Cellular Basis for the ECG Features of the LQT1 Form of the Long-QT Syndrome

Effects of β-Adrenergic Agonists and Antagonists and Sodium Channel Blockers on Transmural Dispersion of Repolarization and Torsade de Pointes

Wataru Shimizu, MD, PhD; Charles Antzelevitch, PhD

Background—This study examines the cellular basis for the phenotypic appearance of broad-based T waves, increased transmural dispersion of repolarization (TDR), and torsade de pointes (TdP) induced by β-adrenergic agonists under conditions mimicking the LQT1 form of the congenital long-QT syndrome.

Methods and Results—A transmural ECG and transmembrane action potentials from epicardial, M, and endocardial cells were recorded simultaneously from an arterially perfused wedge of canine left ventricle. Chromanol 293B, a specific IKs blocker, dose-dependently (1 to 100 μmol/L) prolonged the QT interval and action potential duration (APD90) of the 3 cell types but did not widen the T wave, increase TDR, or induce TdP. Isoproterenol 10 to 100 nmol/L in the continued presence of chromanol 293B 30 μmol/L abbreviated the APD90 of epicardial and endocardial cells but not that of the M cell, resulting in widening of the T wave and a dramatic accentuation of TDR. Spontaneous as well as programmed electrical stimulation (PES)-induced TdP was observed only after exposure to the IKs blocker and isoproterenol. Therapeutic concentrations of propranolol (0.5 to 1 μmol/L) prevented the actions of isoproterenol to increase TDR and to induce TdP. Mexiletine 2 to 20 μmol/L abbreviated the APD90 of M cells more than that of epicardial and endocardial cells, thus diminishing TDR and the effect of isoproterenol to induce TdP.

Conclusions—This experimental model of LQT1 indicates that a deficiency of IKs alone does not induce TdP but that the addition of β-adrenergic influence predisposes the myocardium to the development of TdP by increasing transmural dispersion of repolarization, most likely as a result of a large augmentation of residual IKs in epicardial and endocardial cells but not in M cells, in which IKs is intrinsically weak. Our data provide a mechanistic understanding of the cellular basis for the therapeutic actions of β-adrenergic blockers in LQT1 and suggest that sodium channel block with class IB antiarrhythmic agents may be effective in suppressing TdP in LQT1, as they are in LQT2 and LQT3, as well as in acquired (drug-induced) forms of the long-QT syndrome. (Circulation. 1998;98:2314-2322.)

Key Words: long-QT syndrome ■ arrhythmia ■ KvLQT1 ■ chromanol 293b ■ isoproterenol

The long-QT syndrome (LQTS) is characterized by the appearance of long QT intervals in the ECG and atypical polymorphic ventricular tachycardia that can lead to sudden cardiac death.1-6 It has long been appreciated that some forms of congenital and acquired LQTS are exquisitely sensitive to the activity of the sympathetic branch of the autonomic nervous system. An imbalance of sympathetic inputs to the heart was at one time thought to underlie congenital LQTS.1,6 Recent studies have shown that congenital LQTS is a primary electrical disease caused by mutations in specific ion channel genes.7 Genetic linkage analysis has identified 4 forms of congenital LQTS caused by mutations in ion channel genes located on chromosomes 3, 7, 11, and 21.8-11 Chromosome 3–linked LQT3 is associated with a mutation in SCN5A, a gene that encodes for the α-subunit of the sodium channel in heart,9 whereas chromosome 7–linked LQT2 is associated with a mutation in HERG, a gene that encodes for the channel that carries the rapidly activating delayed rectifier potassium current (IKr).12 Chromosome 11–linked LQT1 is associated with a mutation in KvLQT1, which encodes for the slowly activating delayed rectifier potassium current (IKs),13,14 and chromosome 21–linked LQT5 is caused by a mutation in KCNE1 (minK), whose product coassembles with that of KvLQT1 to form the IKs channel.11,13,14

In the clinic, Moss and coworkers15 reported that patients with these ion channel defects often display different phenotypic T wave patterns in the ECG. LQT3 patients show distinctive late-appearing T waves, whereas LQT1 or LQT2 patients display broad-based, prolonged T waves or low-amplitude T waves, respectively.
Among the 3 forms of congenital LQTS, cardiac events (cardiac arrhythmias and sudden cardiac death) are more likely to be associated with adrenergic factors (defined as either physical or emotional stress) in the LQT1 syndrome than in either the LQT2 or LQT3 syndrome. Moreover, β-blockers were reported to reduce cardiac events dramatically in LQT1 patients. The mechanisms responsible for these actions of the β-adrenergic system remain largely unknown.

Using an arterially perfused left ventricular wedge preparation, we recently developed models of LQT2 and LQT3 and showed that sodium channel block with mexiletine is effective in decreasing transmural dispersion of repolarization (TDR) and in suppressing TdP in both.

