Effects of amiodarone on wave front dynamics during ventricular fibrillation in isolated swine right ventricle

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INTRANOVUS AMIODARONE is a commonly used antiarrhythmic agent in the treatment of life-threatening ventricular tachyarrhythmia (13). However, few studies have examined the mechanisms by which amiodarone is effective against ventricular fibrillation (VF). We (27) previously proposed that transition from ventricular tachycardia (VT) to VF is a transition to spatiotemporal chaos, with similarities to the quasi-periodic route to chaos seen in fluid turbulence. In this scenario, chaos results from the interaction of multiple causally independent oscillatory motions. Computer simulations and animal experiments suggest that the destabilizing oscillatory motions during spiral-wave reentry arise from restitution properties of action potential duration (APD). Modifying APD restitution characteristics can prevent spiral-wave breakup in simulated cardiac tissue, suggesting that drugs with similar effects in real cardiac tissue may have antifibrillatory efficacy (the restitution hypothesis). Intravenous amiodarone is effective in treating patients with life-threatening ventricular arrhythmias and is now included in the new American Heart Association guidelines for advanced cardiopulmonary life support (7). The purpose of this study was to investigate the mechanisms underlying antifibrillatory effects of amiodarone and to determine whether flattening of APD restitution may be involved in its antifibrillatory actions.

METHODS

The research protocol was approved by the institutional animal care and use committee and followed the guidelines of the American Heart Association. The details of the isolated right ventricle (RV) preparation have been reported elsewhere (9). Briefly, six farm pigs (25–32 kg) were anesthetized and the hearts were removed. The RV was placed in tissue bath for electrical defibrillation. Two bipolar electrodes were attached to the epicardial surface: one for continuous recording and the other for pacing. Two Endotak defibrillation electrodes (Guidant) were placed on two opposing sides of the tissue bath for electrical defibrillation. Optical mapping system. We stained four of six RVs and optically mapped the patterns of epicardial activation. The optical mapping system used in the present study was similar to the one described previously (15). Fluorescence from...
RV epicardium was elicited by a solid state, frequency doubled laser (Verdi, Coherent) at a wavelength of 532 nm. Laser light was delivered to the RV with the use of multiple 1-mm optical fibers (model SP-SF-960, FIS). The RVs were stained for 20 min with 4-[2(di-2-butylamino)-6-naphthyl]vinylpyridinium (di-4-ANEPPS; Molecular Probes) 10 μmol/l in the perfusate. The emitting fluorescence was imaged with a 12-bit digital charge-coupled device camera (model CA-D1-0128T, Dalsa) through a 600-nm long-pass glass filter (model R60, Nikon) and a 25-mm/f0.85 video lens (model CF25L, Fujinon). Video images at 128 × 128 pixels were acquired over 30 × 30 mm² at 2.3 ms/frame and were transferred to a personal computer with a frame grabber (Imaging Technology). An excitation-contraction uncoupler was not used in the current study. We recorded 2.3 s of data during each acquisition.

A moving median filter was applied to the optical signal, after which the signals were normalized so that the range of the maximum signal amplitude was the same for each pixel. The signals of each pixel were then spatially averaged. Each pixel was then assigned a shade of gray between white (fully depolarized) and black (fully repolarized). The computer first finds every adjacent pair of pixels in the frame that cross the average value of the data. If the intensity of the data on which the line coincides is increasing, that edge is identified as the wave front and colored red. Otherwise, if it is decreasing, the edge is identified as the wave back and colored green. A point where the red line meets the green line is a wave break (14, 16, 24).

Transmembrane potential recordings and the APD restitution curves. Transmembrane potentials (TMPs) were recorded from an epicardial site using a standard glass microelectrode (9) or pure iridium metal microelectrode (18). For APD measurements, a custom-written program selected as time of activation (phase 0) if the voltage change over time (dV/dt) at that time was greater than both of its temporal neighbors and that the dV/dt was ≥5 V/s. The program then looked forward in time to determine AP peak (voltage greater than both neighbors) and looked backward in time to determine baseline (voltage less than both neighbors). The voltage difference between the peak and the baseline was the AP amplitude. The program then looked forward in time from the AP peak until the voltage dropped by a value equal to 90% of the AP amplitude. That time is the time of 90% repolarization and the temporal difference between phase 0 and 90% repolarization is the APD₉₀. The diastolic interval (DI) was defined as the difference between 90% repolarization and the onset of the next activation. Cycle length (CL) was defined by the temporal difference between consecutive activations. Manual editing was then performed to eliminate noise.

