A Common Antitussive Drug, Clobutinol, Precipitates the Long QT2 Syndrome

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tables: 1
figures: 8
references: 41

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Abbreviations
AP: action potential; HERG: human ether-a-go-go-related gene product; I_{Kr}: rapidly activating component of the cardiac delayed rectifier K^+ current; LQT: long-QT syndrome; QTc: rate-corrected QT interval
Abstract

QT prolongation, a classical risk factor for arrhythmias, can result from a mutation in one of the genes governing cardiac repolarization and also can result from the intake of a medication acting as blocker of the cardiac K+ channel HERG. Here, we identified the arrhythmogenic potential of a non-opioid antitussive drug, clobutinol. The deleterious effects of clobutinol were suspected when a young boy, diagnosed with congenital long QT syndrome, experienced arrhythmias while being treated with this drug. Using the patch-clamp technique, we showed that clobutinol dose-dependently inhibited the HERG K+ current with a half-maximum block concentration of 2.9 µM. In the proband, we identified a novel A561P HERG mutation. Two others LQT mutations (A561V and A561T) had previously been reported at the same position. None of the three mutants led to sizeable current in heterologous expression system. When co-expressed with wild-type (WT) HERG channels, the three A561 mutants reduced the trafficking of WT and mutant heteromeric channels resulting in decreased K+ current amplitude (dominant-negative effects). In addition, A561P but not A561V and A561T mutants induced an ≈ -11 mV shift of the current activation curve and accelerated deactivation, thereby partially counteracting the dominant-negative effects. A561P mutation and clobutinol effects on the human ventricular action potential characteristics were simulated using the Priebe-Beuckelmann model. Our work shows that clobutinol has limited effects on WT action potential but should be classified as a 'drug to be avoided by congenital long QT patients' rather than as a 'drug with risk of torsades de pointes'.
QT prolongation is a risk factor in a number of cardiovascular and noncardiovascular diseases. Among these, the congenital form of the long QT syndrome (LQT) associates prolonged rate-corrected QT interval (QTc) with recurrent syncope and sudden cardiac death resulting from torsades de pointes tachyarrhythmias. The long QT syndrome may also result from the effects of numerous chemically unrelated medications (acquired LQT) in patients with pre-existing normal QT or in patients carrying a long QT gene mutation. At the cellular level, prolongation of the QT interval reflects lengthening of the ventricular action potential (AP). In the human heart, a key repolarizing potassium current is the rapidly activating component of the delayed rectifier, \( I_{Kr} \) (Sanguinetti and Jurkiewicz, 1990). Its activation initiates repolarization and terminates the plateau phase of the cardiac AP concomitantly to the T wave on the ECG. \( I_{Kr} \) is related to pore-forming channel proteins encoded by the human ether-a-go-go-related gene (\( HERG \)) (Curran et al., 1995; Sanguinetti et al., 1995). Mutations in \( HERG \) account for chromosome 7-linked inherited long QT syndrome 2 (LQT2; Keating, 1995; Sanguinetti et al., 1996). Finally, the vast majority of drugs that produce the acquired LQT are blockers of \( HERG \) channels (Roden et al., 1996).

In the present work, we have identified the arrhythmogenic potential of a common drug, clobutinol, a centrally acting non-opioid antitussive drug widely used in Europe as treatment for dry cough of infectious origin. The deleterious effects of the molecule were suspected when a young boy, diagnosed with LQT2, experienced syncopes and arrhythmias while being treated with clobutinol. We have evaluated the inhibitory potency of clobutinol on wild-type \( HERG \) current. In the proband, we identified a novel LQT2 mutation (A561P), which we functionally characterized in
recombinant expression system. Interestingly, two others mutations (A561V and A561T) at the same position were previously reported (Curran et al., 1995; Dausse et al., 1996) in congenital LQT2 patients. We thus examined and compared the mechanism for HERG channel dysfunction in each of these three A561 mutations. Our work shows that a common drug not previously identified as a QT prolonging drug can precipitate the LQT2 syndrome.
Materials and methods

Clinical studies

The proband, an 11 year old boy, was diagnosed with a long QT duration in 1997. In 1999, he developed first symptoms in relation to torsades de pointes upon clobutinol treatment. A familial investigation was initiated. All family members enrolled gave written informed consent. Signature was applied by parents in case of children under 18. The protocol was approved by the local Committee for the Protection of Human Subjects in Biomedical Research of Nantes University, France. Participants were evaluated by history, review of medical records, and 12-lead electrocardiogram. Correction of the duration of the QT interval as a function of cycle length was performed using both Bazett's and Fridericia's formulae (QTcBazett=QT/2√RR and QTcFridericia=QT/3√RR with RR expressed in seconds).

Mutation analysis

Genomic DNA was prepared from peripheral blood lymphocytes by standard methods. Mutation analysis was conducted by direct sequencing of the gene using an ABI 377 automated sequencer (Applied Biosystems, Foster City, CA). PCR reactions for each of the amplicons representing the entire coding sequence and splicing sites of KCNH2 but also KCNQ1, KNCE1 and SCN5A genes were performed as previously described (Splawski et al., 1998; Wang et al., 1995).

