Mutation in the \textit{KCNQ1} Gene Leading to the Short QT-Interval Syndrome

Chloé Bellocq, BSc; Antoni C.G. van Ginneken, PhD; Connie R. Bezzina, PhD; Mariel Alders, PhD; Denis Escande, MD, PhD; Marcel M.A.M. Mannens, PhD; Isabelle Baró, PhD; Arthur A.M. Wilde, MD, PhD

\textbf{Background}—The electrocardiographic short QT-interval syndrome forms a distinct clinical entity presenting with a high rate of sudden death and exceptionally short QT intervals. The disorder has recently been linked to gain-of-function mutation in \textit{KCNH2}. The present study demonstrates that this disorder is genetically heterogeneous and can also be caused by mutation in the \textit{KCNQ1} gene.

\textbf{Methods and Results}—A 70-year man presented with idiopathic ventricular fibrillation. Both immediately after the episode and much later, his QT interval was abnormally short without any other physical or electrophysiological anomalies. Analysis of candidate genes identified a g919c substitution in \textit{KCNQ1} encoding the K$^+$ channel KvLQT1. Functional studies of the KvLQT1 V307L mutant (alone or coexpressed with the wild-type channel, in the presence of IsK) revealed a pronounced shift of the half-activation potential and an acceleration of the activation kinetics leading to a gain of function in I_{Ks}. When introduced in a human action potential computer model, the modified biophysical parameters predicted repolarization shortening.

\textbf{Conclusions}—We present an alternative molecular mechanism for the short QT-interval syndrome. Functional and computational studies of the \textit{KCNQ1} V307L mutation identified in a patient with this disorder favor the association of short QT with mutation in \textit{KCNQ1}. (\textit{Circulation}, 2004;109:2394-2397.)

\textbf{Key Words:} death, sudden \textbullet genetics \textbullet arrhythmia \textbullet ion channels \textbullet fibrillation, ventricular

In recent years, extensive progress has been made in unraveling the pathophysiology of the monogenic arrhythmia syndromes among which are long-QT syndrome, Brugada syndrome, and catecholaminergic polymorphic ventricular tachycardia. The latest addition to this class of disorders is the description of families with a high rate of sudden death and exceptionally short QT intervals, recently attributed to gain-of-function mutation in \textit{KCNH2}. In this study, we demonstrate that this disorder is genetically heterogeneous and can also be caused by mutation in the \textit{KCNQ1} gene that encodes the KvLQT1 K$^+$ channel, which, in association with the $\beta$-subunit IsK, forms the slow component of the cardiac delayed rectifier K$^+$ current (I_{Ks}).

\textbf{Methods}

\textbf{Patient Characteristics}

A 70-year-old man was successfully resuscitated after a ventricular fibrillation episode. He had been without complaints up until then, and his family history was unremarkable. Physical examination revealed no abnormalities. His ECG is presented in Figure 1. Sinus rhythm was present with normal conduction intervals and a QT interval of 290 ms (QTc, 302 ms). Similarly short QT intervals were observed on every ECG up to 3 years of follow-up. Biochemical analysis at the time of admission, including echocardiography, exercise testing, coronary angiography, left (LV) and right ventricular (RV) angiography, scintigraphy, and ergonovine coronary spasm test, revealed no abnormalities. Nuclear LV ejection fraction was 49%. During electrophysiological study, no arrhythmias could be induced. The electrophysiology protocol used was ventricular stimulation from two sites (RVA, RVOT), with 2 cycle length (600, 430 ms) and up to 2 extras (coupling interval $\geq$ 180 ms with capture, effective refractory period $\leq$ 180 ms). LV myocardial biopsies revealed no abnormalities.

\textbf{Genetic Studies}

Genetic studies were approved by the Medical Ethical Committee of the Academic Medical Center. Mutation screening of the coding region of the \textit{KCNQ1} (minK, IsK), \textit{KCNQ2} (MIRP1), \textit{KCNH2} (HERG), and \textit{KCNQ1} (except for exon 1) genes was performed either by direct sequencing, single-strand conformation polymorphism analysis followed by sequencing of aberrant conformers, or denaturing high-performance liquid chromatography analysis followed by direct sequencing of fragments displaying an abnormal elution profile.

