Targeting the late component of the cardiac L-type Ca\(^{2+}\) current to suppress early afterdepolarizations

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Early afterdepolarizations (EADs) associated with prolongation of the cardiac action potential (AP) can create heterogeneity of repolarization and premature extrasystoles, triggering focal and reentrant arrhythmias. Because the L-type Ca\(^{2+}\) current (I\(_{\text{Ca,L}}\)) plays a key role in both AP prolongation and EAD formation, L-type Ca\(^{2+}\) channels (LTCCs) represent a promising therapeutic target to normalize AP duration (APD) and suppress EADs and their arrhythmogenic consequences. We used the dynamic-clamp technique to systematically explore how the biophysical properties of LTCCs could be modified to normalize APD and suppress EADs without impairing excitation–contraction coupling. Isolated rabbit ventricular myocytes were first exposed to H\(_2\)O\(_2\) or moderate hypokalemia to induce EADs, after which their endogenous I\(_{\text{Ca,L}}\) was replaced by a virtual I\(_{\text{Ca,L}}\) with tunable parameters, in dynamic-clamp mode. We probed the sensitivity of EADs to changes in the (a) amplitude of the noninactivating pedestal current; (b) slope of voltage-dependent activation; (c) slope of voltage-dependent inactivation; (d) time constant of voltage-dependent activation; and (e) time constant of voltage-dependent inactivation. We found that reducing the amplitude of the noninactivating pedestal component of I\(_{\text{Ca,L}}\) effectively suppressed both H\(_2\)O\(_2\) and hypokalemia-induced EADs and restored APD. These results, together with our previous work, demonstrate the potential of this hybrid experimental–computational approach to guide drug discovery or gene therapy strategies by identifying and targeting selective properties of LTCC.

INTRODUCTION

Early afterdepolarizations (EADs) are arrhythmogenic membrane potential oscillations that occur before repolarization of the cardiac action potential (AP) is complete. Although the mechanistic link between EADs in single cells and triggered arrhythmias in the heart is still a subject of intense investigation (Wit and Rosen, 1983; Rosen, 1988; Antzelevitch and Sicouri, 1994; El-Shereif et al., 1996; Yan et al., 2001; Xie et al., 2010; Yang et al., 2010), it is firmly established that EADs are capable of triggering fatal arrhythmias such as polymorphic ventricular tachycardia, torsade de pointes, and ventricular fibrillation (Yan et al., 2001; Choi et al., 2002; Wu et al., 2002; Antzelevitch, 2007; Bapat et al., 2012), which often exhibit a mixture of focal and reentrant mechanisms (Asano et al., 1997; Sato et al., 2009; Weiss et al., 2010; Chang et al., 2012). Not only are EADs capable of generating triggered activity to produce focal arrhythmias, but they are also associated with a prolonged AP duration (APD). Thus, they can markedly increase dispersion of refractoriness in tissue, predisposing to initiation of reentry (Sato et al., 2009; Weiss et al., 2010; Chang et al., 2012).

The onset of EADs (i.e., the reversal of the normal repolarization phase of the AP) occurs within a range of the membrane potentials where the steady-state activation and inactivation curves of the L-type Ca\(^{2+}\) current (I\(_{\text{Ca,L}}\)) overlap, known as the I\(_{\text{Ca,L}}\) window current region (January et al., 1988). Within this membrane potential range, I\(_{\text{Ca,L}}\) reactivation plays a key role in reversing the normal repolarization phase during EAD formation (January et al., 1988). Although other ionic currents also participate in EAD formation, a regenerative inward current such as I\(_{\text{Ca,L}}\) is required for EADs to propagate in the tissue (Zeng and Rudy, 1995; Chang et al., 2012). Using the dynamic-clamp technique (Dorval et al., 2001) in isolated rabbit ventricular myocytes, we recently demonstrated that EADs are highly sensitive to subtle changes in the half-activation or half-inactivation potentials of I\(_{\text{Ca,L}}\), suggesting that a reduction of the I\(_{\text{Ca,L}}\) window current may represent an effective maneuver to...
suppress EADs and normalize APD without blocking the early peak $I_{Ca,L}$ required to maintain a normal excitation-contraction coupling (Madhvani et al., 2011). The dynamic clamp is a powerful technique that allows one to introduce a model conductance, such as $I_{Ca,L}$, with programmable properties into a cell in real time to study its effects on AP characteristics (Fig. 1 E). The proof-of-concept provided by our initial study (Madhvani et al., 2011) prompted us to perform a comprehensive analysis of biophysical parameters influencing the time- and voltage-dependent properties of the window (late) $I_{Ca,L}$ to identify whether additional parameters could be modified to suppress EAD formation and normalize APD. Accordingly, we systematically investigated the slopes of the voltage dependence of activation and inactivation, the noninactivating (or very slowly inactivating) late pedestal current, and the time constants of activation and inactivation, which shape the $I_{Ca,L}$ window current (Fig. 1, A and C) during the cardiac AP.

The results demonstrate that of all the $I_{Ca,L}$ biophysical parameters explored in this and previous work (Madhvani et al., 2011), three stand out as highly effective targets both to suppress EAD formation and normalize APD to reduce dispersion of repolarization: the half-activation and half-inactivation potentials and the noninactivating pedestal current. Collectively, these findings provide a drug discovery target to search for new antiarrhythmic agents to suppress EADs and normalize APD without blocking the half-activation and half-inactivation potentials and voltage-dependent properties of the window (late) $I_{Ca,L}$ to identify whether additional parameters could be modified to suppress EAD formation and normalize APD. Collectively, these findings provide a drug discovery target to search for new antiarrhythmic agents to suppress EADs and normalize APD without blocking $I_{Ca,L}$.