Cell culture and transfection

African green monkey kidney cells (COS-7) were obtained from the American Type Culture Collection. Cells were cultured at 37°C in a 5% CO2 humidified incubator in Dulbecco’s modified Eagle medium supplemented with 10% fetal calf serum, 2 mM L-glutamine and antibiotics (100 UI/mL penicillin, 100 µg/mL streptomycin, all from GIBCO, Paisley, Scotland). Human wild-type HERG cDNA were subcloned into the
mammalian expression vector pBK under the control of the cytomegalovirus promoter/enhancer (Stratagene, La Jolla, CA). A561P, A561T, or A561V mutations were introduced using standard molecular techniques. Cells were transfected using the intranuclear microinjection technique or using polyethylenimine (PEI) as a transfection reagent. A green fluorescence protein plasmid (pEGFP; Clonetech, Palo Alto, CA) was used as an inert plasmid to ensure a constant plasmid concentration and also to permit cell detection. The microinjection protocol using the Eppendorf ECET microinjector 5246 system (Hamburg, Germany) has been previously described by Mohammad-Panah et al. (1998). Plasmids (3 µg/mL pBK-CMV-WT or mutated HERG plus 3 µg/mL pEGFP for homomeric channels, and 3 µg/mL pBK-CMV-WT HERG plus 3 µg/mL pBK-CMV- mutated HERG for heteromeric channels) were diluted in a buffer containing 40 mM NaCl, 50 mM HEPES, 50 mM NaOH, pH = 7.4 and supplemented with 0.5% fluorescein isothiocyanate-dextran (150 kDa). Alternatively, cells were transfected when the culture reached 60-80% confluence with plasmids complexed with PEI as previously reported (Pollard et al., 1998) with 2 µg plasmids per mL of culture medium. In patch-clamp experiments we used 20% pBK-CMV-WT or mutated HERG plus 80% pEGFP for homomeric channels, and 20% pBK-CMV-WT HERG plus 20% pBK-CMV- mutated HERG and 60% pEGFP for heteromeric channels. For immunolocalization experiments, we used 100% pBK-CMV-WT or mutated HERG for homomeric channels and 50% pBK-CMV-WT HERG plus 50% pBK-CMV- mutated HERG for heteromeric channels.

**Patch-clamp recordings**

Twelve to 24 hours after transfection, K⁺ currents from HERG-transfected COS-7 cells were recorded at 35°C using the whole cell configuration of the patch-clamp technique. Cells were placed on the stage of an inverted microscope and
continuously superfused with Tyrode's solution. During the current measurements, a microperfusion system allowed local application and rapid change of the different extracellular solutions used to specifically record the K⁺ currents. Patch pipettes with a tip resistance of 2.5-5 MΩ were electrically connected to a patch-clamp amplifier (Axopatch 200A; Axon Instruments, Foster City, CA). Stimulation, data recording and analysis were performed through an A/D converter (Tecmar TM100 Labmaster, Scientific solutions, Mentor, Ohio) using Acquis1 software (Bio-logic, Claix, France). WT and mutant HERG currents were measured using the following voltage protocol. The membrane potential was clamped at a holding potential of −90 mV and every 3 s, a voltage prepulse to +10 mV was applied for 500 ms followed by the test pulse to −70 mV for another 500 ms. The deactivating K⁺ current (or tail current) was measured during polarization to -70 mV and normalized for each cell using the cell capacitance. To evaluate the current activation, the prepulse voltage varied from -100 to +60 mV for 500 ms. To evaluate the deactivation kinetics, the voltage test pulse varied from -70 to -40 mV. Recorded human sub-endocardiac action potential acquired at 1000 ms pacing length was also used to clamp the cells.

**Immunolocalization experiments**

Cells were plated 12 h after transfection on coverslips, left for 48 h in the incubator to allow protein expression and then fixed in 4% PFA, permeabilized in 0.1% TRITON X-100 and incubated overnight at 4 °C with a rabbit anti-erg antibody (1:1000; Alomone, Jerusalem, Israel) in 1% BSA. Cells were rinsed in PBS and incubated for 1 hour at room temperature with a FITC-conjugated goat anti-rabbit antibody (1:200; Sigma). Cells were mounted between slips and coverslips and placed on the stage of an inverted Leica TCS NT confocal microscope (Wetzlar, Germany). Cells were observed using a X63 oil objective.
**Solutions and drugs**

Tyrode’s solution used for patch-clamp experiments contained (mM): 145 NaCl, 4 KCl, 1 MgCl₂, 1 CaCl₂, 5 HEPES, 5 glucose, pH = 7.4. The standard extracellular solution to record K⁺ current contained (mM): 145 Na-gluconate, 4 K-gluconate, 7 hemi-Ca-gluconate (free-Ca²⁺: 1), 4 hemi-Mg-gluconate (free-Mg²⁺: 1), 5 HEPES, 5 glucose, 20 mannitol, pH = 7.4. Patch-clamp pipettes contained (mM): 145 K-gluconate, 2 K₂ATP, 2 hemi-Mg-gluconate (free-Mg²⁺: 0.1), 5 HEPES, 2 EGTA, pH = 7.2. Free activities were calculated using a software designed by GL Smith (University of Glasgow, UK). Clobutinol (SILOMAT® 20 mg/2 mL solution, Boehringer Ingelheim) was diluted in extracellular solution as a 10⁻⁴ M stock solution. The test solutions were prepared by further successive dilutions. E-4031 was prepared as 10⁻³ M stock solution with distilled water.

**Computer modeling**

Functional effects of the HERG mutations were tested by computer simulations using the Priebe and Beuckelmann human ventricular cell model (1998). The experimentally observed ≈70% reduction in HERG tail current density was implemented by a 70% decrease in the fully activated conductance of I_{Kr}. The experimentally observed −11 mV shift in voltage dependence of WT + A561P HERG current activation was incorporated by a −11 mV shift in the I_{Kr} steady-state activation curve, whereas the ≈30% decrease in the fast and slow time constants of HERG channel deactivation were implemented by a 30% decrease in the corresponding I_{Kr} time constant. Action potentials were elicited by repetitive stimulation with a 2 ms, ≈20% suprathreshold stimulus current.

