Augmentation of late sodium current unmasks the proarrhythmic effects of amiodarone

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Received 5 September 2007; revised 19 October 2007; accepted 5 November 2007; online publish-ahead-of-print 13 November 2007

Time for primary review: 21 days

1. Introduction

Amiodarone has long been used to treat atrial and ventricular arrhythmias1 and is reported to decrease mortality in patients with structural heart disease.1-3 The pharmacological actions of amiodarone are complex. Amiodarone has the electrophysiological characteristics of all four classes of antiarrhythmic agents, because it blocks rapidly and slowly activating delayed rectifier K\(^+\) currents (I\(_{Kr}\) and I\(_{Ks}\)), Na\(^+\) current (I\(_{Na}\)), L-type Ca\(^{2+}\) current (I\(_{Cal}\)), and adrenergic receptors.4

Although acute administration of amiodarone does not increase the QTc interval, cases of torsade de pointes (TdP) with acute administration of the drug have been reported.5-7 Recently, Lehtonen and colleagues5 reported 17 cases of drug-induced TdP, of which six cases were induced by acute (iv) administration of amiodarone. In another study of 23 patients with the SCN5A polymorphism S1102Y, three developed TdP while medicated with amiodarone.8 This finding is somewhat surprising because amiodarone alone caused an insignificant increase in duration of MAP (MAPD\(_{90}\)) without causing TdP. In the presence of 3 nM sea anemone toxin (ATX-II), amiodarone (1-30 nM) prolonged MAPD\(_{90}\) from 217 ± 5 to 250 ± 8 ms (n = 16, P < 0.01), increased transmural dispersion of repolarization (TDR) from 59 ± 9 to 70 ± 10 ms and beat-to-beat variability (BVR) of MAPD\(_{90}\) from 0.75 ± 0.03 to 1.06 ± 0.13 ms (P < 0.05). At 30-300 nM, amiodarone induced TdP in 16 out of 17 hearts. A further increase of amiodarone concentration to 1-10 \(\mu\)M abbreviated MAPD\(_{90}\) to 211 ± 9 ms, decreased BVR to 0.5 ± 0.01 ms, decreased TDR (n = 7, P < 0.05), and suppressed TdP. Amiodarone inhibited HERG K\(^+\) and late Na\(^+\) currents with IC\(_{50}\)s of 0.8 ± 0.1 and 3.0 ± 0.9 \(\mu\)M, respectively.

Conclusion In hearts in which late I\(_{Na}\) is augmented to mimic congenital or acquired pathological conditions, amiodarone has a concentration-dependent biphasic effect to induce and then suppress arrhythmia activity, secondary to inhibition of HERG K\(^+\) and late Na\(^+\) currents. This is the first preclinical model demonstrating the potential for amiodarone to induce TdP.

Aim Clinical use of amiodarone is associated with occasional development of torsade de pointes (TdP). However, preclinical models have failed to demonstrate the proarrhythmic potential of amiodarone. The objective of this study was to reveal and explain the pro- and anti-arrhythmic effects of acute exposure to amiodarone in an animal model.

Methods and results Endo- and epicardial monophasic action potentials (MAPs) and 12-lead electrocardiogram were recorded in female rabbit isolated hearts. Ion channel currents were measured in human embryonic kidney cells expressing SCN5A Na\(^+\) and HERG K\(^+\) channels. Acute amiodarone alone caused an insignificant increase in duration of MAP (MAPD\(_{90}\)) without causing TdP. In the presence of 3 nM sea anemone toxin (ATX-II), amiodarone (1-30 nM) prolonged MAPD\(_{90}\) from 217 ± 5 to 250 ± 8 ms (n = 16, P < 0.01), increased transmural dispersion of repolarization (TDR) from 59 ± 9 to 70 ± 10 ms and beat-to-beat variability (BVR) of MAPD\(_{90}\) from 0.75 ± 0.03 to 1.06 ± 0.13 ms (P < 0.05). At 30-300 nM, amiodarone induced TdP in 16 out of 17 hearts. A further increase of amiodarone concentration to 1-10 \(\mu\)M abbreviated MAPD\(_{90}\) to 211 ± 9 ms, decreased BVR to 0.5 ± 0.01 ms, decreased TDR (n = 7, P < 0.05), and suppressed TdP. Amiodarone inhibited HERG K\(^+\) and late Na\(^+\) currents with IC\(_{50}\)s of 0.8 ± 0.1 and 3.0 ± 0.9 \(\mu\)M, respectively.

