Drug-Induced Long-QT Syndrome Associated With a Subclinical SCN5A Mutation

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Background—Subclinical mutations in genes associated with the congenital long-QT syndromes (LQTS) have been suggested as a risk factor for drug-induced LQTS and accompanying life-threatening arrhythmias. Recent studies have identified genetic variants of the cardiac K⁺ channel genes predisposing affected individuals to acquired LQTS. We have identified a novel Na⁺ channel mutation in an individual who exhibited drug-induced LQTS.

Methods and Results—An elderly Japanese woman with documented QT prolongation and torsade de pointes during treatment with the prokinetic drug cisapride underwent mutational analysis of LQTS-related genes. A novel missense mutation (L1825P) was identified within the C-terminus region of the cardiac Na⁺ channel (SCN5A). The L1825P channel heterologously expressed in tsA-201 cells showed Na⁺ current with slow decay and a prominent tetrodotoxin-sensitive noninactivating component, similar to the gain-of-function phenotype most commonly observed for SCN5A-associated congenital LQTS (LQT3). In addition, L1825P exhibited loss of function Na⁺ channel features characteristic of Brugada syndrome. Peak Na⁺ current density observed in cells expressing L1825P was significantly diminished, and the voltage dependence of activation and inactivation was shifted toward more positive and negative potentials, respectively.

Conclusions—This study demonstrates that subclinical mutations in the LQTS-related gene SCN5A may predispose certain individuals to drug-induced cardiac arrhythmias. (Circulation. 2002;106:1269-1274.)

Key Words: long-QT syndrome • drugs • genetics • torsade de pointes • ion channels

Congenital long-QT syndrome (LQTS) is a rare inherited disorder of cardiac repolarization that predisposes affected individuals to life-threatening arrhythmias. The molecular basis of LQTS is the prolongation of action potential duration attributable to defects in several ion channel genes encoding delayed rectifier K⁺ currents (I_K) or Na⁺ current (I_Na).¹ The cardiac Na⁺ channel α subunit gene SCN5A is responsible for a subgroup of LQTS (LQT3),²,³ idiopathic ventricular fibrillation (IVF), or Brugada syndrome (BrS).⁴,⁵ The cellular mechanism for QT prolongation in most LQT3 is believed to be persistent Na⁺ current during the action potential plateau attributable to the defects in Na⁺ channel fast inactivation (gain of function) that delay repolarization.⁶ Pathophysiological mechanisms underlying BrS include diminished myocardial Na⁺ current (loss of function) and a resultant increase in transmural voltage gradient and ST-elevation on ECG.⁷

Acquired LQTS, on the other hand, is a more prevalent disorder and is often caused by several drugs that preferentially block the rapid component of delayed rectifier K⁺ current (I_Kr).⁸,⁹ However, development of drug-induced LQTS is unpredictable and most likely occurs in a subset of susceptible individuals. It is therefore suggested that these individuals have a genetic substrate possibly involving cardiac ion channels that determine the susceptibility to life-threatening arrhythmias yet whose phenotype remains clinical until drug exposure.

Recent studies indicate that drug-induced torsade de pointes (TdP) can be associated with silent mutations and common polymorphisms in K⁺ channel genes responsible for congenital LQTS.¹⁰–¹² In this study we describe the first reported case of drug-induced LQTS associated with a novel SCN5A mutation (L1825P) and characterize its functional consequences. Despite the patient’s normal QT interval before exposure to cisapride and the anticipated normal sodium channel function, the heterologously expressed Na⁺ channel mutant L1825P exhibited severe abnormalities characteristic of both LQT3 and IVF/BrS. Our study suggests that...
subclinical mutations or polymorphisms in SCN5A may predispose to life-threatening drug-induced arrhythmias.