In the present study, we use this preparation to develop an experimental model of LQT1 in which we (1) elucidate the cellular basis of catecholamine-induced phenotypic appearance of broad-based T wave, increased TDR, and TdP and (2) examine the effects of rapid pacing as well as of β-adrenergic and sodium channel blockers to abbreviate the QT interval, diminish TDR, and prevent TdP.

**Methods**

**Arterially Perfused Wedge of Canine Left Ventricle**

Dogs weighing 20 to 25 kg were anticoagulated with heparin and anesthetized with pentobarbital 30 to 35 mg/kg IV. The chest was opened via a left thoracotomy, and the heart was excised and placed in a cardioplegic solution consisting of cold (4°C) or room-temperature Tyrode’s solution containing 8.5 mmol/L [K+]0. Transmural wedges with dimensions of ~2×1.5×0.9 to 3×2×1.5 cm were dissected from the left ventricle. The tissue was cannulated via a small (diameter, ~100 μm) native branch of left anterior descending coronary artery and perfused with cardioplegic solution. Unperfused tissue, readily identified by its maintained red appearance (erythrocytes not washed away), was carefully removed with a razor blade. The preparation was then placed in a small tissue bath and arterially perfused with Tyrode’s solution of the following composition (mmol/L): NaCl 129, KCl 4, NaH2PO4 0.9, NaHCO3 20, CaCl2 1.8, MgSO4 0.5, and glucose 5.5, buffered with 95% O2 and 5% CO2 (37±1°C). The perfusate was delivered to the artery by a roller pump (Cole Parmer Instrument Co.). Perfusion pressure was monitored with a pressure transducer (World Precision Instruments, Inc) and maintained between 40 and 50 mm Hg by adjustment of the perfusion flow rate. The preparations remained immersed in the arterial perfusate, which was allowed to rise to a level 2 to 3 mm above the tissue surface when possible. To facilitate impalement with the floating microelectrodes, in some experiments the bath perfusate was brought to a level just shy of the top of the wedge and the chamber was covered to the extent possible so as to avoid a temperature gradient between the top and lower segments of the wedge.

**Recordings of a Transmural ECG and Transmembrane Action Potentials**

The ventricular wedges were allowed to equilibrate until electrically stable, usually 1 hour, and stimulated with bipolar silver electrodes insulated except at the tips and applied to the endocardial surface. In the present study, we use this preparation to develop an experimental model of LQT1 in which we (1) elucidate the cellular basis of catecholamine-induced phenotypic appearance of broad-based T wave, increased TDR, and TdP and (2) examine the effects of rapid pacing as well as of β-adrenergic and sodium channel blockers to abbreviate the QT interval, diminish TDR, and prevent TdP.

**Methods**

**Arterially Perfused Wedge of Canine Left Ventricle**

Dogs weighing 20 to 25 kg were anticoagulated with heparin and anesthetized with pentobarbital 30 to 35 mg/kg IV. The chest was opened via a left thoracotomy, and the heart was excised and placed in a cardioplegic solution consisting of cold (4°C) or room-temperature Tyrode’s solution containing 8.5 mmol/L [K+]0. Transmural wedges with dimensions of ~2×1.5×0.9 to 3×2×1.5 cm were dissected from the left ventricle. The tissue was cannulated via a small (diameter, ~100 μm) native branch of left anterior descending coronary artery and perfused with cardioplegic solution. Unperfused tissue, readily identified by its maintained red appearance (erythrocytes not washed away), was carefully removed with a razor blade. The preparation was then placed in a small tissue bath and arterially perfused with Tyrode’s solution of the following composition (mmol/L): NaCl 129, KCl 4, NaH2PO4 0.9, NaHCO3 20, CaCl2 1.8, MgSO4 0.5, and glucose 5.5, buffered with 95% O2 and 5% CO2 (37±1°C). The perfusate was delivered to the artery by a roller pump (Cole Parmer Instrument Co.). Perfusion pressure was monitored with a pressure transducer (World Precision Instruments, Inc) and maintained between 40 and 50 mm Hg by adjustment of the perfusion flow rate. The preparations remained immersed in the arterial perfusate, which was allowed to rise to a level 2 to 3 mm above the tissue surface when possible. To facilitate impalement with the floating microelectrodes, in some experiments the bath perfusate was brought to a level just shy of the top of the wedge and the chamber was covered to the extent possible so as to avoid a temperature gradient between the top and lower segments of the wedge.

**Recordings of a Transmural ECG and Transmembrane Action Potentials**

The ventricular wedges were allowed to equilibrate until electrically stable, usually 1 hour, and stimulated with bipolar silver electrodes insulated except at the tips and applied to the endocardial surface. In the present study, we use this preparation to develop an experimental model of LQT1 in which we (1) elucidate the cellular basis of catecholamine-induced phenotypic appearance of broad-based T wave, increased TDR, and TdP and (2) examine the effects of rapid pacing as well as of β-adrenergic and sodium channel blockers to abbreviate the QT interval, diminish TDR, and prevent TdP.