The Priebe-Beuckelmann model produces an action potential that is typical for an epicardial cell. To obtain endocardial and M cell models, we reduced the current...
densities of the transient outward current ($I_{to}$), the slow component of the delayed rectifier current ($I_{KS}$) and the inward rectifier current ($I_{K1}$) in the Priebe-Beuckelmann model by 75%, 8%, and 11%, and by 13%, 54%, and 26%, respectively (see Conrath et al., 2004), based on canine and human data (Liu et al., 1993; Liu et al., 1995; Näbauer et al., 1996).

To measure restitution of action potential duration (APD restitution) in the single human ventricular cell model, we used an S1-S2 stimulus protocol (Qu et al., 1999). Following a period of pacing at a basic S1-S1 pacing interval of 1000 ms, S2 was applied after a variable S1-S2 interval. The strengths of the 2 ms S1 and S2 stimuli were fixed at 2.5 times threshold, and APD was defined using a threshold voltage of $-77.2$ mV, which is near the voltage at which the action potential is 90% repolarized. Models were coded using Compaq Visual Fortran 6.6 and run on a 3-GHz Intel Pentium 4 processor workstation, applying an Euler-type integration scheme with a 5-µs step. All simulations were run for a sufficiently long time to reach steady-state behavior.

**Statistics**

All data are presented as mean ± SEM. Statistical significance of the observed effects was assessed by means of the Student t-test, Mann-Whitney rank sum test, or two-way ANOVA when appropriate. A value of $p < 0.05$ was considered significant.
Results

Clinical characteristics

The proband, a boy born in 1992, was diagnosed for a tetralogy of Fallot and had surgery several years before the drug-induced arrhythmia. His ECG follow-up is illustrated in Figure 1Aa-d. Lengthening of the QT interval ($QTC_{Bazett} = 628$ ms and $QTC_{Fredericia} = 597$ ms) was initially detected in 1997 in the absence of associated symptoms (Figure 1Aa). In 1999, he experienced for the first time syncope and torsades de pointes arrhythmias under clobutinol, a common antitussive drug (Figure 1Ab). The baseline serum $K^+$ level indicated a moderate hypokalaemia to 3.5 mmol/L before any treatment (Feb 05). However, the arrhythmic episodes did not cease under potassium, magnesium or $\beta$-blocker therapy, even when the serum potassium was normalized to 4.1 mmol/L. Torsades de pointes only ceased when the heart was paced. After clobutinol treatment was discontinued, the QTc interval progressively decreased to pre-treatment values with a time course comparable to clobutinol half-life (23-32h; Zimmer et al., 1977) (Figure 1Ac). The kidney function was considered as normal from urea and creatinine levels (Feb 05: 1.8 mmol/L (BUN: 5 mg/dL) and 44 mg/dL, respectively). Since 1999, the proband has no further arrhythmia or symptoms, although he has retained a long QTc interval (Figure 1Ad). Altogether, these data correlate the clobutinol intake to the torsades de pointes episodes. Repolarization abnormalities were also detected in his asymptomatic father (Figure 1B) and in his elder brother (Figure 1C). Neither the brother nor the father has had a history of cardiac surgery. The other relatives including his mother (Figure 1D) presented normal ECG.
**Mutation analysis**

DNA sequencing of exon 7 in the proband (III-1; Figure 2) identified a heterozygous G-to-C mutation at position 1681. This missense mutation was predicted to change an Arginine for a Proline (A561P) within the S5 region of HERG. This mutation was also identified in the proband's father and in his elder brother (II-1; III-2). DNA sequencing of other genes related to LQT i.e. KCNQ1, KCNE1 and SCN5A, encoding the α- and β-subunits of the I\textsubscript{Ks} current and the α-subunit of the I\textsubscript{Na} channel, respectively, did not reveal other mutations.

**Clobutinol blocks HERG current.**

We investigated the sensitivity of homomeric wild-type (WT) channels to the non-opioid antitussive clobutinol. Transfected COS-7 cells expressed a large K\textsuperscript{+} current with biophysical properties reminiscent to those of the rapid component of the cardiac delayed rectifier K\textsuperscript{+} current recorded in human cardiac cells (Figure 3A; Wang et al., 1994). When repolarized to –70 mV, expressing COS-7 cells exhibited a large deactivating current (I\textsubscript{tail}). The half-activation potential (V\textsubscript{1/2}) for this current was calculated as –10.4 ± 5 mV (n = 10). Clobutinol at 10\textsuperscript{-5} M induced a slow decay of the activating current recorded at +10 mV suggesting voltage-dependent block and a lesser blocking effect at the initial phase of activation. This pattern of inhibition was observed at the steady-state. After full activation at +10 mV, clobutinol inhibited the HERG tail current with a half-maximum block concentration (IC\textsubscript{50}) of 2.9 · 10\textsuperscript{-6} ± 0.7 · 10\textsuperscript{-6} M and a Hill coefficient of 0.9 (n = 9; Figure 3B).