MATERIALS AND METHODS

Electrophysiology.

3–4m-old New Zealand male rabbits were euthanized by an intravenous injection of 1,000 U heparin sulfate and 100 mg/kg sodium pentobarbital; adequacy of anesthesia was confirmed by the lack of pedal withdrawal reflex, corneal reflex, and motor response to pain stimuli. Ventricular myocytes were dissociated using a retrograde Langendorff perfusion system as described previously (Chen et al., 2003), and washed and bathed in Tyrode’s solution containing (mM): 136 NaCl, 5.4 KCl, 1 MgCl$_2$, 0.33 NaH$_2$PO$_4$, 1.8 CaCl$_2$, 10 glucose, and 10 HEPES, adjusted to pH 7.4. The intracellular solution contained (mM): 110 K-aspartate, 30 KCl, 5 NaCl, 10 HEPES, 0–0.1 EGTA, 5 MgATP, 5 creatine phosphate, and 0–0.05 cAMP adjusted to pH 7.2. EADs were induced by perfusing 600 µM H$_2$O$_2$ or reducing the external [K’] from 5.4 to 2.7 mM. All chemicals were purchased from Sigma-Aldrich. All electrophysiological recordings were performed using an Axopatch 200B amplifier (Axon Instruments) in current-clamp mode at ≈34–36°C using 1–2-MΩ borosilicate pipettes (Warner Instruments). Data were acquired and analyzed using custom-made software (G-Patch; Analysis).

Dynamic clamp.

Under dynamic-clamp mode, a virtual $I_{Ca,L}$ with the properties of the native $I_{Ca,L}$ is injected into the myocytes. To predict $I_{Ca,L}$ and its Ca$^{2+}$-dependent inactivation, our ventricular myocyte model also computes intracellular Ca$^{2+}$ cycling. To predict the spatiotemporal distribution of intracellular calcium, average [Ca$^{2+}$] was computed in four different cellular compartments, namely the “submembrane space” in proximity of the sarcolemma ($C_s$), the “bulk myoplasm,” the “junctional SR,” and “network SR,” as described previously (Shiferaw et al., 2003; Mahajan et al., 2008; Madhvani et al., 2011). The main Ca$^{2+}$-regulated ionic conductance was also included in the model, i.e., the fast sodium current ($I_{Na}$), the Na$^{+}$/K$^{+}$ pump current ($I_{NaK}$), the Na$^{+}$/Ca$^{2+}$ exchange current ($I_{NCX}$), and the Ca$^{2+}$-dependent slow component of the delayed rectifier potassium channel ($I_{Ks}$). Calcium-modulated currents sense the [Ca$^{2+}$] at submembrane space ($C_s$), which is higher than the global [Ca$^{2+}$] ($C$) (Weber et al., 2002). The average $C_s$ is used to calculate Ca$^{2+}$-dependent inactivation in the $I_{Ca,L}$ formulation, whereas $C_s$ was acquired during the course of the experiments to predict the amplitude and shape of the Ca$^{2+}$ transient.

In brief, the Ca$^{2+}$ flux into the cell caused by $I_{Ca,L}$ is given by:

$$J_{Ca} = g_{Ca} P_{Ca} i_{Ca}$$

where $g_{Ca}$ is the Ca$^{2+}$ permeability, $P_{Ca}$ is the membrane potential, $F$ is the Faraday constant, and $T$ is temperature. $P_{Ca}$ was formulated as:

$$P_{Ca} = d \cdot f \cdot q,$$

where $d$ is the voltage-dependent activation gate, $f$ is the VDI gate, and $q$ is the Ca$^{2+}$-dependent inactivation gate. The steady states of these gating variables as functions of the membrane potential ($V_m$) were formulated as follows:

$$d = \frac{1}{1.0 + \exp(-(V_m - dhalf)/dslope)}$$

$$f = \frac{1 - f_{dest}}{1.0 + \exp((V_m - fhalf)/fslope)} + f_{dest}$$

$$q = \frac{1}{1.0 + \left(C_s/C_{est}\right)^{\gamma}}$$

$$\tau_j = \frac{d_j(1 - \exp(-(V_m - (dhalf + a_j)))}{a_j(dslope + a_j)(V_m - (dhalf + a_j))}$$

$$\tau_f = \frac{1}{b_j \exp(-b_j(V_m - (fhalf + b_j))^{2}) + b_j}$$
where \( \text{half} \) and \( \text{half} \) are the potentials at half-maximum of activation and inactivation, respectively; \( \text{pedest} \) is the noninactivating pedestal of the inactivation gate; and \( \text{slope/} \text{slope} \) are the steepness of the voltage dependence of activation and inactivation, respectively. These two parameters are called slope factors (k) in this study, and are related to effective charge (z) by \( RT/2z \), where \( R \) is the gas constant and \( T \) is temperature. \( C_i \) is the submembrane \( (\text{Ca}^2+) \); \( C_i \) is the affinity for \( \text{Ca}^2+ \) of the inactivation gate; \( \gamma_i \) and \( \gamma_f \) are the time constants of the d gate and the f gate, respectively; and \( a_1, b_1, a_2, b_2, b_3 \), and \( b_4 \) are additional factors used for fitting.

The control parameters in the \( \text{ICaL} \) formulation were determined by fitting formulated current to experimental nifedipine-sensitive \( \text{ICaL} \) records (Madhvani et al., 2011) using Berkeley Madonna and then implemented for dynamic clamp in RTXI (http://www.rtxi.org; Lin et al., 2010). In each experiment, as soon as the whole-cell configuration was obtained, the cell capacitance of the myocyte was measured (usually ranging within 100–150 pF) and entered as one of the parameters of the dynamic-clamp model to scale the computed \( \text{ICaL} \) accordingly to the cell size. The sampling/computation frequency was 10 KHz.