**Methods**

**Arterially Perfused Wedge of Canine Left Ventricle**

Dogs weighing 20 to 25 kg were anticoagulated with heparin and anesthetized with pentobarbital 30 to 35 mg/kg IV. The chest was opened via a left thoracotomy, and the heart was excised and placed in a cardioplegic solution consisting of cold (4°C) or room-temperature Tyrode’s solution containing 8.5 mmol/L [K+]0. Transmural wedges with dimensions of ~2×1.5×0.9 to 3×2×1.5 cm were dissected from the left ventricle. The tissue was cannulated via a small (diameter, ~100 μm) native branch of left anterior descending coronary artery and perfused with cardioplegic solution. Unperfused tissue, readily identified by its maintained red appearance (erythrocytes not washed away), was carefully removed with a razor blade. The preparation was then placed in a small tissue bath and arterially perfused with Tyrode’s solution of the following composition (mmol/L): NaCl 129, KCl 4, NaH2PO4 0.9, NaHCO3 20, CaCl2 1.8, MgSO4 0.5, and glucose 5.5, buffered with 95% O2 and 5% CO2 (37±1°C). The perfusate was delivered to the artery by a roller pump (Cole Parmer Instrument Co.). Perfusion pressure was monitored with a pressure transducer (World Precision Instruments, Inc) and maintained between 40 and 50 mm Hg by adjustment of the perfusion flow rate. The preparations remained immersed in the arterial perfusate, which was allowed to rise to a level 2 to 3 mm above the tissue surface when possible. To facilitate impalement with the floating microelectrodes, in some experiments the bath perfusate was brought to a level just shy of the top of the wedge and the chamber was covered to the extent possible so as to avoid a temperature gradient between the top and lower segments of the wedge.

**Recordings of a Transmural ECG and Transmembrane Action Potentials**

The ventricular wedges were allowed to equilibrate until electrically stable, usually 1 hour, and stimulated with bipolar silver electrodes insulated except at the tips and applied to the endocardial surface. In the present study, we use this preparation to develop an experimental model of LQT1 in which we (1) elucidate the cellular basis of catecholamine-induced phenotypic appearance of broad-based T wave, increased TDR, and TdP and (2) examine the effects of rapid pacing as well as of β-adrenergic and sodium channel blockers to abbreviate the QT interval, diminish TDR, and prevent TdP.
Study Protocols

The I_Ks blocker chromanol 293B 1 to 100 \( \mu \)mol/L was used to create a model that mimics the defect in KvLQT1, which results in a reduced I_Ks, believed to underlie the congenital LQT1 syndrome. Isoproterenol 10 to 100 nmol/L was used to mimic increased \( \beta \)-adrenergic tone. The effects of \( \beta \)-adrenergic blockade were evaluated with propranolol 0.1, 0.3, 1, and 3 \( \mu \)mol/L and those of sodium channel blocker with mexiletine 2, 5, 10, and 20 \( \mu \)mol/L.

Control measurements were generally obtained after 1 hour of equilibration. The chromanol 293B data were collected for a period of up to 30 minutes starting 30 minutes after addition of the drug. Isoproterenol data in the absence and presence of chromanol 293B were collected within 10 minutes after addition of isoproterenol. Mexiletine and propranolol data were recorded after 30 minutes of exposure to each concentration of drug.

APD was measured at 90% repolarization (APD_{90}). TDR was defined as the difference between the longest and the shortest repolarization times (activation time + APD_{90}) of transmembrane APs recorded across the wall. The QT interval was defined as the time between QRS onset and the point at which the line of maximal downslope of the T wave crossed the baseline. Graphic correlation of transmembrane and ECG activity was achieved by dropping a dotted line from the point of full repolarization of the AP (APD_{100} approximated by eye) to the ECG trace.

The development of spontaneous and programmed electrical stimulation (PES)–induced polymorphic ventricular tachycardia displaying characteristics of TdP was assessed in the presence of chromanol 293B 30 \( \mu \)mol/L or isoproterenol 10 to 100 nmol/L alone and after the combination of chromanol 293B and isoproterenol 50 to 100 nmol/L. PES-induced arrhythmias were evaluated with a single extrastimulus applied to the epicardium.

Statistics

Statistical analysis of the data was performed with a Student’s \( t \) test for paired data or ANOVA coupled with Scheffe’s test, as appropriate. Data are expressed as mean±SD values, except for those shown in the figures, which are expressed as mean±SEM values.

Results

Dose-Dependent Effect of Chromanol 293B on QT Interval, APD, and TDR

Figure 1A illustrates the dose-dependent effect of chromanol 293B on transmembrane and ECG activity. Chromanol 293B, in concentrations \( \geq 10 \mu \)mol/L, significantly prolonged the QT interval and APD_{90} of the 3 cell types (Figure 1B). However, because the prolongation of APD_{90} of the 3 cell types was homogeneous, chromanol 293B did not widen the T wave or significantly increase TDR (Figure 1C).