As illustrated in Figure 3C, the HERG-related K\textsuperscript{+} current activated at potentials positive to –50 mV and exhibited strong inward rectification. Deactivating K\textsuperscript{+} currents reached a maximum after a prepulse to 10 mV and did not further increase with more positive depolarizing prepulses (Figure 3D). As depicted in Figures 3 C and D,
clobutinol decreased activating and deactivating currents. The inset in Figure 3D shows that clobutinol blocked the tail current more effectively at depolarized potentials \((p < 0.001)\). Recovery from block was also analyzed when the membrane potential was repolarized to -70 mV. After a depolarization to +10 mV, the initial deactivating current measured at the beginning of the repolarizing pulse \((I_{tail \ init})\) was significantly more inhibited than that measured 500 ms later \((I_{tail \ late})\) \((10^{-5} \text{M clobutinol, } 71 \pm 5\% \text{ versus } 45 \pm 13\%; \text{ inhibition percentage of } I_{tail \ init} \text{ and } I_{tail \ late}, \text{ respectively; } n = 7; \ p < 0.05)\). We conclude that the HERG block as produced by clobutinol was voltage-dependent inasmuch as it was more pronounced at depolarizing voltages, and as it developed with depolarization and relaxed with repolarization.

**Electrophysiological properties of the HERG A561P, HERG A561T and HERG A561T channels**

Since the non-opioid antitussive drug clobutinol had triggered arrhythmias in the A561P HERG carrier, we evaluated the effects of this mutation on the channel function. The functional effects of A561P were also compared to those caused by A561T and A561V mutations. In cells injected into the nucleus with either A561P HERG, A561T HERG or A561V HERG, no current was recorded unlike in cells injected with WT HERG, suggesting that the three mutations led to a complete loss of function (Figure 4A). Since LQT patients are heterozygous for these HERG mutations, mutant and WT proteins were co-expressed with appropriate ratios to mimic the genotype of the mutation carriers. As shown in Figure 4B, the tail K⁺ current density measured at -70 mV (depolarizing test pulse to +10 mV) was markedly reduced to about 30% of the control current. We concluded that the three mutations altered the WT HERG channel function in a dominant negative manner.
The absence of measurable $K^+$ currents for mutated homomeric channels can be related to either a defect in channel targeting to the plasma membrane or to altered gating properties of channels. To test whether homomeric channels are inserted into the cell membrane, immunolocalization experiments were conducted. As illustrated in Figure 4A, WT HERG expressing cells showed an intracellular and plasma membrane staining whereas membrane staining was undetectable with A561P, A561T and A561V HERG channels suggesting that these channels do not insert into the cell membrane. In cells co-transfected with WT and mutant HERG, confocal microscopy revealed that membrane staining was still detectable though less intensely (Figure 4B). These results suggest that the mutated channels are poorly processed to the plasma membrane, and that heterotetramers coexpressed with the WT protein are mostly retained in intracellular compartments.

In addition to the strong reduction in current amplitude, the A561P mutation also modified the voltage-dependence of activation of the WT + A561P heteromeric channels (Figure 5A and B) and produced a significant shift of $V_{1/2}$ towards more negative potentials (Table 1). The small 3–3.5 mV shift seen in cells co-expressing WT and A561V or A561T HERG was not significant. On the other hand, the slope factor of activation was slightly albeit significantly modified demonstrating the alteration of the channel gating induced by the mutations.

In cells co-expressing WT and A561P HERG, we also observed a reduction in the fast and slow deactivation time constants when the deactivating current traces were fitted using a double exponential function (Figure 5C). The fast deactivating component contributed to about 40% of the WT or WT + A561P current at any tested potential. Altogether, the modifications as induced by the A561P mutation, i.e. current reduction and faster deactivation kinetics counterbalanced by the shift in the
activation curve should lead to a milder loss of function of the WT + A561P channels compared to the A561V or A561T mutations which only produced a decrease in current amplitude.

In order to visualize more accurately the functional effects of the mutants, a human ventricular action potential voltage clamp waveform was applied to cells expressing WT or WT + mutated HERG channels. The normalized currents resulting from this stimulation are depicted in Figure 6. The HERG current, shown as the E-4031-sensitive current increased progressively as the action potential repolarized to reach a peak. In accordance with the shift of the activation curve of WT + A561P channels, an earlier WT + A561P HERG current peak was seen during the action potential time course. Presumably, this behavior should prelude to a less pronounced QT interval lengthening in comparison with WT + A561T or WT + A561V channels.

**Clobutinol blocks WT + A561P HERG current**

The effects of clobutinol were further tested in cells co-expressing WT and A561P HERG channels. Figure 7 illustrates that the sensitivity of heteromeric channels to the block produced by clobutinol was similar to that of homomeric channels (IC$_{50}$ for clobutinol on heteromeric WT + A561P HERG: $1.9 \times 10^{-6} \pm 0.7 \times 10^{-6}$ M; Hill's coefficient: 1.1; n = 5).