Conclusion In hearts in which late I\(_{Na}\) is augmented to mimic congenital or acquired pathological conditions, amiodarone has a concentration-dependent biphasic effect to induce and then suppress arrhythmia activity, secondary to inhibition of HERG K\(^+\) and late Na\(^+\) currents. This is the first preclinical model demonstrating the potential for amiodarone to induce TdP.
chronic administration of amiodarone has not been demonstrated in experimental animal models.\textsuperscript{13–15} Regardless, the proarrhythmic activities of \( I_{Na} \)-blocking drugs with a recognized but low risk of prolonging the QT interval have been demonstrated in female rabbit hearts exposed to a low concentration of the sea anemone toxin II (ATX-II), which increases late \( I_{Na} \) and thus mimics the gain of function of Na\(^+\) channels caused by some congenital SCN5A mutations and polymorphisms.\textsuperscript{16} An increase of late \( I_{Na} \) both reduces repolarization reserve\textsuperscript{11} and may lead to cellular calcium overload, which is proarrhythmic.\textsuperscript{17} The objective of this study was to simulate and define the mechanisms responsible for the clinical observations that acute (iv) administration of amiodarone can cause TdP. Although rare, this observation has yet to be explained.

2. Methods

2.1 Female rabbit isolated heart model

This investigation conformed with the ‘Guide for the Care and Use of Laboratory Animals’ published by the US National Institutes of Health (NIH publication No. 85–23, revised 1996). Animal use for this project was approved by the Institutional Animal Care and Use Committee of CV Therapeutics (Palo Alto, CA). New Zealand White female rabbits, weighing 2.5–3.5 kg, were sedated then anesthetized using im and iv injections, respectively, of xylazine and ketamine. The heart was excised and placed in a modified Krebs–Henseleit (K–H) solution (pH 7.4, gassed with 95% O\(_2\) and 5% CO\(_2\)). The K–H solution contained (in mM): 118 NaCl, 2.8 KCl, 1.2 KH\(_2\)PO\(_4\), 2.5 CaCl\(_2\), 0.5 MgSO\(_4\), 2.0 pyruvate, 5.5 glucose, 0.57 Na\(_2\)EDTA, and 25 NaHCO\(_3\). The aorta was cannulated and the heart was perfused by the method of Langendorff with K–H solution warmed to 36.5°C at a rate of 20 mL/min. Complete atrioventricular (AV) block was induced by thermoablation of the AV nodal area. A bipolar Teflon-coated electrode was placed on the right ventricular septum to pace the heart. Electrical stimuli 3 ms in width and three-fold threshold amplitude were delivered to the pacing electrode at a frequency of 1 Hz using a digital stimulation generator (EP MedSystems, West Berlin, NJ). After initiation of ventricular pacing, a 10–20 min period was allowed for equilibration of heart rhythm. The total duration of the experimental protocol was \( \leq 3 \) h.

2.1.1 MAP recording

Two pressure-contact Ag–AgCl monophasic action potential (MAP) electrodes were placed on the epicardial ventricular free wall below the level of the atrial–ventricular valve at the base of the left ventricle and on the apex area of the left ventricle. One MAP electrode was placed on the endocardium of the left ventricle through a trans-septal pathway from the right ventricle. Transmural MAPD\(_{90}\) was calculated as the difference of values of endocardial and epicardial MAPD\(_{90}\) measured from the base of the left ventricular free wall. MAP signals were displayed in real time and digitized to determine the duration of the MAP at the level at which repolarization is 90% completed (MAPD\(_{90}\)). Steady-state responses to drug(s) are reported in this study.

2.1.2 BVR of MAPD\(_{90}\)

Values of MAPD\(_{90}\) for 30 consecutive beats were used for calculation of the beat-to-beat variability (BVR) of ventricular repolarization. The mean orthogonal distance on the Poincaré plot from the diagonal to each point was determined for a 30-beat interval using the following equation: \( \sum |\text{MAPD}_{n+1} - \text{MAPD}_{n}| / [30 \times \sqrt{2}] \).\textsuperscript{18}

2.1.3 12-Lead ECG recording

A 12-lead electrocardiogram (ECG) from an isolated heart was recorded using a circular Einthoven-Goldberger ECG electrode system (Harvard Apparatus, Inc., Holliston, MA) connected to a Biopac Wilson ECG amplifier (Biopac, Goleta, CA). ECG parameters, such as the duration of QT interval and the duration of the T wave from \( T_{\text{peak}} \) to \( T_{\text{end}} \) (\( T_{\text{peak}} - T_{\text{end}} \)), were calculated using the leads with the best monophasic T wave signals. QT dispersion was measured as the difference between the longest and the shortest QT intervals of a heart beat recorded during a steady-state response to drug in 12-lead ECG record.