Methods

Patient
A 70-year-old woman was admitted to the hospital because of recurrent syncope. She had been treated with acebutolol (200 mg/d) and pirmenol (200 mg/d) for hypertension and frequent premature ventricular contractions, respectively. Her ECG while taking these medications exhibited complete right bundle-branch block (CRBBB) and a normal QT interval (QTc, 435 ms, Figure 1A). Soon after the addition of cisapride (5 mg/d) because of bowel transit dysfunction, she experienced general malaise and syncope. ECG telemetry on admission showed severe bradycardia (junctional rhythm, heart rate ~30 bpm) with QT prolongation (QTc, 480 ms) and repetitive TdP (Figure 1B). Emergency pacing was performed (pacing rate, 80 bpm) at the first day. Marked QT prolongation was observed (QTc, 731 ms). It was shortened the next day after withdrawal of drugs (QTc, 594 ms). QT interval was normalized at the sixth day (QTc, 417 ms). D, ECG recordings on V2 lead during treadmill exercise test before exercise and at the maximum exercise are shown. Heart rate was increased from 66 to 93 bpm, and the QTc was prolonged from 408 to 457 ms.

Figure 1. Electrocardiographic findings of the patient. A, ECG recording obtained from the proband during treatment with acebutolol and pirmenol before prescription of cisapride. Normal sinus rhythm (heart rate, 73 bpm) with complete right bundle-branch block was evident, and the QT interval was within normal limits (QTc, 435 ms). B, ECG telemetry on admission showed severe bradycardia after prescription of cisapride (junctional rhythm, heart rate ~30 bpm) with QT prolongation (QTc, 480 ms) and repetitive TdP. C, Time course of QT interval. Emergency pacing was performed (pacing rate, 80 bpm) at the first day. Marked QT prolongation was observed (QTc, 731 ms). It was shortened the next day after withdrawal of drugs (QTc, 594 ms). QT interval was normalized at the sixth day (QTc, 417 ms). D, ECG recordings on V2 lead during treadmill exercise test before exercise and at the maximum exercise are shown. Heart rate was increased from 66 to 93 bpm, and the QTc was prolonged from 408 to 457 ms.
Molecular Genetics
Genomic DNA was extracted from peripheral blood leukocytes by a standard method. All exons of SCN5A were amplified by polymerase chain reaction (PCR) using primers designed by Wang et al. and analyzed by single-strand conformational polymorphism (SSCP), as previously reported. Genetic screening of KCNQ1, HERG, KCNE1, and KCNE2 was carried out as previously described. The PCR product showing an aberrant conformer was subcloned into pGEMTEasy (Promega), and multiple independent clones were sequenced using an ABI Prism 310 genetic analyzer (Applied Biosystems).

Site-Directed Mutagenesis and Electrophysiology
Wild-type (WT) human heart sodium channel α subunit (hH1) cDNA was subcloned into the pRcCMV plasmid (Invitrogen). Site-directed mutagenesis of hH1 was performed by an overlap-extension PCR strategy, as described. A 183-bp HindIII/SacII fragment (No. 5290-5473 of hH1) of the mutant PCR fragment was subcloned back into the pRcCMV-WT plasmid to generate a mutant plasmid pRcCMV-L1825P. Correct assembly of the mutant was verified by restriction analysis, and the mutated regions generated by PCR were sequenced completely to identify clones without polymerase errors. The human cell line tsA-201 was transiently transfected using the calcium phosphate method in combination with a bicistronic plasmid plasmid pCD8-IRES-hH1α to express CD8 and the human heart sodium channel α subunit (hH1α) encoding CD8 and the β1 subunit (hβ1). To visually identify cells expressing heterologous hH1α channel with CD8, Dynabeads M-450 CD8 (Dynal).

Na+ currents were recorded 24 to 72 hours after transfection using the whole-cell patch-clamp technique and analyzed, as we described elsewhere. The holding potential was −120 mV unless otherwise stated, and details of each pulse protocol are described elsewhere. The holding potential was 0 mV for test pulse potentials of −20 mV to measure the peak current in all cases. The experiments were performed at 34 °C (data not shown). Macroscopic current decay fit was derived according to the biexponential function revealed that the fraction of slowly inactivating component (A1) was significantly larger and the time constants for both fast and slow components (τf, τs) were significantly larger in L1825P relative to WT at all test pulse potentials (P < 0.001).