**Functional implications**

Electrophysiological data demonstrate that each of the WT + A561P, WT + A561T, and WT + A561V HERG currents is characterized by a decrease in current density to ≈30% of the control WT value. In addition, the WT + A561P HERG current shows alterations in kinetics *i.e.* a -11 mV shift in voltage dependence of activation as well as a ≈30% decrease in fast and slow time constants of deactivation. To assess the functional consequences of these alterations, we carried out computer simulations
using the comprehensive human ventricular cell model by Priebe and Beuckelmann (1998). Figure 8A (top) shows the model action potential with normal $I_{Kr}$ (dotted line) and with a 70% reduction in $I_{Kr}$ (solid line), representing the experimentally observed reduction in HERG current density. The reduction in repolarizing current induces a prolongation of the action potential by 124 ms (arrow). The experimentally observed alterations in kinetics result in an earlier activation of HERG channels and thus in a larger $I_{Kr}$ amplitude (Figure 8B). Despite the more rapid deactivation of the current, repolarization is accelerated and the action potential shortened by 33 ms. When combined, the two effects, i.e., the reduction in current density and alterations in kinetics, are almost additive, with an AP prolongation of 97 ms (Figure 8C). We also tested the effects of the experimentally observed changes in slope of the HERG channel activation curve (Table 1), but the effects thereof were very small, with a change in APD$_{90}$ ($\Delta$APD$_{90}$) typically less than 1–2 ms (data not shown). We also determined $\Delta$APD$_{90}$ for pacing cycle lengths other than 1 s (Figure 8D). In all cases, the effects are more pronounced at shorter cycle lengths, i.e., at higher heart rate, which was also observed in a canine AP model for other mutations that affect $I_{Kr}$ (Mazhari et al., 2001). Figure 8D also shows that the A561P HERG mutation (open triangles) exerts milder effects than the A561T or A561V mutations (open squares). However, application of clobutinol (simulated by a 30% block of $I_{Kr}$, in accordance with the estimated circulating drug concentration of 0.55–0.75 µM and the dose-response curve in Figure 7; Zimmer et al. 1977) increases AP prolongation for the A561P mutation to values larger than those for the more severe A561T or A561V mutations (Figure 8D, closed triangles). With wild-type HERG channels, clobutinol per se produces a mild prolongation of the action potential at all pacing cycle lengths (Figure 8D, closed circles).
Increased dispersion of repolarization across the ventricular wall, either arising from
dynamic factors (steeper APD restitution) or from enhanced heterogeneity in intrinsic
electrophysiological properties among different cell types, is an important
determinant of the susceptibility to ventricular arrhythmias (see Qu et al., 2000).
Therefore, we first tested whether the HERG channel mutations would steepen the
APD restitution curve (Figure 8E). Again, the largest effects are observed for the
A561T or A561V mutations. However, application of clobutinol significantly steepens
the APD restitution curve for the A561P mutation, yielding a slope near 1 for the
steepest part of the curve. With wild-type HERG channels, clobutinol produces only
moderate alteration in the restitution curve. Second, we assessed the effects of the
HERG channel mutations on the intrinsic differences among the different cell types.
Figure 8F shows that the mutations preferentially prolong the M cell action potential,
thereby increasing the dispersion of repolarization. The largest dispersion is obtained
for the WT + A561P HERG current in the presence of clobutinol (189 ms vs. a control
value of 59 ms).
It has been hypothesized that the AP prolongation associated with LQT favors the
development of early afterdepolarizations (EADs) and triggered activity due to
reactivation of the L-type calcium current (I_{Ca,L}) during the AP plateau. In contrast
with simulation studies using the Luo-Rudy guinea pig-type AP model (Viswanathan
& Rudy, 1999), we did not observe EADs in any of the three cell types studied. As
discussed by Priebe and Beuckelmann (1998), the lower susceptibility of their human
ventricular cell model to the generation of EADs could reflect an inherent property of
human tissue. We did, however, observe considerably delayed repolarization for the
M cell model in case of the A561 HERG channel mutations, especially in response to
moderate increases in I_{Ca,L}, with, e.g., APD_{90} values exceeding 1 s upon a 25% increase in I_{Ca,L} (data not shown).

In summary, Figure 8 shows that the effects of the A561P mutation on basic AP properties are constantly less severe than those of the A561V or A561T mutation, but become more severe if the WT + A561P HERG current is further reduced by the application of clobutinol.
Discussion

This report is the first to detail the effects of clobutinol, a commonly used antitussive drug, on the HERG cardiac K⁺ channel. The rhythmic incident correlated to clobutinol intake in the proband revealed the potential effects of the drug and instigated the present study, which also resulted in the identification of a novel HERG mutation responsible for LQT2.

**Drug-induced action potential prolongation**

We found that clobutinol displays an IC₅₀ value of ≈2 µM on HERG. As illustrated by computer modeling, clobutinol would induce only mild modifications in the ventricular action potential duration of unaffected individuals. The effects of clobutinol displayed a positive voltage dependence, suggesting that the molecule interacts with an activated state of the HERG channel. Drugs that block HERG current, are often associated with QT prolongation and development of the ventricular arrhythmia known as torsades de pointes. Among them, are terfenadine, astemizole and cisapride. Published IC₅₀ ranged between 56 nM and 431 nM for terfenadine (Rampe et al., 1997, Chachin et al., 1999), and 69 nM and 480 nM for astemizole (Chachin et al., 1999, Taglialetela et al., 1998). Cisapride IC₅₀ values ranged between 4.3 nM in HEK293 cells (Anson et al., 2004) and 124 nM in Xenopus oocytes (Fernandez et al., 2004). We previously investigated the effects of cisapride and measured an IC₅₀ value of 240 nM (Potet et al., 2001). We and others (Walker et al., 1999) showed that the inhibition produced by cisapride increases during depolarization and is partially removed during repolarization. In our previous and present works, the cells were depolarized for 500 ms only, a duration close to the human action potential duration but much shorter than the duration used by previous investigators (2 to 20 s-duration prepulses). Since cisapride produces a time-dependent open-channel block, the
affinity of cisapride for HERG may be overestimated when long depolarization duration protocols are used. Because clobutinol is also a voltage-dependent blocker, it is more accurate to compare clobutinol and cisapride IC$_{50}$ for relatively brief depolarizations. Under these conditions, clobutinol has an IC$_{50}$ value about 10 times higher than that of terfenadine, astemizole or cisapride. This may explain why clobutinol, despite widespread clinical use in Europe, has not yet been reported to produce QT prolongation. On the other hand, the long QT syndrome may often be missed in patients presenting syncope, seizures or drop attacks (Pacia et al., 1994). This may hold for a previously reported case of grand mal seizure associated with clobutinol overdose (Ramirez et al., 1993). In conclusion, the absence of other case reports involving clobutinol and its relatively high IC$_{50}$ value exclude this drug from the list of drugs with risk of torsades de pointes, although the potential inhibitory activity of clobutinol may represent an aggravating factor when the cardiac repolarization reserve is already reduced as in congenital LQT patients like the proband in the present study.