2.1.4 Determination of pro-arrhythmic activity of amiodarone in the absence and presence of ATX-II

Ectopic ventricular beats (EVBs), early after-depolarizations (EADs), and ventricular tachycardia (VT) were monitored continuously during drug treatment of a heart. Post-drug control values of MAPD were obtained after drug washout. An EVB was defined as a spontaneous beat occurring earlier than the next paced beat. The maximal number of EVBs in one minute was counted as beats per minute (bpm). VT was defined as a sequence of three or more consecutive spontaneous ventricular depolarizations at a rate exceeding the pacing rate. An EAD was defined as the positive depolarization during phase 0 and/or 3 of an MAP signal. A 3- or 5-s pause in ventricular electrical stimulation was used to induce pause-triggered EVBs, EADs, and VT in the absence and presence of drugs (ATX-II and ATX-II + amiodarone). Pauses were repeated three times in the presence of each concentration of test drug. Pause-triggered EADs and ventricular arrhythmias were defined as EAD, EVBs, or VT that occurred within the first three beats after ventricular pacing was resumed.

2.1.5 Determination of concentration-response relationships for effects of amiodarone on electrophysiological parameters in the absence and presence of ATX-II

Hearts were exposed to increasing concentrations of amiodarone (1 nM–10 \( \mu \)M) in a cumulative manner, allowing 7–15 min between increases in drug concentration to facilitate the recording of a steady-state, maximal effect. To test the effects of amiodarone in the presence of ATX-II, hearts were perfused with 3 nM ATX-II for 20 min and then exposed to amiodarone in the continued presence of 3 nM ATX-II.

2.2 Recording of electrophysiological effects of amiodarone on HEK 293 cells expressing SCN5A Na\(^+\) and HERG (KCNH2) K\(^+\) channels

Heterologous expression of SCN5A Na\(^+\) and HERG K\(^+\) channels: human embryonic kidney (HEK293) cells stably expressing either the human \( \alpha \)-subunit of SCN5A (purchased from Cytomix, Cambridge, UK) or the HERG \( K^+ \) channel (purchased from Dr Craig T. January, University of Wisconsin-Madison, WI) were used and were maintained as previously described.\textsuperscript{19} Voltage-clamp technique: for recording peak and late \( I_{Na} \), cells were superfused with bath solution containing (in mM): 140 NaCl, 4.0 KCl, 1.8 CaCl\(_2\), 0.75 MgCl\(_2\), and 5 HEPES (pH adjusted to 7.4 with NaOH). The pipette solution contained (in mM): 20 CsCl, 120 CsF, 2 EGTA, and 5 HEPES (pH adjusted to 7.4 with CsOH). For recording HERG \( K^+ \) current (\( I_{\text{HERG}} \)), cells were superfused with bath solution containing (in mM): 137 NaCl, 4.0 KCl, 1.8 CaCl\(_2\), 5 HEPES and 10 glucose (pH adjusted to 7.4 with NaOH). The pipette solution contained (in mM): 130 KCl, 1.0 MgCl\(_2\), 5 EGTA, 5 MgATP and 10 HEPES (pH adjusted to 7.2 with KOH). All experiments were performed at \( \pm 1^\circ \)C.

Whole-cell membrane current was recorded as previously described.\textsuperscript{20} Briefly, patch-clamp electrodes with a resistance of 1–1.5 M\( \Omega \) were made from borosilicate glass capillaries (World Precision Instruments, Sarasota, FL) using a DMZ-Universal puller (Dagan, Minneapolis, MN). Computer software (pCLAMP 9.0, Molecular Devices, Sunnyvale, CA) was used to generate voltage-clamp
procedures. Patch-clamp amplifier (Axopatch 200B, Molecular Devices) data sampling rates varied from 5 to 100 kHz, depending on the ion channel studied. Whole-cell capacitance was compensated using the internal voltage-clamp circuitry and ~75–80% of series resistance was compensated. Membrane potentials were not corrected for junction potentials that arise between the pipette and bath solution. To minimize possible voltage errors, small HEK293 cells of <20 pf cell capacitance (membrane capacitance; $C_m = 14.96 \pm 0.81$, $n = 13$), expressing peak $I_h$ amplitudes of <10 nA were selected and cells were held at $-140 mV$ and dialyzed for ~5 min before $I_h$ recording. The reversal potential of $I_h$ was +60 mV. Data analysis of all measured currents was performed using pCLAMP 9.0 and Origin 7.0 (MicroCal, Northampton, MA) software.