Fig. 1. Transmembrane potentials (TMPs) at baseline (A), 10 min (B), and 20 min (C) after amiodarone infusion. D: example of 90% action potential duration (APD₉₀) and difference between 90% repolarization and onset of next activation [diastolic interval (DI)] determination (from area marked by dashed lines in A). Note that the cycle length (CL) and APD increased progressively with amiodarone infusion, evolving to a periodic activation resembling ventricular tachycardia (VT).
Table 1. Effects of amiodarone

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>10 min</th>
<th>20 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacing at 400 ms CL (dV/dt)\text{max}, V/s</td>
<td>40.6 ± 4.9</td>
<td>NA</td>
<td>27.4 ± 2.6*</td>
</tr>
<tr>
<td>APD\text{90}, ms</td>
<td>194 ± 25</td>
<td>NA</td>
<td>205 ± 14*</td>
</tr>
<tr>
<td>Effective refractory period, ms</td>
<td>205 ± 45</td>
<td>NA</td>
<td>238 ± 25*</td>
</tr>
<tr>
<td>Dynamic Pacing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Maximum APD\text{90} restitution curve slope by dynamic pacing</td>
<td>2.16 ± 0.44</td>
<td>1.23 ± 0.02</td>
<td>1.20 ± 0.14*</td>
</tr>
<tr>
<td>DI at maximum APD\text{90} restitution curve, ms</td>
<td>22.0 ± 2.6</td>
<td>30.5 ± 13.4</td>
<td>34.0 ± 9.8</td>
</tr>
<tr>
<td>VF</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CL, ms</td>
<td>83.3 ± 17.8</td>
<td>101.3 ± 17.3</td>
<td>118.4 ± 25.8*</td>
</tr>
<tr>
<td>APD\text{90}, ms</td>
<td>71.1 ± 14.7</td>
<td>77.6 ± 14.6</td>
<td>89.9 ± 19.0*</td>
</tr>
<tr>
<td>DI, ms</td>
<td>12.2 ± 9.0</td>
<td>23.7 ± 12.7</td>
<td>28.6 ± 17.0*</td>
</tr>
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<td>Wavelet density, N/cm²</td>
<td>0.65 ± 0.08</td>
<td>0.47 ± 0.05*</td>
<td>0.41 ± 0.10*</td>
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<td>Spontaneous wavebreaks, N/s</td>
<td>35.0 ± 3.4</td>
<td>20.9 ± 2.7*</td>
<td>15.0 ± 2.2*</td>
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<tr>
<td>Reentrant wavefront CL, ms</td>
<td>78.2 ± 19.0</td>
<td>96.0 ± 16.4</td>
<td>114.4 ± 15.5*</td>
</tr>
<tr>
<td>Core size, mm²</td>
<td>0.9 ± 0.3</td>
<td>2.5 ± 1.0</td>
<td>4.1 ± 3.8*</td>
</tr>
<tr>
<td>Maximum APD\text{90} restitution slope during VF</td>
<td>5.24 ± 2.47</td>
<td>3.70 ± 4.40</td>
<td>1.69 ± 1.73*</td>
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<tr>
<td>DI at maximum APD\text{90} restitution curve during VF, ms</td>
<td>0.46 ± 0.5</td>
<td>0.8 ± 1.1</td>
<td>0.8 ± 0.3</td>
</tr>
</tbody>
</table>

Values are means ± SD. CL, cycle length; NA, not available; (dV/dt)\text{max}, maximum derivative of voltage in relation to time; APD\text{90}, 90% action potential duration; DI, diastolic interval; VF, ventricular fibrillation. *P < 0.05 vs. baseline.

VF up to 1 h after the beginning of washout. In no RV was the VF inducible.

Amiodarone infusion progressively increased CL, reduced the density of wavelets, and the incidence of spontaneous wave breaks (Table 1). Single-cell TMP recordings showed that amiodarone resulted in a reduction of the low amplitude and fast activations in VF, leading to the transition to VT or to a slower CL VF (Fig. 1). We identified 11, 4, and 3 reentrant wavefronts in VF episodes shown in Fig. 1, A–C. There was a progressive increase of the CL of reentrant wavefront after amiodarone infusion (Table 1).