**Trafficking of mutant HERG proteins**

Among the mechanisms underlying LQT2, impaired trafficking of HERG protein is increasingly recognized as a leading cause. *In vitro*, the A561P mutation caused defects in intracellular protein transport to the plasma membrane. Furthermore, the mutant subunit co-expression reduced the WT HERG function by a dominant negative effect. Similar results were obtained with A561V or A561T HERG, two previously identified LQT2 mutations (Curran et al., 1995; Dausse et al., 1996). Studying the A561V dominant-negative mechanism, Ficker et al. (2000) observed that co-assembly of WT with A561V HERG prevented the traffic of the heteromeric channels to the plasma membrane. Our results are in favor of a similar mechanism
concerning A561T or A561P HERG mutants. Numerous HERG mutations leading to trafficking deficiency have been described throughout the protein (see Paulussen et al., 2002 for examples). Key regions of the protein for trafficking have been described in the C-terminal part of the protein as well as in the N-terminal located PAS domain (Kupershmidt et al., 2002; Akhavan et al., 2003; Paulussen et al., 2002). Retention of mutant proteins has also been associated with increased affinity with the chaperones Hsp70 and Hsp90 (Ficker et al., 2003). However the amino acids involved in this association are localized in the S5-p-loop linker or in the C-terminal tail, unlike the A561.

**HERG channel mutations at position 561**

Assuming random co-assembly of WT and mutant HERG subunits, and also that only WT homotetramers are conductive, the K⁺ current resulting from heterozygous expression should be reduced to 1/16th of the WT current value. Subsistence of a current > 1/16th of WT K⁺ current indicates that the association of WT and mutated HERG is less frequent than homomeric association or, alternatively, that some heteromeric channels can reach the plasma membrane and effectively conduct K⁺ current. Concerning the A561P mutation, modifications of the heteromeric K⁺ current characteristics, *i.e.* ≈-11 mV shift of the activation $V_{1/2}$ and change in deactivation kinetics, are in favor of the second hypothesis. Investigating the effects of A561V HERG mutant, Kagan et al. (2000) suspected a small fraction of current being passed by heteromeric channels. These authors also observed a shift of the activation $V_{1/2}$ in CHO cells from +0.7 mV in WT HERG expressing cells to -10.9 mV in WT + A561V HERG expressing cells. We failed to observe such a ≈-10 mV shift in COS-7 cells. It has to be mentioned however that the Kagan et al. study was performed at room temperature unlike our (35°C). Studying WT HERG biophysical
properties in HEK293 cells at various temperatures, Zhou et al. (1998) calculated a shift of $V_{1/2}$ value from -14.2 mV at 23°C to -25.9 mV at 35°C. The latter value is close to that of -21.5 mV obtained at the same temperature by Sanguinetti and Jurkiewicz (1990) for the native $I_K$ in guinea pig ventricular myocytes and to -20.7 mV as in the present study. Since no shift due to co-expression of WT and A561V HERG proteins could be detected at +35°C, one can suspect that the mutation alters the temperature sensitivity of the heteromeric channel activation. Alternatively, this discrepancy may be explained by the cell model difference: CHO versus COS-7 cells.

Substitution of the alanine to a valine or a threonine at position 561 appears to have no effect on heteromeric channels activity. Conversely, the substitution to a proline that may induce a kink in the S5 helix altered its activation and deactivation. By analogy to the Shaker channel structural model, A561 is the homolog of Shaker V414 and faces the S1-S4 voltage sensor (Torres et al., 2003; Neale et al., 2003).

Mutations of amino acids facing the voltage-sensor may impair the inter-subunit interactions and the coupling of the voltage-sensing function to the channel opening. Additionally, S5 structure modification may also alter the pore stability. Finally, since the S4-S5 linker of HERG is involved in the voltage-dependence and kinetics of channel activation and deactivation, it can be suggested that mutations in the S5 helix may be the origin of the heteromeric channels behavior changes by simple allosteric changes with repercussions on S4-S5 function. However, the activation modifications counterbalance the impaired trafficking consequences and overall lead to milder mutation effects.
**Novel LQT2 mutation**

The penetrance of a mutation can be quite variable depending on the family but also among carriers in the same family as reported for the A561V substitution (Priori et al., 1999). In A561P gene carriers, the only symptom was the lengthening of the QT interval until the proband experienced the drug-induced torsades de pointes. As illustrated in the model simulation provided here, reduction of the resulting K+ current induces the AP lengthening responsible for the QT interval prolongation. Unlike the other A561 substitutions, the A561P mutation induced a more premature I_{Kr} current that, despite its smaller amplitude, limits the AP duration prolongation. This difference from A561V or T mutation could, at least in part, explain the milder phenotype of A561P carriers.