Rate Dependence of QT Interval, APD, and Dispersion of Repolarization

The rate-dependent changes in the QT interval were closely approximated by changes in the repolarization time of the M cell both under control conditions and after chromanol 293B, as illustrated in Figures 2 and 3. Chromanol 293B 30 \( \mu \)mol/L produced a steepening of the APD-rate relations and a significant prolongation of APD_{90} and of the QT interval at all rates studied (Figures 2B, 3A, 3B, and 3C). TDR did not change significantly at any rate (Figures 2B and 3D) because
of the effect of chromanol 293B to prolong the APD\textsubscript{90} of the 3 cell types homogeneously.

**Influence of Isoproterenol on Phenotypic ECG Pattern, Transmembrane APD, TDR, and TdP**

Figure 4 shows transmembrane activity recorded simultaneously from endocardial (Endo), M, and epicardial (Epi) sites together with a transmural ECG in the absence and presence of chromanol 293B \(30 \mu\text{mol/L}\) and chromanol 293B (basic cycle length [BCL], 2000 ms). In all cases, the peak of the T wave in the ECG was coincident with the repolarization of the epicardial cell, whereas the end of the T wave was coincident with the repolarization of the M region (deep subendocardium). Repolarization of the endocardial AP was intermediate between that of the M cell and epicardial cell. Thus, TDR across the ventricular wall was defined as the difference in the repolarization time between the M cell (longest AP) and epicardial cell (shortest AP). Once again, 30 \(\mu\text{mol/L}\) of chromanol 293B prolonged the APD of the 3 cell types and the QT interval, but it neither increased TDR nor widened the T wave (Figure 4B). Isoproterenol 10 to 100 nmol/L in the continued presence of chromanol 293B significantly prolonged the QT interval, from 314±9 to 383±23 ms (n=8; \(P<0.0005\)) at a BCL of 2000 ms. The change in QT interval was paralleled by an increase in \(\text{APD}_{90}\) of the M cell (286±10 to 354±24 ms; n=8; \(P<0.0005\)). Chromanol 293B homogeneously prolonged the \(\text{APD}_{90}\) of the M cell and the epicardial cell (234±14 to 298±22 ms; n=8; \(P<0.0005\)), resulting in no significant increase of TDR (43±6 to 47±7 ms; n=8). Isoproterenol in the continued presence of chromanol 293B significantly shortened the \(\text{APD}_{90}\) of the epicardial cell (267±15 ms; n=8; \(P<0.0005\) versus 293B) but not that of the M cell (350±19 ms; n=8) (Figure 5A), resulting in a significant increase of the TDR (75±9 ms; n=8; \(P<0.0005\) versus 293B) (Figure 5B).

In 4 preparations, we examined the influence of isoproterenol 10, 50, and 100 nmol/L on transmembrane and ECG activity. Isoproterenol homogeneously abbreviated the \(\text{APD}_{90}\) of the 3 cell types in a dose-dependent manner, thus abbreviating the QT interval with no major changes in TDR or width of the T wave.

**Figure 4.** Transmembrane APs and transmural ECG under control conditions (A), after addition of chromanol 293B \(30 \mu\text{mol/L}\) (B), and after further addition of isoproterenol \(100 \text{nmol/L}\) (C). All traces depict APs recorded simultaneously from endocardial (Endo), M, and epicardial (Epi) sites together with a transmural ECG, BCL, 2000 ms. A, Control. B, Chromanol 293B prolonged APs of 3 cell types and QT interval but did not increase TDR (42 to 46 ms) or widen T wave. C, Isoproterenol in continued presence of chromanol 293B abbreviated AP of epicardial and endocardial cells but not that of M cell, resulting in an accentuated TDR (85 ms) and broad-based T waves as commonly seen in LQT1 patients.

**Figure 5.** Composite data of influence of isoproterenol (Iso, 100 nmol/L) on QT interval (A, •), \(\text{APD}_{90}\) in M (A, □) and epicardial (A, ◇) cells, and TDR time (RT) (B, ●); BCL, 2000 ms. *\(P<0.0005\) vs control; †\(P<0.05\), ††\(P<0.0005\) vs 293B.
repolarization (first grouping). A single extrastimulus (S2) applied
of chromanol 293B produced very significant dispersion of
induced TdP. Perfusion of isoproterenol (4 minutes) in presence
of chromanol 293B to prolong the APD90 of the M cell and the
epicardial cell. 293B produced a homogeneous prolongation of the QT
interval and of APD90. In the continued presence of chromanol
293B, 0.1 to 1 μmol/L of propranolol exerted no significant effect, whereas the highest concentration
(3 μmol/L) significantly abbreviated the APD90 of the M cell, probably because of its effect to block the late sodium current (I\textsubscript{Na}), which is intrinsically larger in the M cell than in the
epicardial cell.