The \textit{KCNQ1} gene was analyzed in 200 unrelated control individuals to exclude the possibility that the identified \textit{KCNQ1} mutation (V307L) represented a common polymorphism. This was done by direct sequencing (n=86) or by denaturing high-performance liquid chromatography analysis (n=114) of the exon concerned.
Electrophysiological Analysis
The V307L KvLQT1 cDNA was subcloned from the pSGEM vector (a kind gift from Klaus Steinmeyer, Aventis Pharma Deutschland GmbH) into pCI-CMV. COS-7 cells were transfected with pRC-CMV-IsK and wild-type (WT) or V307L KvLQT1 construct in a ratio of 2:1. To mimic the heterozygous state, COS cells were transfected with pRC-CMV-IsK, and WT and V307L KvLQT1 constructs in a ratio of 2:0.5:0.5. To investigate further IsK-V307L KvLQT1 interactions, a ratio of pRC-CMV-IsK to V307L of 1:2 was also studied. In all cases, pEGFP (BD Biosciences Clontech) was cotransfected as reporter. Twenty-four hours after transfection, whole-cell currents were recorded at 35°C using the permeabilized-patch configuration. The pipette solution contained (in mmol/L) potassium gluconate 145, EGTA 1, and HEPES 10, and 0.2 to 0.4 μg/mL amphotericin B added extemporarily, pH 7.3 with KOH. The extracellular medium contained (in mmol/L) sodium gluconate 145, potassium gluconate 4, hemi-calcium gluconate 7 (free Ca²⁺: 1), hemi-magnesium gluconate 4 (free Mg²⁺: 1), HEPES 5, and glucose 5, pH 7.4 with NaOH. Patch-clamp data are presented as mean±SEM. Statistical significance was assessed by means of the Student t test or 2-way ANOVA when needed.

Computer Modeling
To investigate the impact of the altered characteristics of the V307L mutation on the ventricular action potential (AP), we used the human ventricular cell model of Priebe and Beuckelmann. Intracellular [Na⁺] and [K⁺] were kept constant, and steady-state values and time constants of activation and inactivation of all currents were precalculated and stored in look-up tables. Steady-state activation of I_{Na} was replaced by a Boltzmann equation to incorporate the findings with respect to half-activation voltage (V_{0.5}) and slope factor. For the calculations we used a fixed time step of 200 ms. The last AP of each 10-s run was analyzed.

Results
Genetic studies on the patient’s DNA excluded mutation in KCNE1, KCNE2, and KCNH2. Analysis of the KCNQ1 gene identified a G>C substitution at nucleotide 919 (GTG>CTG) leading to the substitution of the valine at position 307 by leucine (V307L), which was not detected in 400 normal chromosomes.

Illustrative WT and V307L KvLQT1 K⁺ currents recorded in the presence of IsK are shown in Figure 2A (a and c). The V307L channel produced a K⁺ current with an amplitude similar to WT (tail current density at 40 mV elicited by a prepulse from −80 mV to +40 mV for 1 s, 13.93±2.01 pA/pF for V307L and 10.58±1.67 pA/pF for WT [n=16 cells in each group; NS, t test]). As illustrated in Figure 2B, compared with WT, V_{0.5} for the mutant channel was more negative (P<0.001) and the slope of the voltage sensitivity was unchanged (17.40±1.19 and 16.09±1.00 for WT and V307L, n=9 and 14 cells, respectively; NS). In addition, activation kinetics were accelerated at each potential as depicted in Figure 2A and 2C. When the activating current traces were fitted using a double exponential function, both fast (τ_{fast act}) and slow (τ_{slow act}) activation time constants were significantly decreased for the mutant (P<0.01, 2-way ANOVA for repeated measurements). The fast activating component contributed to ≈75% of the WT or V307L current at each potential. Kinetics of deactivating currents at various test-pulse potentials after depolarization to +60 mV were not significantly different between mutant and WT (not shown). Altogether, the shift in activation and the faster activation kinetics imply a gain of function for the mutant.

The effects of the V307L mutation were also evaluated in conditions mimicking the heterozygous state of the patient. As compared with WT alone, coexpression of WT
and mutant channels (Figure 2Ab and 2C) led to an accelerated activation of K⁺ current (P<0.01 for both time constants), whereas the current density was not different (tail current density at −40 mV, 11.79±0.80 pA/pF; n=13). In addition, compared with WT alone, activation was shifted toward more negative potentials (Vₐ₅ = −5.9 mV, s=17.4 mV; a), heterozygous expression (Vₐ₅ = −5.9 mV, s=19.86 mV, activation time constant tau set at 70% of WT; b), homozygous mutant expression with reduced IsK (Vₐ₅ = −5.9 mV, 40 mV, 11.79 pA/pF; n=9), and V₃₀₇L (c, c; n=14). C. Fast (τ_fast asc; bottom) and slow (τ_slow asc; top) activation time constants of WT (a, •; n=6 to 9), WT+V₃₀₇L (b, □; n=9), and V₃₀₇L (c, c; n=12 to 13, and d, •; n=9). D. Computer model of the ventricular AP. Stimulus pulse, 1 Hz, 2 ms, 2.9 nA. Steady-state activation was calculated by a Boltzmann function 1/(1+exp([Vₐ₅−V₅ₐ]/s)). Left panel, APs of WT (Vₐ₅ = −5.9 mV, s=17.4 mV; a), heterozygous expression (Vₐ₅ = −20.62 mV, s=10.96 mV, activation time constant tau set at 70% of WT; b), homozygous mutant expression (Vₐ₅ = −24.05 mV, s=16.9 0 mV, tau set at 52% of WT; c), and homozygous mutant expression with reduced IsK (Vₐ₅ and s as in c; tau set at 32% of WT [d]). AP durations at 50% repolarization were 280, 223.5, 206, and 177 ms, respectively. Right panel, Iₖₛ currents during APs in left panel.