Results

Molecular Genetics
Initial SSCP analysis was performed to screen for genetic variations in the LQTS-related K+ channel genes KCNQ1, HERG, KCNE1, and KCNE2. Because aberrant conformers were not detected in these genes, we screened SCN5A. An aberrant SSCP conformer was identified in exon 28 of the proband. DNA sequencing confirmed a T to C transition leading to amino acid substitution of proline for leucine1825 (L1825P; Figure 2B) located within the C-terminal region of hH1 (Figure 2C). The amino acid residue corresponding to L1825 of SCN5A is highly conserved among different Na+ channel isoforms (Figure 2D). This sequence variation was not observed in 200 normal chromosomes, consistent with a disease-related mutation. Heterozygous state of the proband and the WT sequence of the proband’s sister were confirmed by direct sequencing of the genomic DNA (data not shown).

Functional Analysis of the L1825P Mutation
Because the basal QT-interval of the patient was normal, it was expected that functional defects exhibited by the L1825P mutant channel, if any, might be minor when heterologously expressed in mammalian cells. Contrary to this assumption, the recombinant L1825P channel showed profound biophysical abnormalities. Figure 3A illustrates representative whole-cell current traces from cells expressing WT or L1825P Na+ channels in the presence of coexpressed hβ1. Current density of L1825P channel measured at test pulse potential of −20 mV was approximately one third of WT (WT, 459 ± 99 pA/pF; n = 13; L1825P, 136 ± 21 pA/pF; n = 12; P < 0.001). L1825P showed a robust persistent late current and slower current decay. The amplitude of the persistent late current after 200 ms of depolarization at −20 mV was approximately 8-fold larger in L1825P (WT, 0.32 ± 0.05% of the peak current, n = 15; 2.56 ± 0.27%, n = 22; P < 0.001), and it was almost completely abolished by either 30 μmol/L tetrodotoxin (Figure 3B) or 10 μmol/L mexiletine but was not affected by higher temperature at 34°C (data not shown). Macroscopic current decay fit with a biexponential function revealed that the fraction of slowly inactivating component (A1) was significantly larger and the time constants for both fast and slow components (τf, τs) were significantly larger in L1825P relative to WT at all test pulse potentials (P < 0.05).
test pulse voltages between −40 and 30 mV (Figure 3C). These data suggest that the onset of inactivation was significantly slowed and was incomplete in L1825P.

The voltage dependence of steady-state inactivation of L1825P showed a significant hyperpolarizing shift (V_{1/2}: WT, −91.0±1.3 mV, n=13; L1825P, −102.0±1.1 mV, n=16; P<0.001) (Figure 4A). Conversely, voltage dependence of activation of L1825P significantly shifted toward depolarizing direction (V_{1/2}: WT, −47.2±1.1 mV; L1825P, −38.3±0.74 mV; P<0.001). Slope factors for both inactivation and activation were significantly larger in L1825P (k_{\text{act}}: WT, 6.93±0.23 mV; L1825P, 8.78±0.23 mV, P<0.001; k_{\text{inact}}: WT, −6.08±0.26 mV; L1825P, −8.48±0.16 mV; P<0.001) (Figure 4A). Large negative shift of steady-state inactivation and positive shift of activation do not alter the point at which 2 curves cross; however, they do result in larger window current than WT, probably attributable to noninactivating Na⁺ channel even at higher prepulse potentials (Figure 4B).

Recovery from inactivation was assessed by a standard double-pulse protocol using a recovery potential of −120 mV. Although the time constants of either fast or slow recovery components were comparable between WT (n=12) and L1825P (n=16) (τ₁: WT, 10.8±2.0 ms; L1825P, 9.5±0.4 ms; τ₂: WT, 154±28 ms; L1825P, 181±27 ms), the fraction of the slow component (A₂) was significantly larger in L1825P (WT, 0.16±0.02; L1825P, 0.25±0.02; P<0.01), indicating that the recovery from inactivation was significantly slower in L1825P (Figure 4C). The severe abnormalities in activation and fast inactivation gating properties exhibited by L1825P will potentially result in greater reduction in Na⁺ channel availability during excitation.

In addition to the dysfunction of activation and fast inactivation, some mutant Na⁺ channels associated with IVF/BrS show defects in inactivation kinetics intermediate between fast and slow inactivation, referred to as I_k, which is now recognized as an important biophysical feature underlying certain Na⁺ channelopathies. The voltage dependence of steady-state inactivation of L1825P was virtually identical to WT (Figure 4D).