Video images revealed the effects of amiodarone on wave dynamics during VF. At baseline, VF was characterized by the presence of multiple irregular wavefronts and spontaneous wave breaks (Fig. 2, top). These gave rise to the irregular TMP recordings (Fig. 1A). Figure 2, bottom, illustrates typical activation patterns during amiodarone infusion. A single wavefront propagated from the bottom right to the top left corner of Fig. 2. The wavefront propagates repeatedly without breaking, leading in this example to complete elimination of spontaneous wave breaks in the mapped region and a decrease in the number of wavelets. These
changes also gave rise to the periodic activity in the TMP recordings (Fig. 1C).

Reentrant wave fronts were occasionally seen during VF at baseline (Fig. 3, left). The white arrows indicate counterclockwise reentrant excitation and the tip of the wave front propagates around the central core with a period of 69 ms. The trajectory encircles an area of 0.7 mm². During amiodarone infusion, reentrant wave fronts were also observed. Figure 3, right, shows a reentrant wave front with a period of 131 ms. A major difference between the reentry circuit at baseline compared with that during amiodarone infusion was the size of the central core around which the wave front rotated (6.8 mm²). Amiodarone infusion significantly increased the central core area and increased the CL of the reentrant wave fronts (Table 1).

**Effects of amiodarone on APD restitution.** Figure 4A shows action potential recordings at baseline (left) and during amiodarone infusion (Fig. 4A, right). During dynamic pacing, the pacing intervals were fixed for eight beats (S₁), followed by an abrupt shortening of pacing interval. The first beat of the shortened interval is equivalent to a premature stimulus (S₂). This figure shows the AP induced by the last two S₁ and the S₂. The shortest S₁/S₂ achieved at baseline was 160/150 ms, with a corresponding S₂ APD of 113 ms. During amiodarone infusion, the shortest S₁/S₂ increased to 200/190 ms, resulting in an S₂ APD of 148 ms. Figure 4B shows an example of dynamic APD restitution curve. Amiodarone increased the APD at all diastolic intervals. Amiodarone significantly reduced the maximum slope of APD₉₀ restitution curve. It also appeared to have increased the shortest DI achieved during dynamic pacing. However, the latter increase was not statistically significant (Table 1). Figure 5 shows examples of APD restitution curves during VF at baseline and during amiodarone infusion while RV was still fibrillating. Amiodarone flattened the slope of APD₉₀ restitution curve, particularly at short DIs. Table 1 shows the effects of amiodarone infusion in all RVs studied. The DIs associated with the maximum slope of APD₉₀ restitution curve at baseline and during amiodarone infusion were <10 ms (Table 1).

We also analyzed APD restitution curve by including the negative DI in the graph. However, the APs with negative DIs were <1% of the total number of APs analyzed during baseline VF. Adding these negative DIs did not change the restitution curve. For VF after amiodarone infusion, there were fewer (Fig. 1B) or no negative DIs recorded.

**DISCUSSION**

In this study we demonstrated that amiodarone infusion reduced the slope of the APD restitution curve, enlarged the core of reentrant wave front and suppressed spontaneous wave breaks in VF. These changes were associated with a decreased number of
wavelets, the termination of VF, or the transition from VF to VT.

**Mechanism of antiarrhythmic drug action.** An explanation for the antifibrillatory action of amiodarone is its β-blocking effects (8). Because the RVs were isolated from the rest of the body, they were not influenced by the systemic sympathetic activity. However, local sympathetic nerve terminals might still be active during VF. It is therefore possible that some of the antifibrillatory effects of amiodarone in swine RV were due to β-blocking effects.

A second possible mechanism relates to effects of amiodarone on the CL of the reentrant wave fronts. Recently, Samie et al. (21) proposed that the size and the dynamics of the core of the reentrant wave front, in addition to the effective refractory period, are important determinants of VF. In support of that hypothesis, the authors demonstrated that verapamil increased the size of the core and converted VF to VT in Langendorff-perfused rabbit heart. In the present study, we demonstrate that amiodarone increased the size of the core and reduced the wave front number and spontaneous wave breaks. Therefore, our results are also consistent with the hypothesis proposed by Samie et al. (21).