To measure the extent of tonic block (first-pulse) by amiodarone of peak $I_h$, 24-ms depolarizing steps to $-20 mV$ from a holding potential of $-140 mV$ were applied to cells at a rate of 0.1 Hz. The magnitude of peak $I_h$ in the presence of amiodarone was normalized to the respective control value.

To measure the effect of amiodarone on late $I_h$, the normally small late $I_h$ was augmented by exposure of cells to 3 nM ATX-II, and the effect of amiodarone to reduce the ATX-II-induced late $I_h$ was determined. Late $I_h$ was defined as the magnitude of $I_h$ between 650 and 700 ms after application of a 700-ms depolarizing step to $-20 mV$ from a holding potential of $-140 mV$ applied at a rate of 0.1 Hz.

To study the concentration-response relation for inhibition of $I_{HERG}$ by amiodarone, $I_{HERG}$ was activated with a 4-s depolarizing step to $20 mV$, and tail current was recorded following a 5.7-s repolarizing step to $-50 mV$. Reductions of peak tail $I_{HERG}$ by increasing concentrations of amiodarone were normalized to the respective control (no drug) values of current and plotted as relative current amplitude.

2.3 Data Analysis

Data are reported as mean ± SEM. Concentration-response relationships were analyzed using Prism version 3.0 (GraphPad, San Diego, CA). Data from experiments to measure effects of amiodarone to inhibit peak and late $I_h$ and $I_{HERG}$ were fit with the Hill equation: $I_{current}/I_{control} = 1/[1+(D/C50)^n]$, where $I_{drug}/I_{control}$ is fractional block, $D$ is drug concentration, $I_{50}$ is half-maximal inhibitory concentration and $n$ is the Hill coefficient ($n_h$). To compare values of measurements obtained from the same heart before and after a drug treatment, repeated measures one-way analysis of variance (ANOVA) was used and Student-Newman-Keuls test was applied to determine which pairs of group means were significantly different. Paired and non-paired Student $t$-tests were used to determine the significance of a difference between two means before (as control) and after drug treatment in the same or different hearts, respectively. A significant difference between two group means was defined as one having a $P < 0.05$.

2.4 Materials

Amiodarone (Sigma-Aldrich, MO, USA) was dissolved in dimethylsulfoxide (DMSO) at concentration of $2 \times 10^{-2} M$ as stock in $-4$ C, and further diluted to $4 \times 10^{-4} M$ in physiological saline for use in experiments. The final content of DMSO in saline during experiments was not >0.05%. ATX-II (Alomone Labs, Israel) was dissolved in normal saline.

3. Results

3.1 Proarrhythmic effects of amiodarone in the presence of ATX-II in female rabbit isolated hearts

Amiodarone alone (0.01–10 μM) did not cause EVBs, EAD, or VT (Figures 1 and 3, Table 1). At a concentration of 30 nM, amiodarone caused small and significant ($P < 0.05$) increases in BVR, $T_{peak} - T_{end}$, and the index of $T_{peak} - T_{end}/QT$ interval, but did not significantly prolong either epicardial or endocardial MAPD$_{90}$, or transmural dispersion of MAPD$_{90}$ ($n = 6–9$, $P > 0.05$, Figure 3, Table 1). At a concentration of 10 μM, amiodarone caused a small and significant ($P < 0.05$) shortening of epicardial and endocardial MAPD$_{90}$ and a reduction of dispersion of MAPD$_{90}$ (Figure 3). Amiodarone (10 μM) prolonged the QT (Figure 3) and QRS intervals but did not change the JT interval and QT dispersion (Table 1).