Although L1825P channel shows slower open-state inactivation, a population of Na⁺ channels enters an inactivated state without channel opening by a mechanism called closed-state inactivation. Closed-state inactivation greatly affects the availability of the channels at voltages near the resting membrane potentials, thereby controlling the Na⁺ current amplitude of the action potential. The time course of the development of closed-state inactivation at −100 mV was significantly facilitated in L1825P (Figure 4E). These data suggest that a substantial fraction of L1825P channels are inactivated at voltages near the resting potential.

To test whether the I_k blocker cisapride has direct effects on Na⁺ channels, 1 μmol/L cisapride, a sufficient concentration to block I_k, was applied to the bath solution. However, cisapride did not change the peak Na⁺ current in either WT or L1825P channels (% control; WT, 99.8±3.6%, n=6; L1825P, 88.8±4.3%, n=8; NS). Cisapride failed to change the kinetics or the amplitude of the persistent Na⁺ current in either WT or L1825P, confirming that cisapride-induced QT prolongation in the proband was mediated through mechanisms other than direct effects on cardiac Na⁺ channels. We also examined the effect of the Na⁺ channel blocker pirmenol, which the proband had been actively taking by the time she developed TdP. However, 10 μmol/L pirmenol did not affect the persistent late current of L1825P, whereas it
Figure 4. Gating properties of L1825P mutant channels. A, Steady-state availability for inactivation and conductance-voltage relationship were measured with standard pulse protocols, as shown in the inset. Curves were fit with the Boltzmann equation, \( I/Imax = \frac{1 - \exp(-V - V1/2)}{exp(V - V1/2)} \), to determine the membrane potential for half-maximal inactivation or activation (\( V1/2 \)) and the slope factor \( k \).

Data for WT and L1825P are shown with ○ and ●, respectively. B, Close-up of the window region. C, Recovery from inactivation was measured by a double-pulse protocol shown in the inset and analyzed by fitting data to two exponentials: \( I/I_{\text{max}} = A_0 \times [1 - \exp(-t/t_f)] + A_1 \times [1 - \exp(-t/t_s)] \). Data for WT and L1825P are shown with ○ and ●, respectively. D, Onset of slow inactivation was measured by a double-pulse protocol shown in the inset. A brief repolarization pulse was applied to allow most fraction of the channels recover from fast inactivation. Curve was well fit with a single exponential equation. Time courses of slow inactivation of WT (○) and L1825P (●) were nearly identical. E, Closed-state inactivation was measured by a double-pulse protocol in the inset. Cells were prepulsed to −100 mV for various durations from a holding potential of −150 mV and then stepped to −20 mV to determine the availability of \( I_{\text{Kr}} \) during the prepulse. Time course for development of closed-state inactivation were fit with the following monoexponential equation: \( I/I_{\text{max}} = y_0 + A_0 \times \exp(-t/t_f) \). L1825P channels showed significantly larger extent of closed-state inactivation (WT, \( A = 0.28 \pm 0.03 \), \( n = 20 \); L1825P, \( A = 0.80 \pm 0.03 \), \( n = 5 \); \( P < 0.001 \)) and slower time constant (WT, \( t_f = 96.4 \pm 9.9 \) ms; L1825P, \( t_f = 41.8 \pm 8.4 \) ms; \( P < 0.02 \)) than WT.

Discussion

Drug-induced LQTS is a prevalent life-threatening disorder with uncertain etiologies but shares substantial clinical features with congenital LQTS. It has been inferred that a subset of individuals with normal or borderline QT-interval may carry subclinical mutations in LQTS disease genes and are susceptible to life-threatening arrhythmias on drug exposure.21,22 In fact, several lines of evidence have suggested genetic variations of LQTS-related K⁺ channel genes.10–12 Our study suggests that Na⁺ channel mutations can predispose apparently stable patients to life-threatening arrhythmias when treated with agents that inhibit K⁺ channels.