In some experiments, 10% of the computed slow component of the delayed rectifier K+ current (\( \text{IKs} \)) was injected together with \( \text{ICaL} \). \( \text{IKs} \) was modeled as in Mahajan et al. (2008).

### Data analysis

APD at 90% repolarization (APD\(_{90} \)) was calculated using custom-made software, whereas EAD amplitude was calculated manually by measuring the difference in \( V_m \) from the local minimum where d\( V_m \)/dt is 0 to the peak of the EAD where d\( V_m \)/dt is also 0. In APs that displayed multiple EADs, only the EAD with the largest voltage excursion was included in the analysis. EAD occurrence is reported as the percentage of APs that displayed at least one EAD. Error bars show the SEM.

### Computer simulations

Single-cell AP simulations were produced using the rabbit ventricular myocyte AP model developed by Mahajan et al. (2008), with some modifications. For details, see the supplemental text.

### Online supplemental material

Online supplemental figures show the effects of varying the slope \( (k) \) of the steady-state inactivation curve (Fig. S1) and the predicted Ca\(_{\text{transient}} \) before and after reduction of \( \text{ICaL} \) pedestal (Fig. S2) under the dynamic clamp. Fig. S3 demonstrates that the reduction of \( \text{ICaL} \) noninactivating component effectively suppressed EADs under hypokalemia condition. Fig. S4 shows results from computer simulation using a model of rabbit myocytes with properties of M, endo, and epi cell layers. Table S1 reports the mean values for EAD occurrence and APD\(_{90} \) for different \( \text{ICaL} \) activation and inactivation time constants. Table S2 shows the biophysical parameters of \( \text{ICaL} \) in the dynamic-clamp model for control, \( \text{H}_2\text{O}_2 \), and hypokalemia conditions. Tables S3 and S4 provide parameter values for maximal ionic conductances used in the computer simulation using a model of rabbit AP with properties of epi, endo, and M cell layers. The online supplemental material is available at http://www.jgp.org/cgi/content/full/jgp.201411288/DC1.

### RESULTS

**Sensitivity of EAD occurrence to the noninactivating component of \( \text{ICaL} \)**

In our previous study (Madhvani et al., 2011), we demonstrated that modest shifts (<5 mV) in the half-activation and half-inactivation potentials of \( \text{ICaL} \), which reduce the overlap between steady-state activation and inactivation curves (i.e., the window current region; Fig. 1 A), potently suppressed EADs, without adversely altering APD or the computed intracellular Ca\(_{\text{transient}} \). However, other parameters also affect the \( \text{ICaL} \) window current and its ability to contribute to EAD formation. Using dynamic clamp, we have explored the extent to which the other properties affecting activation and inactivation contribute to EAD formation.

To induce an EAD regimen, myocytes were paced at 5-s cycle length under current-clamp mode and superfused with 600 \( \mu \text{M} \) \( \text{H}_2\text{O}_2 \) until EADs appeared consistently. The native \( \text{ICaL} \) was then blocked with 20 \( \mu \text{M} \) nifedipine, which eliminated EADs and markedly shortened the APD (Fig. 1 D). Next, the dynamic clamp was added of 20 \( \mu \text{M} \) nifedipine blocked the native \( \text{ICaL} \) (right). Under dynamic clamp (E), the myocyte membrane potential is fed into the model, which computes and injects a virtual \( \text{ICaL} \) into the cell in real time and reconstitutes EADs in the continuous presence of \( \text{H}_2\text{O}_2 \).

![Figure 1.](image-url)
Early afterdepolarizations and \( I_{Ca,L} \)

engaged to replace the native \( I_{Ca,L} \) (blocked by nifedipine) by injecting, in real time, a \( I_{Ca,L} \) computed from Eqs.1–8, causing EADs to reappear (Fig. 1 E). The membrane potential of the myocyte was continuously sampled and fed into the dynamic-clamp model, creating a bidirectional relationship between the cell and the model, in real time (Fig. 1 E). The injected \( I_{Ca,L} \) had the properties of the native \( I_{Ca,L} \) in the presence of 600 µM \( H_2O_2 \) (Madhvani et al., 2011). Importantly, all dynamic-clamp experiments were performed in the continuous presence of \( H_2O_2 \) or hypokalemia, maintaining a pathological state that resulted in EAD formation.

The inactivation of \( I_{Ca,L} \) caused by voltage- and \( Ca^{2+} \)-dependent mechanisms (voltage-dependent inactivation, VDI, and \( Ca^{2+} \)-dependent inactivation, CDI, respectively) (Catterall, 2000) is incomplete during the time course of an AP. This noninactivating component was previously found to be elevated (from \( \sim 3 \) to \( \sim 10\% \) of the peak current) in myocytes exposed to an EAD-promoting regimen (\( H_2O_2 \)) (Madhvani et al., 2011), suggesting that this residual current contributes to EAD formation by effectively increasing \( I_{Ca,L} \) window region (Fig. 1, A and B). Motivated by these pieces of evidence, we directly probed EAD sensitivity to changes in the amplitude \( I_{Ca,L} \) noninactivating component (pedestal) (Rose et al., 1992; Qu and Chung, 2012). As demonstrated in Fig. 2, after inducing EADs in a myocyte by \( H_2O_2 \) superfusion (Fig. 2 B), the EADs were abolished by nifedipine (Fig. 2 C) and reconstituted by injecting a virtual \( I_{Ca,L} \) (Fig. 2 D). Under these conditions, APs were markedly prolonged, displaying a consistent EAD regimen, although with oscillations that tended to be smaller in amplitude than the ones typically observed experimentally (Fig. 2). Because nifedipine abolishes the \( Ca \) transient, which is important for activating \( I_K \) (Tohse, 1990; Nitta et al., 1994), we compensated by adding 10% of the computed \( I_K \) to the injected current. This maneuver reduced the voltage plateau into a range promoting greater \( I_{Ca,L} \) reactivation and larger EAD oscillations (Fig. 2 E), more closely resembling \( H_2O_2 \)-induced EADs before nifedipine blockade. The reduction of the \( I_{Ca,L} \) pedestal from 10 to 4% of the peak completely suppressed EAD occurrence and shortened the APD90 from \( 1,090 \pm 80 \text{ ms} \) to \( 197 \pm 3 \text{ ms} \) (Figs. 2 F and 3) whether or not EAD amplitude was increased by adding \( I_K \). Importantly, the reduction of the \( I_{Ca,L} \) pedestal suppresses the EAD regimen without attenuating the amplitude of the predicted \( Ca \) transient (Fig. S2).