ATX-II (3 nM) alone caused infrequent EVBs (Figure 2B) and short episodes of TdP in two of 17 (12%) hearts (Figure 1) and significantly prolonged the epicardial and endocardial MAPD$_{90}$ ($n = 16$, $P < 0.001$, Figure 3, Table 1), transmural dispersion (endo-epi) of MAPD$_{90}$, BVR, $T_{peak} - T_{end}$, QT interval and QT dispersion, and JT interval, as well as the index of $T_{peak} - T_{end}/QT$ interval (Figure 3, Table 1). ATX-II (3 nM) caused no change in the QRS interval ($P > 0.05$; Table 1). ATX-II was subsequently used to sensitize the rabbit heart to amiodarone, in an attempt to unmask the proarrhythmic potential of the drug.16

In the presence of 3 nM ATX-II, a stepwise increase in the concentration of amiodarone was associated with a biphasic response, initially inducing arrhythmic activity and then suppressing it (Figures 1–3). Episodes of spontaneous TdP were observed in 16 of 17 (94%) hearts exposed to amiodarone at concentrations of 30–300 nM (Figures 1 and 2C), but not observed in any of these same hearts when the concentration of amiodarone was increased to 10 μM (Figures 1 and 2D). EVBs and VTs triggered by 3- or 5-s pauses were seen in six out of eight (75%) hearts when the concentration of amiodarone was increased from 1 to 30–60 nM (Figure 2G). Neither spontaneous nor pause-triggered TdP was observed when the amiodarone concentration was 3–10 μM (Figures 1 and 2D and H). The maximum number of EVBs per minute was significantly increased by 30 nM amiodarone in the presence of 3 nM ATX-II from 3 ± 2 to 13 ± 3 bpm ($n = 8$, $P < 0.001$), but decreased to 4 ± 1 bpm when the concentration of amiodarone was further increased to 10 μM (Table 1).

In the continuous presence of 3 nM ATX-II, amiodarone at a concentration of 30 nM caused significant ($n = 6–16$,
Table 1

<table>
<thead>
<tr>
<th>ATX-II (3 nM) alone</th>
<th>ATX-II (3 nM) + amiodarone</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 nM</td>
<td></td>
<td></td>
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<tr>
<td>QT interval</td>
<td>176 ± 1.7 (n = 6)</td>
<td>169 ± 1.8 (n = 6)</td>
</tr>
<tr>
<td>JT interval</td>
<td>174 ± 1.7 (n = 6)</td>
<td>168 ± 1.8 (n = 6)</td>
</tr>
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<td>Peak MAPD 90</td>
<td>285 ± 6.1 (n = 6)</td>
<td>279 ± 6.2 (n = 6)</td>
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<td>End/QT interval</td>
<td>0.13 ± 0.01 (n = 6)</td>
<td>0.13 ± 0.01 (n = 6)</td>
</tr>
<tr>
<td>BVR</td>
<td>0.24 ± 0.04 (n = 6)</td>
<td>0.24 ± 0.04 (n = 6)</td>
</tr>
<tr>
<td>TDR</td>
<td>51 ± 2.2 (n = 6)</td>
<td>51 ± 2.3 (n = 6)</td>
</tr>
<tr>
<td>VAT</td>
<td>68 ± 2.5 (n = 6)</td>
<td>68 ± 2.6 (n = 6)</td>
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<tr>
<td>AMAPD 90</td>
<td>59 ± 2.3 (n = 6)</td>
<td>59 ± 2.4 (n = 6)</td>
</tr>
<tr>
<td>EVBs</td>
<td>0.07 ± 0.00 (n = 6)</td>
<td>0.07 ± 0.00 (n = 6)</td>
</tr>
</tbody>
</table>

3 nM ATX-II and 3 nM ATX-II + 10 nM amiodarone, respectively. BVR, beat-to-beat variability of MAPD90; EVB, ectopic ventricular beat; TDR, transmural dispersion (endocardial–epicardial) of MAPD90; VAT, ventricular effective refractory period.

ATX-II: Angiotensin II; BVR: beat-to-beat variability of MAPD90; EVB: ectopic ventricular beat; TDR: transmural dispersion (endocardial–epicardial) of MAPD90; VAT: ventricular effective refractory period.
of $T_{\text{peak}} - T_{\text{end}}/\text{QT interval}$, QT dispersion, and JT intervals (Table 1). However, at concentrations of 10 μM, amiodarone shortened epicardial MAPD$\text{90}$ ($n = 6$, Figure 3A, Table 1, $P < 0.01$), and decreased transmural MAPD$\text{90}$ dispersion (Table 1), QT interval prolongation (Figure 3B, Table 1), BVR (Figure 3C, Table 1), $T_{\text{peak}} - T_{\text{end}}$ (Figure 3D, Table 1), index of $T_{\text{peak}} - T_{\text{end}}/\text{QT interval}$, and JT intervals, ($n = 5–16$, $P < 0.05–0.001$, Table 1). Polymorphic VTs (TdP) occurred at the peak of the concentration-response relationship for amiodarone in the presence of 3 nM ATX-II (i.e. at 10–300 nM amiodarone; Figures 1–3).