Characteristics of WT, V₃₀₇L, and WT+V₃₀₇L KvLQT1/IsK currents. A, Superimposed currents activated by a 3-s prepulse to various potentials (from −100 to +60 mV, 20-mV increments) and repolarized by a 500-ms test-pulse to −40 mV (holding potential: −80 mV; 0.14 Hz). Current scale, 10 (a and c) or 20 (b and d) pA/pF. Time scale, 500 ms (left), 100 ms (right, time-expended framed zone). B, Current-voltage relation for the tail current of WT (a, •; n=9) and V₃₀₇L (c, c; n=9). C. Fast (τ_fast asc; bottom) and slow (τ_slow asc; top) activation time constants of WT (a, •; n=6 to 9), WT+V₃₀₇L (b, □; n=9), and V₃₀₇L (c, c; n=12 to 13, and d, •; n=9). D. Computer model of the ventricular AP. Stimulus pulse, 1 Hz, 2 ms, 2.9 nA. Steady-state activation was calculated by a Boltzmann function 1/(1+exp([Vₐ₅−V₅ₐ]/s)). Left panel, APs of WT (Vₐ₅ = −5.9 mV, s=17.4 mV; a), heterozygous expression (Vₐ₅ = −20.62 mV, s=10.96 mV, activation time constant tau set at 70% of WT; b), homozygous mutant expression (Vₐ₅ = −24.05 mV, s=16.9 0 mV, tau set at 52% of WT; c), and homozygous mutant expression with reduced IsK (Vₐ₅ and s as in c; tau set at 32% of WT [d]). AP durations at 50% repolarization were 280, 223.5, 206, and 177 ms, respectively. Right panel, Iₖₛ currents during APs in left panel.

Discussion

Herein we present an alternative molecular substrate for the short QT-interval syndrome. We demonstrate that gain-of-function mutation affecting Iₖₛ also results in shortening of the QT interval. Abbreviation of the AP, particularly when occurring inhomogeneously, should provide a substrate for reentrant arrhythmias. Because the contribution of Iₖₛ is different in the various cell layers of the heart, such inhomogeneity in AP duration is to be expected.

The V₃₀₇L mutation has previously been investigated in Xenopus oocytes, although in the absence of IsK. V₃₀₇L led to suppression of KvLQT1 inactivation, a characteristic that is exclusively observed in the absence of IsK. In the presence of IsK, we show that the major effects of the V₃₀₇L mutation, even in the heterozygous state, are an acceleration of the activation kinetics and a shift in the Vₐ₅ of activation, both effects leading to a gain of function. As a result, the K⁺ current resulting from association of WT and V₃₀₇L subunits can be recruited earlier during the AP. The studies involving different ratios of V₃₀₇L to IsK suggest that V₃₀₇L subunit trafficking is less dependent on the presence of IsK than WT even if its activation kinetics remain under the control of IsK.

A S₁₄₀G KCNQ1 mutation with gain-of-function characteristics was recently linked to familial atrial fibrillation. It is not immediately clear why the S₁₄₀G mutation, which has not been associated with shortened QT intervals. However, a major difference between the S₁₄₀G and the V₃₀₇L mutations is that the former leads to a time-independent current in the presence of IsK, whereas the latter conserves its time dependency. A time-independent K⁺ current is reminiscent of the current activated by acetylcholine in the atria that is known to precipitate atrial tachyarrhythmias.

Although the present report does not definitely prove a causal relation between the short QT interval, the occurrence of ventricular fibrillation, and the KCNQ1 mutation, circumstantial evidence for a causal relationship is provided on several levels. Firstly, the mutation has not been found in 200 control individuals. Secondly, it concerns a residue that is well conserved in different species. Thirdly, the observed basic electrophysiological characteristics associated with the mutation are expected to lead to enhanced repolarization with shortening of the QT interval.
Acknowledgments
This work was supported by the Fondation de France. Chloé Bellocq is financially supported by INSERM/Pays-de-Loire, Dr Bezzina by the Netherlands Heart Foundation (grant 2000.059), and Dr Wilde by the Dutch Organization for Scientific Research (grant 902-16-193) and Interuniversity Cardiology Institute of the Netherlands project 27. We thank Maxence Fretaud (U533) and Faranak Hosseininia-Salehi and Karin van der Lip (Academic Medical Center) for expert technical assistance.

References
Mutation in the KCNQ1 Gene Leading to the Short QT-Interval Syndrome
Chloé Bellocq, Antoni C.G. van Ginneken, Connie R. Bezzina, Mariel Alders, Denis Escande, Marcel M.A.M. Mannens, Isabelle Baró and Arthur A.M. Wilde

Circulation. 2004;109:2394-2397
doi: 10.1161/01.CIR.0000130409.72142.FE
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2004 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/109/20/2394

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/