These results indicate that the reduction of the non-inactivating \( I_{Ca,L} \) pedestal current can be an effective therapeutic strategy to suppress EADs.

Sensitivity of EADs to the steepness of steady-state activation and inactivation curves

Another set of parameters affecting the \( I_{Ca,L} \) window region are the steepness of the voltage dependence of activation and inactivation. However, modification of either parameter did not completely suppress EADs, nor did it restore normal APD, in contrast to the consequences of noninactivating pedestal current reduction.

After reconstitution of the EADs with dynamic clamp in the presence of \( H_2O_2 \) in the superfuse, we first examined the effects of altering the slope factor (k) of the voltage dependence of activation from 4 mV (effective valence, \( z = 5.7 e^0 \)) to 1 mV (\( z = 25.6 e^0 \)) or 8 mV (\( z = 3.2 e^0 \)) to increase or decrease, respectively, the steepness of the EAD regimen (Fig. 2).

Figure 2. Potent suppression of EAD by reduction of the noninactivating (pedestal) \( I_{Ca,L} \) component. (A) APs recorded from rabbit ventricular myocytes at a pacing cycle length of 5 s at 35–37°C in control conditions. (B) Perfusion of 600 µM \( H_2O_2 \) to the bath solution–induced EADs within 5–10 min. (C) The addition of 20 µM nifedipine blocked the native \( I_{Ca,L} \) shortened APD, and abolished EADs. (D) Under dynamic clamp and in the presence of \( H_2O_2 \), we evaluated the injection of virtual \( I_{Ca,L} \) or (E) the combination of \( I_{Ca,L} \) plus 10% of the computed \( I_K \). Note that both conditions regenerate the EAD regimen, although the amplitude of the oscillations tended to be larger with the addition of 10% \( I_K \). (F) Varying a single \( I_{Ca,L} \) parameter, the noninactivating (pedestal) component completely abolished EADs, despite the presence of \( H_2O_2 \).
We next studied the effects of altering the time constants of ICa,L activation and inactivation on EAD formation during oxidative stress. Overall, we found that changes in the rates of ICa,L activation or inactivation by up to 10-fold had limited efficacy at suppressing EADs induced by H2O2 (Figs. 5 and 6).

Specifically, in the presence of H2O2, slowing ICa,L activation by twofold \((\tau_a \times 2)\) maintained an average APD90 of 1,550 ± 130 ms, and EAD occurrence remained high at 91 ± 4% (Table S1). A 10-fold slowing of ICa,L activation \((\tau_a \times 10)\) prolonged APD90 from 1,376 ± 200 ms to 2,711 ± 548 ms, whereas EAD occurrence increased from 76 ± 8% to 100% of APs. Conversely, increasing the rate of ICa,L activation by twofold \((\tau_a \times 0.5)\) or by 10-fold \((\tau_a \times 0.1)\) had only a modest impact on both APD90 (1,122 ± 126 ms or 1,104 ± 165 ms) and EAD occurrence (79 ± 15% or 77 ± 10%), respectively (Fig. 5 and Table S1).

When the rate of VDI in the dynamic-clamp model was increased by twofold \((\tau_f \times 0.5)\), neither APD90 (from 1,104 ± 319 ms to 3,140 ± 771 ms (Fig. S1, B and E) as the steepness of the inactivation curve was reduced from \(k = 4 \text{ mV} (z = 6.4 \text{ e}^0)\) to \(k = 8 \text{ mV} (z = 3.2 \text{ e}^0)\) (Fig. S1 A).

We also investigated the effects of changing the slope of the voltage dependence of inactivation (Fig. S1 A) by increasing or decreasing the effective charge to \(k = 1 \text{ mV} (z = 25.6 \text{ e}^0)\) or \(k = 8 \text{ mV} (z = 3.2 \text{ e}^0)\), respectively. We did not observe a significant difference in either EAD amplitude or in percentage of APs with EADs (Fig. S1, C and D). APD90 prolonged from 1,104 ± 319 ms to 3,140 ± 771 ms (Fig. S1, B and E) as the steepness of the inactivation curve was reduced from \(k = 4 \text{ mV} (z = 6.4 \text{ e}^0)\) to \(k = 8 \text{ mV} (z = 3.2 \text{ e}^0)\) (Fig. S1 A).