3.2 Reproducibility and reversibility of ventricular arrhythmias in the presence of ATX-II

The proarrhythmic effect of amiodarone in the presence of ATX-II was reversible and reproducible. As shown in Fig. 2J, in a group of six hearts, 3 nM ATX-II caused occasional EVBs but no VT. In the presence of 3 nM ATX-II, amiodarone (60 nM) caused frequent EVBs (18 ± 4 bpm, $n = 6$), EADs, and VTs in all six hearts (Figure 2K). Following washout of amiodarone (in the continued presence of ATX-II), there was a decrease in the number of EVBs 3 ± 2 bpm ($n = 6$, $P < 0.01$) and no VT was observed (Figure 2L, Table 1). In the continued presence of 3 nM ATX-II, reintroduction of amiodarone again led to an increase of EVBs to 28 ± 6 bpm and polymorphic VT in all six hearts tested (Figure 2M, Table 1).

3.3 Effects of amiodarone on peak and late $I_{\text{Na}}$, and $I_{\text{HERG}}$ in HEK 293 cells

Amiodarone inhibited both late $I_{\text{Na}}$ that was induced by ATX-II and peak $I_{\text{Na}}$ (peak $I_{\text{Na}}$ was recorded in the absence of ATX-II) (Figure 4A and B). A representative record of the effect of amiodarone to reduce late $I_{\text{Na}}$ in the presence of 3 nM ATX-II is shown in Figure 4A. The IC$50$ and $n_H$ values for inhibition of late $I_{\text{Na}}$ by amiodarone were $3.0 \pm 0.9$ and $0.6 \pm 0.2$ μM, respectively (Figure 4B). The IC$50$ and $n_H$ values for tonic block of peak $I_{\text{Na}}$ by amiodarone were $178.1 \pm 17.2$ and $1.5 \pm 0.2$ μM, respectively. The magnitude of peak tail $I_{\text{HERG}}$ was also reduced by amiodarone (Figure 4C and D). The IC$50$ and $n_H$ values for reduction of peak tail $I_{\text{HERG}}$ by amiodarone were $0.8 \pm 0.1$ and $1.3 \pm 0.2$ μM, respectively.

3.4 Correlation of $I_{\text{HERG}}$ inhibition and proarrhythmic risk in the presence of ATX-II

In HEK293 cells, 0.1 μM amiodarone inhibited $I_{\text{HERG}}$ by 13 ± 4% (Figure 4D, inset). In the presence of 3 nM ATX-II, 0.1 μM amiodarone caused TdP in rabbit isolated hearts (Figures 1–3). To confirm that a small (~13%) inhibition of $I_{\text{HERG}}$ by amiodarone in the presence of 3 nM ATX-II may be sufficient to cause TdP, the effect of a low concentration of E-4031, a pure $I_{\text{Kr}}$ blocking agent, on rabbit isolated hearts in the absence and presence of 3 nM ATX-II was determined. E-4031 at a concentration of 1 nM caused a 10% inhibition of $I_{\text{HERG}}$ similar to 0.1 μM amiodarone (Figure 4D, inset). In female rabbit isolated heart, E-4031 (1 nM) alone caused neither MAPD prolongation ($n = 9$, $P > 0.05$) nor TdP. However, in presence of 3 nM ATX-II, E-4031 (1 nM) caused a significant increase in MAPD$\text{90}$ from 300 ± 18 to 361 ± 10 ms ($n = 8$, $P < 0.01$) and TdP in five of eight hearts (not shown).
Figure 4  Inhibition of peak and late $I_{Na}$, and peak tail $I_{HERG}$ by amiodarone. (A) The voltage clamp protocol (top) and a representative recordings of late $I_{Na}$ from a single cell in the absence of drug (control, a), during superfusion with 3 nM ATX-II (b), and during superfusion with 0.3 (c), and 3 μM (d) amiodarone in the continued presence of 3 nM ATX-II. Inset shows representative recordings of peak $I_{Na}$ from a single cell in the absence (control), and in the presence of increasing concentrations of amiodarone. Scale bars represent 1 ms and 1 nA, respectively. (B) Concentration–response relations for inhibition of peak and late $I_{Na}$ by amiodarone. (C) $I_{HERG}$ traces from a single cell exposed to 0 (control), 0.3, 1, and 3 μM amiodarone. (D) Concentration–response relation for inhibition of peak tail $I_{HERG}$ by amiodarone. Inset shows $I_{HERG}$ inhibitions by 100 nM amiodarone and 1 nM E-4031. Number of determinations is indicated in parentheses.