**Effect of Propranolol on Repolarization Changes and TdP Induced by Isoproterenol**

Figure 7 illustrates the effect of propranolol 1 μmol/L to inhibit the influence of isoproterenol in a wedge preparation pretreated with chromanol 293B 30 μmol/L. Therapeutic concentrations of propranolol (0.5 to 1 μmol/L), which block β-adrenergic receptors in the heart with little or no block of I\textsubscript{Na}, completely prevented the influence of isoproterenol to increase TDR (Figures 7C and 7D).

The average data of 6 experiments are shown in Figure 8. Propranolol 1 μmol/L in the continued presence of chromanol 293B 30 μmol/L completely suppressed the influence of isoproterenol to shorten the APD90 of the epicardial cell and to increase TDR (see Figures 4C, 5A, and 5B). Moreover, therapeutic concentrations of propranolol (0.5 to 1 μmol/L) totally suppressed the spontaneous as well as PES-induced TdP produced in the presence of isoproterenol and chromanol 293B.

**Dose-Dependent Effect of Mexiletine on QT Interval, APD, and TDR**

Table 2 summarizes the effects of mexiletine on QT interval, APD\textsubscript{90}, and TDR in the continued presence of chromanol 293B 30 μmol/L (BCL, 2000 ms; n=6). In the continued presence of chromanol 293B, 2 to 20 μmol/L of mexiletine dose-dependently abbreviated the QT interval and APD\textsubscript{90} of M cells more than those of epicardial cells, thus reducing TDR. Mexiletine 20 μmol/L reversed 70% of the effect of chromanol 293B to prolong the APD\textsubscript{90} of the M cell and the QT interval but only 45% of the effect of chromanol 293B to prolong the epicardial AP.

**Effect of Mexiletine on Repolarization Changes and TdP Induced by Isoproterenol**

Figure 9 illustrates the effect of mexiletine 20 μmol/L to inhibit the influence of isoproterenol on transmembrane and ECG activity in the continued presence of chromanol 293B 30 μmol/L. Mexiletine 10 to 20 μmol/L decreased TDR in...
Shimizu and Antzelevitch  November 24, 1998  2319

Figure 7. Effect of propranolol (Prop) 1 μmol/L to prevent influence of isoproterenol (Iso) 100 nmol/L on APD and QT interval in continued presence of chromanol 293B 30 μmol/L. Each trace shows superimposed APs recorded simultaneously from M and epicardial (Epi) cells together with a transmural ECG at a BCL of 2000 ms. A, Control. B, Chromanol 293B homogeneously prolonged APD of M cell and epicardial cell as well as QT interval but did not increase TDR (42 to 46 ms) or widen T wave. C, Propranolol produced a slight abbreviation of APD of both cells, QT interval, and TDR (44 ms). D, Propranolol totally suppressed influence of isoproterenol to increase TDR (44 ms). Same preparation as shown in Figure 4.

The presence of chromanol 293B and prevented the influence of isoproterenol to increase TDR (Figures 9C and 9D).

Composite data of 6 experiments are shown in Figure 10. Mexiletine 20 μmol/L, in the continued presence of chromanol 293B 30 μmol/L abbreviated the M cell AP more than that of the epicardial cell, resulting in a significant decrease of TDR. In the continued presence of mexiletine, isoproterenol 50 to 100 nmol/L slightly abbreviated the APD of the epicardial cell but not that of the M cell, resulting in a slight but statistically insignificant increase in TDR.

In concentrations of 10 to 20 μmol/L, mexiletine totally suppressed the spontaneous as well as PES-induced TdP provoked with isoproterenol.

Discussion

Catecholamine-Induced Broad-Based Long-QT and Increased Dispersion of Repolarization

Sympathetic stimulation or the administration of exogenous catecholamines is known to produce paradoxical QT prolongation and TdP, often associated with syncope or sudden cardiac death in patients with congenital LQTS.1–6 Cardiac arrhythmias and sudden death are more often associated with adrenergic factors, defined as physical and emotional stress, because of the presence of a strong net repolarizing current (weak \( I_{Ks} \)). This response is different from that observed with all other APD-prolonging agents. Agents that block \( I_{Ks} \), augment \( I_{Ca} \), or slow the inactivation of \( I_{Ks} \) all produce a dramatic prolongation of the M-cell APD but a much more modest prolongation of the APD of epicardium and endocardium, presumably because of the presence of a strong net repolarizing current (strong \( I_{Ks} \) and weak \( I_{Ca} \)) in the latter and weak net repolarizing current (weak \( I_{Ks} \) and strong \( I_{Ca} \)) in the former. The homogeneous response to chromanol 293B is best explained by the presence of unequal levels of \( I_{Ks} \) in the 3 cell types. Because epicardial and endocardial cells have a larger \( I_{Ks} \) than M cells, the same percentage inhibition of \( I_{Ks} \) in the 3 cell types would be expected to decrease total repolarizing current more in the epicardial and endocardial cells than the M cell, resulting in a greater prolongation of the APD of epicardial and endocardial cells. However, the smaller intrinsic repolarizing current of the M cell provides a greater input (membrane) resistance during phases 2 and 3 of the AP. As a consequence, a smaller absolute decrease in \( I_{Ks} \) can cause an APD prolongation in M cells comparable to that seen in epicardial and endocardial cells. Consistent with this reasoning, on a percentage basis, 293B-induced APD prolongation in epicardium and endocardium is greater than in the M cell.