**Sensitivity of EADs to the kinetics of ICa,L activation and inactivation**

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Figure 5. Time constant of I_{Ca,L} activation has a limited effect on H_{2}O_{2}-induced EADs. (A) I_{Ca,L} model outputs in response to depolarizing pulses from −80 to 10 mV using three different time constants of activation (τ_{d}). (B) Representative APs recorded under dynamic-clamp conditions from myocytes in which the endogenous I_{Ca,L} was replaced with a virtual I_{Ca,L} with modified activation time constants. The injected virtual I_{Ca,L} in dynamic clamp is shown in gray under each AP trace. Increasing or decreasing I_{Ca,L} activation rate by a factor of 10 did not significantly shorten APD or suppress EADs. For each value of τ_{d} tested, EAD occurrence (C) and APD_{90} (D) are shown. Data from individual cells are shown as closed circles, and the means for all experiments are plotted as open rectangles (n = 7 from five to six rabbits). Note that in all cases, APD_{90} remained prolonged (≥500 ms). Error bars indicate SEM. *, instances when the AP failed to repolarize before the next pacing stimulus are reported as RF (repolarization failure).

Figure 6. I_{Ca,L} time constant of inactivation has limited efficacy for suppressing EADs induced by H_{2}O_{2}. (A) I_{Ca,L} model outputs in response to depolarizing pulses from −80 to 10 mV using four different time constants of inactivation (τ_{f}). (B) Representative APs recorded under dynamic-clamp conditions from myocytes in which the endogenous I_{Ca,L} was replaced with a virtual I_{Ca,L} with modified inactivation time constants. The injected virtual I_{Ca,L} in dynamic clamp is shown in gray under each AP trace. For each value of τ_{f} tested, EAD occurrence (C) and APD_{90} (D) are shown. Data from individual cells are shown as closed circles, and the means for all experiments are plotted as open rectangles (n = 4–7 from three to five rabbits). A limited favorable effect on EAD occurrence was observed for decreasing τ_{f} by a factor of 2; however, on average, APs remained prolonged (>500 ms). Error bars indicate SEM. *, instances when the AP failed to repolarize before the next pacing stimulus are reported as RF (repolarization failure).

1,376 ± 200 ms to 1,838 ± 435 ms) nor EAD occurrence (from 76 ± 8% to 70 ± 16%) was dramatically altered (Table S1). Accelerating VDI by 10-fold (τ_{f} × 0.1; Fig. 6 A) increased APD_{90} (to 2,433 ± 290 ms) (Fig. 6 D), and EAD occurrence remained high (85 ± 8%; Fig. 6 C and Table S1). Conversely, decreasing the rate of VDI by twofold (τ_{f} × 2; Fig. 6 A) reduced EAD occurrence to 24 ± 14% (Fig. 6 C), but APD_{90} remained prolonged (802 ± 183 ms; Fig. 6 D). Decelerating inactivation by 10-fold (τ_{f} × 10), on the other hand, did not reduce EAD occurrence (73 ± 24% of APs), and significantly prolonged APD_{90} (1,506 ± 102 ms; Fig. 6, C and D, and Table S1).

Reduction of I_{Ca,L} noninactivating component is effective at suppressing EADs under hypokalemia, another EAD-favoring condition

In addition to our previously reported finding that EADs could be suppressed, and the APD could be normalized, by modest shifts of the half-voltage of steady-state activation or inactivation (Madhvani et al., 2011), the present results indicate that suppressing the noninactivating I_{Ca,L} pedestal current is an effective strategy, whereas the modification of other biophysical parameters affecting the steepness or kinetics of activation and inactivation is unreliable. To ascertain whether reducing I_{Ca,L} pedestal is effective at suppressing EADs caused by a mechanism other than oxidative stress, we also examined its potency at suppressing hypokalemia-induced EADs. As shown previously (Sato et al., 2010), lowering extracellular [K+] from 5.4 to 2.7 mM readily induced EADs within 5–10 min. Using the same dynamic-clamp approach, the endogenous nifedipine-sensitive current was replaced by a virtual I_{Ca,L} the parameters of which were modified to simulate the effects of hypokalemia on the native I_{Ca,L} (Table S2). The virtual I_{Ca,L} in dynamic clamp is shown in gray under each AP trace. For each value of τ_{f} tested, EAD occurrence (C) and APD_{90} (D) are shown. Data from individual cells are shown as closed circles, and the means for all experiments are plotted as open rectangles (n = 4–7 from three to five rabbits). A limited favorable effect on EAD occurrence was observed for decreasing τ_{f} by a factor of 2; however, on average, APs remained prolonged (>500 ms). Error bars indicate SEM. *, instances when the AP failed to repolarize before the next pacing stimulus are reported as RF (repolarization failure).

Effects of noninactivating pedestal of I_{Ca,L} on simulated EADs in epicardial, endocardial, and M cell types

Across the ventricular wall, there are regional differences in the ionic basis underlying ventricular APs (Antzelevitch et al., 1991; Antzelevitch and Sicouri, 1994). To explore how these regional differences affect the ability of a therapeutic reduction in the I_{Ca,L} pedestal to suppress EADs, we modified the rabbit ventricular AP model to simulate epicardial, endocardial, and M cell
layer APs, respectively. When paced at a 5-s cycle length under control conditions, with a 3% $I_{\text{Ca,L}}$ pedestal current (Fig. S4 A), APD$_{90}$ averaged 229, 258, and 268 ms for the epicardial, endocardial, and M cells, respectively. We then simulated the effects of H$_2$O$_2$ as described above, including increasing the $I_{\text{Ca,L}}$ pedestal current to 6%. The APD$_{90}$ prolonged to 540, 504, and 811 ms, respectively, and EADs appeared in all three cell types (Fig. S4 B). When the $I_{\text{Ca,L}}$ pedestal current was reduced to 0%, while maintaining all other H$_2$O$_2$ effects, APD$_{90}$ shortened to 273, 293, and 309 ms, respectively, and EADs disappeared (Fig. S4 C). Thus, suppressing the $I_{\text{Ca,L}}$ pedestal current was effective at eliminating EADs regardless of transmural AP heterogeneity.