Rodet et al3 hypothesized repolarization reserve as a potential mechanism underlying susceptibility to drug-induced LQTS. The cardiac action potential is orchestrated by a fine balance between inward and outward currents expressed in myocardial cells. The action potential duration is prolonged by either an increase of inward currents or a decrease of outward currents. Because the outward currents consist of multiple distinct K⁺ currents, such as \( I_{\text{Na}} \), \( I_{\text{K}} \), or \( I_{\text{Kr}} \), K⁺ channel dysfunction attributable to mutations or polymorphisms could be potentially compensated by other K⁺ currents, and thereby the repolarization is tolerated (repolarization reserve). To extrapolate this hypothesis, it is assumed that repolarization reserve allows the dysfunction of the L1825P mutation to be tolerated until the time of drug exposure. However, administration of cisapride blocked \( I_{\text{Kr}} \) and exhausted the repolarization reserve, leading to manifest the action potential prolongation and TdP. There are several lines of evidence supporting the existence of functional interplay between Na⁺ and outward K⁺ currents in the in vivo myocardium. Using a canine perfused ventricular wedge model, Shimizu et al24 have shown that mexiletine reduced transmural dispersion of repolarization and prevented TdP in the LQT2 model as well as in LQT3. Moreover, K⁺ channel opener nicorandil prevents TdP in congenital or acquired models of LQT1, LQT2, and LQT3.25 The functional association between gain of function of \( I_{\text{Kr}} \) and loss of function of \( I_{\text{Kr}} \) attributable to cisapride may be responsible for the manifestation of drug-induced QT prolongation in the present case.

Moreover, QT-prolonging drugs usually require multiple risk factors, such as hypokalemia, female sex, or slow heart rate to manifest life-threatening arrhythmias.1 In the present case, bradycardia, presumably induced by acebutolol, was the additional risk factor to trigger QT prolongation and TdP. Another explanation is that the contribution to persistent Na⁺ current of L1825P to the cardiac action potential duration may be relatively small, because the persistent current is offset by the concomitant loss of function phenotype (Figures 4A, 4D, and 4E). Alternatively, biophysical dysfunctions of the L1825P allele could be functionally compensated by the WT allele. Furthermore, manifestation of LQTS is variable and seems to be determined in genotype-specific, mutation-specific, or individual-specific manners, and up to 75% of the
gene carriers show normal QT interval. It is speculated that this condition could be a congenital LQTS with an SCN5A mutation that exhibits reduced penetrance. Moreover, contribution of other genes, such as P450 3A4, a major metabolizing enzyme of cisapride, remains to be examined.

Mutations in SCN5A result in multiple arrhythmic syndromes, including LQT3, \textsuperscript{1-3} IVF/BrS, \textsuperscript{4-5} an inherited cardiac conduction defect, \textsuperscript{6-7} and sudden infant death syndrome, \textsuperscript{8-9} constituting a spectrum of disease entities termed cardiac Na\textsuperscript{+} channelopathies. \textsuperscript{10} Heterologously expressed L1285P channels exhibit biophysical properties strikingly similar to an SCN5A mutation 1795insD found in an unusual LQT3 family, in which affected individuals exhibited rate-dependent QT prolongation and ST elevation. \textsuperscript{11} The L1285P and 1795insD mutations, both located at the C-terminal of the Na\textsuperscript{+} channel, share the following biophysical properties: (1) prominent persistent late Na\textsuperscript{+} current; (2) negative shift of steady-state inactivation; and (3) decreased current density. These results suggest that LQT3 and IVF/BrS are closely related Na\textsuperscript{+} channelopathies with overlapping phenotypes and that L1285P is another example of a mutation that can explain this clinical overlap. Nonetheless, clinical manifestations of these 2 mutations are not identical. Exercise-induced ST elevation observed in 1795insD was not evident in L1285P despite the fact that both channels exhibited BrS-like properties. This phenotypic difference in ST elevation may be attributed to the difference in the kinetics of \(I_{\text{Na}}\), the physiological mechanism for the rate-dependent ST elevation in 1795insD, \textsuperscript{12} but it was not evident in L1285P.

In summary, we propose that subclinical mutations in the LQTS-related gene SCN5A may predispose the subset of individuals to life-threatening arrhythmias during drug therapy.

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