A third possible mechanism relates to the wavelength hypothesis of cardiac fibrillation (19). Wavelength is a product of refractory period and conduction velocity. Drugs that prolong wavelength are antifibrillatory, whereas drugs that shorten wavelength may be proarrhythmic. Amiodarone and other type III antiarrhythmic agents, such as d-sotalol, block the potassium channels (11, 26) and prolong the APD and the refractory period (28). However, amiodarone also blocks the sodium channel (3, 22) and decreases the conduction velocity. A decreased conduction velocity might result in a longer reentrant CL, which could independently lengthen the APD. Furthermore, a uniform reduction of conduction velocity could result in reduced conduction velocity dispersion, a factor that may be associated with improved defibrillation efficacy (23). However, because we mapped only the surface of a three-dimensional RV, we cannot accurately determine the conduction velocity during VF. It cannot be determined in this study whether or not amiodarone alters the wavelength.

Fig. 3. Reentrant wave front during baseline VF (left) and during amiodarone infusion (right). A single rotation of the reentrant wave front is displayed at baseline. White arrows indicate counterclockwise reentrant excitation and the wave break point propagates around the central core area. Data are from the same preparation showing one reentrant wave front rotated in a clockwise direction during amiodarone infusion. Note that a major difference between the reentry circuit at baseline compared with that during amiodarone infusion was the central core area around which the front rotated. Amiodarone infusion increased the core area from 0.7 to 6.8 mm².
A fourth possible explanation is the effect of amiodarone on APD restitution. The restitution hypothesis posits that the APD restitution is a major factor underlying wave break in VF (1, 4, 17, 27). Drugs that flatten the APD restitution curve have antifibrillary effects (5, 20).

Fig. 4. A: APD recordings at baseline and during amiodarone infusion. In each panel, the last 2 paced action potentials and a premature stimulus (S1 and S2, respectively), applied at progressively shorter coupling intervals, are shown. B: APD restitution curves at baseline and during amiodarone infusion. Note that amiodarone increased the APD at all DIs. A dashed line with a slope of 1 is included for comparison.

A major finding of this study is that amiodarone results in the flattening of the APD restitution slope. This effect could explain the reduced incidence of wave breaks during amiodarone administration. Therefore, our findings are also compatible with the restitution hypothesis.

Fig. 5. Examples of APD restitution curve during one episode of VF at baseline (A) and one episode 10 min after (B) the commencement of amiodarone infusion. Note that amiodarone reduced the slope of the APD restitution curve, particularly at short DIs.
Comparing amiodarone with bretylium and verapamil. Bretylium and verapamil are also effective in flattening the restitution curve (5, 20) but are less useful than amiodarone in treating or preventing clinical VF in human patients. Bretylium (10) results in norepinephrine release during initial administration. It also results in significant orthostatic hypotension and is therefore poorly tolerated. For verapamil to flatten the restitution curve, a concentration of 1,000–3,000 ng/ml is needed (2, 20). This concentration is at least twice as high as what can be achieved with a maximum oral dose of verapamil (120 mg every 6 h) (25). These data indicate that a very high (or toxic) dose of verapamil is needed to reach a serum concentration sufficient to flatten the restitution curve. In comparison, we showed in this study that amiodarone 2.5 μg/ml may flatten restitution curve and exerts significant effects on the patterns of activation in VF. This serum concentration can be easily achieved with 5 mg/kg intravenous amiodarone (6). Therefore, amiodarone is clinically more useful than verapamil or bretylium in treating patients with VT and VF.

Limitation of the study. The first limitation is that acute effects of amiodarone cannot be reversed. Therefore, we were not able to test whether or not the effects of amiodarone are reversible on washout. A second limitation is that we used isolated normal RV in the study. It is unclear whether or not the results are applicable to diseased human hearts. A third limitation is that calcium channel blockers (20) and bretylium (5) are also known to flatten APD restitution. However, these drugs are not as effective as amiodarone in treating human VF. Therefore, flattening of APD restitution may only partially explain the antiarrhythmic effects of amiodarone.

In conclusion, amiodarone infusion reduced spontaneous wave breaks and the density of VF wavelets. It might terminate VF or convert VF to VT. These effects were associated with the flattening of APD restitution slope and increased the core size of reentrant wave fronts.

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