**DISCUSSION**

Although many ionic currents can contribute to EAD formation, reactivation of $I_{\text{Ca,L}}$ plays a central role in providing a regenerative inward current required for EADs to propagate, thereby causing triggered activity in multicellular tissue (January et al., 1988; January and Riddle, 1989). The main finding of the present study is that, even though H$_2$O$_2$ is likely to promote EADs by affecting multiple ionic currents such as late $I_{\text{Na}}$ (Song et al., 2006), the modification of $I_{\text{Ca,L}}$ is sufficient to prevent EADs even in the presence of H$_2$O$_2$. Furthermore, this intervention does not diminish the amplitude of the predicted Ca transient (Fig. S2) and therefore is expected to maintain normal cell contractility. Conventional Ca$^{2+}$ channel blockers such as nifedipine, which indiscriminately block both peak and window $I_{\text{Ca,L}}$, are highly effective at suppressing EADs (e.g., Fig. 1 D). However, by blocking peak $I_{\text{Ca,L}}$, these drugs also potently suppress excitation–contraction coupling, precluding clinical usefulness for EAD suppression.

In this study, we applied the dynamic-clamp technique to systematically evaluate the hypothesis that EADs...
can be suppressed by selectively targeting the biophysical properties regulating the $I_{Ca,L}$ window current. Fig. 7 summarizes the effects of the various parameter changes on both APD and EAD occurrence, illustrating that three parameter modifications (depolarizing shift of the half-activation potential, hyperpolarizing shift of the half-inactivation potential, and reduction of the pedestal current) both effectively suppress EADs and restore APD toward a normal value. From these findings, we predict that the ideal Ca$^{2+}$ channel agent for suppressing EAD-mediated arrhythmias (drugs or genetic intervention) would leave peak $I_{Ca,L}$, hence excitation–contraction coupling, intact but selectively suppress late $I_{Ca,L}$ in the window region. An important novel contribution of the present study is the finding that the $I_{Ca,L}$ pedestal current has an equivalent promise to the half-activation and half-inactivation potentials as a novel anti-arrhythmic target to suppress EAD formation, which is robust across the spectrum of simulated transmural AP differences in the ventricular epicardial, M cell, and endocardial layers (Fig. S3). Moreover, it is effective for different mechanisms of EAD generation, as H$_2$O$_2$ primarily causes EADs by increasing inward currents including late $I_{Na}$ and $I_{Ca,L}$ as a result of oxidative CaMKII activation (Ward and Giles, 1997; Xie et al., 2009; Wagner et al., 2011), whereas hypokalemia causes EADs by reducing K$^+$ conductances, i.e., $I_{Ks}$ and Na$^+$/K$^+$ ATPase activity, which in turn causes accumulation of intracellular Na$^+$ and Ca$^{2+}$. The finding that selective blockade of the $I_{Ca,L}$ pedestal has potent EAD-suppressing effects is particularly intriguing because of the precedent in Na$^+$ channels, in which selective blockers of the late Na$^+$ current (e.g., $I_{Na}$) can prevent late Na$^+$ current activation in the ventricular myocyte, previous studies have shown that the $I_{Ca,L}$ properties are generally similar to human myocytes, although the results from this study need to be validated in human myocytes, previous studies have shown that the $I_{Ca,L}$ properties are generally similar in both species (Grandi et al., 2010; Verkerk et al., 2011), suggesting that suppression of $I_{Ca,L}$ noninactivating component could be an effective therapeutic strategy.

### Limitations and Implications

There are several limitations in this experimental–computational approach:

**Rabbit versus human ventricular myocytes.** This study was performed in rabbit ventricular myocytes, which differ in some respects from human myocytes. Although the results from this study need to be validated in human myocytes, previous studies have shown that the $I_{Ca,L}$ properties are generally similar in both species (Grandi et al., 2010; Verkerk et al., 2011), suggesting that suppression of $I_{Ca,L}$ noninactivating component could be an effective therapeutic strategy.

**Virtual $I_{Ca,L}$.** To study how the biophysical properties of $I_{Ca,L}$ affect EAD formation, it was required to replace the endogenous $I_{Ca,L}$ with a computed, “virtual” $I_{Ca,L}$, with tunable parameters under dynamic-clamp conditions. The current injected under the dynamic clamp, although incorporating Ca$^{2+}$-dependent inactivation in response to the virtual Ca$^{2+}$ transient in the model, did not trigger SR Ca$^{2+}$ release in the myocytes. Thus, endogenous Ca$^{2+}$-sensitive currents in the myocyte, such as Na$^+$/Ca$^{2+}$ exchange and $I_{Ko}$, were not activated. One consequence was that EADs reconstituted after virtual $I_{Ca,L}$ injection were smaller than before nifedipine blockade (Fig. 2): this could be corrected by increasing additional $I_{Ko}$ via the dynamic clamp to simulate Ca$^{2+}$-induced activation of $I_{Ko}$ (Fig. 2 E). Importantly, whether or not additional $I_{Ko}$ were injected, reduction of the noninactivated pedestal was equally potent at suppressing EADs and restoring the APD.
Off-target effects of nifedipine. Our experimental approach required the full block of the endogenous I_{Ca,L} to correctly evaluate the EAD sensitivity to the relatively small I_{Ca,L} pedestal. We used 20 μM nifedipine, one of the most selective L-type Ca^{2+} channel blockers available. At the concentration used in this work, nifedipine may have had off-target effects, and possibly partially blocked I_{Ks} conductance (Gotoh et al., 1991). This effect may have contributed to the reduction of EAD amplitude, as observed in some of the experiments under dynamic clamp (e.g., Fig. 2 D); however, we were able to effectively restore EAD amplitude by the addition of a fraction of the computed I_{Ks} to the injected current (Fig. 2 E). We are confident that off-target effects of nifedipine have not biased the overall conclusion of this work, as the consequences of reducing I_{Ca,L} pedestal current were also tested and confirmed in pure computer simulations, presented in Fig. S4.