**Proarrhythmic effect of clobutinol**

Since the torsades de pointes episode was independent of serum potassium, the drug may be supposed to be the direct trigger of the arrhythmia. Clobutinol has a renal elimination and no known metabolite (Zimmer et al., 1977). The normal kidney function of the proband rules out a possible accumulation of the drug. As illustrated by the computer simulation, clobutinol has only a minor effect on the WT AP duration. Nevertheless, additive moderate reductions of I_{Kr}, (i) by the HERG A561P mutation and (ii) by clobutinol, may enhance heterogeneity in intrinsic electrophysiological properties among different ventricular cell types, an important determinant of the susceptibility to ventricular arrhythmias. Finally, our work shows that less severe mutation carriers are still at risk of developing arrhythmias when exposed to additional pro-arrhythmic drug or pathophysiological triggers. It emphasizes the necessity of information on risk factors such as the QT Drug List provided by the University of Arizona Center for Education and Research on Therapeutics.
the pro-arrhythmic drugs (http://www.qtdrugs.org/). The reported accident does not necessarily classify clobutinol in list 1 as a 'drug with risk of torsades de pointes' but rather in list 3 listing 'drugs to be avoided by congenital long QT patients'.
Acknowledgements

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References


Footnotes

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**Figure 1**: ECG tracings in lead V5 of the proband (A), his father (B), his eldest brother (C) and his mother (D). Only the mother was not A561P HERG carrier. QTc\textsubscript{Bazett} and QTc\textsubscript{Fredericia} (italic between brackets) values are also indicated.

**Figure 2**: Pedigree of the family. Empty symbols (circles indicate females, and squares males) depict unaffected members, gray symbols depict members presenting a long QTc only whereas the black symbol represents the member who experienced torsades de pointes. Carriers of A561P HERG mutations are indicated with + sign and tested non-carriers with - sign.

**Figure 3**: A: Effects of clobutinol on HERG K\(^+\) currents expressed in COS-7 cells. Representative current traces recorded in cells expressing WT HERG in control condition, and in the presence of increasing clobutinol concentrations. Voltage protocol (500-ms steps) as in the inset. B: Dose-response curve for clobutinol to block the HERG tail current (n = 9). Voltage protocol as in A. Tail current was normalized to the control value and expressed as a function of the drug concentration. *Solid line*, fit of experimental data to the Hill equation:

\[
y = a + \frac{d}{1 + (x/c)^b}
\]

where x is the drug concentration, and b the Hill coefficient. IC\(_{50}\) value was calculated as the drug concentration for which y = 50%. **: p < 0.01; ***: p < 0.001. C: Current-voltage relation for activated current (prepulse current, I\(_{pp}\)) density in control (I\(_{pp}/Cm\); ○) and in the presence of 2.10\(^{-6}\) M clobutinol (●; n = 10). Voltage protocol consisted of 500 ms depolarizing and hyperpolarizing prepulses to various potentials between −100 and +60 mV followed by a test pulse to −70 mV for 500 ms. Holding potential: -90 mV; frequency: 0.33 Hz. D: Current-voltage relation for the deactivating
tail current ($I_{\text{tail}}$) density under control conditions ($I_{\text{tail}}/C_m; O$) and with $2.10^{-6}$ M clobutinol ($\bullet$; $n = 10$). ***: $p < 0.001$. Inset, Inhibition ratio ($1 - [I_{\text{tail}} \text{ in the presence of } 2.10^{-6} \text{ M clobutinol} / I_{\text{tail}} \text{ control}]$) versus prepulse potential ($n = 9 \text{ to } 10$).

**Figure 4:** A: Current recorded from WT HERG, A561P HERG, A561T HERG or A561V HERG injected COS-7 cells. Voltage protocol as in Fig 3B. B: Tail current density recorded at $-70\text{mV}$ after a depolarization to $+10 \text{ mV}$ in cells either injected with cDNA coding for WT HERG, or co-injected with WT HERG cDNA plus A561P, A561T or A561V HERG cDNA. Statistical significance vs. WT: ***, $p < 0.001$. Insets: confocal laser scanning images of COS-7 transfected with the different cDNAs. White arrows: membrane staining.

**Figure 5:** A: Prepulse current density ($I_{\text{pp}}/C_m$) versus potential in cells either injected with WT HERG ($n = 13$) or co-injected with WT HERG plus A561P HERG ($n = 12$), A561T HERG ($n = 9$) or A561V HERG ($n = 9$). Same voltage protocol as Fig 3C. B: Relative tail current vs. prepulse potential. Inset: representative current traces recorded in cells polarized at $-100$, $-40$ (black arrows), $0$, $+20$ and $+40 \text{ mV}$ (scales : $5 \text{ pA/pF and 200ms}$) in cells expressing WT HERG or WT + A561P HERG channels. C: The tail current recorded at various potentials after a depolarization to $+10 \text{ mV}$ was fitted using the following equation:

$$I(t) = a_f \exp(-t/\tau_f) + a_s \exp(-t/\tau_s)$$

where $a_f$ and $a_s$ represent the respective proportion of the fast ($\tau_f$) and slow ($\tau_s$) deactivation processes. $\tau_f$ (bottom) and $\tau_s$ (top) are plotted as a function of test pulse potential for HERG WT tail currents ($n = 13$), and for WT + A561P HERG tail currents ($n = 7$). Statistical significance vs. WT: **: $p < 0.01$; *: $p < 0.05$. 
**Figure 6**: Respective contribution of HERG current during a cardiac action potential. An action potential waveform recorded from a human ventricular myocyte was used as the command voltage to clamp HERG transfected COS-7 cells. HERG currents are expressed as the normalized E-4031-sensitive current (control current - residual current in 300 nM E-4031).