Figure 8. Composite data of effect of propranolol (Prop, 1 μmol/L) to suppress influence of isoproterenol (Iso) 100 nmol/L on QT interval (A, •) and APD90 in M (A, ○), and epicardial (A, □) cells and TDR time (RT) (B, ○) in continued presence of chromanol 293B 30 μmol/L. *P<0.0005 vs control.

**Figure 7.** Effect of propranolol (Prop) 1 μmol/L to prevent influence of isoproterenol (Iso) 100 nmol/L on APD and QT interval in continued presence of chromanol 293B 30 μmol/L. Each trace shows superimposed APs recorded simultaneously from M and epicardial (Epi) cells together with a transmural ECG at a BCL of 2000 ms. A, Control. B, Chromanol 293B homogeneously prolonged APD of M cell and epicardial cell as well as QT interval but did not increase TDR (42 to 46 ms) or widen T wave. C, Propranolol produced a slight abbreviation of APD of both cells, QT interval, and TDR (44 ms). D, Propranolol totally suppressed influence of isoproterenol to increase TDR (44 ms). Same preparation as shown in Figure 4.

The presence of chromanol 293B and prevented the influence of isoproterenol to increase TDR (Figures 9C and 9D).

Composite data of 6 experiments are shown in Figure 10. Mexiletine 20 μmol/L, in the continued presence of chromanol 293B 30 μmol/L abbreviated the M cell AP more than that of the epicardial cell, resulting in a significant decrease of TDR. In the continued presence of mexiletine, isoproterenol 50 to 100 nmol/L slightly abbreviated the APD of the epicardial cell but not that of the M cell, resulting in a slight but statistically insignificant increase in TDR.

In concentrations of 10 to 20 μmol/L, mexiletine totally suppressed the spontaneous as well as PES-induced TdP provoked with isoproterenol.

Discussion

Catecholamine-Induced Broad-Based Long-QT and Increased Dispersion of Repolarization

Sympathetic stimulation or the administration of exogenous catecholamines is known to produce paradoxical QT prolongation and TdP, often associated with syncope or sudden cardiac death in patients with congenital LQTS.1–6 Cardiac arrhythmias and sudden death are more often associated with adrenergic factors, defined as physical and emotional stress, because of the presence of a strong net repolarizing current (weak \( I_{Ks} \)). This response is different from that observed with all other APD-prolonging agents. Agents that block \( I_{Ks} \), augment \( I_{Ca} \), or slow the inactivation of \( I_{Ks} \) all produce a dramatic prolongation of the M-cell APD but a much more modest prolongation of the APD of epicardium and endocardium, presumably because of the presence of a strong net repolarizing current (strong \( I_{Ks} \) and weak \( I_{Ca} \)) in the latter and weak net repolarizing current (weak \( I_{Ks} \) and strong \( I_{Ca} \)) in the former. The homogeneous response to chromanol 293B is best explained by the presence of unequal levels of \( I_{Ks} \) in the 3 cell types. Because epicardial and endocardial cells have a larger \( I_{Ks} \) than M cells, the same percentage inhibition of \( I_{Ks} \) in the 3 cell types would be expected to decrease total repolarizing current more in the epicardial and endocardial cells than the M cell, resulting in a greater prolongation of the APD of epicardial and endocardial cells. However, the smaller intrinsic repolarizing current of the M cell provides a greater input (membrane) resistance during phases 2 and 3 of the AP. As a consequence, a smaller absolute decrease in \( I_{Ks} \) can cause an APD prolongation in M cells comparable to that seen in epicardial and endocardial cells. Consistent with this reasoning, on a percentage basis, 293B-induced APD prolongation in epicardium and endocardium is greater than in the M cell.
TABLE 2. Dose-Dependent Effects of Mexiletine on the QT Interval, APD<sub>90</sub>, and Dispersion of Repolarization in Perfused Wedge Preparation Pretreated With Chromanol 293B

