Molecular Pharmacology of the Sodium Channel Mutation D1790G Linked to the Long-QT Syndrome

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Background—Multiple mutations of SCN5A, the gene that encodes the human Na⁺ channel α-subunit, are linked to 1 form of the congenital long-QT syndrome (LQT-3). D1790G (DG), an LQT-3 mutation of the C-terminal region of the Na⁺ channel α-subunit, alters steady-state inactivation of expressed channels but does not promote sustained Na⁺ channel activity. Recently, flecainide, but not lidocaine, has been found to correct the disease phenotype, delayed ventricular repolarization, in DG carriers.

Methods and Results—To understand the molecular basis of this difference, we studied both drugs using wild-type (WT) and mutant Na⁺ channels expressed in HEK 293 cells. The DG mutation conferred a higher sensitivity to lidocaine (EC₅₀, WT=894 and DG=205 μmol/L) but not flecainide tonic block in a concentration range that is not clinically relevant. In contrast, in a concentration range that is therapeutically relevant, DG channels are blocked selectively by flecainide (EC₅₀, WT=11.0 and DG=1.7 μmol/L), but not lidocaine (EC₅₀, WT=318.0 and DG=176 μmol/L) during repetitive stimulation.

Conclusions—These results (1) demonstrate that the DG mutation confers a unique pharmacological response on expressed channels; (2) suggest that flecainide use–dependent block of DG channels underlies its therapeutic effects in carriers of this gene mutation; and (3) suggest a role of the Na⁺ channel α-subunit C-terminus in the flecainide/channel interaction.

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Key Words: sodium ■ ion channels ■ antiarrhythmia agents ■ pharmacology ■ electrophysiology ■ genes

The congenital long-QT syndrome is an inherited cardiac disorder defined by prolonged ventricular repolarization, recurrent syncpe, a propensity to polymorphous ventricular tachycardia (torsades de pointes), and sudden death.¹² Molecular genetic studies have identified defects in the gene that encodes the human Na⁺ channel α-subunit, are linked to 1 form of the congenital long-QT syndrome (LQT-3). D1790G (DG), an LQT-3 mutation of the C-terminal region of the Na⁺ channel α-subunit, alters steady-state inactivation of expressed channels but does not promote sustained Na⁺ channel activity. Recently, flecainide, but not lidocaine, has been found to correct the disease phenotype, delayed ventricular repolarization, in DG carriers.

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of DG compared with WT channels that underlies its therapeutic efficacy. The results of this study provide further support for the approach of mutation-specific pharmacology as a basis for the management of inherited cardiac arrhythmias.

Methods

Expression of Recombinant Na\(^+\) Channels

HEK 293 cells (Cold Spring Harbor Laboratories) were grown under culture conditions and transfected with equal amounts of Na\(^+\) channel α-(WT or DG, respectively), hβ2, and/or hβ3-subunit cDNAs subcloned individually into the pcDNA3 (Invitrogen) vector (total cDNA, 2.5 μg) by a lipofection procedure previously described by us.\(^7\) Control experiments (data not shown) indicated no significant differences in channel activity with or without drug for these subunit combinations. β-Subunit cDNAs were gifts of Drs L. Isom (University of Michigan, hβ2) and A. George (Vanderbilt University, hβ3), and the DG mutation was constructed as previously described.\(^7\)

Electrophysiology

Membrane currents were measured by whole-cell patch-clamp procedures\(^6\) with Axopatch 200B amplifiers (Axon Instruments) and the following solutions (mmol/L): internal: CsCl 60, aspartic acid 50, correct to 7.2 with CsOH; external: NaCl 130, CsCl 5, CaCl 2 2, H2O. Experiments were carried out with pClamp7 software (Axon Instruments), and data were analyzed with Origin software (Microcal Software). Unless otherwise specified in the figure legends, experiments were carried out at room temperature (22°C). Measurements at higher temperature were performed with a solution heater (In-line Heater SH-27B, Warner Instrument Corp) warming the superfusate to 37°C. Recordings were made during 25-ms test pulses to −10 mV from −100-mV holding potentials. Tonic block (TB) was used to compare means; a value of "P<0.05 was considered statistically significant.