Despite its limitations, we believe that this approach outlines a useful new strategy for drug discovery, potentially adaptable to high throughput screening of small molecules or genetic interventions, to identify new antiarrhythmic agents. In this context, the dynamic-clamp approach represents a powerful method to move beyond simple screening for indiscernible ion channel blockers and toward identifying and targeting subtle and selective aspects of ion channel biophysics to guide drug discovery.

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SUPPLEMENTAL METHODS

Computer simulations
The Markovian formulation for L-type Ca\(^{2+}\) channel open probability \(P_o\) was replaced by the Hodgkin–Huxley formulation, as used in the dynamic-clamp experiments described in the main text. The formulation of Ito was replaced by that of Dong et al. (2006) as modified by Zhao et al. (2012) to more accurately reflect experimental data on APD restitution. In the rabbit ventricular myocyte, the APD restitution curve is biphasic, as the APD at intermediate heart rates is greater than at fast and slow heart rates (Zhao et al., 2012). This has been attributed to the slow recovery of \(I_{\text{to}}\) in this type of cell (Bassani et al., 2004).

To model the effects of \(H_2O_2\), we made several changes to ionic currents (see below). A late \(I_{\text{Na}}\) current was implemented with a magnitude \(\approx 1\%\) of peak \(I_{\text{Na}}\) based on the findings of Song et al. (2010) of increased late \(I_{\text{Na}}\) in the presence of 200 \(\mu M\) \(H_2O_2\) in isolated rabbit ventricular myocytes.

The maximum conductance of \(I_{Ca,L}\) was increased by a factor of 2, which is within the range reported by Xie et al. (2009), who found that in rabbit ventricular myocytes, the peak \(I_{Ca,L}\) increased from 7.3 ± 0.8 pA/pF in a control environment to 12.1 ± 1.8 pA/pF in the presence of 1 mM \(H_2O_2\).

The maximum conductance of \(I_{\text{to}}\) was also increased by a factor of 1.57 based on experimental data from Zhao et al. (2012) on isolated rabbit ventricular myocytes. Finally, the maximum conductance of \(I_{\text{NCX}}\) was increased by a factor of 1.5 following the mathematical model of Zhao et al. (2012) (Table S3).

\[ I_{Ca,L} = \frac{g_{Ca,L}(m^3h^j)}{R} (V-E_{Na}) \]

where \(\alpha\) reflects a non-inactivating component of the channel. For the \(H_2O_2\) model, \(\alpha = 0.01\).

\[ I_{Na} = g_{Na}(m h R + \alpha) (V-E_K) \]

\[ R = e^{V/500} \]

\[ a_n = \frac{4}{1 + e^{(V-250)/20}}, \beta_n = \frac{3.5}{1 + e^{(V+110)/20}}, m_n = \frac{1}{1 + e^{(V+110)/30}} \]

\[ a_h = \frac{0.016}{1 + e^{(V+390)/50}}, \beta_h = \frac{0.11}{1 + e^{(V+270)/60}}, \theta_h = \frac{1}{1 + e^{(V+50)/30}} \]

To model the experimentally reported differences in APD and ionic current strength between the epicardial, endocardial, and M cell, three model cells were created with different combinations of maximal conductances for \(I_{Ca,L}\) and \(I_{Na}\). Fedida and Giles (1991) reported isolated rabbit endocardial cells to have a maximum \(I_{Ca,L}\) current that was 85% of that of epicardial cells, which is reflected in the model. Idriss and Wolf (2004) reported APDs of rabbit endocardial and M cells to be 12 and 18% longer, respectively, than APs of epicardial cells. The control endocardial and M cells have APDs that are 13 and 17% longer, respectively, than the epicardial cell. Cell model code was written in the C++ language and implemented using Microsoft Visual Studio 2008. The model, which consists of 22 differential equations, was integrated using the Euler method with an adaptive time step ranging from 0.1 to 0.01 ms. Analysis was performed using custom scripts written in MATLAB.

Transmural \(I_{\text{to}}\) and \(I_{\text{NCX}}\) gradients. To establish epi, endo, and M cell types, three different cell models were created by scaling the original values for the maximal conductances of \(I_{Na}\) and \(I_{Ca,L}\) by different scaling factors. These scaling factors were chosen to reflect the transmural \(I_{Ca,L}\) gradient reported by Fedida and Giles (1991), as well as the transmural APD gradient reported by Idriss and Wolf (2004). The original values and scaling factors are shown in Table S4.
Figure S1. Relevance of the slope of ICa,L steady-state inactivation curve to EADs and APD. (A) Under dynamic clamp and in the presence of H2O2, we evaluated the effects of varying the slope (k) of the steady-state inactivation curve. The steady-state activation curve was kept constant, whereas the slope of the steady-state inactivation curve was varied under dynamic clamp from k = 1 mV to k = 8 mV. The pair of curves in the center, k = 4 mV, corresponds to the native ICa,L modified by H2O2. (B) Representative APs obtained for each k value studied. For each value of k tested, the mean EAD amplitude (C), EAD occurrence (D), and APD90 (E) are shown. Individual experiments are shown as closed circles, and the means for all experiments are plotted as open rectangles. Error bars indicate SEM. *, instances when the AP failed to repolarize before the next pacing stimulus are reported as RF (repolarization failure).