<table>
<thead>
<tr>
<th>Control</th>
<th>293B 30 μmol/L</th>
<th>+ Mex 2 μmol/L</th>
<th>+ Mex 5 μmol/L</th>
<th>+ Mex 10 μmol/L</th>
<th>+ Mex 20 μmol/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT</td>
<td>308±15</td>
<td>385±12*</td>
<td>362±9†</td>
<td>351±12§</td>
<td>342±11§</td>
</tr>
<tr>
<td>APD&lt;sub&gt;90&lt;/sub&gt; (M cell)</td>
<td>284±16</td>
<td>359±10*</td>
<td>336±12‡</td>
<td>327±9†</td>
<td>315±5§</td>
</tr>
<tr>
<td>APD&lt;sub&gt;90&lt;/sub&gt; (Epi)</td>
<td>232±17</td>
<td>299±11*</td>
<td>286±17</td>
<td>282±15</td>
<td>275±12†</td>
</tr>
<tr>
<td>Dispersion of RT</td>
<td>40±6</td>
<td>47±10</td>
<td>36±5</td>
<td>32±5†</td>
<td>28±7‡</td>
</tr>
</tbody>
</table>

Mex indicates mexiletine; other abbreviations as in Table 1.

*Ρ<0.0005 vs control; †Ρ<0.05, ‡Ρ<0.005, §Ρ<0.0005 vs 293B.

In the continued presence of chromanol 293B, β-adrenergic stimulation with isoproterenol abbreviates the APD<sub>90</sub> of epicardial and endocardial cells but not that of the M cell, resulting in an accentuated TDR and a broad-based T wave, consistent with the phenotypic appearance of the ECG in patients afflicted with the LQT1 syndrome. The differential response to isoproterenol is probably the result of intrinsic differences in β<sub>K</sub> among the 3 cell types. A large augmentation of residual β<sub>K</sub> would be expected in epicardial and endocardial cells but not in M cells, in which β<sub>K</sub> is intrinsically weak. The weaker endocardial response is most likely due to the strong electrotonic influence of the M cells, which reside in the deep subendocardium in this part of the left ventricular wall. When studied as isolated strips, epicardial and endocardial APs prolonged by chromanol 293B display a marked abbreviation in response to isoproterenol, whereas the M-cell preparations usually exhibit a prolongation of APD within the first few seconds of exposure to isoproterenol (unpublished data).

Our data indicate the lack of an arrhythmogenic substrate when β<sub>K</sub> is diminished in the absence of β-adrenergic influence. Because sympathetic tone is always present under normal physiological conditions, decreased levels of β<sub>K</sub> may be arrhythmogenic under conditions in which the sympathetic system has not been pharmacologically or surgically disabled. The concordance of our results in the wedge with the phenotypic ECG and pharmacological manifestations of LQT1 observed in patients suggests that chromanol 293B is a reasonable surrogate for the LQT1 syndrome.

Catecholamine-Induced TdP

TdP is an atypical polymorphic ventricular tachycardia most often associated with QT prolongation in both the congenital and acquired forms of LQTS. Although the precise mechanism of TdP has not been established, several experimental and clinical observations using monophasic AP recordings and perfused-wedge studies from our group suggest a role for early afterdepolarization (EAD)–induced triggered activity in the genesis of TdP. Recent in vivo studies from El-Sherif et al and perfused-wedge studies from our group present evidence in support of the hypothesis that an EAD-induced triggered response initiates TdP but that the arrhythmia is maintained by a reentrant mechanism. Our data, showing induction of TdP only in the presence of chromanol 293B and isoproterenol under conditions in which TDR is increased, provide further support for reentry as the basis for the maintenance of TdP. Conversely, several experimental studies have suggested that inward current through β<sub>I</sub> channels or through sodium-calcium exchange contributes to development of EADs. These mechanisms are thought to contribute to the effect of β-adrenergic agonists to induce EADs and triggered activity in M cells and Purkinje fibers, in which repolarizing currents are reduced. Thus, sympathetic stimulation may create the substrate for EAD-induced triggered activity as well as the substrate for reentry in the LQT1 syndrome.

Effect of Rapid Pacing on QT Interval, APD, and TDR

The present study shows a reduction of TDR as a function of rate and a steeper APD-rate relation for APD<sub>90</sub> and QT interval under LQT1 conditions compared with control. Unlike β<sub>K</sub> block, whose APD-prolonging effects are abolished at fast rates, β<sub>K</sub> block with 293B prolongs APD<sub>90</sub> and QT even at BCLs as short as 300 ms (Figures 2 and 3). The

Figure 9. Effect of mexiletine (Mex) 20 μmol/L to suppress influence of isoproterenol (Iso) 100 nmol/L on APD and QT interval in perfused-wedge preparations treated with chromanol 293B 30 μmol/L. Each trace shows superimposed APs recorded simultaneously from M and epicardial (Epi) cells together with a transmural ECG at a BCL of 2000 ms. A, Control. B, Chromanol 293B. C, Mexiletine preferentially abbreviated M cell AP more than that of epicardial cell, resulting in a decrease of TDR (32 ms). D, Mexiletine suppressed marked influence of isoproterenol to increase TDR (38 ms).
Effect of Propranolol on Repolarization and TdP