Figure 1. Effects of flecainide and lidocaine on steady-state inactivation of WT and DG channels. Steady-state availability of channels was measured (Methods) in absence and presence of each drug. A and B, Current traces, normalized to peak drug-free currents, illustrate effects of lidocaine (300 μmol/L) and flecainide (30 μmol/L). Arrows indicate drug-induced changes in peak currents for each condition. C and D, Averaged steady-state availability curves are shown in absence (circles) and presence of lidocaine (300 μmol/L, squares) and flecainide (30 μmol/L, triangles) for WT (C) and DG (D) channels. Na\(^+\) currents elicited by −10-mV test pulses were normalized to largest currents obtained in control conditions from hyperpolarized holding potentials. Graphs show normalized current plotted against conditioning pulse voltage. Smooth lines are according to 1/(1+exp([Vc−V1/2]/k)), where Vc is conditioning potential, V1/2 is voltage for which half the channels are not available, and k is a slope factor. V1/2 (mV) for WT is −66.2±0.9 for control, −69.8±1.9 with flecainide, and −85.7±1.4 with lidocaine; V1/2 (mV) for DG is −81.8±1.4 for control, −87.3±2.4 with flecainide, and −102.5±2.7 with lidocaine; n=4 cells per condition.

The DG mutation alters the voltage-dependence of steady-state inactivation of expressed channels,\(^7\) we first tested for differences between the interactions of lidocaine and flecainide with the inactivated state of WT and DG channels. Figure 1 shows that lidocaine, but not flecainide, induces marked hyperpolarizing shifts in the steady-state inactivation relationship for both WT and DG channels. Furthermore, the effects of lidocaine on inactivation are approximately the same for WT and DG channels.

The lidocaine selective shift in inactivation predicts greater TB of DG versus WT channels by lidocaine, but not flecainide, at physiologically relevant holding potentials. This prediction is confirmed in the experiments summarized in Figure 2. However, at clinically relevant concentrations\(^27\) of lidocaine (≥30 μmol/L) and flecainide (≥3 μmol/L), neither drug discriminates between WT and DG channels on the basis of TB.

UDB: Distinctions Between WT and DG Channels

Therefore, we next compared block that accumulates with repetitive activity when DG mutant and WT channels are exposed to lidocaine and flecainide (Figure 3). Again at clinically relevant concentrations (30 μmol/L), there is no difference between lidocaine block of WT and DG channels (Figure 3A). In contrast, there is a statistically significant (P<0.001) difference between flecainide UDB of DG and WT channels at the clinically relevant concentration of 3 μmol/L. This difference is evident over a broad concentration range: EC50 for flecainide UDB of DG channels is roughly 5 times lower than for block of WT channels (Figure 3B). In contrast, UDBs of WT or DG channels by lidocaine are approximately the same over all concentrations tested. In addition, the distinction in use-dependent drug action between WT and DG channels is retained when the frequency range of pulse application is extended to a broader frequency range (Figure 3C and 3D).

Effect of DG Mutation on Recovery From Flecainide Block

Block that accumulates as a consequence of repetitive channel activity (UDB) is caused by a balance between the time...
course of the onset of block (during depolarization) and the recovery from block (during repolarization). To understand the marked sensitivity of DG channels to UDB, we next investigated the time course of the recovery from UDB. Here, we focused only on the effects of flecainide, because there was little difference between WT and DG channels in response to UDB by lidocaine (Figure 3A and 3C).

In these experiments, we applied a “conditioning” train of pulses for a fixed duration and frequency to induce flecainide block of channels. As illustrated in Figure 4, in the absence of drug, DG channels tend to recover faster from inactivation that occurs as a consequence of the conditioning train. In the presence of flecainide, repriming of channels is very different: now DG channels recover very slowly. Even after 10 seconds at the holding potential (−2100 mV) under pulse-free conditions, only a small fraction of the flecainide-blocked current recovers. This result suggests that the flecainide-bound DG channel is very stable and that infrequent pulsing can still be very effective at accumulating block because once blocked, channels remain nonconducting for tens of seconds.