4. Discussion

Amiodarone is known to have both anti- and pro-arrhythmic effects in patients and its use is associated with a low incidence of TdP. It has been difficult to study these effects because they are not easily mimicked in animal preparations. The results of this study indicate that acute pro-arrhythmic activities of amiodarone can be reliably unmasked when late $I_{Na}$ is increased by ATX-II. Low concentrations of amiodarone (e.g. 30 nM) that alone caused no significant APD prolongation or TdP did cause significant APD prolongation and TdP when administered in combination with 3 nM ATX-II. Furthermore, although 30 nM amiodarone alone did not cause significant prolongation of APD, it did significantly increase BVR, $T_{peak}-T_{end}$, and the index of $T_{peak}-T_{end}/QT$ interval, suggesting that these three parameters are more sensitive than QT interval and AP duration to detect the pro-arrhythmic potential of amiodarone. The results are consistent with the recent report of amiodarone-induced TdP in patients with the SCN5A polymorphism S1102Y. An increase of late $I_{Na}$ is associated with a wide variety of pathophysiological conditions. The risk of ventricular arrhythmic activity in patients with these conditions or with gain-of-function SCN5A polymorphisms or mutations may be expected to increase during administration of low concentrations of amiodarone (this study) and other $I_{HERG}$ blocking agents.

The occurrence of TdP in rabbit hearts exposed to amiodarone in the presence of 3 nM ATX-II can be attributed to amiodarone because: (i) TdP induced by a low concentration of amiodarone could be suppressed by increasing the concentration of amiodarone in the presence of a fixed concentration of ATX-II and (ii) the incidence of TdP in the presence of 3 nM ATX-II alone was much lower (two of 17 hearts) than in the presence of both ATX-II and amiodarone (16 of 17 hearts). However, the risk factors for TdP are multiple. The observation that the combination of low concentrations of ATX-II and amiodarone yielded a high incidence of TdP in rabbit heart is consistent with the clinical observation that TdP occurs when multiple risk factors (congenital and acquired) are present.

Reported acute effects of amiodarone on APD in single cell preparations from different tissues and animal species vary. In the female rabbit isolated heart, amiodarone alone induced only small changes in electrophysiological parameters (Table 1) and did not cause TdP. However, in the presence of ATX-II, which increases late $I_{Na}$ and thereby reduces repolarization reserve, both anti- and pro-arrhythmic, concentration-dependent effects of amiodarone were observed. The pro-arrhythmic effect of amiodarone occurred at lower concentrations (30–300 nM) than the anti-arrhythmic effect, and at concentrations lower than the therapeutic range of 0.5–7.8 μM. Amiodarone (30 nM) in the presence of ATX-II not only caused frequent EIBs, EADs, and polymorphic VTs, but also increased the transmural dispersion in MAPD90 (endocardial MAPD90–epicardial MAPD90), BVR of MAPD90, $T_{peak}-T_{end}$, and the index of $T_{peak}-T_{end}/QT$ interval. These electrophysiological changes correlated with the occurrence of ventricular arrhythmias, which is consistent with the knowledge that BVR, transmural dispersion of ventricular repolarization, and the index of $T_{peak}-T_{end}/QT$ interval are important determinants or markers of the pro-arrhythmic effects of QT-prolonging drugs. When the concentration of amiodarone was increased to 1–10 μM in the presence of ATX-II, the ventricular
arrhythmias, and increases in MAPD, transmural MAP dispersion, QT interval (JT interval), T_{peak}−T_{end}, index of T_{peak}−T_{end}/QT interval, and BVR were reduced.