β-Blockers are widely reported to reduce the incidence of syncope and sudden death in patients with congenital LQTS. Consistent with reports of a high sensitivity of patients with the LQT1 syndrome to adrenergic stimulation, greater than those with either LQT2 or LQT3 syndrome, β-blockers have been shown to reduce cardiac events very effectively in LQT1 patients. Priori et al. reported that in patients with the Romano-Ward form of LQTS, cardiac events were reduced more in patients in whom β-blockers caused a large decrease in corrected QT (QTc) dispersion. In contrast, other clinical studies have shown that β-blockers modified neither QTc interval nor QTc dispersion as measured with a 12-lead ECG or an 87-lead body surface mapping system in the LQTS patients. Our finding of little or no effect of therapeutic levels of propranolol (0.1 to 1 μmol/L) on the APD₉₀ of the M cell in either the presence or absence of isoproterenol is in agreement with the latter observations. Nevertheless, the effects of isoproterenol to increase TDR and to produce spontaneous as well as PES-induced TdP were completely inhibited by propranolol in therapeutic concentrations. Our data point to a diminution of TDR during normal sympathetic tone or prevention of an augmentation in TDR in response to strong sympathetic stimulation as the basis for the antiarrhythmic effectiveness of propranolol. TDR under these conditions is measured by the difference in repolarization time of the epicardial and M regions; the interval between the peak and end of the T wave has been shown to provide an ECG index of this parameter. This index may prove useful in discerning between the actions of propranolol to reduce TDR already augmented by normal sympathetic tone or prevention of an augmentation in TDR in the absence of isoproterenol and to reduce the action of isoproterenol to accentuate TDR and induce TdP. Our results suggest that sodium channel block with mexiletine in combination with β-blockade warrants further consideration as a therapeutic approach in the treatment of the LQT1 syndrome.

Limitations of the Study

Our interpretations of the data are based on the assumption that the activity recorded from the cut surface of the perfused-wedge preparation is representative of cells within the respective layers of the wall throughout the wedge. Such validation was provided in 2 previous studies that used the perfused-wedge preparation. The extent to which chromanol 293B–induced inhibition of Iₛₖ mimics the KvLQT1 defect responsible for the LQT1 syndrome is difficult to quantify, because the current density of Iₛₖ is intrinsically heterogeneous in the 3 cell types. Our data demonstrate the ability of the model to closely mimic the ECG and pharmacological features of the LQT1 syndrome, including a prolonged QT interval, broad-based T waves, a moderately steep QT-rate relation, and exceptional sensitivity to β-adrenergic influences. We believe that these qualitative similarities validate chromanol 293B as a surrogate for LQT1.

Our LQT1 model is less than physiological with respect to the manner in which sympathetic influences are examined. An imbalance between left and right stellate inputs to the heart was first suggested to underlie LQTS in 1975. The sympathetic-imbalance hypothesis as a primary cause lost ground when genetic linkage analysis uncovered 4 gene mutations responsible for ion channel defects. The role of the sympathetic system remained largely unexplained. The present study advances our understanding of the action of β-adrenergic influences to amplify transmural dispersion of repolarization. However, perfusion of the wedge preparations with isoproterenol causes homogeneous stimulation of β₁-receptors only and does not take into account differences in the distribution of left and right sympathetic stellate inputs to the heart or the possibility that a pathophysiological sympathetic imbalance may further amplify transmural and interventricular dispersion of repolarization. This disclaimer notwithstanding, the available data suggest the hypothesis that differences in the distribution and characteristics of M cells in right versus left ventricle coupled with physiological differences in right versus left sympathetic innervation of the heart can explain the preeminent role of the left stellate in LQTS. This hypothesis remains to be tested.
Cellular Basis for the ECG in LQT1

Acknowledgments
This study was supported by grant HL-4778 from the National Institutes of Health and grants from Medtronic Japan and the Sixth, Seventh, and Eighth Manhattan Masonic Districts and New York State and Florida Grand Lodges of Free and Accepted Masons. Dr Shimizu was a finalist in the Young Investigator Award Competition of the American College of Cardiology on the basis of this work (47th Annual Scientific Sessions, Atlanta, Ga, March 30, 1998). Chromanol 293B was generously donated by Hoechst. We gratefully acknowledge the expert technical assistance of Judy Hefferson and Di Hou. We are grateful to Brandon McMahon, a participant in our summer fellowship program, for his help with some of the experiments.

References
Cellular Basis for the ECG Features of the LQT1 Form of the Long-QT Syndrome: Effects of β-Adrenergic Agonists and Antagonists and Sodium Channel Blockers on Transmural Dispersion of Repolarization and Torsade de Pointes
Wataru Shimizu and Charles Antzelevitch

Circulation. 1998;98:2314-2322
doi: 10.1161/01.CIR.98.21.2314
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1998 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/98/21/2314

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/