Clinical Efficacy of Flecainide: Distinctions Between UDB of WT and DG Channels

The dramatic slowing of flecainide unblock caused by the DG mutation (Figure 4) has important implications for the clinical usefulness of this compound in the treatment of LQT-3 in

**Figure 2.** TB of WT and DG mutant Na⁺ channels. A and B, Inhibition of Na⁺ current elicited in HEK cells expressing WT or DG channels with lidocaine (A) or flecainide (B). Traces show currents in control solution and after steady-state TB was attained (arrows) 2 to 4 minutes after cell superfusate was changed to one containing lidocaine (300 μmol/L) or flecainide (30 μmol/L), respectively. C and D, Concentration-dependence of TB of WT (○) and DG (○) channels by lidocaine (C) and flecainide (D). Graph shows peak current after drug application, normalized to peak current in absence of drug, plotted as a function of drug concentration. Smooth lines are according to 1/(1+([drug]/EC_{50})^n). EC_{50} for lidocaine is 894 (WT) and 205 (DG); EC_{50} for flecainide is 59.3 (WT) and 48.2 (DG); n=3 to 6 cells per condition.

**Figure 3.** DG mutation increases sensitivity of channels to UDB by flecainide but not lidocaine. Concentration dependence of UDB of WT (○) and DG (○) channels by lidocaine (A) and flecainide (B). Currents were evoked by pulses applied at a frequency of 5 Hz in presence of drugs until steady-state UDB was achieved and normalized to TB levels before high-frequency train protocol was started. Smooth lines are according to 1/(1+([drug]/EC_{50})^n). EC_{50} for lidocaine is 318 (WT) and 176 (DG); EC_{50} for flecainide is 11.0 (WT) and 1.7 (DG); n=3 to 6 cells per condition. C and D, Frequency-dependence of lidocaine and flecainide block of WT (○) and DG (○) channels at fixed drug concentrations. Trains of 100 to 600 pulses were applied at various frequencies in presence of lidocaine (300 μmol/L, C) or flecainide (10 μmol/L, D). Graphs show peak current during steady-state UDB normalized to peak current during first pulse of train plotted against stimulus frequency; n=4 cells per condition. *P<0.05, **P<0.01, ***P<0.001.
The DG mutation is a nonconservative change from an aspartic acid to a glycine only 18 amino acids away from transmembrane segment S6 in the C-terminus of the Na\(^+\) channel α-subunit, a region of the channel not previously considered to play a major role in the molecular interactions of flecainide. Our data clearly show that this is not the case and raise the possibility that other residues of the C-terminus may also be important in determining pharmacological responses of Na\(^+\) channels. Importantly, 1 other nonconservative C-terminus LQT-3 mutation (E1784K) has been reported recently, and a C-terminus insertion mutation (1795insD) has been linked to both Brugada’s syndrome and LQT-3. Our work strongly suggests that these mutations may also modify the interactions of the encoded channels by flecainide (and probably other drugs), raising the possibility of pharmacological targeting of a broad range of mutation-induced phenotypes. As has been shown for ∆KPQ and DG channels, however, determination of the pharmacological profile must be carried out systematically on a mutation-by-mutation basis before this would be possible.

**Relationship Between Molecular Pharmacology and Therapeutic Efficacy**

Our data on recombinant human Na\(^+\) channels complement those of Benhorin et al, which have shown that flecainide, but not lidocaine, significantly decreased the QTc interval in DG carriers by ≈10% but was without effect in control patients. This difference was even more striking when the effect of flecainide on the marked repolarization heterogeneity seen in DG carriers was considered. Our experiments indicate that over the clinically relevant drug concentration range and under physiological conditions, flecainide discriminates between WT and DG primarily because of the pronounced effect of the DG mutation on flecainide UDB. The correlation between the clinical results and our data strongly suggests that it is this mechanism of action that underlies the therapeutic usefulness of flecainide compared with lidocaine in the treatment of carriers of the DG mutation. Interestingly,
flecainide has also recently been shown to be very effective in treating carriers of the ΔKPQ LQT-3 mutation (A.J. Moss, personal communication), even though, as discussed above, the interactions of flecainide with ΔKPQ and DG mutant channels differ. In the case of both channel defects, however, recovery from the drug-blocked state is markedly slowed compared with WT channels, and it may be this common mode of action that makes this drug so useful as a therapeutic tool in the treatment of carriers of these gene defects.

In summary, we have found that the LQT-3 ΔG mutation changes the pharmacological response of encoded channels in a manner that differs not only from WT but also from other LQT-3 mutant channels. The pharmacological profile of DG channels shows distinct changes that occur over a therapeutically relevant concentration range. Our data provide further support for the usefulness of a mutation-specific pharmacological approach for the management of distinct inherited ion channel defects.

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