Figure S2. Predicted Ca transient before and after reduction of the ICa,L pedestal. (A) A representative AP recorded in control conditions. (B) The predicted Ca transient upon AP clamp of the ventricular AP model with the AP waveform in A. (C) Representative AP recorded in dynamic clamp in the presence of H2O2 (10% ICa,L pedestal), reconstituted EADs, and prolonged the APD. (D) The ventricular AP model predicts the Ca transient in real time during the AP recorded in C. (E) Upon a reduction in the ICa,L pedestal to 4%, the AP is restored to ~250 ms and EADs are abolished. (F) The ventricular AP model predicts the Ca transient in real time during the AP recorded in E. Note that the expected amplitude and shape of the Ca transient is also restored compared with control conditions shown in B.
Figure S3. Reducing the noninactivating $I_{Ca,L}$ pedestal effectively suppresses hypokalemia-induced EADs. Under dynamic clamp and hypokalemia (2.7 mM K$^+$), we evaluated the effect of lowering the noninactivating pedestal from 5 to $\leq$0.5% of the peak current. (A) Enlarged view of the steady-state activation and inactivation curves of $I_{Ca,L}$ shows the changes introduced to the noninactivating component (pedestal). (B) Representative AP recorded in dynamic clamp in the presence of hypokalemia at different values of pedestal. Lowering the pedestal value of $I_{Ca,L}$ from 5 to $\leq$0.5% caused EADs to be significantly reduced or completely abolished, and normal APD was restored (C and D). Individual experiments are shown as closed circles, and the means for all experiments are plotted as open rectangles. Error bars indicate SEM.

Figure S4. Reducing the noninactivating $I_{Ca,L}$ pedestal is an effective maneuver to suppress simulated H$_2$O$_2$-induced EADs in a computer model of rabbit ventricular cell layer types. (A) APs for M, endocardial, and epicardial versions of the Mahajan cell model under control conditions. (B) Modeling the effects of H$_2$O$_2$ produces AP prolongation and EADs in all cell models. (C) A reduction of the $I_{Ca,L}$ pedestal current from 6 to 0%, while maintaining other H$_2$O$_2$ effects, suppresses EADs and restores normal APDs in all cell models. See Materials and methods in the main text and supplemental text for detailed description of simulations.
### Table S1

**EAD occurrence and APD\(_{90}\) for changes in the time constant of I\(_{Ca,L}\) activation and inactivation**

| Kinetic parameter modification | APs with EADs | APD\(_{90}\) |
|-------------------------------|--------------|-------------|
| \(\tau_d \times 0.1\)        | 77 ± 10%     | 1,104 ± 165 |
| \(\tau_d \times 0.5\)        | 79 ± 15%     | 1,122 ± 126 |
| \(\tau_d \times 1\)          | 76 ± 8%      | 1,376 ± 200 |
| \(\tau_d \times 2\)          | 91 ± 4%      | 1,550 ± 130 |
| \(\tau_d \times 10\)         | 100%         | 2,711 ± 548 |
| \(\tau_f \times 0.1\)        | 85 ± 8%      | 2,433 ± 291 |
| \(\tau_f \times 0.5\)        | 70 ± 16%     | 1,838 ± 435 |
| \(\tau_f \times 1\)          | 76 ± 8%      | 1,376 ± 200 |
| \(\tau_f \times 2\)          | 24 ± 14%     | 802 ± 183   |
| \(\tau_f \times 10\)         | 73 ± 24%     | 1,506 ± 102 |

### Table S2

**Biophysical parameters of I\(_{Ca,L}\) in the dynamic-clamp model and computer model in control environment, H\(_2\)O\(_2\), and hypokalemia conditions**

| I\(_{Ca,L}\) model fitting parameter | Control | H\(_2\)O\(_2\) | Hypokalemia |
|-------------------------------------|---------|---------------|-------------|
| dhalf (mV)                          | −1.033  | −5            | −5          |
| dslope (mV)                         | 5.11    | 4.6           | 6.8         |
| fhalf (mV)                          | −18.65  | −17           | −17         |
| fslope (mV)                         | 5       | 4             | 3.9         |
| pdest                               | 0.03    | 0.1           | 0.05        |
| Gs (mM)                             | 0.32    | 0.32          | 0.32        |
| Cst (mM)                            | 0.11    | 0.02          | 0.11        |
| a\(_1\)                             | 10      | 6.36          | 10          |
| a\(_2\)                             | 4.24    | 0.097         | 4.24        |
| a\(_3\)                             | 0.0693  | 0.095         | 0.0693      |
| b\(_1\)                             | 0.0361  | 0.024         | 0.0361      |
| b\(_2\)                             | 0.00692 | 0.005         | 0.00692     |
| b\(_3\)                             | 25.1    | 14.91         | 25.1        |
| b\(_4\)                             | 0.00968 | 0.012         | 0.00968     |
### Table S3

Parameter values for maximal ionic conductances of \( I_{Ca,L} \), \( I_{NCX} \), and \( I_{to} \) for control and \( H_2O_2 \) models of rabbit ventricular AP

| Ionic conductance parameter | Control \( mS/\mu F \) | \( H_2O_2 \) \( mS/\mu F \) |
|----------------------------|-------------------------|-----------------------------|
| \( G_{Ca,L} \)            | 0.48                    | 0.96                        |
| \( G_{NCX} \)             | 0.84                    | 1.68                        |
| \( G_{to} \)              | 0.07                    | 0.11                        |

### Table S4

Original values and scaling factors of maximal conductance of \( I_{to} \) and \( I_{KS} \) for Epi, Endo, and M cell models of rabbit ventricular AP

| Ionic conductance parameter | Original value | Scaling factor |
|----------------------------|----------------|----------------|
|                            | Control \( mS/\mu F \) | \( H_2O_2 \) | Epi | Endo | M |
| \( G_{to} \)               | 0.07            | 0.11           | 1.35 | 1.15 | 1.3 |
| \( G_{KS} \)               | 0.32            | 0.32           | 1.45 | 1.3  | 1  |
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