G-to-A transition at nucleotide 254 that is predicted to create a nonconservative missense mutation of aspartic acid to asparagine at codon 76 (D76N) (Fig 2C). The aspartic acid at position 76 is close to the putative transmembrane region in the intracellular carboxyl-terminal domain of IsK,14 and this residue is completely conserved in mammalian IsK genes (Fig 3).

Because the SSCP shift was subtle and difficult to appreciate on gels containing the normal control PCR products, a PCR restriction digest assay was designed to allow unambiguous identification of the mutation. The D76N mutation was not detected in DNA samples from 104 North American control individuals with no clinical signs of LQTS (Fig 2D). The proband was homozygous for the change, whereas her mother and half sister were both heterozygous for this mutation. Additional family members were not available for study.

Because the sensitivity of SSCP analysis is well below 100%, we amplified by PCR and directly sequenced the KCNE1 genes of all JLN probands to look for additional mutations that might have been missed in the initial screen. The D76N mutation was readily identified in both the homozygous patient and her heterozygous mother and half sister. None of the other three unrelated JLN patients had any identifiable mutations in their KCNE1 genes.

Discussion

The identification of KvLQT1 and HERG as major structural subunits of the $I_{Ks}$ and $I_{Kr}$ channels established that abnormalities of these currents were responsible for LQTS.11,12,23 Therefore, it was logical to speculate that mutations of IsK, a probable regulatory subunit that associates with KvLQT111,12 and HERG,13 might also be involved in causing heritable defects in cardiac repolarization. The present data implicate the KCNE1 gene as a fifth locus for LQTS (LQT5). A unique missense mutation, D76N, was found in a homozygous patient with JLN syndrome and was not detected in 104 normal
control individuals. The proband’s DNA was also included in screens of the other three known LQTS genes, KVLQT1, HERG, and SCN5A, and no mutations were identified (data not shown). The patient’s clinical presentation included congenital deafness, extremely prolonged QT intervals, and recurrent syncopal events that were refractory to β-blockade, eventually necessitating surgical intervention. It may be that this relatively severe clinical picture is related to the fact that IsK most likely regulates both the I\textsubscript{Ks} and I\textsubscript{Kr} currents. Coinjection of D77N IsK proteins were expressed and incorporated efficiently in the plasma membrane, yet these peptides exhibited a drastic reduction in channel activity resulting in syncope, seizures, partial hearing loss, and/or prolonged QT intervals. These findings are consistent with previous reports of JLN pedigrees in which homozygous individuals have severe cardiac disease and complete hearing loss, whereas obligate heterozygotes may have a milder phenotype more closely resembling the Romano-Ward form of LQTS.5,7,9,24

A previous study did not find evidence for involvement of IsK in JLN syndrome in four autosomal recessive JLN families,8 and subsequently, these workers did identify a frame shift mutation in the carboxyl terminus of K\_LQT1 for two of their four JLN families. However, linkage data for both KCNE1 and KVLQT1 were inconclusive in the two remaining families. Although our initial screen failed to detect any aberrant conformers, a slight change in the location of primer 4R (eg, 8R) resulted in increased sensitivity for the G-to-A transition at nucleotide 254, leading to our identification of this mutation. This illustrates how the sensitivity of SSCP analysis can be altered in unpredictable ways by apparently subtle changes to the assay conditions. To date, we have found a homozygous KVLQT1 mutation in one of the remaining three JLN families (unpublished data, 1997), but the apparent absence of mutations in the other two suggests the possibility of additional genetic heterogeneity in this disorder.

There have been numerous previous studies of IsK structure and function; however, many of these are difficult to interpret because they were performed before the appreciation that IsK is probably a regulatory subunit and not a primary (alpha) channel subunit. Nevertheless, studies performed in Xenopus oocytes recorded currents that result from the coassembly of IsK and an endogenous K\textsubscript{v}LQT1-like peptide and probably reflect true functions of IsK. Fortuitously, the rat equivalent of the D76N mutation was identified from the coassembly of IsK and an endogenous K\textsubscript{v}LQT1-like peptide and probably reflect true functions of IsK.

Rat D77N IsK proteins were expressed and incorporated efficiently in the plasma membrane, yet these peptides exhibited a drastic reduction in channel activity resulting in virtually undetectable potassium currents.25 Coinjection of equal amounts of D77N and wild-type mRNAs resulted in only a small fraction of the current seen with wild-type protein alone, suggesting that incorporation of a single mutant IsK subunit was sufficient to disrupt channel function and possibly explaining the dominant phenotype seen in family LQTS086.26 Functional studies of D76N mutant human IsK coexpressed with human K\_LQT1 will be important to determine the molecular mechanism of this relationship as well as to prove that human IsK-D76N has a pathological effect on I\textsubscript{Kr} currents. Identification of additional KCNE1 mutations in LQTS patients will also confirm this relationship and provide new insights into the structure and function of IsK.

In the absence of information on the proband, the mother and half sister of family LQTS086 would probably have been given a diagnosis of Romano-Ward syndrome. Therefore, as is the case for KVLQT1, mutations of IsK should be looked for in patients with either the Romano-Ward or the JLN forms of LQTS. We suggest that the KCNE1 gene, which encodes the IsK protein, be designated as a fifth LQTS locus, LQT5.

Note Added in Proof

KCNE1 mutations in patients with LQTS have also recently been reported by Schultzz-Bahr et al. and Splawski et al. (Nat Genet. 1997;17:267–268 and 338–340, respectively).

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References


Mutation of the Gene for \( L_{\text{sk}} \) Associated With Both Jervell and Lange-Nielsen and Romano-Ward Forms of Long-QT Syndrome

Priya Duggal, Mark R. Vesely, Duangrurdee Wattanasirichaigoon, Juan Villafane, Vineet Kaushik and Alan H. Beggs

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