The biphasic (pro- and anti-arrhythmic) concentration-dependent effects of amiodarone are best explained by inhibition of a different combination of ion channels at low vs. high concentrations of the drug. At a low concentration (~0.1 μM), amiodarone is a relatively pure I_{Kr} blocking agent. The synergistic effects of selective I_{Kr} inhibition at these low concentrations of amiodarone (or E-4031) and the ATX-induced increase in late I_{Na} would be expected to reduce repolarization reserve, resulting in a proarrhythmic effect. In fact, as shown here, in the presence of 3 nM ATX-II relatively small reductions of I_{Kr} by amiodarone and E-4031 (13 and 10%, respectively), were sufficient enough to cause TdP. Thus, patients with congenital (e.g. LQT3) or acquired pathological conditions (e.g. structural heart disease) associated with an increase in late I_{Na} may be at increased risk of proarrhythmia when I_{Kr} is inhibited by as little as 10%. Furthermore, amiodarone has been shown to preferentially bind to the inactivated state of the cardiac sodium channel. The inhibition by amiodarone of late I_{Na} serves to counterbalance the effect of inhibition of I_{Kr} thus reducing the drug-induced decrease in net repolarizing current (repolarization reserve). The IC_{50} values for amiodarone inhibition of I_{HERG} and late I_{Na} in HEK 293 cells expressing either HERG or SCN5A were 0.8 ± 0.1 and 3.0 ± 0.9 μM, respectively. IC_{50} values for amiodarone-induced inhibition of I_{Kr} and late I_{Na} in rabbit and human hearts were reported to be 2.8 and 6.7 μM, respectively. The IC_{50} values reported in our study have to be interpreted with caution as the Hill coefficient fit was forced to zero. Nevertheless, at therapeutic concentrations (1–10 μM), amiodarone inhibits both I_{Kr} and late I_{Na}, and this may be responsible, at least in part, for the antiarrhythmic effects and the low risk of long-QT-related arrhythmias attending common use of the drug. High concentrations of amiodarone also inhibit peak I_{Na} in a use-dependent manner, and this may explain amiodarone's effect to increase the QRS interval in the female rabbit heart (Table 1). Similarly, cinapride was also shown to have the biphasic concentration–response relationship to induce long-QT syndrome and TdP.

Our findings support reports that an abnormal increase of late I_{Na} due either to heritable SCN5A mutations, structural heart disease (e.g. heart failure), or exposure to reactive oxygen species may diminish the repolarization reserve of the myocardium and lead to an increased susceptibility to drug-induced TdP. For example, amiodarone- and sotalol-induced repeated episodes of TdP were reported in patients with KCNQ1 and KCNH2 mutations, and amiodarone-induced TdP appears to be more common in subjects with inherited mutations or structural heart diseases, including congestive heart failure and dilated cardiomyopathy.

5. Study limitations

(i) This study was concerned with the acute effects of amiodarone and these are likely to differ from those seen during chronic therapy with the drug. (ii) The calcium channel blocking effects of amiodarone may contribute in part to the shortening of MAPD at high concentrations (4–10 μM) but were not investigated; (iii) the pacing rate of 1 Hz, although chosen to increase the sensitivity of the rabbit heart to the proarhythmic effect of amiodarone (i.e. bradyarrhythmia is a risk factor for TdP), is a slow rate and the proarrhythmic effects of amiodarone at normal or higher pacing rates are expected to be less than at 1 Hz.

6. Conclusion

A proarrhythmic effect of amiodarone was observed at low concentrations (30–300 nM) of the drug at which the APD was prolonged in the presence but not in the absence of ATX-II. BVR, T_{peak}−T_{end}, and the index of T_{peak}−T_{end}/QT interval were better predictors of the proarrhythmic potential of amiodarone than was the magnitude of APD prolongation. An antiarrhythmic effect of amiodarone was observed in the presence of ATX-II during administration of higher concentrations (1–10 μM) of the drug. The biphasic pro- and anti-arrhythmic effects of amiodarone appear to reflect the action of the drug to inhibit I_{Kr} at lower concentrations than it inhibits late I_{Na}. A possible implication of our finding is that a drug that causes minimal (e.g. ≤ 10 ms) prolongation of QTc interval in an otherwise normal heart may be proarrhythmic in hearts with acquired or congenital reductions in repolarization reserve. Consequently, the absence of a drug action to prolong the QTc interval in a heart with normal repolarization reserve is not a reliable predictor of drug safety.

Conflict of interest: C.A. received research support from and is a consultant to CV Therapeutics, Inc., L.W, S.R, J.C.S, H.L and L.B are employees of CV Therapeutics, Inc., J.R. has no conflict of interest to declare.

Funding

This study was supported and conducted at CV Therapeutics, Inc.

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