**Figure 7**: Effects of clobutinol on WT + A561P HERG K⁺ currents expressed in COS-7 cells. A: Representative current traces recorded in cells expressing WT + A561P HERG in control condition, and in the presence of growing clobutinol concentrations. Voltage protocol as in Fig 3A. B: Dose-response curve for WT + A561P HERG K⁺ tail current (n = 4). Normalization and fitting as in Fig 3B.

**Figure 8**: The A561P HERG channel mutation exerts smaller effects on the cardiac action potential than the A561V or A561T mutation, but not if the WT + A561P HERG current is partially blocked by clobutinol. A–C: Action potentials elicited at 1 Hz (top) and associated I_{Kr} (bottom) in case of (A) a 70% decrease in HERG current density, as observed for all three mutations, (B) alterations in HERG current kinetics as observed for the A561P mutation i.e. a –11 mV shift in voltage dependence of activation as well as a ≈ 30% decrease in fast and slow time constants of deactivation, and (C) both changes. Dotted lines indicate WT control. D: Change in APD_{90} (ΔAPD_{90}) at various pacing cycle lengths. E: APD restitution curves for each of the HERG channel mutations. F: Effects of the HERG channel mutations on differences in APD_{90} of endocardial, midmyocardial, and epicardial cells upon 1-Hz stimulation.
Table 1: Activation parameters of WT, WT + A561P, WT + A561T, and WT + A561V HERG currents

<table>
<thead>
<tr>
<th></th>
<th>$V_{1/2}$ (mV)</th>
<th>$k$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>-20.7 ± 3.0</td>
<td>8.0 ± 0.4 ns</td>
<td>13</td>
</tr>
<tr>
<td>WT + A561P</td>
<td>-31.8 ± 2.1 **</td>
<td>10.0 ± 0.6 **</td>
<td>12</td>
</tr>
<tr>
<td>WT + A561T</td>
<td>-24.2 ± 2.1 NS</td>
<td>6.0 ± 0.4 **</td>
<td>9</td>
</tr>
<tr>
<td>WT + A561V</td>
<td>-23.5 ± 3.6 NS</td>
<td>6.2 ± 0.3 **</td>
<td>9</td>
</tr>
</tbody>
</table>

Voltage protocol as described in Fig 3C. Tail currents were fitted using a Boltzmann equation:

$$\frac{I_{\text{tail}}}{I_{\text{tail max}}} = \frac{1}{1 + \exp[-(V_{\text{pp}} - V_{1/2})/k]}$$

where $I_{\text{tail max}}$ is peak $I_{\text{tail}}$, $V_{\text{pp}}$ is the prepulse potential, $V_{1/2}$ is the prepulse voltage for which $I_{\text{tail}}$ is half of $I_{\text{tail max}}$ and $k$ is the slope factor. WT was tested versus data obtained when PEI was used as transfection vector (see clobutinol experiments) and WT + A561's versus WT. Statistical significance: NS (or ns): not significant; **: $p < 0.01$. 

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Fig 1

- May-30-97  
  597 ms  
  (628 ms)

- Feb-05-99
- clobutinol

- Feb-08-99
- 584 ms
- (599 ms)

- Apr-09-03
- 594 ms
- (607 ms)

- May-30-97
- 531 ms
- (528 ms)

- Feb-05-99
- 563 ms
- (587 ms)

- Apr-09-03
- 401 ms
- (411 ms)

father

elder brother

proband

mother
**Fig 3**

**A**

- Prepulse potential (mV)
  - -90 mV
  - -70 mV
  - Control
  - 10⁻⁶ M
  - 10⁻⁵ M

- Test pulse (+10 mV)
- Prepulse (+10 mV)

- 10 pA/pF
- 200 ms

**B**

- Inhibition ratio
  - 0.0
  - 0.5
  - 1.0

- IC₅₀ = 2.9 · 10⁻⁶ M
- Hill coeff = 0.9

**C**

- Clobutinol 2 · 10⁻⁶ M

- L_pp/Cm (pA/pF)
  - 0
  - 5
  - 10
  - 15

- Prepulse potential (mV)
  - -100
  - -50
  - 0
  - 50

**D**

- Inhibition ratio
  - 0.0
  - 0.1
  - 0.2
  - 0.5
  - 1.0

- Prepulse potential (mV)
  - -100
  - -50
  - 0
  - 50

- Clobutinol 2 · 10⁻⁶ M

- Inset: Significant differences (*** p < 0.001)
A

WT HERG

A561P HERG

A561T HERG

A561V HERG

300 pA
200 ms

B

WT + A561P

WT + A561T

WT + A561V

I tail (pA/pF)

(34)

(26)

(19)

(15)

Fig 4

(15)

(19)

(26)

(34)

***

***

***
Fig 5

(A) prepulse potential (mV)
-100 -80 -60 -40 -20 0 20 40
I pp/Cm (pA/pF)
0 5 10 15 20
τ slow (ms)
100 150 200 250

(B) prepulse potential (mV)
-100 -80 -60 -40 -20 0 20 40
I tail/Cm (pA/pF)
0 0.5 1
τ fast (ms)
20 30 40

(C) test pulse potential (mV)
-80 -70 -60 -50 -40 -30
τ slow (ms)
-100 -90 -80 -70 -60 -50 -40 -30
τ fast (ms)
0 10 20

WT
WT + A561P
WT + A561T
WT + A561V
Fig 6
Fig 7

IC$_{50}$ = 1.9 \times 10^{-6} M
Hill coeff = 1.1